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Alice Issanchou

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**Gestion de la variation de la qualité
des sols par les agriculteurs :
enjeux pour la rentabilité et la
durabilité des exploitations
agricoles françaises**

Alain CARPENTIER

Directeur de recherche, UMR SMART LERECO / *président*

Florence JACQUET

Directrice de recherche, UMR MOISA Montpellier /
rapporteuse

Marc BAUDRY

Professeur, Université Paris Ouest Nanterre / *rapporteur*

Sylvain PELLERIN

Directeur de recherche, UMR ISPA, Bordeaux / *examinateur*

Pierre DUPRAZ

Directeur de recherche, UMR SMART LERECO /
co-directeur de thèse

Karine DANIEL

Directrice de recherche, LARESS ESA Angers /
co-directrice de thèse

.....
Alain MONTEBAULT

Directeur R&D, Coopérative Terrena / *membre invité*

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Résumé Substantiel en Français

Gestion de la qualité des sols par les agriculteurs : enjeux pour la rentabilité et la durabilité des exploitations agricoles françaises

0.1 Introduction

Avec une population mondiale qui devrait atteindre les 9 milliards d'individus d'ici le milieu de ce siècle, l'agriculture fait face à des prévisions d'augmentation de la demande alimentaire. A l'échelle de la France, cela représente des enjeux de compétitivité et de croissance économique. Afin de répondre à cette augmentation de la demande agricole en matière de production, deux solutions sont possibles : augmenter la proportion des terres agricoles au détriment des écosystèmes naturels et augmenter la productivité des terres agricoles.

C'est cette dernière solution que promeut l'Agriculture Ecologiquement Intensive (AEI). L'AEI est un concept de "double révolution verte" dont Michel Griffon a développé une définition vers 1998 (Musson et Rousselière, 2016). L'AEI est née de la remise en question d'une agriculture intensive (au sens économique du terme) en produits chimiques, au profit d'une agriculture intensive en écologie. L'AEI propose une agriculture qui soit productive, rentable et durable, basée sur l'usage des fonctions écosystémiques, parmi lesquelles celles liées au sol et à la qualité du sol. L'agriculteur joue un rôle central dans la mise en place du système de réflexion AEI sur son exploitation. Depuis les années 2013/2014, le concept de l'AEI a été accolé à celui d'agro-écologie. Les techniques associées

à l'AEI et à l'agro-écologie sont les mêmes, et appliquées à la ressource naturelle qu'est le sol, ces techniques correspondent à celles de l'agriculture de conservation. Cependant c'est le terme d'agro-écologie qui a été utilisé dans la Loi d'avenir agricole présentée en 2014 (Musson et Rousselière, 2016). Ainsi, bien que nous axions notre propos sur le concept de l'AEI et les pratiques qui y sont liées, nos raisonnements et les résultats obtenus et discutés dans nos travaux ont une portée plus générale, et s'appliquent à l'agro-écologie telle que définie à l'échelle de la France et de l'Union Européenne.

Les enjeux de la préservation de la qualité physique, chimique et biologique des sols relèvent également de l'intérêt public, en raison de l'existence d'externalités, des propriétés de bien commun de cette ressource, ainsi que de son rôle dans l'atténuation du changement climatique (c.f. l'Initiative 4/1000¹). En effet, environ 20% des gaz à effet de serre (GES) sont d'origine agricole. A ce sujet, Pellerin et al (2013) ont identifié 10 actions pour réduire les émissions de GES dans le secteur agricole, décomposées en 26 sous-actions. Une des catégories d'actions consiste à stocker le carbone dans le sol et la biomasse, notamment en développant les techniques culturales de non-labour, et en introduisant des cultures intermédiaires. De plus, la ressource sol peut être considérée comme un bien commun de subsistance (Bollier, 2014) dans la mesure où le sol peut être considéré comme une ressource collective (indépendamment du régime de propriété observé) dont la gestion impacte la collectivité.

Pour autant, la terre est principalement la propriété d'agents privés. Ainsi, les initiatives publiques telles que l'initiative 4/1000 se doivent d'être décentralisées au niveau de ces agents. Pour que de telles initiatives publiques soient suivies, elles doivent prendre en compte la perception du sol qu'ont ces agents privés, la manière dont ils gèrent leurs sols, et l'intérêt privé qu'ils auraient à stocker le carbone dans leurs sols, pourtant le sujet de l'"initiative 4/1000".

Ainsi, notre travail se concentre sur les agriculteurs, dont les pratiques agricoles et la gestion de leurs sols impactent la collectivité. Plus particulièrement, nous nous attachons à déterminer si les concepts de l'AEI et de l'agro-écologie appliqués à la ressource représentent une stratégie optimale pour les agriculteurs, et plus généralement quelles sont les pratiques à mettre en place par l'agriculteur quand celui-ci maximise son revenu

1. "L'Initiative 4/1000 : les sols pour la sécurité alimentaire et le climat" est un plan d'action volontaire, international et multi-partenaires, présenté à la 21ème session de la Conférence des Parties à la Convention des Nations Unies sur le changement climatique (COP 21) à Paris le 1er décembre 2015. L'idée de l'initiative 4/1000 consiste à augmenter annuellement le stock de carbone des sols de 4g pour 1000 g de carbone dans les premiers 40 cm de la partie superficielle du sol. Théoriquement, cela permettrait de stopper l'augmentation de la concentration de CO₂ dans l'atmosphère, si toutefois dans le même temps la déforestation était stoppée.

à long terme, tout en tenant compte de la dynamique de la qualité de ses sols, dans un contexte économique tendu, et quels sont les déterminants de ces choix.

Notre recherche se positionne au niveau microéconomique. Puisque nous traitons de la gestion par les agriculteurs de la ressource naturelle qu'est le sol, nous utilisons les outils de l'économie des ressources naturelles et de l'environnement, tout en essayant d'y intégrer le mieux possible les aspects biologiques et agronomiques propres aux enjeux de la gestion de la qualité des sols étudiée ici.

Le manuscrit est organisé comme suit.

Dans le premier chapitre, nous exposons le contexte général de la recherche ainsi que la problématique traitée de manière plus détaillée. A partir d'une revue de la littérature agronomique et économique, nous expliquons et justifions l'intérêt pour l'agriculture de considérer les interactions entre les pratiques agricoles et la qualité du sol. En effet, les agriculteurs font face à des enjeux de compétitivité, de productivité et de durabilité, auxquels l'AEI se propose d'être une solution, en réconciliant productivité et préservation de l'environnement. La qualité du sol joue un rôle important dans ces enjeux, d'une part en tant que paramètre important de la productivité et de la durabilité des exploitations agricoles, et d'autre part en ce qu'elle est affectée positivement et négativement par les pratiques agricoles. Ce rôle de la qualité des sols peut être modélisé en utilisant des outils économiques et écologiques.

Dans le second chapitre, nous présentons le cadre théorique de notre modèle bioéconomique, établi à partir de notre revue de littérature. En premier lieu, nous proposons une revue plus détaillée de modèles bioéconomiques de qualité du sol à l'échelle de l'exploitation. Ces modèles sont utilisés dans l'étude de la dégradation des sols et des mesures de conservation, où le sol et la qualité des sols sont considérés comme des facteurs de production et des variables endogènes dans les modèles d'optimisation. Ensuite, le cadre théorique de notre modèle est présenté, de même que l'objectif de notre modèle bioéconomique ainsi que les éléments à considérer lors de la construction du modèle. Nous proposons ensuite notre modèle dynamique théorique détaillé. Dans ce modèle, nous considérons un agent-agriculteur rationnel avec information parfaite, qui a pour objectif de maximiser son profit au cours du temps. Il n'y a pas de défaillances de marché dans notre modèle. A partir de ce modèle théorique, il apparaît que la relation entre la dynamique de la qualité du sol et les intrants productifs est d'une importance cruciale dans l'équilibre étudié. Toutefois, le modèle théorique détaillé présenté dans ce chapitre, bien que permettant une discussion approfondie des hypothèses du modèle, basées sur

la littérature agronomique, est trop complexe pour être résolu analytiquement. Afin de pouvoir résoudre le problème d'optimisation présenté dans ce modèle, nous devons en simplifier la structure et les hypothèses. En particulier, nous considérons la possibilité de simplifier l'hypothèse relative à la coopération entre les intrants productifs (intrants chimiques notamment) et la qualité du sol.

A cet effet, dans le troisième chapitre, nous étudions statistiquement les relations entre la dynamique de la qualité des sols, les rendements de cultures et les intrants productifs (engrais minéraux) dans le Grand Ouest de la France², qui est un important bassin de production agricole. Il s'agit ici de confronter les résultats de notre revue de littérature avec nos résultats statistiques, afin de déterminer au mieux les simplifications à apporter à notre modèle théorique. Tout d'abord, nous présentons les caractéristiques géographiques, pédologiques et économiques de la zone étudiée. Ensuite, nous examinons la dynamique des paramètres de la qualité du sol (ici, carbone organique du sol, pH du sol, et azote totale du sol) dans le Grand Ouest afin de tester statistiquement l'existence de corrélations entre les changements de pratiques agricoles et l'évolution des paramètres de la qualité du sol dans la zone étudiée. Nous testons également les relations entre les paramètres de la qualité du sol et les pratiques agricoles dans la production agricole, en considérant leurs corrélations avec les rendements de cultures observés pour les principales cultures présentes dans cette zone (blé tendre et maïs grain).

Dans le quatrième chapitre, nous proposons un modèle théorique simplifié d'investissement dans la qualité du sol. Nous présentons tout d'abord l'objectif et l'intérêt d'utiliser ce type de modèle dans un cadre dynamique. Les outils analytiques utilisés sont décrits. Le modèle d'investissement dans la qualité du sol est décliné en plusieurs cas : quand les pratiques agricoles n'impactent que positivement les variations de qualité du sol, et quand les pratiques agricoles impactent positivement et négativement ces variations de qualité. Dans chaque cas, nous étudions deux relations possibles entre les intrants productifs et la qualité du sol en termes de production : le cas où les intrants productifs et la qualité du sol sont coopérants, et le cas où ils ne le sont pas. En effet, l'un des résultats de notre chapitre statistique est que, selon l'intrant productif considéré, par exemple les engrais azotés ou les engrais phosphatés, certains seront coopérants avec la qualité du sol, et d'autres non. Il nous semblait donc important de considérer ces deux cas. Nous déterminons l'existence d'un équilibre optimal et des trajectoires y menant pour chacun des cas mentionnés. Nous considérons également les impacts d'une variation des para-

2. Ici, le Grand Ouest de la France représente une zone géographique composée de quatre régions administratives françaises : la Bretagne, la Normandie, les Pays de la Loire et le Poitou-Charentes (ancienne région, faisant maintenant partie de la région Grande Aquitaine).

mètres économiques (tels que le prix des cultures ou le prix des intrants) sur l'équilibre du système lorsqu'il existe. Cela permet de simuler les impacts d'évolution des prix ou d'introduction de taxes sur les niveaux optimaux de qualité du sol, d'investissements dans le sol ou d'utilisation des intrants productifs vers lesquels tendrait l'agriculteur lorsqu'il optimise son profit.

Ce modèle théorique simplifié sert de base à l'application de notre modèle de contrôle optimal présenté dans le chapitre 5. Les dynamiques des indicateurs de la qualité du sol, tels que la matière organique des sols, sont très dépendants des contextes pédologiques et climatiques dans lesquelles elles sont étudiées. Cela rend difficile voire inapproprié le transfert de résultats d'une zone géographique à une autre lorsqu'elles sont trop différentes, comme par exemple le transfert des résultats d'une étude menée au Canada à un contexte français, et ce, même lorsque les modèles bioéconomiques utilisés sont semblables. C'est pourquoi notre modèle empirique est basé sur un cas d'étude portant sur une exploitation céréalière du Grand Ouest de la France, située dans le département de la Vienne. Au début de ce cinquième chapitre, nous présentons ce cas d'étude. Ensuite, nous décrivons le modèle empirique bioéconomique de contrôle optimal utilisé, en présentant les variables, paramètres et contraintes du modèle. Nous présentons plus en détails la méthodologie utilisée pour que notre modèle soit le plus réaliste possible : les données que nous avons utilisées, la manière dont ces données ont été obtenues, et surtout notre démarche pour estimer et paramétrer les fonctions de dynamique de la qualité du sol, et les différentes fonctions de production. De par les limites du logiciel utilisé et des données disponibles, la qualité du sol est approchée dans ce modèle par la quantité de matière organique du sol (MO). C'est un indicateur fiable de la qualité du sol et de ses variations (Lal, 2015). Lorsque nous avons validé les fonctions de production des différentes cultures et les fonctions de la dynamique de la matière organique des sols, nous présentons les différents scénarios économiques testés ainsi que les horizons de planification sur lesquels les scénarios sont simulés de manière inter-temporelle. Le logiciel et le solveur utilisés pour nos simulations, GAMS/MINOS, sont ensuite décrits et nous proposons une discussion des principales limites de notre modèle empirique avant de présenter et de discuter les résultats de nos simulations.

Dans le chapitre 6, nous proposons une discussion générale de la thèse. Nous rappelons tout d'abord les résultats théoriques, statistiques et empiriques de la thèse, et nous montrons comment ils éclairent notre question de recherche. Toutefois nous devons garder à l'esprit les limites de nos modèles théoriques et empiriques : bien qu'ils nous permettent de clarifier les principaux enjeux de notre problématique, de nombreuses approfondissements et pistes restent à poursuivre. Certains de ces aspects sont discutés

dans ce chapitre, tels que l'intérêt de considérer les nombreux aspects de la qualité des sols et une plus grande variété de pratiques agricoles, ce qui n'est pas possible présentement. L'importance de considérer le risque et l'incertitude dans les processus de prise de décision de l'agriculteur est aussi discutée, ainsi que la possibilité de considérer le changement technique. Une piste intéressante de recherche pourrait traiter des interactions entre agents. Enfin, nous ouvrons la discussion sur les enseignements qui peuvent être tirés de nos résultats en matière d'actions ou d'incitations à développer dans un cadre public ou privé, dans la mesure où les intérêts publics et privés dans la gestion de la ressource sol peuvent converger.

0.2 L'AEI : Réconcilier productivité et préservation environnementale

L'objectif de notre revue de littérature est d'expliquer et de justifier l'intérêt pour les agriculteurs de prendre en compte les interactions entre les pratiques agricoles et la qualité des sols dans un contexte agricole global tendu ; d'autant plus que la France a mis plus de temps que d'autres pays à considérer et adopter des pratiques agricoles qui préservent la qualité des sols (Lahmar, 2010).

Dans cette revue de littérature, nous exposons tout d'abord les enjeux de compétitivité, productivité et durabilité auxquels fait face le secteur agricole français, afin d'explicitier l'intérêt qu'ont les agriculteurs d'augmenter leur productivité de manière durable afin d'être compétitifs. Nous démontrons aussi que l'importance donnée par l'AEI et l'agroécologie aux sols est justifiée, en utilisant des définitions de ce que sont la terre, le sol, la qualité du sol, et en fournissant des éléments empiriques sur les liens existant entre la qualité des sols, la productivité des sols et les pratiques agricoles. Nous présentons également de quelle manière les enjeux de gestion du sol peuvent être considérés comme des problèmes économiques, et comment cela est traité via les outils d'analyse et de modélisation économiques.

L'augmentation de la population mondiale devrait entraîner une hausse notable de la production alimentaire. D'un point de vue mondial, cela représente des enjeux de stabilité politique et sociale et d'équité (Tilman et al, 2002), mais à l'échelle d'un pays, cela peut représenter des enjeux de compétitivité et de croissance économique. Afin d'être compétitive, l'agriculture française se doit d'être productive et durable, ce en quoi la qualité du sol joue un rôle important, à la fois comme un levier de productivité et de durabilité. En effet, la diminution de la qualité des sols induite par certaines pratiques agricoles peut être irréversible si un seuil critique est atteint, ce qui pourrait avoir des

conséquences durables pour l'agriculture et la production alimentaire, avec une baisse à terme des rendements de cultures agricoles. Ainsi, la problématique d'une agriculture durable et productive est profondément liée à celles de la qualité et de la dégradation des sols (Lal, 2015).

C'est dans ce contexte que les concepts tels que l'AEI paraissent prometteurs : ils proposent de parvenir à une agriculture à la fois hautement productive et durable, basée sur l'utilisation des fonctions écosystémiques ; parmi lesquelles celles fournies par le sol et la qualité du sol ont un rôle primordial. Un autre aspect intéressant de l'AEI est la place importante donnée à l'agriculteur, qui est placé au centre de l'approche. Toutefois le concept de l'AEI n'est pas encore largement adopté, et pour remédier à cela, une bonne compréhension des points de vue et contraintes des différentes parties prenantes serait nécessaire (Bonny, 2011). C'est ainsi que nous axons notre propos sur les mesures de préservation ou d'amélioration de la qualité des sols par l'agriculteur ainsi que sur les contraintes affectant l'adoption de telles mesures.

La qualité des sols est mentionnée dans des études économiques portant sur de nombreux thèmes : choix d'occupation des sols (Chomitz et Fray, 1996 ; Brown et al, 2012 ; Verburg et al, 2006), durabilité des agrosystèmes (Belcher, Boehm et Fulton, 2004), ou déterminants de la productivité des exploitations agricoles (Bhalla et Roy, 1988 ; Schreinemachers, 2006). Il y a deux raisons principales à l'étude économique de la variation de la qualité des sols en agriculture : (1) la compréhension des motifs des agriculteurs pour investir ou non dans les pratiques de conservation (Saliba 1985 ; Barbier, 1998 ; Foudi, 2012) puisqu'il peut y avoir un arbitrage à faire entre les objectifs de rentabilité et de durabilité (Barbier, 1990 ; Quang, Schreinemachers et Berger, 2010) ; (2) l'analyse des différences entre les taux optimaux de dégradation des sols privés et sociaux (McConnell, 1983 ; Hediger, 2003), qui peuvent entraîner des divergences entre ce qui est souhaitable du point de vue privé de l'agriculteur et d'un point de vue sociétal.

D'après la littérature étudiée, il apparaît que l'adoption des mesures de conservation du sol dépend de l'impact de la qualité du sol ou du potentiel de productivité du sol sur le prix de revente de l'exploitation, des coûts encourus par l'adoption de telles mesures en comparaison des bénéfices obtenus en termes de productivité, et de la possibilité de substitution entre la fertilité du sol et les intrants conventionnels. Le problème est que les agriculteurs peuvent ne pas avoir un taux de dégradation de leur sol optimal à cause d'un manque d'informations, d'imperfections de marchés, ou bien de distorsions politiques. Or, nous avons vu que les effets de la dégradation des sols pouvaient ne pas être immédiatement décelés lorsque l'on utilise parallèlement des engrais par exemple,

alors qu'à partir d'un certain stade, le sol sera dégradé irréversiblement. Par ailleurs, les études empiriques portant sur la conservation ou la dégradation des sols sont souvent limitées par un accès difficile aux données, tant en quantité qu'en qualité (Barbier, 1998). De plus, dans les modèles économiques étudiés, la qualité du sol est souvent réduite à la profondeur de sol, et la dégradation du sol au phénomène d'érosion du sol (McConnell, 1983 ; Barbier, 1990 ; Hediger, 2003). Toutefois, les modèles intégrés permettent de modéliser plus finement et de manière plus pertinente la qualité du sol et les interactions entre qualité du sol, productivité des cultures et pratiques agricoles.

Ainsi, il y a un réel enjeu économique à la dégradation des sols qui doit être étudié. Bien qu'il y ait un intérêt établi dans la littérature au maintien de la qualité des sols afin d'assurer une production agricole durable, cela requiert des coûts d'investissement à court terme, qui associés aux marchés fonciers imparfaits, aux substituts de court terme de la fertilité des sols et aux conséquences inattendues de politiques agricoles, peuvent décourager les agriculteurs à investir dans la qualité de leurs sols. Tout ceci peut mener à des taux de dégradation des sols non-optimaux. Cela peut avoir des effets négatifs sur la productivité, la rentabilité et la durabilité des exploitations agricoles. L'AEI propose de réconcilier les objectifs de long terme de durabilité, et les objectifs de court terme de rentabilité, via la réappropriation par les agriculteurs de l'optimisation des fonctions écosystémiques, qui passent pour beaucoup par les sols. De plus, les relations entre la qualité des sols et la production agricole ont été abondamment étudiées et établies tant dans la littérature agronomique qu'économique, ce qui rend l'approche AEI ou agro-écologique pertinente.

Pour ce faire, nous attachons ici à déterminer si considérer la qualité du sol comme un facteur de production endogène peut favoriser le développement de l'AEI et de l'agro-écologie en France, et favoriser la rentabilité et la durabilité des exploitations. Il est ainsi nécessaire d'établir la manière dont les interactions entre qualité du sol, productivité du sol et rentabilité des exploitations peuvent être modélisées afin de mieux les comprendre. Ensuite, l'objectif est de déterminer si, dans un contexte et un ensemble de contraintes donnés, les pratiques agricoles visant à maintenir ou à augmenter la qualité des sols peuvent assurer la productivité et la durabilité de l'exploitation. En pratique, un tel modèle pourrait permettre de déterminer un taux optimal de dégradation du sol pour une exploitation donnée, et pourrait être utilisé comme un outil de décision. Toutefois, cela nécessiterait de prendre en compte des aspects qui ne sont pas spécifiquement étudiés ici, tels que la manière dont les agricultures perçoivent leur sols et leur qualité, et quelles sont les variables qui sont vraiment considérées par les agriculteurs quand ils décident ou non d'investir dans la conservation de leurs sols.

Afin de répondre à notre problématique, nous utilisons un modèle dynamique de contrôle optimal au niveau de l'exploitation. Comme ce type de modèle détermine les niveaux optimaux des variables de décision à travers le temps, cela devrait nous permettre d'estimer si les pratiques de conservations, telles que proposées par l'AEI, sont en effet optimales pour la rentabilité et la durabilité des exploitations. Il est à noter que nous considérons ici les décisions de l'agriculteur sans tenir compte des externalités de la variation de la qualité de ses sols.

Le chapitre suivant présente le cadre théorique de notre étude.

0.3 Modélisation bioéconomique : cadre théorique

Afin de construire notre cadre théorique, nous avons plus particulièrement étudié la littérature économique traitant de la gestion des sols au niveau de l'exploitation agricole. Dans ces modèles, la qualité du sol est considérée comme un facteur de production endogène, et la plupart des approches sont dynamiques (McConnell, 1983 ; Saliba 1985 ; Smith et al, 2000 ; Hediger, 2003 ; Yirga et Hassan, 2010). En effet, la dynamique des sols est soumise à de lents processus et elle est le fruit de changements cumulés. Ainsi, pour bien la prendre en compte, l'approche dynamique est la plus appropriée, bien qu'une approche statique puisse permettre de donner un premier diagnostic des enjeux rencontrés dans une situation donnée. De plus, intégrer un élément récursif au sein du modèle économique permet de considérer les propriétés de résilience des sols. Ici, nous considérons comme ayant un aspect récursif les modèles où, au minimum, la qualité du sol à un instant donné dépend de la qualité du sol à la période précédente.

Nous utilisons ici l'approche du contrôle optimal. En effet, les modèles de contrôle optimal permettent une étude dynamique de notre problème et l'intégration d'éléments récursifs. De plus, ces modèles permettent de traiter les enjeux de la gestion optimale des ressources (Zilberman, 1982 ; Nakhumwa, 2004 ; Lobo Pereira et al, 2013) tout en considérant les arbitrages entre la dégradation des services naturels du sol par les pratiques agricoles et la conservation du sol par les pratiques adaptées (Foudi, 2012). Ainsi, les modèles de contrôle optimal permettent de formaliser les processus de long terme que nous étudions.

Le cadre théorique proposé ici est basé sur les éléments qui sont ressortis de notre revue de littérature de sorte à être adaptés au mieux à l'objectif de notre modèle. Cet objectif est de déterminer si les pratiques agricoles associées à l'AEI relatives au maintien ou à l'amélioration de la qualité du sol sont pertinentes et optimales pour parvenir à une

agriculture rentable, productive et durable au niveau de l'exploitation.

C'est ainsi que nous proposons un modèle mécaniste normatif, construit à partir de notre revue de littérature économique et agronomique. C'est un modèle dynamique avec une composante réursive, qui contient les relations fonctionnelles existant entre les pratiques agricoles (intrants chimiques, intensité de la rotation culturale, usage des résidus de culture, intensité de labour), les caractéristiques de la qualité des sols et les fonctions de rendements des cultures. Dans ce modèle, la qualité du sol est considérée comme un facteur de production endogène dans le processus de prise de décision de l'agriculteur, et la qualité du sol n'est pas réduite à la profondeur du sol, ni la dégradation des sols à l'érosion de ceux-ci. Ainsi, nous considérons les attributs endogènes et exogènes de la qualité du sol. Les conséquences liées à la qualité du sol en termes de productivité du sol sont capturées à travers la relation entre les attributs du sol et les rendements de cultures. En effet, la qualité des sols et l'intensité d'utilisation d'intrants, tels que les intrants chimiques, sont les deux facteurs de production directs considérés ici. Nous prenons également en compte les arbitrages et interdépendances entre les pratiques de conservation et celles dites conventionnelles.

Dans ce modèle, l'agriculteur maximise son profit sous contrainte de la dynamique de la qualité de son sol, dans une situation où le signe de la coopération entre la qualité du sol et les intrants chimiques (ou productifs) en termes de production est indéterminé. Sont considérés comme des facteurs de production coopérants, des facteurs qui travaillent en équipe (Alchian et Demsetz, 1972). Dans certains cas, l'usage d'intrants chimiques et la qualité du sols sont coopérants, lorsque la qualité du sol est faible, ou dans une situation de transition entre les pratiques conventionnelles et de conservation (Smith et al, 2000 ; Mekuria et Waddington, 2002). La qualité du sol et les intrants chimiques peuvent également être non-coopérants et la qualité du sol peut être un substitut des intrants chimiques lorsque la qualité du sol est suffisamment élevée pour que la productivité marginale des intrants chimiques soit décroissante.

De même, les hypothèses émises quant aux dynamiques de la qualité du sol sont discutées, dans la mesure où une même pratique peut avoir des effets contradictoires sur un même aspect de la qualité du sol, selon la manière dont elle est effectuée, le contexte climatique, ou la qualité initiale du sol. Par exemple, le labour est considéré comme pouvant avoir des impacts à la fois positifs et négatifs sur la qualité du sol : selon les conditions climatiques, la saison et la structure initiale du sol, le labour peut être recommandé (Heddadj et al, 2005) et certains systèmes requièrent un certain niveau de labour pour fonctionner (Verhulst et al, 2010), alors qu'un haut niveau de matière

organique des sols est favorisé par un non-labour ou un labour superficiel (Barthès et al, 1998).

Ainsi, les principaux éléments à considérer dans une version empirique de ce modèle sont présents, et la discussion que nous proposons de nos hypothèses relatives aux impacts des pratiques agricoles sur la qualité du sol montre combien ces relations sont complexes, même simplifiées.

Toutefois, pour simplifié qu'il soit, notre modèle reflète fidèlement les relations de substitution et de complémentarité entre les différentes variables, et en particulier la relation de coopération entre la qualité du sol et les intrants chimiques. De plus, notre modèle permet une discussion intéressante des conditions nécessaires pour atteindre l'équilibre, et des conditions dans lesquelles surviennent les solutions en coin. Cependant, une analyse théorique plus approfondie de l'équilibre stationnaire et de ses dynamiques requiert une simplification du modèle, dans lequel les variables de décisions en termes de pratiques sont groupées selon leur impact, positif ou négatif, sur la qualité du sol. Avec de tels modèles simplifiés, les prix et les effets d'instruments politiques peuvent être plus facilement appréhendés, notamment à travers l'analyse qualitative de la situation d'équilibre. Cette simplification pourrait nécessiter entre autres une simplification de nos hypothèses sur la relation de coopération entre les facteurs de production.

0.4 Relations empiriques entre qualité du sol, rendements et pratiques agricoles : étude statistique dans le Grand Ouest de la France

L'objectif de notre étude statistique est d'établir la relation de coopération entre la qualité du sol et les intrants productifs dans le cas des fonctions de production des grandes cultures dans le Grand Ouest de la France. Il s'agit également ici de confronter à des données empiriques les hypothèses de notre cadre théorique quant aux impacts des pratiques culturales sur la dynamique de la qualité des sols.

Pour ce faire, nous avons utilisé différentes bases de données publiques contenant des informations sur la qualité des sols, les pratiques agricoles et les rendements des cultures (respectivement, la BDAT, Base de Données d'Analyse de la Terre, les Enquêtes Pratiques Agricoles menées par l'Agreste pour les années 2001, 2006 et 2011, les recensements agricoles et les statistiques agricoles annuelles). Par manque de données, nous avons dû réduire le nombre de pratiques agricoles considérées aux engrais minéraux azotés et phosphatés et aux pratiques de labour. La dynamique de la qualité des sols est capturée à travers les changements observés en termes de pH du sol, azote total du sol et carbone

organique du sol (CO). Pour les régressions des fonctions de production, nous considérons les deux principales cultures présentes dans le Grand Ouest : le blé tendre et le maïs grain.

Ici, l'intrant productif considéré lors des régressions sur les variations de CO est l'usage d'engrais azotés. Les résultats de nos régressions montrent qu'une augmentation de l'usage des engrais azotés a un impact statistiquement significatif et négatif sur les variations du CO du sol. De plus, il semble qu'au niveau cantonal, l'augmentation de la proportion de surfaces labourées est positivement et significativement corrélée à une augmentation du niveau médian cantonal de CO dans les sols.

Les résultats de nos régressions concernant la dynamique du pH du sol sont moins significatifs, puisque les pratiques agricoles susceptibles d'avoir le plus d'impact sur le pH du sol, telles que le chaulage, n'ont pu être considérées, faute de données. De même, les régressions effectuées sur les variations d'azote total du sol ne montrent pas de corrélation statistiquement significatives entre les pratiques considérées et les changements en azote total.

Quant aux régressions effectuées sur les rendements de culture au niveau régional, leurs résultats au sujet de la relation de coopération entre les facteurs de production considérés sont intéressants. Ainsi, pour le blé tendre, le CO du sol et les engrais azotés ont chacun un impact positif et significatif sur les rendements. Toutefois, l'effet combiné du CO du sol et des engrais azotés est significativement négatif : les engrais azotés et le CO ne sont pas coopérants. Quant au maïs grain, l'impact du CO sur les rendements n'est pas significatif, cependant les engrais azotés ont un impact significativement positif sur les rendements. Dans ce cas également, le CO et les engrais azotés ne sont pas coopérants en termes de production. Toutefois, dans le cas du maïs grain, le CO et les engrais phosphatés sont coopérants en termes de production. Il semble donc que selon l'intrant productif considéré (ici engrais azotés ou phosphatés), la coopération en termes de production avec un paramètre de la qualité du sol (ici CO) peut être effective ou non.

Les résultats de nos régressions nous servent par la suite de base pour construire les hypothèses simplifiées de nos modèles théoriques d'investissement dans la qualité du sol.

0.5 La ressource sol, la rentabilité et la durabilité des exploitations : modèles d'investissement dans la qualité du sol

Dans nos modèles simplifiés d'investissement dans la qualité du sol, nous considérons deux facteurs de production : un intrant productif et la qualité du sol. Les mesures

de conservation du sol sont comprises au sein d'une unique variable qui représente un investissement dans la qualité du sol. Nous considérons deux cas : l'un où l'intrant productif n'impacte pas la dynamique de la qualité du sol ; et l'autre où l'intrant productif impacte négativement cette dynamique. Sur la base de nos résultats statistiques, nous ne simplifions pas l'hypothèse sur la relation de coopération entre l'intrant productif et la qualité du sol, et nous considérons les deux cas (coopérants ou non).

Ces modèles d'investissement sont des modèles de contrôle optimal dynamique, qui nous permettent de discuter les stratégies optimales permettant d'atteindre un équilibre stable. Nous utilisons également les différents outils analytiques, tels que le diagramme de phase, les statiques comparatives et les dynamiques comparatives pour illustrer et discuter la position du point d'équilibre, et comment celui-ci évolue lorsque les conditions économiques exogènes (coûts des intrants, prix des cultures...) varient.

Nous montrons que lorsque les intrants productifs n'impactent pas la qualité du sol, il existe toujours un équilibre optimal. Selon la qualité initiale du sol, l'agriculteur peut être amené à augmenter ou diminuer la qualité de son sol afin de la maintenir au niveau optimal et de n'être ni en sur-investissement ni en sous-investissement dans la qualité de son sol. Ainsi, même lorsque les impacts négatifs de ses pratiques sur la qualité du sol sont ignorés, l'agriculteur a un intérêt privé à maintenir la qualité de son sol à un niveau auquel il puisse maintenir son activité de production à un niveau stable.

Dans le cas plus réaliste où l'agriculteur inclut dans son problème de maximisation l'impact négatif des intrants productifs sur la qualité du sol, la relation de coopération en termes de production entre la qualité du sol et les intrants productifs est importante dans la détermination d'un équilibre. Un équilibre est trouvé analytiquement lorsque la qualité du sol et l'intrant productif sont coopérants *et* que la productivité marginale de cette coopération en termes de production est plus importante que les dommages marginaux de l'intrant productif sur la qualité du sol. Dans ce cas, les stratégies optimales suivies par l'agriculteur sont les mêmes que dans le cas simple où l'agriculteur ne prend pas en compte les impacts négatifs de ses pratiques sur son sol. Dans les autres cas, si les facteurs de production sont coopérants mais que la productivité marginale de cette coopération est inférieure aux dommages marginaux causés au sol, ou bien si les facteurs de production ne sont pas coopérants, nous ne pouvons pas conclure sur l'existence d'un équilibre. Un équilibre stable peut être atteint, mais il est également possible que les stratégies optimales de l'agriculteur partent d'un nœud instable, ou du centre d'une spirale instable en termes de représentation graphique, de telle sorte que le système ne converge pas vers l'état stationnaire. Néanmoins, l'équilibre instable peut également être considéré comme

un cas limite entre des trajectoires qui, elles, convergent vers un état stationnaire.

Si la relation de coopération entre l'intrant productif et la qualité du sol a un impact sur l'existence d'un équilibre, elle en a également un sur la manière dont l'équilibre varie avec un changement de l'un des paramètres exogènes du modèle, tels que le prix des cultures, les coûts des facteurs de production, ou le prix de l'investissement dans la qualité du sol.

Lorsqu'il y a un équilibre stationnaire, il est possible d'utiliser les statiques comparatives pour étudier comment cet équilibre va varier lorsque l'un de ses paramètres change. D'après nos statiques comparatives, plusieurs instruments peuvent être utilisés pour augmenter le niveau optimal de qualité du sol, comme par exemple la subvention (c'est-à-dire la diminution) du prix des investissements dans la qualité du sol. Cependant, dans le cas où les facteurs de production sont coopérants, à mesure que la qualité du sol augmente, l'utilisation de l'intrant productif augmente également. Cela peut être non désirable, notamment si l'on prend l'exemple d'intrants productifs tels que les engrais azotés ou les pesticides, qui peuvent entraîner des externalités négatives, telles que la pollution diffuse. En revanche, dans le cas où les facteurs de production sont non-coopérants, pour une même subvention aux investissements dans la qualité du sol, l'augmentation de la qualité du sol qui en résulte entraîne une diminution de l'usage de l'intrant productif, ayant ainsi un effet multiplicateur positif.

Les différents modèles théoriques proposés ici introduisent la modélisation empirique proposée dans le chapitre suivant.

0.6 Application du modèle de contrôle optimal : un cas d'étude

Le modèle empirique que nous proposons est basé sur notre cadre théorique, conforté par nos résultats statistiques, et contient les principaux éléments à prendre en compte lors de l'étude des arbitrages de l'agriculteur entre les objectifs de court terme de rentabilité et productivité et les objectifs de long terme de durabilité.

Nous utilisons également ici un modèle de contrôle optimal inter-temporel, sans incertitude, qui nous permet de simuler les stratégies de long terme de l'agriculteur en termes de pratiques lorsque celui-ci maximise son profit tout en prenant en compte la dynamique de la qualité de ses sols. L'objectif du modèle est de déterminer si la stratégie optimale de l'agriculteur dans ces conditions correspond aux concepts de l'AEI et de l'agro-écologie ; c'est-à-dire une stratégie où l'agriculteur fait face à la hausse des prix de

l'énergie et des engrais en investissant dans les fonctions écosystémiques de son sol, et pour ce faire dans la qualité de son sol, ici approchée par le CO du sol.

Notre modèle prend en compte l'impact des choix de gestion de l'agriculteur (quantité d'engrais azotés, intensité de labour, choix de rotation culturale et résidus de culture) sur la qualité du sol (CO) et inclut des fonctions de production qui comprennent des attributs et déterminants du sol (le CO du sol de manière explicite, et les caractéristiques climatiques moyennes de manière implicite), les possibilité de substitution (entre engrais azotés et CO du sol) et une variable de gestion (engrais azotés).

Notre modèle empirique est calibré sur une exploitation céréalière de la Vienne. L'agriculteur s'est engagé dans les pratiques de conservation depuis les années 1990. Nous avons utilisé ses registres de fertilisation, ses déclarations informelles ainsi que celles de son conseiller agricole afin de reproduire au mieux ses pratiques dans le logiciel de simulation biophysique CropSyst. Nous avons également eu accès aux analyses de sol de trois parcelles représentatives des principaux types de sol sur l'exploitation, à deux dates différentes pour chacune des parcelles (à 5, 6 et 7 ans d'écart). Nous avons utilisé CropSyst afin de simuler et d'estimer les fonctions de production et les fonctions de dynamique de la matière organique (MO) spécifiques à chaque type de sol et aux principales cultures présentes sur l'exploitation. Les paramètres de CropSyst sont calibrés en utilisant les données réelles de l'agriculteur. Les fonctions obtenues à partir des régressions des simulations faites avec CropSyst ont été validées en comparant les résultats simulés et observés.

Nous simulons quatre scénarios : (1) un scénario de base où les prix et les coûts sont constants tout au long de l'horizon de planification ; (2) un scénario de coûts dynamiques, où les prix des engrais azotés et du fuel augmentent annuellement de respectivement 1.5 % et 2 % ; (3) un scénario de coûts dynamiques où en plus de l'augmentation annuelle des prix des engrais azotés et du fuel, une prime bonus/malus liée au carbone des sols est introduite dès la première période, bonus/malus qui est indexé sur la variation de MO entre deux périodes, avec augmentation annuelle de la prime carbone ; (4) un scénario de coûts dynamiques avec les mêmes composantes que le troisième scénario, auquel nous avons ajouté une prime à la luzerne doublée. Ces scénarios sont simulés dans différentes situations (long terme (30 ans), court terme (5 ans), avec des taux d'intérêt de 1 et 5 %, des rotations longues ou courtes (choix entre 7 cultures, ou rotations blé-colza)).

Pour résoudre notre problème de maximisation, nous utilisons le logiciel GAMS (General Algebraic Modeling System) et le solver MINOS. GAMS/MINOS permet de résoudre des problèmes où les fonctions non-linéaires sont continues.

Les principales limites de notre modèle sont les suivantes. Tout d'abord, ce modèle a été calibré sur une exploitation particulière, où toutes les actions mises en place pour la conservation des sols n'ont pas pu être représentées et simulées, ni dans notre modèle empirique sous GAMS, ni dans le logiciel CropSyst. Il aurait été nécessaire de calibrer et valider notre modèle sur une exploitation qui ne soit pas en agriculture de conservation, toutefois nous n'avons pas eu accès à de telles données. Il est probable que l'insensibilité de notre modèle à des scénarios économiques extrêmes soit expliquée par ces omissions en termes de pratiques. Cette piste doit être étudiée.

De plus, notre modèle ne prend pas en compte le risque et l'incertitude, ce qui rend le modèle moins réaliste, surtout lorsque l'on considère l'importance du risque et de l'incertitude tant dans les choix économiques de l'agriculteur que dans les aspects agronomiques de la conduite de l'exploitation.

Les fonctions simulées sur CropSyst présentent des similitudes avec nos résultats statistiques : la MO du sol et les engrais azotés sont des facteurs de production non-coopérants et l'intensité de labour a un impact sur la variation de MO du sol qui diffère selon les cultures et le type de sol. Ainsi, d'après nos résultats théoriques, nos scénarios de coûts dynamiques offrent des contextes favorables à une diminution des engrais azotés et à une augmentation de l'investissement dans la qualité du sol.

Conformément à nos résultats théoriques, l'augmentation annuelle des prix des engrais et de l'énergie entraîne une diminution des doses d'engrais azotés dans la stratégie de fertilisation de l'agriculteur. De plus, l'agriculteur investit dans la qualité de son sol à travers la mise en place de labour profond. Toutefois, dans chacun des scénarios, nous observons la même diminution linéaire de la concentration de MO dans les sols tout au long de l'horizon temporel, pour chaque type de sol. Cette diminution de la MO n'est pas impactée par les changements de pratiques de l'agriculteur. L'introduction de différents instruments économiques tels que la prime carbone ou la prime à la luzerne ne parvient pas à endiguer cette chute de MO dans les sols. Ainsi, ce que semblent suggérer les résultats de nos simulations, c'est qu'il est néanmoins optimal pour l'agriculteur d'investir dans la qualité de ses sols, ce qui est prôné dans l'AEI. Toutefois, dans nos simulations et compte tenu des options en termes de pratiques agricoles données à l'agriculteur, cet investissement est insuffisant pour maintenir la quantité de MO dans les sols. Bien que dans nos simulations l'agriculteur réussisse à maintenir ses revenus à niveau stable dans un horizon de 30 ans, une telle baisse continue de MO ne saurait être durable à une plus grande échelle de temps.

0.7 Discussion

Notre objectif est de déterminer si le concept de l'AEI, qui consiste à adopter une agriculture non plus basée sur les intrants chimiques, mais sur l'usage des fonctions écosystémiques dont celles du sol, est en effet une stratégie optimale pour que l'agriculteur ait une exploitation rentable, productive et durable, le tout dans un contexte de hausse des prix des engrais et de l'énergie.

Ce que montrent nos résultats théoriques, c'est que même lorsque l'agriculteur ne prend pas en compte l'impact négatif de ses pratiques sur la qualité de son sol, il a tout de même toujours intérêt à investir dans la qualité de son sol afin de la maintenir à un niveau optimal. Toutefois, il sur-estime alors le niveau de qualité de son sol, de sorte que son niveau optimal d'investissement est en réalité un sous-investissement dans la qualité de son sol. Cette évaluation erronée de l'impact négatif des pratiques sur les sols par l'agriculteur peut être corrigée par les politiques publiques appropriées, selon la relation de coopération entre les facteurs de production.

Dans notre étude statistique, nous avons vu que pour les deux cultures principales du Grand Ouest, le blé tendre et le maïs grain, les engrais azotés (intrants productifs de notre modèle théorique) et la MO des sols ne sont pas coopérants en termes de production. Ainsi, d'après nos statiques comparatives, l'augmentation prévue des prix des engrais devrait entraîner une baisse de l'usage des engrais azotés et une augmentation des investissements des agriculteurs dans la qualité de leur sol.

Une telle situation serait favorable à la lutte contre le changement climatique : en effet, deux des grands groupes d'actions proposées par Pellerin et al (2013) entraînant une diminution des émissions de GES consistent à diminuer l'usage des engrais azotés minéraux et à séquestrer le carbone dans les sols. De plus, même si les décisions privées des agriculteurs ne permettaient pas d'atteindre l'objectif socialement désirable de "l'initiative 4/1000", nous avons vu que des instruments économiques pouvaient y remédier, avec un effet multiplicateur positif lié à la relation de non-coopération entre MO du sol et engrais minéraux azotés.

Nos résultats suggèrent que les enjeux économiques auxquels font face les agriculteurs sont favorables à l'adoption des pratiques liées à l'AEI ou à l'agroécologie. En effet, substituer la qualité du sol et de la MO du sol aux engrais azotés minéraux, c'est-à-dire substituer les fonctions écosystémiques aux intrants chimiques, paraît être une opportunité pour les agriculteurs de se confronter au mieux aux augmentations des prix des

engrais et de l'énergie.

En effet, dans nos simulations, la hausse des prix des engrais et du fuel entraîne une stratégie optimale de fertilisation moins importante. De plus, l'agriculteur investit dans la qualité de ses sols à travers l'usage du labour profond qui dans notre cas a un impact positif sur la MO du sol pour les cultures les plus utilisées dans la rotation de l'agriculteur. Toutefois, ces changements de pratiques ne suffisent pas à compenser la baisse linéaire et continue de la MO. Lorsque l'on introduit des instruments économiques, tels que la prime carbone ou la prime luzerne, de même, la MO continue de chuter.

Ainsi, l'enjeu ne serait pas tant d'amener l'agriculteur à changer ses pratiques et à investir dans la qualité de ses sols, mais plutôt de l'accompagner, de sorte à ce que ses changements de pratiques soient efficaces, par exemple à travers des supports techniques ou d'apprentissage.

Bien que nos modèles théoriques et empiriques permettent d'éclairer et d'étudier le rôle des sols dans la durabilité et la rentabilité des exploitations agricoles, il y a un certain nombre de limites à nos modèles, qui pour aller plus loin dans l'analyse et les résultats devraient être traitées.

Tout d'abord, notre modèle empirique devrait intégrer un plus grand nombre de pratiques agricoles et d'indicateurs de la qualité des sols. Pour des raisons de limitations d'accès aux données et des limites propres des logiciels utilisés, tels que CropSyst, cela n'a pas pu être le cas ici. Toutefois, il serait intéressant d'utiliser au moins une autre exploitation agricole, qui ne soit pas en agriculture de conservation, et/ou avec des niveaux plus bas de MO des sols, pour calibrer et simuler nos fonctions de production et de dynamique de la MO. L'étude économique de la gestion des sols par les agriculteurs nécessiterait pour être plus complète une collaboration avec différentes disciplines : par exemple, il existe un logiciel de modélisation de la dynamique des populations de vers de terre (indicateur de qualité biologique des sols) (Pelosi et al, 2008), cependant un tel modèle est destiné à l'usage des écologues, agronomes et biologistes, et nécessite une expertise disciplinaire spécifique.

Une autre limite importante de nos modèles est de ne pas considérer le risque et l'incertitude, alors que ce sont des aspects importants à prendre en compte en agriculture (Boussard, 1987 ; Moschini et Hennessy, 2001). Il y a trois méthodes principales permettant d'inclure le risque dans les processus de décision de l'agriculteur (Boussard, 1987 ; Li, Gian et Fu, 2003 ; Zhou, 2003 ; Ziemba et Vickson, 2014) : l'utilité espérée, la moyenne-

variance, et l'approche sécuritaire. L'approche de la moyenne-variance est intéressante car elle permet de décrire explicitement l'arbitrage entre le revenu espéré et le risque. Avec cette approche, l'agent maximise son revenu espéré moins une mesure du risque qui est multipliée par un coefficient d'aversion au risque.

Il serait également intéressant de considérer les effets de groupes et leurs conséquences sur le contexte économique global. En effet, nous ne prenons pas en compte les interactions entre agents et l'impact que ces interactions ont sur l'environnement économique. Pour prendre cela en compte, on peut considérer l'utilisation d'un modèle de simulation multi-agents. Dans ces modèles, on peut utiliser une approche microéconomique tout en permettant aux agents d'interagir entre eux et au sein d'un environnement dynamique, et de changer leur comportement en fonction de celui des autres (An, 2012).

Bien que dans ce travail de thèse la gestion de la qualité du sol ait été étudiée du point de vue de l'agent privé qu'est l'agriculteur, les enjeux de la conservation des sols revêtent un intérêt public.

Le sol peut être considéré comme un bien commun, qui est principalement géré par des agents privés. Une mauvaise gestion des sols par ces agents peut mener à des externalités négatives significatives en termes de pollution notamment. C'est ainsi qu'il peut y avoir des différences entre la gestion optimale d'un sol d'un point de vue privé ou social. Cela peut justifier une intervention publique. De plus, la ressource sol a un rôle à jouer pour limiter le réchauffement climatique, dans un contexte où 20 % des émissions de GES est d'origine agricole. Cela explique l'intérêt croissant des institutions publiques envers la ressource sol, notamment avec "l'initiative 4/1000". L'AEI est un concept qui peut réconcilier une agriculture rentable et productive et la préservation de l'environnement.

Toutefois, nous avons également vu à travers nos simulations que dans certains cas, bien que l'agriculteur investisse dans la qualité de son sol, ses investissements ne sont pas suffisants pour maintenir la qualité de ses sols à un niveau stable.

Dans la réalité, l'adoption de nouvelles pratiques est liée à des aspects sociaux et anthropologiques (Jansenn et van Ittersum, 2007) ainsi qu'aux processus d'apprentissage (Anatasiadis, 2013). De plus, les croyances et les perceptions peuvent être influencées par l'apprentissage social et public (Hanna, Mullainathan et Schwartzstein, 2014). Le conseil agricole, public ou privé, a un rôle important à jouer dans l'appropriation par les agriculteurs de nouveaux concepts et technologies. Cela peut être inclus dans un contexte

plus large d'orientation politique qui combinerait instruments de politique publique et initiatives pédagogiques du conseil privé et public.

Del Corso, Nguyen et Képhaliacos (2014) ont étudié un exemple de coopération réussie avec une coopérative dans le cadre de la mise en place de Mesures Agro-Environnementales (MAE) territorialisées. Le succès de ce dispositif a notamment été rendu possible par les interactions de qualité entre la coopérative et ses adhérents, avec des conseillers agricoles qui ont su impulser une dynamique d'expérimentation, d'innovation et d'anticipation qui a rendu plus faciles les apprentissages collectifs pour aller vers des changements de pratiques durables et élargis à l'exploitation et non circonscrits aux parcelles inscrites dans le dispositif de MAE. Or l'apprentissage social et public a un impact important sur les croyances et les perceptions de l'agriculteur lorsque celui-ci fait le choix de changer ses pratiques (Hanna et al, 2014). Les coopératives agricoles sont en mesure d'organiser cet apprentissage, de manière d'autant plus aisée que les techniques qu'elles proposent sont en phase avec la conception qu'ont les agriculteurs de leur profession et avec les normes sociales qu'ils considèrent légitimes (Plumecocq, Del Corso et Képhaliacos, 2015).

Dans l'exemple de Del Corso et al (2014), la coopérative a su traduire la MAE en termes de stratégies de pratiques maîtrisées par leurs conseillers, qui en plus de leur propre expertise, ont également su mobiliser les connaissances d'autres agriculteurs. Le climat de confiance entre les conseillers et les agriculteurs a été un accélérateur du changement technique opéré (Del Corso et al, 2014).

Par ailleurs, un changement de pratiques représente un risque pour l'agriculteur. Ayant des intérêts communs avec la coopérative, ces risques ont été perçus comme partagés : ce n'est pas seulement l'agriculteur qui prend le risque de voir sa récolte et son revenu diminuer, mais aussi la coopérative qui risque une moindre collecte, ce qui réduirait ses revenus servant par ailleurs à rémunérer les conseillers agricoles. Les deux partenaires ont donc intérêt à ce que la MAE contractée soit un succès (Del Corso et al, 2014).

Ainsi, l'implantation territoriale des coopératives, le lien privilégié qu'elles entretiennent avec leurs adhérents, peuvent en faire des acteurs importants dans l'accompagnement des agriculteurs dans la transition agro-écologique, si les coopératives s'en saisissent de manière appropriée (Plumecocq et al, 2015).

0.8 Conclusion

L'objectif de ce travail de recherche était de déterminer si l'agriculteur investit dans la qualité de ses sols de sorte à ce que son activité agricole soit rentable et durable lorsqu'il considère la qualité de ses sols comme un facteur de production endogène ainsi que les impacts de ses pratiques sur la dynamique de la qualité de ses sols. Ce comportement correspond à ce qui est promu dans les concepts d'Agriculture Ecologiquement Intensive ou d'agro-écologie, où l'activité agricole ne dépend plus de l'usage intensif des intrants chimiques, mais de l'usage intensif des fonctions écosystémiques des ressources naturelles. A travers ce concept, l'AEI propose de réconcilier environnement et productivité agricole. Un tel enjeu n'est pas seulement pertinent du point de vue de l'intérêt privé de l'agriculteur dans un contexte d'augmentation du prix des engrais et de l'énergie, mais relève également de l'intérêt public. En effet, si les sols sont principalement gérés par des acteurs privés, la gestion des sols entraîne des externalités tant positives que négatives. De plus, le sol a un rôle essentiel à jouer dans la lutte contre le réchauffement climatique, notamment à travers le stockage de carbone dans les sols.

Afin de répondre à notre question de recherche, il a été nécessaire de modéliser les interactions entre la qualité du sol, la productivité du sol et la rentabilité de l'exploitation de sorte à pouvoir déterminer si, dans un contexte et un ensemble donnés de contraintes, les pratiques agricoles visant à maintenir ou à améliorer la qualité des sols peuvent assurer à la fois la rentabilité et la durabilité du système agricole, quand la qualité du sol est explicitement considérée comme un facteur de production endogène. Notre recherche se concentre sur le cas des fermes céréalières.

En utilisant des outils théoriques, statistiques et de modélisation empirique, nous montrons l'importance de considérer la relation de coopération entre la qualité du sol et les pratiques agricoles en termes de production afin de déterminer les niveaux optimaux de qualité du sol et d'investissements dans la qualité du sol. Ces relations de coopération influencent également les réactions de l'agriculteur face à une variation de prix ou de coûts.

Dans nos modèles théoriques, lorsque la qualité du sol et les intrants productifs (tels que les engrais minéraux) sont coopérants en termes de production, la mise en place d'une politique visant à diminuer l'usage des engrais, par exemple en imposant une taxe, est susceptible d'entraîner un effet de rétroaction négatif. En effet, si l'usage des engrais diminue, puisque les engrais sont coopérants avec la qualité du sol, l'agriculteur laissera la qualité de son sol se dégrader. A l'inverse, lorsque la qualité du sol et les intrants

productifs ne sont pas coopérants, un tel effet de rétroaction négatif n'est plus observé.

Or d'après nos résultats statistiques, les engrais azotés et la MO du sol ont tous deux un impact positif et statistiquement significatif sur les rendements de blé tendre et ne sont pas des facteurs de production coopérants. Ainsi, une politique favorisant de plus hauts niveaux de MO ou décourageant l'usage d'engrais azotés n'aurait pas pour conséquence des effets rétroactifs négatifs. Au contraire, on peut s'attendre à ce que de telles politiques entraînent dans chaque cas à la fois une augmentation de l'investissement de l'agriculteur dans ses sols, par exemple par l'adoption de pratiques de conservation, et une diminution de l'usage des engrais azotés minéraux.

En termes de pratiques, c'est ce que nous observons dans nos simulations. Dans notre modèle empirique, les fonctions de production sont estimées en utilisant le logiciel de simulation biologique CropSyst et elles sont calibrées en utilisant les données de notre étude de cas. Dans les fonctions de production estimées, les engrais azotés minéraux et la MO sont également non-coopérants. Dans le cas d'une augmentation progressive des prix des engrais azotés et du fuel, nous observons une diminution de l'usage des engrais azotés dans la stratégie optimale de fertilisation de l'agriculteur ainsi qu'un investissement de l'agriculteur dans ses sols via l'usage coûteux du labour profond par rapport au scénario de référence. Ce dernier résultat peut paraître contre-intuitif. Toutefois, dans les fonctions de dynamique de la MO estimées avec CropSyst, pour certaines cultures et types de sol, le labour profond peut avoir un impact positif sur la MO ; et les cultures concernées sont également celles qui sont les plus présentes dans les rotations optimales de l'agriculteur, ce qui explique l'usage qui est fait du labour profond.

Ainsi, lorsque l'agriculteur fait face à une augmentation des prix des intrants chimiques, cela fait partie de sa stratégie optimale que de diminuer son usage d'engrais azotés et d'investir dans la qualité de ses sols. Autrement dit, cela amène l'agriculteur à adopter des pratiques agroécologiques.

Néanmoins, nous observons également une diminution constante et linéaire de MO au cours du temps : l'investissement de l'agriculteur dans son sol n'est pas suffisant pour maintenir un niveau stable de MO dans les sols, et ce indépendamment des instruments politiques simulés.

Cela peut s'expliquer par la difficulté d'avoir une quantité suffisante de données de qualité qui permette de considérer les multiples aspects de la qualité des sols ainsi que la variété de choix des pratiques agricoles pouvant être mises en place par l'agriculteur.

D'autre part, nous avons calibré notre modèle sur une exploitation qui a la particularité d'optimiser la qualité de son sol. Il aurait été intéressant d'utiliser également les données d'une exploitation où l'agriculteur n'investit pas dans la qualité de ses sols. Pour aller plus loin dans notre analyse, il serait nécessaire de considérer le risque, l'incertitude ainsi que les changements de technologies dans le problème d'optimisation de l'agriculteur. Pour être plus complet, il peut être envisagé de considérer les interactions entre les agents et les impacts que cela peut avoir sur les changements de pratiques.

Néanmoins, nos modèles théoriques et empiriques éclairent la pertinence de considérer la qualité des sols dans le processus de décision de l'agriculteur et le rôle de la transition agroécologique dans un contexte économique tendu. En effet, que ce soit théoriquement ou empiriquement, l'investissement dans la qualité des sols fait partie d'une stratégie optimale de l'agriculteur lorsqu'il maximise son profit sur le long terme. Les résultats mitigés de notre modèle empirique en termes de valeurs finales de MO montrent l'importance de considérer un large panel de pratiques agricoles et celui-ci peut tout de même servir de base de discussion intéressante sur la pertinence de l'usage des instruments de politiques publiques dans les enjeux liés à la ressource sol et du rôle qu'ont à jouer les coopératives agricoles.

En effet, il y a à la fois un intérêt public et privé à la préservation de la qualité des sols et à maintenir la qualité des sols à un niveau soutenable, d'un point de vue agricole et environnemental. Néanmoins, les politiques publiques et les instruments à utiliser doivent être considérés au vu de la complexité de la chaîne de réactions à l'œuvre dans les dynamiques de la qualité des sols. Cette complexité peut être contournée, par exemple dans le cadre des Mesures Agro-Environnementales, en imposant une obligation de résultats en plus des obligations de moyens. Cela requerrait la détermination des niveaux, par exemple du ratio MO/argile, à atteindre appropriés au contexte géographique, climatique et pédologique de la parcelle et de l'exploitation concernée. Les structures de conseil, privées ou publiques, ont un rôle essentiel à jouer dans l'accompagnement des agriculteurs vers une agriculture durable et rentable.

Les coopératives notamment, à travers leurs rapports de confiance avec leurs adhérents, la technicité de leurs conseillers, leur implantation territoriale et leurs réseaux d'agriculteurs, ont un rôle à jouer dans l'appropriation par les agriculteurs de ces nouveaux concepts et technologies. Or, nous l'avons vu, l'agroécologie et l'AEI sont une réponse à l'augmentation des prix des engrais et de l'énergie. De par les intérêts que les coopératives et leurs agriculteurs partagent, il semble essentiel que les coopératives anticipent les réponses à apporter à cette hausse des prix ainsi qu'à la pression réglementaire

et environnementale et accompagnent les agriculteurs dans ces transitions.

Cela passe notamment par un apprentissage social et collectif qui peut être facilité et organisé par les coopératives. En effet, par l'animation de réseaux et la mise en contact de leurs adhérents, les coopératives auraient les moyens d'impulser une dynamique d'expérimentation, d'innovation et d'anticipation. Cela nécessiterait également de proposer une traduction des concepts de l'agroécologie et de l'AEI qui corresponde à la conception qu'ont les agriculteurs de leur profession. Tout ceci présuppose un climat de confiance entre les agriculteurs, leurs conseillers et la coopérative.

Abbreviations and Acronyms

<i>BDAT</i>	Base de Données des Analyses de la Terre	<i>km</i>	Kilometer
<i>C</i>	Carbon	<i>km²</i>	Square kilometer
<i>CGE</i>	Computable General Equilibrium	<i>L</i>	Labour
<i>CRS</i>	Constant Return to Scale	<i>OECD</i>	Organisation for Economic Cooperation and Development
<i>°C</i>	Degree Celsius	<i>LARESS</i>	Laboratory of Research in Social Science
<i>Disar</i>	Diffusion Interactive des Statistiques Agricoles de Référence	<i>m</i>	Meter
<i>DRS</i>	Decreasing Return to Scale	<i>m³</i>	Cubic meter
<i>dS/m</i>	DeciSiemens per meter	<i>mg</i>	Milligram
<i>EC</i>	Electrical Conductivity	<i>Mg/ha</i>	Megagram per hectare
<i>EIA</i>	Ecologically Intensive Agriculture	<i>mm</i>	Millimeter
<i>EPIC</i>	Erosion Productivity Impact Calculator	<i>MP</i>	Marginal Productivity
<i>€</i>	Euro	<i>N</i>	Nitrogen
<i>€/ha</i>	Euro per hectare	<i>NR</i>	Natural Resources
<i>€/kg</i>	Euro per kilogram	<i>%</i>	Percentage
<i>€/L</i>	Euro per liter	<i>P</i>	Phosphorus
<i>FAO</i>	Food and Agriculture Organization	<i>P₂O₅</i>	Phosphoric acid
<i>g</i>	Gram	<i>Π</i>	Profit
<i>g/cm³</i>	Gram per cubic centimeter	<i>PP</i>	Partial Productivity
<i>g/kg</i>	Gram per kilogram	<i>q</i>	Quintal, hundredweight
<i>IC</i>	Inorganic Carbon	<i>RICA</i>	Réseau d'Information Computable Agricole
<i>IRS</i>	Increasing Return to Scale	<i>RISE</i>	Response-Inducing Sustainability Evaluation
<i>IDEA</i>	Indicateur de Durabilité des Exploitations Agricoles	<i>RN</i>	precipitations
<i>INRA</i>	Institut National de la Recherche Agronomique	<i>SAM</i>	Sustainable Agroecosystem Model
<i>ISAP</i>	Indicator of Sustainable Agricultural Practices	<i>SOC</i>	Soil Organic Carbon
<i>K</i>	Capital	<i>SOM</i>	Soil Organic Matter
<i>kg/ha</i>	Kilogram per hectare	<i>t/ha</i>	Ton per hectare
		<i>t/ha/year</i>	Ton per hectare per year
		<i>TSPC</i>	Tropical Soil Productivity Indicator
		<i>US\$/ton</i>	US dollar per ton

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Introduction

AGRICULTURE is faced with an expected increase in food demand caused by an increase in the global population of 9 billion people by the middle of this century. On a national scale, competitiveness and economic growth issues are at stake. To ensure an increase in production, there are two solutions : extend the proportion of agricultural lands at the expense of natural ecosystems and increase agricultural productivity.

The latter is favored by Ecologically Intensive Agriculture (EIA). As both a concept and a decision-making process, EIA proposes productive and sustainable agricultural practices based on the use of ecosystem functionalities, among which soil and soil quality (physical, chemical and biological) play a primary role. EIA emerged as a concept in 1998 ; Michel Griffon developed a definition of this concept as the “double green revolution”. Since 2013/2014, it has been associated with the agro-ecology concept. EIA and agro-ecology techniques are the same ; however, the term agro-ecology was used in the French Outline Agricultural Act of January 2014 (Musson and Rousselière, 2016). Hence, although we mainly discuss the EIA concept here, our reasoning and results have a more general scope. Furthermore, applied to soil resources, EIA and agro-ecology guidelines correspond to the implementation of soil conservation practices.

Soil quality conservation issues are also of public interest with respect to externalities, the common good of soil resources, and the potential role of soil quality in climate change mitigation (c.f. the 4/1000 Initiative³), a consequence of the latter. Indeed, around 20% of greenhouse gas (GHG) emissions are of agricultural origin. Pellerin et al (2013) identified 10 actions in the agricultural sector, decomposed into 26 sub-actions, to reduce

3. The “4/1000 Initiative : Soil for Food Security and Climate”, is an international, multi-stakeholder voluntary action plan presented at the 21st Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) in Paris on December 1, 2015. The 4/1000 initiative consists in annually increasing soil carbon stocks by 4g per 1000g of soil carbon in the first 40 cm of soil. Theoretically, this would make it possible to stop the current continuous increase in CO₂ in the atmosphere, provided there is an end to deforestation.

GHG emissions. One category consists in stocking carbon in soil and biomass by developing no-tillage cultural techniques and introducing more intermediate crops, among other measures. In addition, the soil resource can be considered as a subsistence common good (Bollier, 2014) to the extent that soil can be considered a collective resource (independently of the property regime observed) whose management impacts the collective.

However, land is mainly owned by private agents. Hence, public initiatives such as the 4/1000 initiative have to be decentralized at their level. For such a public initiative to be successful, it has to take into account the soil perception of these private agents, how they manage it and why; and in the specific case of the 4/1000 initiative, would private agents sequester carbon in their soil?

Here, the focus is on farmers, who impact the collective by their farming practices and private soil management decisions. More specifically, in this work, we investigate whether EIA or agro-ecology applied to soil resources is an optimal strategy for French farmers; and more generally, we determine the optimal farming practices chosen by the farmer that maximize his profit in the long term while taking into account the dynamics of soil quality in a tense economic context; we also examine the determinants of such choices.

Hence, our research is positioned at the microeconomic level. Using natural resources economics and environmental economics techniques, we attempt to integrate as best as possible the biological and agronomic aspects of the soil quality management issues addressed here. To do so, the manuscript is organized as follows.

In the first chapter, we address the general context of the study and the problems addressed here in more detail. Based on an agronomic and economic literature review, we explain and justify the interest of French agriculture in considering the interactions between agricultural practices and soil quality. In fact, French farms face competitiveness, productivity and sustainability issues, and the purpose of EIA is to provide a solution to these problems by reconciling productivity and environmental preservation. Soil quality plays an important role in such issues since it is an important productivity and sustainability parameter that is negatively and positively affected by farming practices. This role can be modeled using ecological and economical tools.

In the second chapter, based on the literature review, we propose a theoretical framework of our bioeconomic modeling. We present a more detailed review of farm-level soil quality bioeconomic models designed to study soil degradation and conservation mea-

asures, where soil quality is considered as a production factor and an endogenous variable in the optimization models. Then, the theoretical framework is presented as well as the objective of the model and the elements under consideration. Next, a comprehensive dynamic theoretical model is proposed. We consider a rational agent-farmer with perfect information who aims at maximizing his profits over time. There are no market failures. From this theoretical modeling, it appears that the relationship between soil quality dynamics and productive inputs is of crucial importance. However, the comprehensive theoretical model proposed in this chapter, despite an extensive discussion of the model hypothesis, is too complex to yield an analytical solution. To be solved, it must be simplified. In particular, it may require simplifying the cooperating inputs hypothesis.

In the third chapter, on a statistical basis, we investigate the relationships between soil quality dynamics, crop yields and productive inputs for a specific region of France, the Grand Ouest⁴, which is an important agricultural production area. The objective is to compare the literature review results with our statistical results in order to determine how best to simplify our comprehensive dynamic theoretical model. To this end, we present the characteristics of our study area. Then, we examine the dynamics of soil quality parameters in the Grand Ouest in order to statistically test whether the evolution of soil quality in this region can be correlated with changes in farming practices. We also test the relationships between soil quality parameters and farming practices with respect to the yields of the main crops grown in this region (soft wheat and maize grain).

In the fourth chapter, we propose a theoretical soil quality investment model. We present the objective and rationale for using this model in a dynamic setting. The analytical tools are described. The soil quality investment model is declined in several cases : when farming practices only positively impact soil quality changes and when farming practices both positively and negatively impact soil quality changes. In each case, we study two possible relationships between soil quality and productive inputs in terms of production : the case where productive inputs and soil quality are cooperating and the case where productive inputs and soil quality are not cooperating. In fact, one of the results of the previous statistical chapter is that some productive inputs are cooperating with soil quality parameters in terms of crop yield and some are not, thus emphasizing the need to consider both cases. We determine the equilibrium and optimal paths for each case when they exist. We also consider the impacts of a change in economic parameters (such as crop prices and inputs prices) on the equilibrium that is found.

4. Here, the Grand Ouest of France is composed of four French administrative regions : Brittany, Normandy, Pays de la Loire and Poitou-Charentes (now part of the Grande Aquitaine).

This simplified theoretical model is the basis of our application of the optimal control model presented in chapter 5. The sensitivity of soil quality dynamics to the soil and climatic context makes it difficult or even inappropriate to transfer results of similar simulations to different contexts, for instance, from Canada to France. Hence, this empirical model is based on a study case that has as its subject a cereal farm in the Grand Ouest of France (Vienne department). At the beginning of the chapter, we present our study case. Then, we describe our empirical bioeconomic control model, as well as the different functions and constraints used. Then, we present the methodology that is used to make our model realistic and practical, including the data that are used in our empirical bioeconomic control model and their source and the method used to estimate and parametrize the soil quality dynamics functions and the crop production functions. Because of data and software limitations, the soil quality parameter considered here is soil organic matter. Once the crop production functions and soil organic matter dynamics functions are validated, we present the different economic scenarios that are tested and the planning horizon over which the scenarios are run inter-temporally. The software and solver used to run our simulations, GAMS/MINOS, is then described, and we propose a discussion of the limits of our empirical model in order to better address the results obtained in our simulations.

Finally, in the sixth chapter, we present a general discussion of the thesis. We present a summary of our theoretical, statistical and empirical findings, and we show their relation to our research question. These results are to be considered in light of the limitations of our theoretical framework and dynamic empirical model : Although they shed light on the main issues, there are still many leads to pursue. Some of these issues are addressed, such as the importance of considering the multiple aspects of soil quality and a larger variety of farming practices, which is not currently possible. The importance of considering risk and uncertainty in the decision-making process of the farmer is also discussed, as well as the possibility of considering technical change. An interesting approach would be to take into account agent interactions. Finally, we discuss the significance of our results within a public and a private framework, as the private and public interest in soil quality management may be converging.

Chapitre 1

EIA : Reconciling productivity and environmental preservation

THERE is global concern regarding the sustainability of food production; by the middle of this century, the needs of a global population of 9 billion people will have to be met (Tilman et al, 2002; Goulet, 2012). Global food demand is expected to double, and diets will also change, requiring more meat production (mainly grain-fed). On a worldwide scale, political and social stability as well as equity are at stake; and on a country scale, competitiveness and economic growth (Tilman et al, 2002). Hence, it is of interest to consider how French farms can position themselves in relation to these issues. To ensure this increase in production, there seem to be two solutions: extend the proportion of agricultural land at the expense of natural ecosystems and increase agricultural productivity.

However, agricultural activities have strong impacts on the state of the environment, some of them irreversible and detrimental. With an increase in food production, one could expect an increase in these detrimental effects on natural resources that are scarce. Hence, in addition to being productive, agricultural practices have to be sustainable or, equivalently, ensure the possibility of producing agricultural goods in the long run (Tilman et al, 2002). One detrimental impact of agricultural practices is related to soil degradation, which is considered a serious threat to human well-being (Lal, 1998). In addition, in the long run, soil quality degradation leads to reductions in soil productivity (Dregne, 1995).

One way to address these issues could be to practice Ecologically Intensive Agri-

culture (EIA). EIA proposes solutions that achieve productivity and sustainability by placing the emphasis on ecosystem services in general and soil quality in particular, using practices such as reduced tillage, longer crop rotations and cover crops.

The objective of this literature review is to demonstrate that French agriculture has an interest in the interactions between agricultural practices and soil quality given this global agricultural challenge, in particular since France has dedicated more time than other countries to agricultural practices that preserve soil quality (Lahmar, 2010).

In the first part, the competitiveness, productivity and sustainability issues that French farms are faced with are presented in order to emphasize the interest French farms have in increasing productivity in a sustainable way to be competitive. Definitions and concepts are presented that are considered more or less explicitly in the modeling part of the report. In the second part, the concept of EIA is explained in more detail. Then, in the third part, the importance that EIA places on soil quality is justified. To this end, definitions relative to land and soil quality are provided, as well as the relationship that exists between soil quality, soil productivity and farming practices. Finally, we observe how soil quality can be considered as an economic issue and note its inclusion in economic analysis and models.

1.1 French farms are facing competitiveness, productivity and sustainability issues ...

1.1.1 French farms competitiveness: an economic growth issue ...

The concept of competitiveness refers to the contribution of a sector to the economic growth of a nation based on its ability to compete successfully (Latruffe, 2010). Thus, being competitive means being able to sell products that meet market demand (in terms of price, quality and quantity) and achieve profitability (Latruffe, 2010). The competitiveness of a sector or a firm is a relative measure and can be assessed at several levels (national or international).

In the European Union, competitiveness is relative to the ability of a nation to increase its inhabitants' standard of living in the long run and to achieve a high level of employment and social cohesion (De Kerviler, 2011).

The agricultural sector plays an acknowledged role in economic growth (Hwa, 1988) through both direct and indirect effects. Agriculture plays a direct role in economic growth through the contribution of the agricultural value added to Gross Domestic Product (GDP) (Tiffin and Irz, 2006). Furthermore, agriculture generates resources (capital and labor) that can be exported to the rest of the economy. Moreover, the agricultural sector has historically been used as a supply of capital to finance industrial development as well as in the provision of public goods through direct or indirect taxation (Hwa, 1988; Tiffin and Irz, 2006).

The agricultural sector is a critical sector for numerous countries; it is a sensitive sector since it is related to national food security and safety (Hervieu, 2001). Considering these definitions and given the context of globalization and market liberalization, the agricultural sector is a strategic sector with respect to competitiveness.

In addition, because this sector is given a great deal of support, not only in the European Union, it has been the source of multiple fictions during World Trade Organization (WTO) negotiations (Hervieu et al, 2001; Ball et al, 2010). Under these external and internal pressures (Petit, 1999; Hervieu, 2001), support for agriculture has fallen, and European (and French) agriculture must therefore be (more) competitive (Hervieu, 2001).

Actually, the competitiveness of European agriculture has been one of the objectives of the Common Agricultural Policy (CAP) (Butault and Réquillart, 2011; European Commission, 2011, 2013) since the Agenda 2000 reform, which promoted a European agricultural model based on the acknowledgment of the territorial, environmental and economic role of farmers (Hervieu, 2001).

There are two ways to measure competitiveness. One is to consider the trade dimension using, for instance, the amount of imports and exports (Latruffe, 2010). In this respect, at the international level, the competitiveness of French agriculture has decreased in terms of exports (Butault and Réquillart, 2011; Gambino, 2012); whereas France was the second largest exporter of agricultural products in the world in 1995, it was the fourth largest exporter in 2012 (Gambino, 2012).

In addition, the competitiveness of a sector or a farm can be understood in terms of its strategic management. In this case, competitiveness is illustrated by performance indicators such as cost measures, productivity, efficiency and profitability (Latruffe, 2010).

In the next sections, the definitions of profitability and productivity as privileged indicators of competitiveness are developed. Indeed, when the competitiveness of farms is addressed, productivity is typically mentioned (see, for instance, Butault and Réquillart, 2011; OCDE, 2011; Gambino, 2012), and according to the definition of competitiveness we consider, profitability is inseparable from competitiveness.

1.1.2 ... which is achieved through the profitability ...

Profitability is a leading indicator of long-term competitiveness and is a measure of competitive performance (Thorne, 2005). Profitability can be defined as the ratio between revenues and costs (O'Donnell, 2010) and more generally as a measure taking into account both revenues and costs (Thorne, 2005).

In her study, Thorne (2005) compares the competitiveness of six European cereal farms (in Denmark, France, Germany, Ireland, Italy, and the United Kingdom) using profitability measures between 1996 and 2000. The author computes several measures of profitability, among which are total revenue and total costs per hectare of cereal production, taking into account Area Aid direct payments. Three measures of cost are considered: cash costs, economic costs excluding land, and economic costs including land. With Germany, France is the only country that has a positive margin over total economic costs, so that French cereal farms appear to be competitive in terms of profitability.

Nevertheless, according to O'Donnell (2008; 2010), when studying profitability with respect to economic growth, it is not the absolute value of profitability that is interesting to consider but its variation. The change in profitability can be decomposed into the product of a total factor productivity index and an index measuring changes in relative prices at which goods and services are exchanged (O'Donnell, 2010).

1.1.3 ... and the productivity of the farms ...

Productivity is related to the return in volume between the production factors and the goods or services produced. It is possible to measure partial productivity, where production is considered with respect to only one input (for instance, production per hectare). Partial productivity is a measure of competitive potential and can be used to determine the sources of comparative advantage or disadvantage (Thorne, 2005).

However, as Latruffe (2010) notes, the disadvantage of such an approach is that

it does not allow consideration of any possibility of substitution between the different factors of production. A more complete approach is to measure total productivity by measuring the return between an aggregate input and an aggregate output (Latruffe, 2010; O'Donnell, 2010).

At the European level, French agriculture occupies the first position in terms of production (Gambino, 2012). Furthermore, when Thorne (2005) compares the partial land and partial labor productivity of cereal farms in six European countries, France has the highest wheat production output, the highest land productivity, and the second highest labor productivity in the 1996-2000 period. However, since 1995, French agricultural production has stagnated, and gains in total productivity have decreased (Butault and Réquillart, 2011). This has negative effects on agricultural revenues (Butault and Réquillart, 2011) and also on relative competitiveness: According to O'Donnell (2010), the increase in productivity is a fundamental condition for sustainable economic development.

In the following section, the concept of sustainability is explained to place competitiveness within a long-term perspective.

1.1.4 ... and relies on an objective of sustainability

Sustainability can have numerous definitions depending on the sector or area investigated, but overall, it is about long-term considerations (Pezzey and Toman, 2002). Competitiveness itself is considered over the long run, and being competitive implies following a constant or increasing evolution of the competitiveness index under consideration (Fournier, 2008; Latruffe, 2010), for instance, agricultural productivity or profitability. Nevertheless, sustainability can be considered at different scales: at a global (or national) scale or at a local (or farm) scale. In the first case, the contribution of French farms to the sustainable development of the country is largely considered, whereas in the second case, it is the sustainability of the farm. Since in this report the emphasis is placed on farmers' private decisions, sustainability is defined at the farm scale.

At the farm scale, sustainability can be defined according to four elements: ecological rationality, economic viability, social acceptability and intergenerational link (Landais, 1998).

In this study, we will focus on two aspects of sustainability as described by Landais (1998): economic viability and ecological rationality. These two aspects of sustainable

agriculture can be linked to the profitability and productivity of farms, respectively.

Economic viability is the ability of farmers to achieve acceptable returns from their activities and investments (Yunlong and Smit, 1994), which is similar to the concept of farm profitability, where revenues are compared with costs. Ecological rationality refers to the relationships between agricultural activities and natural resources and the environment; these relationships are managed to make farms reproducible (Landais, 1998) in the sense that the farming activity can be pursued. When considering land as a production factor, maintaining land and soil quality through ecological rationality is beneficial from a productivity perspective. In addition, in some cases, ecological rationality may be a way for farmers to achieve social acceptance. Adopting more environmentally friendly practices can help the integration of farmers and their families into local and non-market networks as well as nurture relationships with other farmers and other social stakeholders. Given that farm transmissibility is based upon the familial agricultural system and closely linked to the economic viability and social acceptability of farms, themselves potentially linked to ecological rationality, the last element mentioned by Landais (1998), the intergenerational link, might be a consequence of all the other elements.

There are various sustainability assessment methods in agriculture (see the review by Binder, Feola and Steinberger, 2010). At the farm level, Binder et al (2010) name three sustainable indicators, the *Indicateur de Durabilité des Exploitations Agricoles* (IDEA), the Indicator of Sustainable Agricultural Practice (ISAP) and the Response-Inducing Sustainability Evaluation (RISE). While the ISAP method is designed for researchers and policy makers, the IDEA method is also addressed to farmers and farmer organizations, whereas the RISE method is only addressed to farmers. It is worth noting that productivity and competitiveness are an explicit part of the definition of sustainable agriculture in the RISE method. Craheix et al (2016) assessed farm sustainability using MASC (Multicriteria Assessment of the Sustainability of Cropping Systems). MASC makes it possible to take into account the economic, social and environmental dimensions of sustainability and to manage the potential conflicts between these objectives. Among the basic criteria used by Craheix et al (2016) are the profitability and economic efficiency of the farm; at a more aggregate level, economic sustainability is captured through the economic incomes of the farm, long-term productive capacity and the contribution to economic development.

Hence, it appears that for French farms to be competitive, sustainable farm productivity and profitability are necessary; these are the objectives of Ecologically Intensive Agriculture.

Productivity, profitability and natural resources

— Production function

- **Productivity** of a farm: return between the production factors and the goods produced. Productivity is described by the farm production function y , depending on the production factors, labour L , capital K and natural resources (NR):

$$y = f(L, K, NR)$$

- **Partial productivity** PP of a factor: production per unit of this factor, other things equal. Partial productivities of labour (PP_L), capital (PP_K) and natural resources (PP_{NR}) are:

$$PP_L = \frac{f(L, K, NR)}{L} \quad PP_K = \frac{f(L, K, NR)}{K} \quad PP_{NR} = \frac{f(L, K, NR)}{NR}$$

- **Marginal productivity** MP of a factor: indicates the increase in output y obtained with one supplementary unit of this factor, other things equal. Marginal productivities of labour (MP_L), capital (MP_K) and natural resources (MP_{NR}) are:

$$MP_L = \frac{\partial f(L, K, NR)}{\partial L} = f_L \quad MP_K = \frac{\partial f(L, K, NR)}{\partial K} = f_K \quad MP_{NR} = \frac{\partial f(L, K, NR)}{\partial NR} = f_{NR}$$

The gain in output obtained by one supplementary unit of a factor can be increasing (increasing return to scale, IRS), constant (CRS) or decreasing (DRS).

- **Production costs** are expressed by the sum of the remuneration of each factor:

$$C(L, K, RN) = wL + rK + cRN + f$$

where w is the wage for one unit of labour used, r is the interest rate of capital, c the cost associated with the use of natural resources and f the fixed costs.

— Profit maximization

- **Farms as capitalist firms**: it is assumed that the objective of the farmer is to maximize his profit:

$$\text{Max}_{L, K, NR} \Pi(L, K, RN) = pf(L, K, NR) - wL - rK - cRN - f$$

where p is the price of the output.

The first-order conditions are:

$$\frac{\partial f(L, K, NR)}{\partial L} = pf_L - w = 0 \quad \frac{\partial f(L, K, NR)}{\partial K} = pf_K - r = 0 \quad \frac{\partial f(L, K, NR)}{\partial NR} = pf_{NR} - c = 0$$

- **Familial farms**: it is assumed that the objective of the farmer is to maximize his revenue

$$\text{Max}_{L, K, NR} \Pi(L, K, RN) + wL = pf(L, K, NR) - rK - cRN - f$$

— Cost and marginal productivity of natural resources

At the profit optimum, the marginal productivity in value of each factor must be equal to its price. In the particular case of natural resources: $\mathbf{pf}_{NR} = \mathbf{c}$. If the prices of natural resources c increase, the farmer has to increase the marginal productivity in value of natural resources to remain at the optimum.

1.2 ... to which the Ecologically Intensive Agriculture intends to be a solution...

In this part, the Ecologically Intensive Agriculture (EIA) concept is first presented. The EIA proposes placing more emphasis on ecosystem services, among which are those related to soil. According to EIA, preserving while using ecosystem services is the solution to productive and sustainable agriculture.

1.2.1 *The Ecologically Intensive Agriculture proposes to achieve a sustainable and productive agriculture . . .*

EIA stems from a context where on the one hand, world population growth, changing diets and heterogeneous opportunities for agricultural land expansion seem to require an increase in global agricultural production; and on the other hand, concerns about the negative and potentially irreversible impacts of the past intensification of agriculture on natural resources and on greenhouse gas emissions have increased the importance of ecological efficiency (Chevassus au Louis and Griffon, 2008; Goulet, 2012; Hochman et al, 2013).

EIA responds to this twofold challenge by proposing a break with conventional intensive agriculture based on chemical inputs (fertilizers and pesticides). However, contrary to other forms of alternative agriculture, such as biological agriculture, EIA aims at being both productive and sustainable (Chevassus au Louis and Griffon, 2008; Ghali et al, 2014). In addition, EIA proposes a holistic view of farming over decades at the farm scale, not solely the parcel area scale (Hochman et al, 2013).

The concept of EIA refers to the “*double green revolution*”, aiming at a highly productive agriculture (much like the green revolution) while respecting the environment (a green agriculture) (Griffon, 2013). The concept is relatively close to those of agroecology, eco-agriculture, high environmental performance agriculture and particularly conservation agriculture¹ (Griffon, 2013) in the sense that all these concepts emphasize the importance of ecosystem services and functions (Bonny, 2011).

Actually, EIA is quite in line with the changes in paradigm that occurred in the nineties in agronomic research and agricultural development (Musson and Rousselière, 2016). Since that time, the productionist model and the constant intensification of labor

1. See definitions in Griffon (2013).

and land use have been questioned, as well as the increasing use of inputs and environmental artificialization (Rieutort, 2009). Competitiveness is no longer simply a question of an increase in production volume but also involves the quality, geographic origin and originality of a product. New expectations emerge relative to the sustainable management of natural resources and the new functions of agriculture (Rieutort,2009). This echoes the concept of EIA, although EIA clearly aims at conciliating productivity and sustainability objectives.

1.2.2 ... that places Farmers at the heart of the approach...

EIA offers a way for farmers to re-appropriate ecosystem functionality optimization (Goulet, 2012; Ghali et al, 2014). Moreover, the objective of constant or increasing production while at the same time respecting the environment implies more complex agricultural practices than are currently found in conventional agriculture (Ghali et al, 2014). Farmers must therefore adopt the logic of research and innovation to achieve greater efficiency while also taking into consideration the importance of the environment (Ghali et al, 2014).

Nevertheless, although the role of farmers is important, EIA development also relies on the support of firms and the political process, as conservation agriculture has in the past. Conservation agriculture practices are frequently named as an example of EIA techniques (Goulet, 2012). Conservation agriculture involves farming practices that protect soil from erosion and other forms of degradation (Griffon, 2013); it has expanded into regions that have experienced soil erosion crises, such as Brazil, Australia and the United States (Ramkrishna, Vittal and Sharma, 2005; Lahmar, 2010). In Brazil, a soil erosion crisis occurred in the 1970s when large-scale farmers began to produce commodities such as soybeans and wheat, encouraged by Brazilian agricultural policy. However, conventional cultivation of these products, along with the high erosivity of rains and the high erodibility of soils, led to serious soil loss. Soil conservation practices appeared to be a solution to this issue and were initiated by farmers (Ribeiro et al, 2007). Conservation tillage was introduced in the United State in the 1930s in response to a tragic dust storm in the mid-western United States (Hobbs, Sayre and Gupta, 2008). In 1938, Utz et al estimated that 60.9% of cropland area was subject to continued erosion under conventional practices or was of poor quality and that 43% of cropland area was in need of good soil conservation practices to prevent serious damage from erosion

In Europe, the expansion of conservation agriculture has been weaker, and it is

mainly adopted for economic reasons. Indeed, conservation practices lead to a significant decrease in production costs (Lahmar, 2010). The relevance of conservation agriculture practices depends on various conditions²: farm and market conditions, biophysical, and also social, cultural and political conditions (Knowler and Bradshaw, 2007; Lahmar, 2010); thus, conservation agriculture is not equally suitable to all agroecosystems (Lahmar, 2010). The last set of conditions explain why the support of firms, governments and other social or public stakeholders is important in the development of EIA (Musson and Rousselière, 2016).

In France, the EIA concept seems to have developed in the West of France, where in 2010 a group of professional stakeholders and scientists created the international association for an ecologically intensive agriculture (EIA). A large diversity of stakeholders can be observed in the administration council of the association, including researchers, farmers, local elected officials, and heads of the Chamber of Agriculture, as well as sponsors of the association, agricultural suppliers, food retail firms, and agricultural cooperative groups (Goulet, 2012; AEI website).

Among the latter, a multi-purpose cooperative from the West of France has shown interest in the EIA concept, which is now part of its strategy (Goulet, 2012; Ghali et al, 2014), in which respect for the environment and ecosystems is clearly stated as a component of innovative agriculture (Terrena website). In addition, the Chambers of Agriculture of Brittany have developed a strong interest in EIA, and visiting its website, one can easily access information on the EIA concept (see *Chambres d'agriculture de Bretagne* website).

1.2.3 ... and gives to Nature a primary role, putting the emphasis on soil properties and soil quality

EIA is an agriculture method based upon intensive use of natural processes and ecosystem functionalities that is sustainable as opposed to intensive use of inputs such as fossil energy, chemicals and pesticides (Chevassus au Louis and Griffon, 2008; Bonny, 2011; Goulet, 2012).

Natural processes refer to the biophysical functions of an ecosystem, which include core and beneficial processes. Core processes (such as nutrient and water recycling)

2. For details about the drivers/constraints to conservation agriculture, see Knowler and Bradshaw (2007) and Lahmar (2010). To some extent, these drivers/constraints can also be applied to EIA, although EIA covers a larger range of practices, which are difficult to name exhaustively.

underpin the beneficial ecosystem processes (such as soil formation, erosion regulation and biomass production) that generate ecosystem functionalities and services, which are end goods that directly affect human welfare (Balmford et al, 2011). Soil quality and the related soil properties are the same as those that contribute to the ecosystem services furnished by soil (Cassman, 1999).

Hence, it seems that the intensive use of natural processes and ecosystem functionalities recommended by EIA necessitates consideration of soil quality. Indeed, one parameter of the effective productivity of a farm is related to the potential capacity of agricultural production, which is determined by the interactions of the chemical, physical and biological properties of the soil, which can be referred to as soil quality (Parr et al, 1992). Hence, for a soil to provide all of its functions, among which is the production function, its quality must be preserved (Lal, 1998).

Actually, the importance given to soil quality by EIA is also revealed by the numerous references to conservation agriculture (Goulet, 2012). Conservation agriculture requires the simultaneous use of three principles: less disturbance of the soil, soil cover and crop rotation to control for weeds and pests and diseases. Reduced-tillage, no-tillage, direct seeding and cover crops are examples of farming practices associated with conservation agriculture (Lahmar, 2010) and by extension with EIA.

In the next part, the importance that EIA places on soil quality is justified. First, land, soil, and soil quality are defined. Next, the links between soil quality, agricultural productivity and sustainability are presented in more detail. The positive relationship between soil quality and agricultural productivity supports the view held by EIA that the soil resource is a critical parameter in a productive and sustainable agriculture that is less dependent on chemical inputs.

1.3 ... and in which the soil quality plays an important role,...

To understand why natural resources and soil in particular are given such importance in EIA, it is necessary to establish what is understood by land, soil and soil quality. Then, the soil functions are presented, one of them being directly related to agricultural productivity. However, for a soil to function, its quality must be preserved, at least above a critical threshold. Actually, we show in the third section that farming practices can either be detrimental or beneficial to soil quality.

1.3.1 Some definitions about soil quality . . .

First, it is useful to specify the difference between land and soil.

The Food and Agriculture Organization (FAO) defines land as “*an area of the earth’s surface, the characteristics of which embrace all reasonably stable, or predictably cyclic, attributes of the biosphere vertically above and below this area including those of the atmosphere, the soil and underlying geology, the hydrology, the plant and animal populations, and the results of past and present human activity, to the extent that these attributes exert a significant influence on present and future uses of the land by man*”.

Hence, land is a more general concept than soil: Soil is one of its components together with water and vegetation, for instance (Lal, 1998). In this report, the soil is understood as being the superficial layer of the earth’s crust considered with respect to its productive nature or characteristics (Larousse; Société Pédologique de Suisse, 1998); it is “*the primary environmental stock that supports agriculture*” (Wood, Sebastian and Sheer, 2000).

Soil quality is defined by Lal (1998) as “*a soil inherent capacity to produce economic goods and perform environmental regulatory functions*”, and by Parr et al (1992) as “*an inherent attribute of a soil that is inferred from its specific characteristics and observations (e.g., compactability, erodibility, and fertility)*”. Letey et al (2003) propose to define soil quality as “*the chemical, physical, and biological properties of soil that affect its use*”.

The definitions proposed by Lal (1998) and Parr et al (1992) describe the intrinsic part of soil quality, which can be characterized by the inherent soil quality attributes that do not vary greatly over time and can be considered static (Carter, 2002). Examples of these attributes are mineralogy and particle size distribution, effective rooting depth, water retention and transmission properties, and physical and chemical rooting conditions (Carter, 2002). In addition, there is also a dynamic part of soil quality that is impacted by the soil user. Dynamic soil quality attributes can vary over relatively short time periods, for example, soil organic matter (SOM), labile SOM fractions, soil structural components and macroporosity (Carter, 2002). SOM is part of both inherent and dynamic soil quality; indeed, it is related to the particle size distribution as well as organic material inputs into the soil (Carter, 2002)³.

3. The distinction between the intrinsic and dynamic parts of soil quality is interesting in that it emphasizes the anthropogenic soil management impact on soil quality; where the inherent quality corresponds to the time before human use, and dynamic soil quality the time after human use. However,

1.3.2 ... which is an important productivity and sustainability parameter ...

In the definitions of land, soil and soil quality, the notion of production is always mentioned, explicitly or implicitly; and in agriculture, land can be considered as a production factor (Balarabé, Dugué and Lifran, 2012).

Soil is considered to have four principal functions: (i) sustain biomass production and biodiversity, (ii) regulate water and air quality, (iii) preserve archaeological, geological and astronomical records and (iv) support the socio-economic structure and cultural and aesthetic value and provide an engineering foundation (Lal, 1998). Agricultural productivity can thus be considered one of the functions of soil, and it depends on the soil quality (Lal, 1998). Hence, when land productivity is used to assess the relative competitiveness of a country's agricultural sector (see Thorne, 2005 and Latruffe, 2010), the partial productivity parameter obtained can be considered a function of soil quality.

However, it is important to acknowledge that the impact of soil quality on land productivity can be confounded by other factors (such as the use of fertilizers or irrigation); in some cases, although soil quality is degraded, one can observe constant or even increasing yields (Lal, 2001). Nonetheless, even in these cases, long-term reduction in soil productivity is to be expected (Dregne, 1995).

Additionally, soil quality is a concept commonly used to assess the sustainability of agricultural land management (Herrick, 2000; Carter, 2002). In agriculture, sustainability is relative to the maintenance of the productivity and profitability of farms; and soil quality can be seen as the ability of a soil to sustain plant and animal productivity (Herrick, 2000). Hence, maintaining or increasing soil quality seems to be one of the requirements for a sustainable (and thus competitive) agriculture.

For example, in the case of the IDEA method mentioned previously, soil quality indicators are part of the “*elementary units of sustainability*” (Briquel et al, 2002). In a study led by Gómez-Limón and Sanchez-Fernandez (2010) about the empirical evaluation of agricultural sustainability for two agricultural systems in Spain, two of the composite indicators are soil quality criteria (minimization of soil loss and maintenance of chemical quality of soil). Soil characteristics also appear in the basic criteria used by (Carheix et al, 2016) to assess farm economic, social and environmental sustainability.

this distinction can be discussed and criticized (see Letey et al, 2003).

From the examples mentioned, it appears that farmers have an impact on soil quality as it is strongly influenced by agricultural practices (Stoate et al, 2001; Carter, 2002; Lal, 2015). We discuss in the next section the extent to which farming practices can be a source of soil degradation as well as a means of addressing it.

1.3.3 ... negatively and positively affected by farming practices

Agriculture is acknowledged as one of the principal causes of soil degradation (Wood et al, 2000; Stoate et al, 2001) along with natural causes (erosion by wind and water and other soil formation processes) and urban and industrial use (Lal, 1998; Wood et al, 2000).

Soil degradation or deterioration is relative to the inability of a soil to fulfill its principal functions (Wood et al, 2000). There are four types of principal soil degradation processes linked to agriculture (Lal, 1998; 2015): (i) chemical processes, related to soil nutrient depletion, acidification and salinization; (ii) physical processes, related to structural decline, compaction, crusting and erosion; (iii) biological processes, related to the loss of soil biodiversity and soil organic carbon (SOC) decline; and (iv) ecological processes, reflecting a combination of the other three degradation processes and leading to disruption in ecosystem functions and the provision of ecosystem services.

Moreover, soil degradation is a relative concept (Lal, 1998, Gis Sol, 2011) and must be defined according to a reference point. However, the problem with soil deterioration is that under a critical threshold, it may be not possible for the soil to recover (Lal, 1993), and it can be considered as a non-renewable resource on the human time scale (Lal, 1993; Arrouays et al, 2003). In this case, soil degradation would be considered irreversible. Nevertheless, when this critical threshold is not reached, it is possible to restore the soil.

Soil resilience, i.e., the ability to recover from degradation, is based on the restoration process and depends on a critical threshold along with the rate of recovery to the initial state and the path of recovery (as opposed to the path of degradation) (Lal, 1993). Sherr (1999) proposes a classification of soil degradation processes according to their relative reversibility based on informal consultation with tropical soil experts. According to this classification, surface sealing and crusting, nutrient depletion and nutrient imbalance are considered largely reversible at low cost. Organic matter loss and eutrophication are considered reversible at a significant cost, and acidification, alkalization and salinization, and top soil loss due to water and wind erosion are considered irreversible (see

Sherr, 1999 for the complete classification).

In France, physical degradation of soil is mainly due to water erosion (Muxart, Guerrini and Auzet, 1992) and soil compaction (Gis Sol, 2011). In metropolitan France, 18 % of soil is characterized by a medium to very strong erosion hazard (Gis Sol, 2011). Soil compaction has a strong impact on several processes, including water erosion and production through the modification of soil properties (Roger-Estrade et al, 2011). However, soil compaction can be reversible in some circumstances, as demonstrated in an experiment led by Roger-Estrade et al (2011). Other soil degradation may be considered irreversible, at least from a human perspective, e.g., contamination by toxic elements and salinization, in particular in areas that were affected by marine water, such as Camargue and the marshes of western France (Charentais, Vendéens and Poitevin marshes) (Stengel and Gelin, 1998).

As for the impacts of farming practices on soil quality, it appears that they can be either positive or negative (see Table 1.1). For instance, in a study led by Lal (1993) about tillage impacts on soil quality, soil degradation and soil resilience, tillage has both negative and positive effects on soil quality. In addition, these effects are confounded by land use, farming, cropping system, management and other environmental factors. Hence, it seems that tillage itself is not detrimental to soil quality, but inappropriate tillage can be: According to Chitrit and Gautronneau (2011), inappropriate and chemical-intensive farming practices are the main cause of soil deterioration in France. Wood et al (2000) provide some examples of farming practices that are detrimental to soil quality: Intensification on irrigated land can cause salinization, and the inappropriate use of mechanized farming in high-quality rain-fed lands can induce compaction. Reciprocally, some agricultural practices are known to be favorable to soil quality.

Chitrit and Gautronneau (2010) propose an indicative list of farming practices that are beneficial to soil quality, such as long crop rotation, regular organic matter supply, mixed crops, and minimal tillage application. From the literature, Lal (2015) proposed strategies to improve soil quality depending on the region considered (tropical and sub-tropical, Mediterranean Europe...) and the process targeted, among which are nutrient management, manuring, residue retention as mulch, and so one.

Hence, there is evidence that farming practices can positively or negatively impact the quality of soil, itself playing a role in farm productivity. In the next part, we examine how these relationships are taken into account and modeled in an economic framework.

Agricultural practices	Impact of practices on soil quality	Impact of soil quality on productivity	References	Remarks
Tillage practices	Erosion (+)	(-)	Richard <i>et al.</i> (2001)	Reduced tillage, under appropriate cropping systems, decreases water erosion. The impact of tillage on porosity can be confounded by other factors or practices, and by inter- and intra-annual variability (Richard <i>et al.</i> (2001)). On Andisols representative of the highlands conditions of Mexico and Latin America, during a 2 year period, in spite of higher SOC under no-tillage (twice the amount of conventional tillage), maize yield was higher in conventional tillage compared to no-tillage. Results might have changed in longer term experiments (Astier <i>et al.</i> , 2006). In the long run, Blevins <i>et al.</i> (1983) observe equivalent or higher corn yield under no-tillage compared to conventional-tillage, under appropriate N fertilization. General result, the impact of tillage on soil micro and meso fauna depends on the organism considered. As for soil microflora, the impact of tillage is detrimental, but usually small (Kladivko, 2001). Under no-tillage, the positive impact on various categories of earthworms affects positively soil structure and aggregation (Kladivko, 2001; Verhulst <i>et al.</i> , 2010). Kladivko (2001) suggests the existence of a control of soil-borne pests by other soil organisms, although such dynamics would require time.
	Soil porosity (-)	(+)	Carter M.R. (1992), Ekeberg and Riley (1997), Richard <i>et al.</i> (2001)	
	Soil Organic Carbon (-)	(?)	Blevins <i>et al.</i> (1983), Astier <i>et al.</i> (2006)	
	Decrease in soil fauna and flora	(-) pests ; (+) auxiliaries	Kladivko (2001), Verhulst <i>et al.</i> (2010)	
Crop rotation	Decrease in pests and diseases pressure	(+)	Cook and Haglund (1991)	Cook and Haglund (1991) have shown that the poor wheat growth and yields under conservation tillage or mulch compared to "clean tillage" was due to root pathogens, favored by a continuous wheat crop. Particular crops have a positive impact on soil structure; however, in the study led by Glab <i>et al.</i> (2013), they were short-term effects. In particular rotations including legume (Migliorina <i>et al.</i> , 2000).
	Soil structure (?)	(?)	Glab, Seigalska and Labuz (2013)	
	Soil Organic Carbon (+)	(+)	Migliorina <i>et al.</i> (2000)	
	Erosion (-)	(-)	Cutforth and McConkey (1997), Malhi and Lemke (2006)	
Crop residue	Soil structure (+)	(+)	Denef <i>et al.</i> (2002)	Increase both stable and unstable macroaggregates, while the relative proportion of stable and unstable macroaggregates depends on the weathering status and clay mineralogy of soils (Denef <i>et al.</i> , 2002). Kumar and Goh (2002) focus their study on soil nitrogen and the impact of antecedent leguminous and non-leguminous crop residues on winter wheat yields. It appears that leguminous crop residues are more beneficial than non-leguminous crop residues. In the case study of Cook and Haglund (1991), root pathogens activity was increased by the straw residues, which were providing energy to the pathogens.
	Soil porosity	(+)	Verhulst <i>et al.</i> (2010)	
	Soil nutrient availability (+)	(+)	Kumar and Goh (2002)	
	Increase in soil fauna and flora	(-) pests ; (+) auxiliaries	Cook and Haglund (1991)	
Fertilizers	SOC (+)	(+)	Verhulst <i>et al.</i> (2010)	
	Soil acidity (+)	(-)	Verhulst <i>et al.</i> (2010), Shukla, Lal and Ebinger (2006)	

Note: the different impacts have to be considered with respect to the location of the parcels, soil type and crop produced.

Table 1.1 – Examples of the impacts of agricultural practices on soil quality.

(Source: from Issanchou (2014))

1.4 ..., a role that can be modelled using ecological and economical tools

In this section, we first justify studying agricultural soil quality from an economic perspective in the context of EIA. In the second part, we present some examples of the estimation of soil erosion costs: They emphasize the importance of soil conservation in the maintenance of soil productivity and thus crop yield. Then, in the third part, theoretical soil resource optimization models are presented. Examples of how these models and their variant can be applied are proposed in a fourth part. Finally, we show how biophysical models can be integrated within optimal control models in order to more accurately model the soil resource dynamics.

1.4.1 *Of the interest of an economic approach of soil quality*

Soil quality, as an important parameter of agricultural productivity, is mentioned in numerous economics studies covering a wide range of topics (see Table 1.2). For instance, soil quality can be considered as a parameter of interest when considering land use and land cover options (Brown et al, 2004; Verburg et al, 2006 ; see, for instance, Chomitz and Gray, 1996); to assess agrosystems sustainability (Belcher, Boehm and Fulton, 2004); and to evaluate the determinants of farm productivity (Bhalla and Roy, 1988; Schreinemachers, 2006).

The relationship between agriculture and soil quality as described by the principles of EIA is close to those described in the soil erosion economics literature. EIA proposes intensive use of ecological resources, with a particular emphasis on soil resources, to achieve the double goal for French agriculture of sustainability and productivity in the face of foreseen increases in food demand. EIA is therefore similar to conservation agriculture, which consists in adopting techniques such as no-tillage or cover crops in order to preserve soil quality and fertility.

From an economic point of view, there are two reasons for studying soil quality (degradation) in agriculture. One is to understand the farmer's motive to invest or not invest in conservation practices that increase soil quality and reduce soil erosion (Saliba, 1985; Barbier, 1990; Barbier, 1998; Foudi, 2012).

References	Type of study	Subject of the study	Method used
		Land degradation optimal control	
McConnell (1983)	Theoretical	Determine when the private and the socially optimal paths of erosion differ	Farm-level dynamic optimal control model
Saliba (1985)	Theoretical	Provide a theoretical model to guide empirical research	Farm-level dynamic optimal control model
Hediger (2003)	Theoretical	Evaluation of sustainability at the farm-level considering both on- and off-farm effects of erosion	Farm-level dynamic optimal control model
Segarra and Taylor (1987)	Empirical (United States)	Apply a general farm-level dynamic model of soil conservation to narrow the linkages among variables that affect soil use to the Piedmont Area of Virginia	Optimal erosion control model / use of a representative farm
Smith <i>et al.</i> (2000)	Empirical (Canada)	Determine optimal cropping systems for dryland grain production in the northern Great Plains	Soil quality dynamic optimal control model / solved using GAMS/MINOS modeling system
Yirga and Hassan (2010)	Empirical (Ethiopia)	Analyze trade-offs between short- and long-term objectives of soil use by smallholder teff farmers in Ethiopia	Static and dynamic farm-level optimal control model - parametric estimation
Fondi (2012)	Theoretical	Analyze the role of property rights in soil conservation, comparing a landlord farmer and a cash rental farmer	Dynamic bioeconomic optimal control model for soil ecosystem services and dis-services
Berazneva <i>et al.</i> (2014)	Theoretical and Empirical application (Kenya)	Investigate the effects of changes in agricultural practices on the natural resource and on farmer livelihoods / Comparison of soil organic carbon level and crop yield modeling optimal practices or current practices	Dynamic bioeconomic model of agricultural households based on the maximum principle framework with estimated production function and calibrated soil organic carbon dynamics
		Costs of Erosion	
Magrath and Arenas (1989)	Empirical (Indonesia, Java)	Estimating benefits and costs of alternative soil conservation policies	Change in productivity approach / Estimations using transfer method
Barbier (1990)	Review & Theoretical	Review the soil conservation packages offered to upland farmers in Java and the factors influencing their adoption	Farm-level dynamic optimal control model (adapted from McConnel (1983))
Bandara <i>et al.</i> (2001)	Empirical (Sri Lanka)	Analyze the economy-wide impact of changes in soil erosion induced by a range of policy reforms, distinguishing between and quantifying the on-site and off-site effects	Computable general equilibrium model / estimation of costs using the replacement cost approach and the change in productivity approach
		Policies	
Vatn <i>et al.</i> (1999)	Methodological & Empirical (Norway)	Policy analysis of environmental problems	Mathematical modelling framework
Louhichi, Flichman and Zekri (1999)	Empirical (Tunisia)	Quantitative evaluation of the impact of water and soil conservation techniques on crop yield, production system, erosion and expected economic returns	Dynamic multi-period recursive model, using non-linear mathematical programming
Quang, Schreinemachers and Berger (2010)	Empirical (Vietnam)	Explore <i>ex-ante</i> the effect of selected policy options on the adoption of soil conservation techniques and the sustainability of agriculture in the northern highlands of Vietnam	Dynamic simulation using a mathematical programming-based multi-agent system (MP-MAS)
		Farm productivity	
Bhalla and Roy (1988)	Empirical (India)	Evaluate whether the inverse relationship between farm size and productivity is due to difference in soil fertility	Reduced form equation of a production function
Schreinemachers (2006)	Empirical (Uganda)	Study the relationship between width of crop-yield gap and farm households food security	Dynamic simulation using a mathematical programming-based multi-agent system (MP-MAS)
		System sustainability	
Belcher, Boehm and Fulton (2004)	Empirical (Canada)	Evaluate regional agrosystem sustainability	Simulation model (SAM)
		Land Use	
Chomitz and Gray (1996)	Empirical (Belize)	Explore the trade-off between rural road building (economic development) and deforestation (environmental preservation)	Static spatially explicit multinomial logit model of land use
		Soil quality economic value	
Pascual <i>et al.</i> (2015)	Methodological	Provide a framework to assess the economic value of soil biodiversity and soil ecosystem services	Total economic value framework

Table 1.2 – Studies considering soil quality: a wide range of topics and models.

(Source: from Issanchou (2014))

Indeed, conflict may exist between the objectives of farm profitability and soil resource sustainable management, as chemical inputs can (over)compensate for soil quality degradation to some extent. In particular in developing countries, it can be too costly for farmers to invest in conservation measures (Barbier, 1990; Quang, Schreinemachers and Berger, 2010). The second reason is related to the difference between the private optimal rate of soil degradation (from the farmer's perspective) and the social optimal rate.

However, as we have seen previously, at some point, soil degradation is irreversible (on the human time scale, considering erosion, pollution or salinization phenomena, for instance), and soil productivity losses are inevitable. In addition, it seems that the soil degradation rate induced by agricultural activities and farmers' decisions is not always optimal, both from a private and a social point of view.

Barbier (1998) gives several explanations for the non-optimality of the rate of soil degradation and, more specifically, the rate of soil erosion in the context of South-east Asia. Among the reasons that can explain why farmers' private rate of soil degradation is not optimal, some can be transferred to the French case. For instance, imperfect land markets where land prices do not reflect the potential land productivity (Bureau and Chalmin, 2007; Cavailhès, Hilal and Waversky, 2011) can explain a non-optimal rate of soil degradation. Furthermore, from a private perspective, the farmer can consider that there are substitutes to soil quality and productivity, whereas at a more global level, this may not be the case. Finally, diverse policies, among which are agricultural policies, can have unexpected and detrimental effects on soil degradation rates.

In the economic literature related to soil erosion and conservation, a number of studies aim at determining an erosion optimal control level (McConnel, 1983; Saliba, 1985; Hediger, 2003)⁴. When this optimal level is not observed, public policy and investment can be considered to correct the problem. To design and implement the appropriate policies, it is necessary to measure the on-site and off-site costs of soil erosion (see Magrath and Arens, 1989; Bandara et al, 2001) to determine the farm-level incentives for soil conservation (Barbier, 1990; Nakhumwa, 2004; see review by Knowler and Bradshaw, 2007; Foudi, 2012) and to better understand and estimate the value of soil quality and ecosystem services (Pascual et al, 2015). Conservation policies and changes in practices can then be evaluated *ex-ante* (see Quang et al, 2010; Berazneva et al, 2014) or *ex-post* (see Louhichi, Flichman and Zekri, 1999).

4. The articles of Saliba (1985), Smith et al (2000), Hediger (2003) and Quang et al (2010) are presented in more detail in Chapter 2.

1.4.2 Estimation of soil erosion costs: soil quality as a determinant of soil productivity

According to Barbier (1998), economic analysis of the soil erosion problem and more generally of soil quality degradation issues must take into account on-site and off-site costs of soil erosion. In fact, estimation of soil quality degradation is necessary for agricultural decision making as well as for *ex-ante* and *ex-post* policy analysis (Kim, Barham and Coxhead, 2001).

The two main ways to estimate the on-site costs of erosion are the changes in productivity approach and the replacement cost approach (Barbier, 1998). One limitation of these approaches is that both compare a situation with and without erosion, while erosion cannot be null. In addition, when considering the change in productivity approach, the costs of mitigating erosion have to be taken into account and be balanced with the impacts of erosion on productivity. According to Barbier (1998), a much more satisfactory measure of on-site costs of soil erosion is the opportunity cost approach, where the on-site cost of soil erosion is the loss in the long-run net profitability of the farm from not investing in soil erosion - in the cases where soil conservation investments are an economically worthwhile alternative. To measure the off-site costs of erosion, standard approaches of estimating environmental externalities are used, for instance, by estimating the environmental effects of erosion and valuing all of these effects. However, this approach can lead to double counting (Barbier, 1998).

For instance, Magrath and Arens (1989) estimated the costs of soil erosion on Java using the change in productivity approach. Their study illustrates both the difficulty of employing data on soil erosion and the potentially important losses that can be incurred due to soil degradation. To calculate the on-site costs of soil erosion, they first estimate the extent of soil erosion in Java using a mathematical model since they could not rely on empirical data. Then, they estimate the productivity effects of erosion through the change in productivity based on the annual percentage change in the yield estimate depending on the sensitivity of the crops to soil loss and the level of erosion. Finally, they estimate the economic implication of the productivity declines induced by soil erosion in terms of choice of crop mix yielding high or low profits: The cost of a one percent loss in productivity is a function of the basic productivity of the cropping system and the structure of the production costs. When the crop mix chosen induces higher output, the losses incurred due to loss erosion will be higher. The farmer can also mitigate the costs of erosion through the variable costs. They estimate the on-site costs of soil erosion in Java as US\$

320 million per year, which is most likely an overestimation due to the limitations of the approach (Barbier, 1998).

Bandara et al (2001) estimate the on-site and off-site costs of soil erosion in Sri-Lanka in order to show that trade liberalization, in addition to combinations of tax and subsidy policies, can reduce the environmental cost of soil erosion in developing countries without significant real output losses. Since the authors' approach is macroeconomic, they use a general equilibrium model. Soil erosion is integrated as an environmental component within the computable general equilibrium (CGE) model they use. They model the on-site and off-site effects of soil erosion within the CGE model, which requires a very large amount of physical and biological information. The on-site effects of soil erosion are estimated through the change in total erosion, which is the weighted sum of sectoral area and erosion rate changes. Each crop is associated with a specific erosion rate (t/ha/year) estimated from past studies. The impact of land quality differences, management practices or soil conservation technologies on the erosion associated with each crop and ecosystem is considered through the land use changes. The off-site costs of erosion are captured by the impact on capital productivity through the productivity impact parameter. Erosion is assumed to impact labor productivity very little or not at all. Their results suggest that trade liberalization has a positive, although small, impact on soil erosion. Tax and subsidy policies achieve more substantial soil erosion abatement more efficiently. However, as noted by the authors, one important limitation of their results is related to the lack of available data.

Although Magrath and Arens (1989) and Bandara et al (2001) do not consider soil quality *per se* in their studies, soil erosion issues are linked to soil quality issues, and both affect soil productivity (Pimentel et al, 1995), as emphasized in the study led by Bhalla and Roy (1988).

Bhalla and Roy (1988) study the role of land quality in the mis-specification of farm productivity analysis, and their conclusion is that agro-climatic and soil factors are important determinants of soil productivity. Although they acknowledge the complexity of interactions between the different components of soil quality - some being exogenous and some endogenous - they integrate soil quality in their static model in a very simplified way. Indeed, land quality parameters are used to control for differences in productivity, so that only exogenous parameters were used for which information were available (soil type, soil color, and soil depth).

1.4.3 Soil resource optimization: basic theoretical models highlighting the main trade-offs

The models addressing soil quality degradation issues usually focus their analysis on soil erosion (Smith et al, 2000; see review by Barbier, 1998). Although in some models the complexity of soil quality processes is acknowledged, they are nevertheless simplified (see for instance McConnell, 1983; Saliba, 1985; Hediger, 2003).

In addition, when considering soil quality and agriculture, optimization models are relevant since such models address the issue of the optimal use of a resource (Zilberman, 1982; Nakhumwa, 2004; Lobo Pereira et al, 2013). Dynamic optimal control models are particularly relevant in agricultural economics when considering farm and production management, where agricultural production can be considered as a process of growth (Zilberman, 1982).

The theoretical article of McConnell (1983) is widely referred to in studies addressing soil degradation or conservation issues (see, for instance, Saliba, 1985; Barbier, 1990; Smith et al, 2000; Hediger, 2003; Yirga and Hassan, 2010). In his study, the author seeks to determine when the private rate of soil erosion of a farmer's land differs from the socially desired one. He uses a private decision model where there are no decisions related to crop choice or crop rotations, which are considered unique and constant. Furthermore, soil quality is also considered as constant based on its substitutability with fertilizer inputs. Hence, in McConnell, crop production is a function of soil loss, soil depth and an index of variable inputs, weighted by a neutral technical change. The farmer maximizes the present value of the stream of profits for T years and the value of farm real estate, which depends on the soil depth (which is assimilated to soil fertility). From this model, McConnell concludes that an increase in soil loss does not mean that farmers ignore physical production relations. In addition, when the soil base affects farm resale value, farmers are likely to conserve it. Foudi (2012) shows that property rights are a necessary condition for soil conservation although not a sufficient condition.

In a study related to farm-level conservation decisions in the Uplands of Java, Barbier (1990) proposes a simple variant of the model proposed by McConnell (1983) that shows how the impacts of soil erosion on profits affect farmers' adoption of conservation measures. In Barbier's setting, crop production is a function of conventional crop production inputs and topsoil depth. The variation in soil depth depends on the balance between conventional and conservation inputs, the former being detrimental to soil depth and the latter increasing soil depth. The costs of conventional crop production inputs

and conservation inputs are different. From this theoretical model together with a case study in Java, Barbier concludes that at the time of the study, farmers did not have incentives to invest in conservation measures: The impact of erosion on crop productivity was perceived as negligible compared to the costs of conservation practices; furthermore, some governmental policies were detrimental to the adoption of conservation measures, such as the subsidization of fertilizers that decreased the cost of conventional inputs.

1.4.4 Applications of soil quality optimal control models

Segarra and Taylor (1987) propose the application of a farm-level dynamic optimal control model to the Piedmont area of Virginia. The theoretical model they propose is based on previous works by McConnell (1983) and Saliba (1985). The study area is subject to serious soil erosion, and soil conservation is a policy issue in this region. They specify their dynamic model using a representative farm established from the 1982 Census of Agriculture data. Four basic farming practices were considered, although analyzed separately: up-and-down-the-slope cultivation, contouring, stripcropping and terracing. In addition, twenty-eight crop rotations were considered as decision variables. Although the authors acknowledge the importance of considering plant nutrients and soil chemistry as state variables when considering the optimal use of the soil resource, they only use topsoil depth in their application. To estimate the budgets for each crop considered, the authors used the Soil Conservation Service Guideline; and for prices of crops and operating costs, the five-year (1980-84) average prices and costs are adapted to the four farming practices. The relationship between crop yields and topsoil depth was obtained using subjective elicited estimates. According to their results, a change from up-and-down-the-slope cultivation to other practices leads to sizable reductions in gross topsoil loss. Furthermore, adopting contouring increases the net present value of returns; this practice leads to outcomes that are both privately and socially desirable. For the other practices (stripcropping and terracing), the net present value of returns decreases compared to traditional farming practices but to a lesser extent than average gross topsoil loss.

Berazneva et al (2014) use an approach similar to Segarra and Taylor (1987). Using a dynamic bioeconomic model of agricultural households, they compare the outcomes in soil carbon stocks and maize yields at the end of a 25 year period depending on the farming practice: current observed ones or optimal ones. Optimal strategies are determined using an optimal control model where the farmer maximizes his profit under a soil organic carbon dynamics constraint. Decision variables are the application rates of

mineral fertilizer and crop residues, with different initial resource endowments and prices. One crop is considered: maize. The production function is estimated econometrically from agronomic experimental sites in the Vihiga and Nandi districts of western Kenya. Maize yield depends on the soil carbon stock and the nitrogen fertilizer inputs. The soil organic carbon equation is a function of the total residue and other natural processes, such as the rate of annual soil carbon loss and carbon turnover in soil. According to their results, optimal strategies make it possible to double maize yields while increasing and maintaining large stocks of soil carbon compared to the simulation with current practices. However, reaching and sustaining these high levels of maize yields and soil carbon stocks require far greater application rates of mineral fertilizer and organic resources than those currently used by western Kenya farmers.

Yirga and Hassan (2010) propose a soil nutrients optimal control model partially based on the work of McConnell (1983). In the farm-level model they propose, the farmer maximizes the sum of discounted streams of future net returns. The control variables are the levels of fertilizer, production and conservation labor and capital inputs for production and soil conservation activities. The optimization program is subject to the soil nutrient initial stock and the soil nutrient dynamics. For the empirical application of their model, the production function has a Cobb-Douglas functional form. Yirga and Hassan were confronted by a lack of data when estimating parameters and relied on previous studies to specify the other functions, although they estimated the yield-input relationship using a cross-section household survey based on an OLS procedure. In addition, they consider only one crop (teff), with no rotation although such a system is not representative of the practices of small-holder farmers. From their optimal control model, they emphasize the importance of considering a dynamic decision rule over static ones to capture the long-term consequences of soil degradation. From their results, current small-holder-farmer practices appear to over-exploit the soil nutrient stock, although to a lesser extent than what is predicted in the optimal solution levels of the static decision rule. This seems to suggest that small-holder farmers have some awareness of the impact of long-term erosion. In addition, sensitivity analysis by Yirga and Hassan shows the critical impact of the discount rate, changes in output and N fertilizer prices on optimal decisions.

A more sophisticated way of associating economic objectives and natural resource considerations is to integrate at least two models: an economic model and a biophysical model that specifically addresses soil quality dynamics.

1.4.5 Integrating biophysical models within an optimization model

Resource optimization models can also integrate both economic and biophysical models. An interesting feature of integrated models is that they allow for more complex and accurate modeling of natural processes - taking into account motives, constraints and institutional contexts determining human decisions (Vatn et al, 1999) - by combining several independent models, for instance, a biological model and an economic model.

In terms of soil quality, there are numerous soil fertility dynamics simulators (see the review in Schreinemachers and Berger, 2011) that make it possible to model more precisely the relationships between soil quality and farm productivity than in more classical economic models.

When studying the relationship between the width of the crop yield gap⁵ and farm household food security, Schreinemachers (2006) integrates three components into his model: one related to the farm household decision-making process; one describing the physical landscape, characterized among other variables by the nitrogen, phosphorus, potassium and soil organic matter contents, acidity and slope length of the soil of the landscape considered for the different agricultural plots sampled; and a biophysical component simulating crop yields and soil property dynamics using the Tropical Soil Productivity Calculator (TSPC). In the theoretical model underlying the TSPC, the crop yield non-linear equation depends on various complementary factors (management, available nitrogen, phosphorus and potassium in the soil, soil organic carbon and acidity). When performing simulations with the multi-agent model, it seems that in the case of Uganda, it is population dynamics rather than soil fertility decline that determines the maize yields, land productivity and labor productivity. One of the limitations of the study is the poor data quality.

The study by Belcher, Boehm and Fulton (2004) is an illustration of how integrated models can help assess the sustainability of an agroecosystem. In this study related to regional agroecosystem sustainability, the authors use an integrated approach in order to consider the dynamics of the multiple components involved. The biophysical model is the Sustainable Agroecosystem Model (SAM), which simulates land use decisions and dynamically integrates an economic model with a maximization profit objective and a soils and crop growth model simulating crop yield, soil quality and soil function. In the model, crop production is a function of climate and soil quality, and in turn, soil

5. The difference in actual average yield level and yield obtained under optimum management practices or yield potential of a given cultivar (Bindraban et al, 2000; Schreinemachers, 2006).

quality is influenced by previous crop management. The indicators used to estimate the soil quality function of the model are the total depth of the A and B horizons of the soil (solum), soil organic matter carbon content to depth of solum, and the quantity of residue carbon on the surface of the soil, specific to soil zone. The initial soil parameters data used for the simulations are estimates that reflect the soil characteristics of the target districts. According to their simulations, the biophysical characteristics of the agroecosystem, including soil characteristics, are critical determinants of the economic performance and sustainability of the system. For instance, in areas where soil water constraints are more important, water management designed to increase soil water, such as summer-fallow, were expected to play an important role, although such a practice is usually linked to soil degradation. This example shows how conflicting economic and sustainability objectives can be.

Actually, one of the motivations of Belcher et al (2004) for using an integrated model is to illustrate the conflict that can exist between economic and sustainability objectives. This conflict can be addressed using a multi-objective model, similarly to Louhichi, Flichman and Zekri (1999).

In the model used by Louhichi et al (1999), there are two objectives, economic and environmental, to which correspond two weighting coefficients, in the 1992-2000 time period. The economic objective is to maximize the expected net actualized revenue while minimizing its deviation with respect to nature and price states. The environmental objective is to minimize the soil loss caused by erosion. For the environmental objective, the Erosion Productivity Impact Calculator (EPIC) model is used. This is a model developed by the USDA-ARS of Temple (USA) in order to simulate the impacts of soil, climate, crop practices and rotations on soil erosion as well as the long-term impact of soil erosion on the crop yield. The authors have calibrated the model using available data relative to wheat production and have validated it for several crop productions. Their model illustrates the conflicts and trade-offs between short-run profits and soil degradation (through erosion).

1.5 Conclusion

We have seen that the expected increase in global population seems to require a considerable increase in global food production. From a global point of view, global political and social stability and equity are at stake (Tilman et al, 2002), but at the country scale, this agricultural production challenge is also related to competitiveness

and economic growth issues. To be competitive, French agriculture has to be productive and sustainable, and soil quality appears to play an important role both as a lever for productivity and sustainability. Actually, the decrease in soil quality induced by agricultural practices can be irreversible if a critical threshold is reached, which would have tragic consequences for agriculture and food production: The problem of achieving sustainable and productive agriculture is deeply linked to the problems of soil quality and degradation (Lal, 2015).

These considerations explain why concepts such as EIA are very appealing: They propose a highly productive and sustainable agriculture based on the use of ecosystem functionalities, among which soil and soil quality play a primary role. Another interesting feature of EIA is that it puts farmers at the center of the approach. However, the EIA concept is relatively new, and for EIA to be widely adopted, a good understanding of the points of view and constraints of the different stakeholders is necessary (Bonny, 2011). Here, the focus is on soil quality preservation and enhancement measures and the constraints affecting the adoption of such measures.

Based on the literature, it appears that the adoption of soil conservation measures depends on whether soil quality or potential soil productivity are linked to the farm resale value; on the costs incurred by adopting such measures compared to its benefits in terms of productivity; and on the possibility of substitution between soil fertility and conventional inputs. The problem is that farmers might not be induced by an optimal soil degradation rate because of a lack of information, market imperfections and political distortions. Indeed, we have seen that soil degradation effects may not be detected at first when using fertilizer inputs, for instance, while at some point, the soil will be irreversibly degraded. Moreover, the empirical studies related to soil conservation and soil degradation are usually limited by data availability and quality (Barbier, 1998). In addition, in economic models, soil quality is usually reduced to soil depth, and soil degradation to soil erosion. Integrated models allow for a more precise and accurate modelling of soil quality and the interactions between soil quality, crop productivity and farming practices.

Overall, it appears that there is a real economic issue of soil degradation that needs to be addressed. While there is an established interest in maintaining soil quality in order to sustain agricultural production in the long run, there are investment costs in the short run; together with imperfect land markets, short-run substitutes to soil fertility and unexpected consequences from agricultural policies, this can lead to a non-optimal rate of soil degradation. This can have detrimental impacts on farm productivity, profit-

ability and competitiveness. EIA seems to provide a solution that reconciles the long-run and short-run objectives of sustainability and profitability. Actually, EIA proposes the re-appropriation of ecosystem functionality optimization, among which soil and soil properties have an important role. Furthermore, the relationships between soil quality and crop production have been widely acknowledged both in agronomic and economic studies, which makes the EIA approach relevant with respect to the emphasis it places on soil quality and soil conservation.

However, in order to establish the legitimacy of EIA as a new agricultural production concept, it is necessary to study whether its propositions are relevant to farmers from an economic point of view.

It is therefore important to determine whether considering soil quality as an endogenous production factor can allow for the success of the EIA in France in terms of profitability and sustainability. It is thus necessary to establish how the interactions between soil quality, soil productivity and farm profitability can be modeled in order to better understand them. Then, the objective is to determine whether, based on a given context and set of constraints, farming practices aiming at maintaining or enhancing soil quality can ensure the profitability and sustainability of the farm system when soil quality is explicitly considered as an endogenous production factor. In practice, such a model should make it possible to determine an optimal soil degradation rate for a given farm system, which might be used as a decision tool. However, this would necessitate taking into account aspects that are not specifically studied here, such as farmers' perceptions of soil and soil quality and the variables that are actually considered by farmers when making decisions to invest in soil conservation.

In order to address this problematic, it seems relevant to use a dynamic farm-level optimization model since it is related to the optimal use of a natural resource. Since such models determine optimal levels of decision variables over time, it should allow us to estimate whether conservation practices, such as those proposed by EIA, are fully optimal with respect to the profitability and sustainability of farms. In addition, since our focus is on farmers' decisions, we do not consider off-site consequences of soil quality degradation.

The next chapter is dedicated to the bioeconomic modelling of soil quality in the context of EIA. In the first part, bioeconomic models designed to study soil degradation and conservation measures are presented. Then, the theoretical framework is presented. Finally a dynamic theoretical model is proposed.

Chapter 2

Bioeconomic Modelling: A theoretical framework

IN this chapter, we present a theoretical bioeconomic model designed to address the relevance of the EIA recommendations, which can be implemented through soil conservation practices to achieve productive, profitable and sustainable agricultural practices. A bioeconomic model is a mathematical representation of a managed biological system describing biological processes and predicting the effects of management decisions on those processes (King et al, 1993; Janssen and van Ittersum, 2007) as well as the consequences of resources management strategies in terms of economic performance measures - for instance, profit (King et al, 1993). Since we focus on farmers' decisions at the farm scale, the model designed here is a farm-level bioeconomic model.

In the first part, we present some farm-level soil quality bioeconomic models that were used as a basis for our framework. Then, the methodological framework of our model is presented, where the objective of the model is explained as well as the elements to consider.

Afterward, our bioeconomic model is exposed. It represents the relationships between farming practices, such as chemical input use, crop rotation, crop residue use, tillage intensity, soil quality, crop production, and the revenue of the farmer. It is assumed that the objective of the farmer is to maximize his revenue in the long run and hence to have a system that is both profitable and sustainable, where soil quality is an endogenous production factor impacted by the farmer's practices. Such a comprehensive model makes it possible to clarify the relationships and trade-offs between farming practices, soil quality

and production.

2.1 Literature Review: Soil quality as a production factor and an endogenous variable in optimization models

There are various levels of bioeconomic modelling according to the sophistication of the economic and environmental features of the model. Integrated models such as biophysical models, presented in the previous part, are well-balanced in the sense that they integrate both economic and environmental models. However, bioeconomic models can emphasize either the economic or the environmental aspects of the situation studied.

This study focuses on farmers' management decisions related to soil quality; when the latter is acknowledged as an endogenous production factor the farmer can have an impact through his or her management decisions. Thus, in this section, farm-level bioeconomic models are presented. Most of the models presented are dynamic models, some of which add recursion in their modelling. In addition, in all these models, soil quality is considered as a production factor that can be impacted by the farmer's agricultural practices (see Table 2.1).

First, models are presented that are dynamic but not recursive, where the interest of considering soil quality changes and the impact on farm productivity over several periods of time is discussed. Then, the relevance of adding a recursive feature to dynamic optimization models is introduced along with studies that include it when considering soil quality.

2.1.1 Of the use of a dynamic approach

Static models do not explicitly take into account time and obtain an optimal value at a given point in time, whereas dynamic models take time into account explicitly (Blanco Fonseca and Flichman, 2002). According to Blanco Fonseca and Flichman (2002), three types of dynamic models can be distinguished: (1) recursive models that are run over several periods, where optimization is performed separately for each period, and the initial conditions of each period are the end values of the previous one; (2) inter-temporal models, where an objective function is optimized over the whole time period (Janssen and van Ittersum, 2007); and (3) dynamic recursive models, where the model is solved inter-temporally over an N-year planning horizon, and the results obtained for the first year of the period are used as the initial resources of a new model solved for the next

References	Agricultural practices	Soil quality variables	Model type
McConnell (1983)	Productive inputs and conservation inputs	Soil depth	Inter-temporal
Saliba (1985)	Management intensity, crop rotation and soil conservation effort	Soil depth and other soil attributes, conditioning soil productivity or quality	Inter-temporal
Louhichi et al (1999)	Tillage, fertilizers, lime, pesticides, irrigation, drainage	Percolation, erosion, nutrients (nitrogen and phosphorus), soil temperature)	Dynamic recursive
Smith et al (2000)	Crop rotation, tillage practice and fertilizers	Soil characteristics: organic carbon, inorganic carbon, pH, salt	Inter-temporal + recursive feature (soil quality)
Hediger (2003)	Management intensity, crop intensity	Soil productivity as a function of soil depth and other attributes	Inter-temporal
Kim et al (2001)	Rotation and fertilizer application	A unique soil quality variable Q	Dynamic recursive
Dogliotti, van Ittersum and Rossing (2005)	Irrigation, mechanization, crop protection level	Exogenous variable : soil type ; Endogenous variables : soil erosion, soil organic matter, N surplus, and indicator for the environmental impact of pesticides in the soil	Static
Quang et al (2010)	Choice of livestock and crops, allocation of crops and inputs to plots of various qualities, adoption of soil conservation techniques	Soil nutrients: nutrient export (harvest removal, erosion, leaching) and nutrient import (manure, crop residues, roots, atmospheric deposition of nitrogen and mineralization)	Recursive
Berazneva et al (2014)	Application rates of nitrogen fertilizer and share of maize residues left on the field	Soil organic carbon - exogenous soil attributes are considered in the calibration of the soil carbon equation (average monthly mean air temperature, monthly precipitation, monthly evaporation, soil depth, soil clay content)	Inter-temporal + recursive feature (soil organic carbon)

Table 2.1 – Agricultural bioeconomic models: management decisions and soil quality variables.

(Source: from Issanchou (2014))

year, considering also an N-year planning horizon, and so on, making the model recursive over the whole period (Barbier and Bergeron, 1999).

When studying soil quality changes, a dynamic approach is particularly relevant. Indeed, soil dynamics involve slow processes, and studying the effect of management practices on soil quality requires taking into account the cumulative changes (Rhoton, 2000). For instance, when Malhi et al (2006) study the impact of tillage and crop residue management on crop yield and various soil quality indicators (soil organic C and N, inorganic N and aggregation,...), they consider the cumulative amount of these different parameters. Consequently, the impact of conservation practices on crop yield is not immediate (Malhi et al, 2006). For similar reasons, Rhoton (2000) consider the evolution of soil characteristics when studying the influence of time on soil response to no-till practices. Thus, in many aspects, a dynamic approach of soil quality conservation practices and its impact on farm productivity and sustainability seems highly relevant, particularly when aiming at considering the feedback on yields of a decrease in soil quality in the long term.

Nevertheless, static models can be used as an exploratory analysis to assess a particular situation (Brown, 2000) as in Dogliotti, van Ittersum and Rossing (2005). In a static model, they study the conflict between two objectives, economic and environmental, in order to determine whether vegetable farmers in Uruguay can increase their income, reduce soil erosion and improve physical and biological soil fertility. Although they are able to consider the impact of some agricultural practices on soil organic matter, for instance, they do not allow for considering farmers' strategic decision making in the long run. Hence, according to the objective and context of the study, a static approach can be considered, even when considering soil quality changes. However, such an approach remains limited and consists more in a preliminary step.

2.1.2 Of the use of an optimal control approach

The optimal control approach seems relevant to our case since such models address the issue of the optimal use of resources (Zilberman, 1982; Nakhumwa, 2004; Lobo Pereira et al, 2013) while considering the trade-offs between degradation of the natural resources of soil by certain farming practices and the conservation of soil resources by other practices (Foudi, 2012). Indeed, soil quality can be considered as a dynamic stock that is renewed or degraded by the actions of the farmer, which can be considered as a flow. Optimal control models make it possible to formalize these processes in the long term. Actually, the optimal control approach has been widely used when addressing soil management

issues, both theoretically and empirically, as in McConnel (1983), Saliba (1985), Smith et al (2000), Hediger (2003) and Berazneva et al (2014), for example.

Saliba (1985) proposes a dynamic framework when studying soil erosion, arguing that it is soil loss cumulative effects on both soil quality and crop yields that are of importance. As a consequence, it is to these cumulative effects that the farmer potentially accommodates his management practices. To make explicit the interactions between management decisions, soil loss and long-term farmland productivity, Saliba (1985) proposes an optimal control dynamic theoretical model. In this model, the farmer maximizes the present value of net revenues from crop production as well as the market value of crop land in the final period. The farmer is constrained by the vulnerability of his lands to erosion, initial soil depth and an upper limit for input and level of management intensity. Soil conservation is expressed as a decision variable and soil depth as a state variable. Even though other soil quality attributes are mentioned, they are considered similar to soil depth in their behavior and impact on soil productivity. The interesting aspect of Saliba's model is that it takes into account the possible trade-offs between production inputs, soil conservation efforts and intensity of crop rotations¹. From this theoretical model, Saliba draws the conclusion that private incentives to reduce soil erosion depend not only on farmland vulnerability to erosion but also on the farmers' perceptions of erosion effects on land productivity and land value.

In his article, Hediger (2003) submits an extension to Saliba's model by proposing an "agricultural Hartwich rule", where when investing soil rents in alternative capital to ensure a constant level of income, both on-farm and off-farm effects of soil erosion are addressed. Similarly to Saliba (1985), soil quality is captured by the soil depth and other attributes that are fixed. The control variable is the intensity of cultivation, which is an aggregate index determined by the input intensity (inputs per hectare) and the crop intensity (the share of erosive crops in the effective crop mix).

The models proposed by Saliba (1985) and Hediger (2003) can be considered as inter-temporal models according to the classification of dynamic models proposed by Blanco Fonseca and Flichman (2002). Indeed, their model is not recursive, although it may be relevant to include a recursion feature in the model.

1. Crop rotation intensity is considered in Saliba (1985) as the percentage of rotation in row crops as opposed to forage crops.

2.1.3 Of the use of a recursive approach

Recursive models are run over several periods, and an optimization program is performed separately for each period. The periods are interlinked due to the fact that the results of one period are the initial conditions of the next period (Blanco Fonseca and Flichman, 2002). According to Blanco Fonseca and Flichman (2002), recursive models are also dynamic models since they take time into account explicitly and the decision variables depend on time. In addition, with respect to natural resources in general and soil quality dynamics in particular, it is important to model soil quality and management choices such that the resulting outcomes can feed back into the biological processes in a dynamic manner (Brown, 2000).

This is the approach adopted by Kim et al (2001) when introducing a dynamic structural model aiming at explaining current soil productivity in terms of previous management choices and predicting its evolution. To do so, they introduce recursion in their model. Actually, as Kim et al (2001) argue, soil quality changes can be considered as recursive since soil quality is not only determined by the chosen farming practices but also depends on the previous state of the soil. Thus, they model soil quality at year t as a function of the rotation index variable and soil quality at year $t - 1$. Consequently, the production itself is recursive since it depends on soil quality.

The article by Smith et al (2000) is interesting in that they explicitly model soil quality as a production factor. Moreover, contrary to Saliba (1985) and Hediger (2003), the authors do not reduce soil quality to soil depth (as a consequence of soil erosion). Their objective is to determine optimal cropping systems for dry-land grain production in the northern Great Plains. The crop production function depends on soil quality attributes, considered as factors of production, and on inputs that impact or not on soil quality attributes. Soil productivity varies through time as a function of the inputs used and controlled by the farmer. Indeed, the authors consider that inputs such as fertilizer, crop rotation and tillage practice determine long-term soil quality levels through biological processes in the soil. The recursive aspect of soil quality dynamics is present in the constraints of the model: Soil quality attributes are a function of past levels of soil quality attributes in addition to the outcome of the soil quality attribute function, which depends on previous soil quality attributes and previous inputs per activity that impact on soil quality. However, there is no recursion with respect to net returns since previous net returns are not modeled to influence the choice of management practices. In the empirical part of the study, the authors use four soil quality attributes that impact

productivity, are measurable and for which data are available: organic carbon, inorganic carbon, pH and salt (electrical conductivity). Then, the crop production function and the optimization component are estimated. According to their results, there is an economic incentive for grain producers in the northern Great Plains to adopt farming practices that maintain and increase soil quality.

Although Quang et al (2010) do not use a farm-level model but a multiple agent system (MAS), they consider individual farmers' private decisions, independently from other farmers and recursively at an annual time step. Actually, using an integrated bio-economic model, Quang et al (2010) analyze the effect of an environmental tax on the unsustainable use of sloping lands in Vietnam; this tax is designed to correct the non-optimal rate of soil erosion induced by farmers due to the short-run conflict between conservation measures and farm profitability. In the short run, improved varieties and mineral fertilizers over-compensate soil fertility losses in spite of the high soil erosion induced by maize and cassava cultivation. However, in the long run, such crops lead to dramatic levels of soil erosion and also have negative externalities in terms of water pollution and downstream soil fertility. One additional interesting aspect of their study is that soil fertility dynamics are endogenous as well as farm decision making. Soil fertility dynamics are modeled and estimated using the Tropical Soil Productivity Calculator (TSPC). The agent optimizes the expected net farm income, subject to resource constraints, food consumption needs, knowledge and innovations and expectations about market prices and crop yields. Control variables include the choice of livestock and crops, allocation of crops and inputs according to the quality of plots, and the adoption of soil conservation techniques.

Based on the various articles we review in this part, it appears that modelling soil quality must consider the dynamic and recursive aspects of the relationship between soil quality changes in agricultural management choices. More precisely, considering the recursive aspects of the dynamics of soil quality, that is, considering the impact of current soil quality on future soil quality, does not imply that the model is recursive in the sense of Blanco-Fonseca and Filchman (2002).

2.2 Theoretical framework

In order to set the boundaries of the bioeconomic theoretical model and clarify them, a theoretical framework is proposed. First, the objective of the model is presented. Then, the elements that have to be considered in the model are mentioned and explained.

2.2.1 Objective of the model

The objective of the model is to determine whether EIA practices related to the maintenance or enhancement of soil quality, considered as an endogenous production factor, are relevant to achieve a profitable, productive and sustainable mode of agriculture at the farm level. To this end, a theoretical optimal control model that optimizes the farmer's profit is proposed under a soil quality motion constraint, where soil quality is also a production factor. Then, from the functional forms of the production and soil quality functions and parameters estimation, optimal values of management practices should be determined. Our hypothesis is that, at optimum, practices that maximize a farmer's profit in the long run correspond to practices proposed within the EIA concept. The EIA practices related to soil quality are the same as conservation practices: reduced or zero-tillage, the use of crop residues and cover crops, and crop rotations.

Compared to the model proposed by Saliba (1985), the model proposed here does not consider only the changes in soil depth but also changes in other soil quality characteristics impacting soil agricultural productivity and crop production. These characteristics are taken into account by Smith et al (2000), although they do not account for the use of crop residues and cover crops, whereas we do. Indeed, these are practices that protect the soil from water and wind erosion and enhance soil quality (Verhulst et al, 2010). In addition, similarly to Quang et al (2010), soil fertility dynamics and farm decision making are considered as endogenous. However, we do not consider the effect of public policies on the farmers' decision to adopt or forego conservation practices. Actually, the objective of the model is to determine the optimality of conservation practices at the farm level from a private perspective.

Hence, the model that is proposed can be classified as a normative mechanistic model² according to the classification proposed by Janssen and van Ittersum (2007). Indeed, normative approaches are used to find optimal solutions or alternatives to resource management problems. In our case, the resource management issue is related to natural soil resource degradation. Our approach can be considered as mechanistic since the model is built on existing theory and knowledge (Janssen and van Ittersum, 2007).

2. To go further and predict actual farmers' behavior, a positive approach might be preferred. It would require taking into account the process of diffusion of an innovation (Janssen and van Ittersum, 2007).

2.2.2 Elements to be considered in a comprehensive farm-level soil quality model

A comprehensive farm-level soil quality model should (Saliba, 1985; Brown, 2000; Smith et al, 2000):

- a) Be dynamic
- b) Be recursive
- c) Contain functional relationships which capture the impact of farm management choices (the control variables) on soil quality characteristics (the state variables)
- d) Include variables which reflect changes in soil quality
- e) Include crop yield functions that incorporate soil attributes, substitution possibilities and management variables

Hence, for a comprehensive understanding of the relationship between soil quality, farming practices and farm productivity and sustainability, it is necessary to consider management decisions; to determine which soil quality characteristics are relevant and how to model soil quality³; to estimate crop-specific yield functions; and to consider land value, which implies taking into account the market value and impact of tenure management. In addition, all these elements have to be considered with respect to the study area characteristics. Before proposing a theoretical bioeconomic model, these elements are discussed.

2.2.2.1 Study area

It is important to consider and describe the study area. In fact, the various characteristics of the study area, such as climatic, topographical and hydrologic parameters, together with intrinsic soil quality attributes, are the determinants of the suitability of a soil to agriculture (Carter, 2002). These characteristics can influence both soil quality attributes and management impacts⁴. Hence, the relationships between management practices, soil quality and crop production are to some extent site specific (Knowler and Bradshaw, 2007; Verhulst et al, 2010).

In a previously mentioned study, Bhalla and Roy (1988) emphasize the importance of the study area characteristics in terms of weather and agro-climatic conditions. They

3. Either using a land quality index or a proxy (Saliba, 1985), considering each soil quality characteristic separately (Smith et al, 2000) or estimating a soil quality function (Kim et al, 2001).

4. For instance, in terms of SOC content, management impacts are sensitive to climate (Ogle et al, 2005).

propose an alternative specification of their reduced form equation using agronomic zones to classify households based on criteria such as moisture index, thermal index and soil class.

2.2.2.2 Management decisions: conservation practices and substitution possibilities

Management decisions correspond to conservation practices and substitution possibilities. There are three farming practices at the core of conservation agriculture: reduced or no tillage, use of crop residues and cover crops⁵, and crop rotations (Knowler and Bradshaw, 2007; Verhulst et al, 2010). According to Verhulst et al (2010), although these three principles can be applied to a wide range of crop production systems and agro-climatic conditions, the application of these principles depends on the biophysical and social conditions of the area considered. Other farming practices fall under conservation practices, such as ridge tillage, contour farming, subsoiling, intercropping, maintenance and establishment of permanent grassland, agroforestry, buffer strips, and bench terraces (Louwagie, Gay and Burrell, 2009).

In 2006, cover crops represented 17 % of the spring crop at the national level in France, mainly in Midi-Pyrénées and in regions where the adoption of cover crop practices were motivated by the implementation of the Nitrates Directive (Bretagne, Champagne-Ardenne, Nord-Pas-de-Calais and Picardie). Simplified tillage practices represented 34 % of the main crop areas in 2006, mainly in the southwest and north of France, and are used more for winter crops (42 %) than for spring crops (17 %) (Louwagie et al, 2009). In 2011, simplified tillage practices represented 39.6 % of the main crop areas (*Enquêtes pratiques agricoles*, 2011). On the other hand, no-tillage was practiced only on 1.5 % of the national agricultural land area in 2006 (Louwagie et al, 2009). It seems that simplified tillage practices in France were used mainly for durum wheat and common wheat, at least in Midi-Pyrénées, which is the region where conservation agriculture practices are the most extensively adopted. The adoption of diversified crop rotation in France is more difficult to assess; however, there seems to be a trend in simplifying crop diversity in specialized areas and rotations including grain maize and durum wheat. Rotations including peas, potatoes, sugar beet, rapeseed, barley or common wheat vary more (Louwagie et al, 2009).

5. Crop residues and cover crops should be distinguished: Crop residues can either be exported, buried or left on the soil surface. The last option corresponds to a land cover strategy. Burying soil residues still corresponds to a soil conservation strategy and can be associated with a land cover.

Other practices, such as the use of fertilizers, herbicides and pesticides can be considered either as substitution possibilities for conservation practices or complements (Wezel et al, 2014). For instance, the use of chemical inputs, such as inorganic fertilizers, is a substitution possibility for soil quality and can mitigate a decrease in soil quality (Smith et al, 2000). However, the use of inorganic fertilizers can also be considered as complementary to organic fertilizers (Mekuria and Waddington, 2002; Giller et al, 2009). Furthermore, the use of herbicides and pesticides can be considered as both a complement to conservation practices (Knowler and Bradshaw, 2007; Giller et al, 2009) and a substitute to the pest and disease maintenance induced by conventional tillage (Knowler and Bradshaw, 2007).

An additional difficulty when modelling conservation practices and substitution possibilities is properly representing the interactions among practices and also their feasibility. Actually, conservation agriculture *combines* the three basic principles (Verhulst et al (2010) mentioned above. Applying just one practice, or several but inappropriately, may not result in significant soil conservation.

2.2.2.3 Soil quality characteristics

The dynamic aspect of the model allows for the integration of changes in soil quality characteristics due to management practices as well as the change in crop yield function. Hence, the soil quality characteristics considered should reflect soil productivity and be sensitive to changes in production practices (Smith et al, 2000).

Actually, as seen previously, when considering soil quality, some attributes reflect the intrinsic soil quality when others reflect the dynamic soil quality. Intrinsic soil quality attributes, which can be considered static, together with climatic, topographical and hydrologic parameters, are the determinant of the suitability of a soil to agriculture. However, agricultural practices strongly influence the dynamic soil quality attributes (Carter, 2002).

Nevertheless, it is more convenient for our modelling purpose to distinguish exogenous soil quality attributes from endogenous soil quality attributes⁶. According to the classification proposed by Carter (2002), one could consider that intrinsic soil quality attributes are exogenous and dynamic attributes endogenous. However, such classifica-

6. Soil quality attributes are said to be exogenous if they determine the values of other variables but are not determined by other variables. Endogenous soil quality attributes designate soil quality variables whose values both determine and are determined by other variables in the model.

tion can be misleading, given that soil and crop management also have an impact on the inherent soil quality (Karlen, 1993). In fact, depending on the subject treated (conservation measures, drivers of farm productivity, and so on) and the objective of the model, some soil indicators that are considered as exogenous are modeled as endogenous in other studies⁷.

Hence, whether a soil quality attribute is considered as endogenous or exogenous depends on the objective of the model and on the other variables included. In Table 2.2, we propose a list of soil quality characteristics that are impacted by conservation practices and are assumed to have an impact on soil productivity and crop yield (Verhulst et al, 2010). Soil quality characteristics are divided into three groups (physical, chemical and biological), as a reference to the three types of processes determining soil quality (see Lal, 1998). Two are considered as exogenous, soil type and soil texture.

From Table 2.2, it appears that not all conservation practices have an impact on a given characteristic, and when they do, they can have adverse impacts. In many cases, the impacts of conservation measures are inconclusive or not well estimated.

7. An example with respect to soil depth: In Bhalla and Roy (1998), soil depth is used as an exogenous variable to explain differences in productivity. However, in Saliba (1985), where erosion issues are addressed, soil depth is considered as an endogenous variable (since it is impacted by the farmers' decision and impacts crop yield).

	Soil Characteristics	Exogenous / Endogenous	Influenced by
Physical soil quality	Soil type	Exogenous	
	Soil erosion (soil depth)	Endogenous	Tillage (+), crop residues (-), climate, topography
	Soil texture or particle size ⁸	Exogenous	
	Soil structure	Endogenous	Tillage, crop rotation
	Soil porosity	Endogenous	Tillage, crop residues (?)
	Hydraulic conductivity and water-holding productivity	Endogenous	Tillage (?), residue (+)
Chemical soil quality	Soil water balance	Endogenous	Tillage (?), crop residues (?)
	Soil temperature	Endogenous	Tillage (+), crop residues (-), ¹⁰ Climate, ¹¹ water content
	Soil organic carbon	Endogenous	Tillage (?) ¹² , crop residues (+) ¹³ , crop rotation (?) ¹⁴ , fertilizer (+) ¹⁵ , climate
	Nutrient availability	Endogenous	Tillage (+) ¹⁶
	Soil acidity (or pH)	Endogenous	No-tillage (?), nitrogen and phosphorus fertilizers (+), residue (-), soil type
	Salinity	Endogenous	No-tillage and crop residue (+), fallow (+), crop rotation (?) ¹⁸ , soil type ¹⁹
Biological soil quality	Soil microfauna and microflora ^{8 17}	Endogenous	Tillage (-), crop residue (+), crop rotation (?), climate
	Soil meso and macro fauna ¹⁶	Endogenous	
(?): Impact not well estimated, complex to estimate or inconclusive; (+): Positive impact; (-): Negative impact ²⁰			

Table 2.2 – Exogenous and endogenous soil quality attributes.

(Sources: from *Karlen (1993)*, *Karlen et al (1997)*, *Edwards and Bohlen (1996)*, *Schreinemachers (2006)*, *Verhulst et al (2010)*, *Issanchou (2014)* and *Palm et al (2014)*)

8. Explain the difference in effects of tillage + influence other soil quality attributes.
9. Linked with Soil Organic Matter.
10. Stabilization of soil temperature.
11. In tropical climate, a lower soil temperature has a positive effect on crop yield, but has a negative one in temperate climate.
12. Combined with soil residue and crop rotation, no-tillage has a positive effect on SOC. This increase is often limited to the near-surface layer
13. In experimental designs, the separate effect of crop rotations is confounded with tillage
14. Depends on the amount and composition of the residues.
15. Increases the amount of labile organic carbon.
16. May be due to the placement of crop residue: in surface with no-tillage and incorporated with tillage.
17. Including pest species.
18. May reduce pathogen carry-over and reduce pest pressure.
19. Has a role in the impact of tillage and crop residue on functional diversity.
20. The terms positive and negative refer to the sign of the expected impact of an agricultural practice on the indicator considered.

2.2.2.4 Crop-specific yield function

A given level of soil characteristics can be considered as bad or good quality depending on the crop grown (Letey et al, 2003). As a consequence, modeling the relationships between changes in soil quality indicators and crop yield requires the use of crop-specific yield functions. Indeed, all crops do not have the same potential yield depending on the agro-ecological conditions of the study site (Bindraban et al, 2000), and they can have different reactions to changes in soil indicators (Letey et al, 2003). In addition, in studies where farmers' choices in terms of crop rotation are studied, it is all the more interesting not only to have crop-specific yield functions but several of them, at least for what concerns the main crops in the study areas considered.

For instance, in their estimation of the on-site costs of erosion, Magrath and Arens (1989) distinguish different groups of crops according to their sensitivity to erosion. Reciprocally, different crops do not have the same impact on the erosion rate, independently of inherent soil characteristics and management practices (Bandara et al, 2001).

According to Flichman, Louhichi and Boisson (2011), such functions should be described using an engineering production function approach. Actually, they argue that such a primal representation of technology, which quantifies physical quantities and not monetary ones, allows for a better understanding of the underlying biophysical processes and for a clearer representation of the production process.

Smith et al (2000) calibrate their crop yield function on wheat using data from a soil quality experiment and an experiment on different soil depths in cultivated plots, both in Canada. From the pooled data, they extracted the mean value or range for the variables contained in their crop yield function. In these experiments, the crop used was spring wheat (Olson et al, 1996).

Louhichi et al (1999) calibrate and validate the EPIC model using five crops (barley, durum wheat, oat, oats of hay and wheatgrass). The EPIC model is a simulation model that can be used as a crop production function that takes into account climate, soil properties, management practices and crop rotation for each crop considered (Vicien, 1991).

In their study, Holden et al (2005) also propose specific-crop yield functions, which for each crop depend on soil type, soil depth, slope, application of fertilizer and manure (converted into nitrogen and phosphorus), and conservation technology. The crops considered by Holden et al (2005) are barley, wheat, horse bean, and other food crops (field pea, lentil and linseed).

Belhouchette et al (2012), in their bio-economic farm model, use the Cropping Systems Simulation Model (CropSyst) to model the relationships between crop production and environmental effects. One of the reasons they use the CropSyst model is that the CropSyst has been evaluated for the main crops in their study area.

2.2.2.5 Land value and planning horizon

Our theoretical comprehensive farm-level soil quality model is a normative model: While comprehensively describing the relationships between farm management choices, soil quality characteristics and production, it also aims at providing insights into the optimal strategies or trade-offs that should be observed to attain an optimum.

From this perspective, one could consider that in this normative framework, where the agent is rational and is not biased toward the present or the future, (*i.e.* the farmer has no preference between the future or the present), the discount rate should be equal to 0 and thus would not play any role in the maximization problem. However, this is not the choice we made here. The discount rate is still considered in order to be able to consider the impact of a change in the discount rate on the choices made by the farmer during the period considered and in the final period.

In the final period of the planning horizon T , the market value of the land is considered. This also allows us to consider the aspects of the transmission of the land, which is then endogenous.

Market value According to Lefebvre and Rouquette (2011)²¹, the determinants of an agricultural parcel price are the soil characteristics in general as well as soil quality, topography, and climate; these determinants are known by the seller and the buyer but do not appear in the data. To account for them, one can use the potential revenue and the principal orientation of the farms located in the same municipality²² (Lefebvre and Rouquette, 2011). Ay et al (2012) use the hedonic method to estimate the economic importance of the natural attributes of the land, taking into account soil attributes (water retention, soil texture, organic matter) and topographical attributes (altitude, slope, exposure). From their analysis, conducted for land transactions in Côte d'Or (France), they find that the land topographical attributes are noticeably higher priced than soil attributes, and both attributes have a significant role in land pricing. Ay et al (2012) interpret their results as emphasizing the natural capital status of land natural attributes and challenging the idea according to which land heterogeneity is based on farm yields; it might rather be based on the complementarity between natural capital and reproducible capital (equipment, labor).

The market value of an area of agricultural land also depends on the agricultural land rent, the location of the land (with respect to the closest town or city to the farm or the accommodation), the landscape quality, government support for agriculture, and the consequences of global warming, as well as the urban influence. Actually, since the land market value is the capitalization of future land rents, residential rents can be included when they are anticipated, which is more likely to be the case in areas under a strong urban influence (Rouquette, Mesrine and Cavailhès, 2011). Hence, the spatial dimension is important in the future value of the land and will have particular importance in the empirical version of our model, whether the farm and the lands associated are regions characterized by arable and livestock production or by strong demographic pressure (Lefebvre and Rouquette, 2011). In France, the land market value and the associated determinants vary depending on the region.

Depending on the land tenure management, the determinants of the land market

21. Lefebvre and Rouquette (2011) study land market evolution, in particular the evolution of arable land and pasture price determinants, using the hedonic pricing method.

22. For instance, whether the farms within the same area are oriented toward arable crops, mixed crops or livestock farming, viticulture or horticulture.

value are different and less numerous. For instance, the size of the parcel has no impact on the price of rented land, whereas it has an impact on that of freehold land (Lefebvre and Rouquette, 2011).

Land tenure and legacy value McConnell (1983) takes into account the impact of land tenure arrangements on the farmer's incentives to invest in soil conservation measures. He names three prevailing land tenure arrangements: owned family farms, rented family farms and corporate farms. The distinction between these tenure arrangements is made according to the planning horizon: The planning horizon is $T\theta$, where $\theta = 1$ for owners and $\theta = 0$ for renters. Since the farm resale value is unimportant to renters, the only reason they have to adopt soil conservation practices is relative to the soil productive capacity (McConnell, 1983). Within the framework proposed by McConnell, there are no distinctions between the behavior of owned family farms and corporate farms.

In France, in 2010, almost two-thirds of the French agricultural surface was cultivated by renters. It seems that productivity investment, including soil fertility enhancement, is similar between renters and owners (Courleux, 2011): Hence, much like what is described in McConnell (1983), if maintaining soil quality affects soil productivity, both renters and owners have incentives to adopt and invest in conservation practices²³. However, contrary to the case described by McConnell (1983), in some cases, renters might have the same planning horizon as owners.

Actually, in France, renters have, to some extent, a lease of unlimited duration²⁴. In addition, the lease can be ceded in favor of their spouse or descendants, which refers to the principle of property transmission (Barthélémy, 2000). As a consequence, although the land is rented, it can have a legacy value. In addition, in the case where the cultivated land is sold, the lease is planned to continue. Furthermore, the renter has priority among the potential buyers (pre-emptive right): Farmers buy more than two-thirds of the agricultural lands exchanged, and 41 % is land where farmers have asserted their pre-emptive

23. Indeed, when contracting a lease, a state of the property is established that aims to determine the enhancements performed by the renter or the degradation suffered by buildings, land and crops based on a precise inventory of the state of the buildings and lands, as well as the level of maintenance of lands and their average yields during the past 5 years (Code rural et de la pêche maritime, article L411-4). Hence, it seems that renters have an incentive to maintain the soil quality and productivity of the land.

24. The term rural lease refers to a period of at least 9 years, but long-term leases exist that are extended to a minimum of 18 or 25 years (Code rural et de la pêche maritime, article L411-5 and articles L416-1 to L416-3). The lease is automatically renewed unless the farmer cannot pay his rent or the owner exercises his right to take over the farm for himself or a member of his family, having provided proof of his ability to exploit the farm, both in terms of equipment and a minimal level of ability and professional experience (Courleux, 2011). The lease can be written

rights²⁵ (Courleux, 2011). Hence, in the French case, the planning horizon is likely to be comparable between renters and owners, in particular since land rent seems more and more to be a transition to land ownership in agriculture (Lefebvre and Rouquette, 2011). However the influence of the tenure arrangement on whether the farm market value is taken into account is less clear: Maintaining and improving land quality has a positive impact on land productivity, which in turn positively impacts crop yield and farm revenue, which would tend to increase the land market value. However, rented lands are less expensive than non-rented lands (Lefebvre and Rouquette, 2011).

Nonetheless, there are leases that are less favorable to farmers and that can be considered more precarious. For instance, the lease can also last the farmer's entire career (Code rural et de la pêche maritime, articles L416-4 to L416-5). However, this kind of lease can be considered more precarious since it cannot be passed on. In addition, the transferable lease created by the Agricultural Outline Act 2006-11 of 5 January 2006, although allowing the farmer to lease outside the family environment, is otherwise less favorable to the farmer than the "classical" rural lease mentioned above. Indeed, the lease lasts 18 years and is then renewable every 5 years, but it is far easier for the lessor to terminate the contract. Moreover, the farmer's preemption right is more restrictive (JORF n°5 du 6 janvier 2006, p. 229).

2.3 A comprehensive theoretical bioeconomic control model

2.3.1 Continuous time versus discrete time analysis

Using optimization in discrete time or continuous time depends on various elements. First, it depends on whether time is viewed as passing in given periods or continuously. In the first case, the control variables are chosen in every time period. In the second case, it is the flow of the value of the profit function that is controlled over time and the lifetime value of the profit function that is maximized. In this case, the solution gives a function of the control variables over time. In this respect, the choice of a continuous or discrete time framework is not clear: On one hand, farmers make their management choices periodically, so that it is relevant to describe their behavior in a discrete manner (see Louhichi et al, 1999); on the other hand, soil (and natural) processes evolve in a continuous manner, so that in this respect, a continuous time framework can be chosen (see Yirga and Hassan, 2010).

25. During the period 2000-2007 (see Courleux, 2011).

In fact, the choice between continuous and discrete time optimization is not clear in the literature either. It appears that in general, at least in the literature reviewed here, theoretical articles use a continuous time framework (see McConnell, 1983; Saliba, 1985; Barbier, 1990; Hediger, 2003) when discrete time frameworks are used in some applied articles (see Louhichi et al, 1999; Smith et al, 2000). The use of continuous time optimization in theoretical articles can be explained by the more powerful mathematical instruments; in addition, it seems that optimal control theory is developed more in continuous time, so that many formulas in continuous time are simpler than similar ones in discrete time (Groth, 2011).

Finally, it depends on the discrete and continuous nature of the variables and data. For instance, in the optimal control model proposed by Yirga and Hassan (2010), farmers maximize the sum of discounted streams of future net returns, and control variables (levels of fertilizer, production and conservation labor, and capital inputs) are continuous: As a consequence, the model describes a continuous optimization problem. Although Smith et al (2000) study similar issues, they apply a discrete time formulation of their optimization problem. Indeed, while maximizing farmers' net returns over time, the control variables they use (number of crop rotations and tillage practices) are not continuous, so that they prefer to use a discrete time framework for their optimization problem.

Since this section is devoted to the proposition of a theoretical bioeconomic model, the continuous time approach is chosen.

2.3.2 A continuous optimal control framework

The theoretical model proposed here is built on the works of McConnell (1983), Saliba (1985), Smith et al (2000), Hediger (2003) and Yirga and Hassan (2010). In the model, conservation practices are used as decision variables. Soil quality is incorporated through the endogenous and exogenous soil attributes that characterize it. The consequence of soil quality in terms of soil productivity is captured by the relationships between soil attributes and crop yields. The trade-offs and inter-dependencies between conservation and conventional practices are highlighted by including them as decision variables (see Figure 2.1).

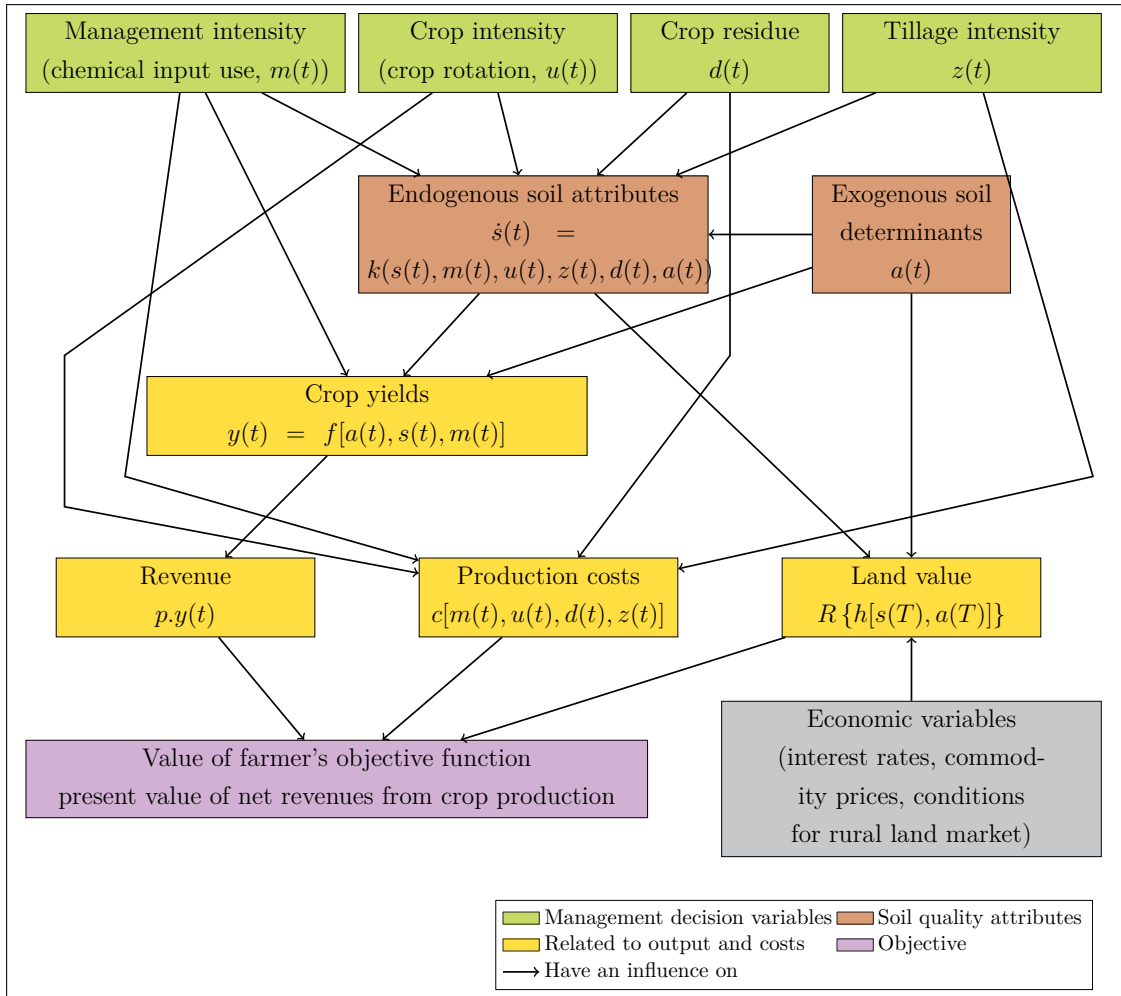


Figure 2.1 – Variables and functions in the farm-level soil quality model.

(Sources: adapted from Saliba (1985) and Smith et al (2000), Issanchou (2014))

Here are the notations used to denote variables in the Figure, model and discussion:

$s(t)$ = endogenous soil attributes,

$a(t)$ = exogenous soil determinants,

$m(t)$ = management intensity,

$u(t)$ = crop intensity,

$d(t)$ = crop residue,

$z(t)$ = tillage intensity,

r = discount rate,

T = terminal year in the planning horizon,

c = per unit cost of inputs,

p = price received for farm output,

$y(t)$ = crop output and

$R\{h[s(T), a(T)]\}$ = market value of land at the end of the planning horizon.

2.3.2.1 Production function

Crop production per hectare $y(t)$ depends on endogenous soil attributes s and on management intensity m :

$$y(t) = f[s(t), m(t), a(t)] \quad (2.1)$$

This function satisfies the following assumptions²⁶:

$$f_s > 0, f_m > 0, f_{ss} < 0, f_{mm} < 0 \quad (2.2)$$

$$f_{sm} \underset{\geq}{\leq} 0, f(\underline{s}, m, a) = 0 \quad (2.3)$$

$$y(t) \leq f(\bar{s}, \bar{m}, \bar{a}) \quad (2.4)$$

The production function is $C^{(2)}$ (twice continuously differentiable) and, as in Goetz (1997) and Hediger (2003), assumed to be strictly concave. If soil endogenous soil quality increases, crop production increases ($f_s \geq 0$), but the higher the soil quality is, the slower the increase in production ($f_{ss} \leq 0$). Similarly, crop production increases with the amount of chemical input ($f_m \geq 0$); however, the higher the chemical input level, the lower the increase in production ($f_{mm} \leq 0$). In some cases, application of chemical inputs and soil quality are cooperating when the latter is low or in transition from conventional to conservation practices ($f_{sm} > 0$) (Smith et al, 2000; Mekuria and Waddington, 2002). This also means that the impacts of chemical inputs and soil quality on crop production are not separable. The combined use of the chemical inputs and soil quality in this case is beneficial to crop production. However, in some cases, the combined use of chemical inputs and soil quality has a negative marginal impact on crop production. In this case, we consider that they are no longer cooperating. This may correspond to a case where soil quality and chemical inputs are substitutes when the marginal productivity of chemical inputs decreases with higher soil quality ($f_{sm} < 0$), which is the argument used by EIA to promote conservation agriculture. Soil is considered as essential for production. The critical threshold under which soil quality is degraded irreversibly is denoted \underline{s} . Below this threshold, input use is not sufficient to ensure agricultural production.

Assumption (2.4) means that the crop production per hectare is equal or inferior to the highest potential crop production, realized by the highest soil quality attainable,

26. We denote by $f_{x_i} = \partial f(\dots, x_i, \dots) / \partial x_i$ the partial derivative of any function f with respect to x_i and by $f_{x_i x_j}$ the partial derivatives at the second order.

the maximum amount of fertilizers, and the most benefits to the crop exogenous determinants. The highest potential crop production corresponds to a situation where biomass growth is unstressed and not limited by factors such as water or nitrogen (following the determination of biomass accumulation in biophysical models such as CropSyst (Stöckle, Donatelli and Nelson, 2003)).

Furthermore, soil quality cannot increase indefinitely. According to Gil-Sotres et al (2005), there are two approaches to what should be considered the maximum soil quality: (1) a soil in equilibrium within its environment, leading to long-term stability in natural ecosystems and (2) a soil capable of maintaining high productivity with the lowest environmental disturbance, where the soil productive function is emphasized. The latter approach corresponds more to our problematic. However, Smith et al (2000) seem to adopt an approach closer to the first one. Considering soil organic carbon (OC) as a proxy for endogenous soil quality, they use a study from Janzen et al (1998) to estimate the biological long-term equilibrium of soil OC.

2.3.2.2 Soil quality function

In addition, the motion of endogenous soil attributes over time depends on management practices²⁷ :

$$\dot{s} = k(s(t), m(t), u(t), z(t), d(t), a(t)) \quad (2.5)$$

For which the following assumptions are made:

$$k_s < 0, k_m \begin{matrix} \geq \\ \leq \end{matrix} 0, k_u > 0, k_z \begin{matrix} \geq \\ \leq \end{matrix} 0, k_d > 0, \quad (2.6)$$

$$k_{ss} > 0, k_{mm} < 0, k_{uu} < 0, k_{zz} < 0, k_{dd} < 0, \quad (2.7)$$

$$k_{du} \geq 0, k_{zu} \leq 0, k_{zd} \leq 0, k_{zm} < 0, k_{um} \begin{matrix} \geq \\ \leq \end{matrix} 0, k_{uz} \geq 0, k_{dm} < 0 \quad (2.8)$$

$$k_{sm} \begin{matrix} \geq \\ \leq \end{matrix} 0, k_{su} > 0, k_{sd} > 0, k_{sz} \begin{matrix} \geq \\ \leq \end{matrix} 0 \quad (2.9)$$

The function describing soil quality is $C^{(2)}$. Such an assumption does not take into account the threshold effects that can be observed in soil quality changes. For instance, when considering soil organic carbon (SOC), SOC changes can be considered as continuous during the transition from one equilibrium to another equilibrium, attained after a sufficient time during which a given practice has been implemented (Janzen et al, 1998).

27. For simplicity and clarity, time indices are dropped from some equations

Four management variables are considered. Three are practices corresponding to the basic principles of conservation agriculture (Knowler and Bradshaw, 2007; Verhulst et al, 2010): tillage intensity $z(t)$, expressed as a percentage, where the maximum tillage intensity corresponds to deep tillage and the minimum to zero-tillage and directly drilled; use of crop residues $d(t)$ and crop rotations $u(t)$ expressed as the percentage of green manure and legumes in the rotation^{28 29}. The fourth management variable is related to the use of chemical inputs $m(t)$ and encompasses substitution possibilities³⁰: The larger that $m(t)$ is, the more chemical inputs that are applied.

It is assumed that the higher the proportion of green manure and legumes in the rotation, the more that soil quality is improved ($k_u > 0$) (Cook and Haglund, 1991, Migliarina et al, 2000), but the effect of green manure diminishes with soil quality ($k_{uu} < 0$). When properly implemented, soil quality is improved when crop residues are left ($k_d > 0$) (Denef et al, 2002; Kumar and Goh, 2002) but more slowly when the amount of crop residue is higher ($k_{dd} < 0$). Crop residues and legume rotation are cooperating with respect to soil quality ($k_{ud} > 0$) as measured by nutrient availability (Kumar and Goh, 2002) or pest control (Kladivko, 2001).

Tillage is assumed to have both positive and negative impacts on soil quality ($k_z \gtrless 0$) (Lal et al, 1993). Indeed, stable aggregation and a high level of organic matter are favored by no or superficial tillage (Barthès et al, 1998). In addition, the impact of tillage alone on soil quality depends on various factors, including climate, seasons and soil structure, so that in some cases, tillage would be recommended (Heddadj et al, 2005). In addition, some systems can require a certain amount of controlled tillage to function (Verhulst et al, 2010). To take this into account, it is assumed that a decrease in tillage intensity slowly increases soil quality ($k_{zz} < 0$). However, reduced tillage has a positive impact on soil quality when associated with green manure in the rotation and

28. With respect to endogenous soil attributes, it seems more significant to consider the presence of green manure in crop rotations than wheat or fallow.

29. Tillage intensity and crop intensity/rotation are described here in a continuous way. However, tillage practice and crop rotations are not continuous variables, so that the way they are included in this simplified model is not totally accurate. In a discrete time framework, the description of these variables is different; however, assumptions relative to their respective effects on soil quality are similar in discrete and continuous time.

30. Integration of management intensity in the soil quality function can be discussed. Indeed, one could consider chemical input impact only through the production function (see Kim et al, 2001). Smith et al (2000) take into account fertilizer inputs both in the production and organic carbon equilibrium functions; however, in the production function, fertilizer inputs are described in terms of the amount of mineral nitrogen and phosphorus applied, whereas in the organic carbon equilibrium function, the impact of fertilizer inputs is captured using a binary variable. In the production function we propose, the impact of chemical inputs on crop-yield is taken into account, as well as its complementarity or substitutability with soil quality.

crop residues (Barthès et al, 1998; Verhulst et al, 2010) and can be seen as cooperating. On the contrary, an increased tillage intensity is not cooperating with the use of green manure and crop residues ($k_{zu} < 0$ and $k_{zd} < 0$). When tillage is intensive, we assume that its impacts on soil quality are not influenced by green manure ($k_{zu} = 0$) or crop residue ($k_{zd} = 0$).

The fourth variable, relative to management intensity and chemical input use m , can either have a negative or positive impact on soil quality ($k_m \geq 0$). Management intensity, in terms of crop protection products, is increasing with the reduction in tillage intensity ($k_{mz} < 0$), so that to some extent, management intensity can be considered as a substitute to tillage practices. When done appropriately and once fully integrated in the system, diversified crop rotations and crop residues can be considered as substitutes to chemical input uses ($k_{um} < 0, k_{dm} < 0$). However, during the transition phase (from conventional to conservation practices) chemical inputs and diversification of crop rotations can be seen as cooperating ($k_{um} > 0$).

As for the relationship between current soil quality and agricultural practices, tillage intensity and management intensity can be considered as cooperating or not cooperating with soil quality with respect to the increase in soil quality ($k_{sm} \geq 0$ and $k_{sz} \geq 0$) depending on the level of soil quality. However, crop rotations and crop residue are assumed to be cooperating with the current soil quality ($k_{su} > 0$ and $k_{sd} > 0$).

2.3.2.3 Maximisation problem

As in Saliba (1985), crop prices, input prices and interest rates are exogenous and constant. For each activity, costs encompass labor and energy costs. Similarly to Hediger (2003), we consider as constant crop prices p , marginal costs of chemical input use c_1 and tillage c_2 , and the marginal costs associated with the increased complexity of higher crop intensity c_3 as well as the opportunity cost of leaving a crop residue c_4 . Thus, the real net revenue per hectare is such that:

$$\pi(t) = pf(s(t), m(t), a(t)) - c_1m(t) - c_2z(t) - c_3u(t) - c_4d(t) \quad (2.10)$$

The sustainability of the system requires the real net revenue per hectare to be constant or increasing. From Eq. (2.10), the differential equation for the inter-temporal change in net revenue is:

$$\dot{\pi}(t) = [pf_m - c_1]\dot{m}(t) + pf_s\dot{s}(t) - c_2\dot{z}(t) - c_3\dot{u}(t) - c_4\dot{d}(t) + pf_a\dot{a}(t) \quad (2.11)$$

The farmer chooses the levels of the control variables $m(t)$, $u(t)$, $d(t)$ and $z(t)$ at each point in time in order to maximize the net present value of returns.

In a continuous optimal control framework, management variables continually respond to accumulating effects on soil quality and crop yields (Saliba, 1985). The maximization problem of the farmer is such that:

$$\text{Max}_{u,z,m,d} \int_0^{T \rightarrow \infty} e^{-rt} [pf(s(t), m(t), a(t)) - c_1 m(t) - c_2 z(t) - c_3 u(t) - c_4 d(t)] dt \quad (2.12)$$

$$\text{subject to: } \dot{s}(t) = k(s(t), m(t), u(t), d(t), z(t), a(t)) \quad \text{Soil quality motion} \quad (2.13)$$

$$s(0) = s_0 \quad \text{Initial soil quality} \quad (2.14)$$

$$0 \leq s(t) \leq s_{max} \quad \text{Bounds on soil quality} \quad (2.15)$$

$$0 \leq z(t) \leq 1 \quad \text{Bounds on tillage intensity} \quad (2.16)$$

$$0 \leq u(t) \leq 1 \quad \text{Bounds on crop intensity} \quad (2.17)$$

$$0 \leq d(t) \leq d_{max} \quad \text{Bounds on crop residues} \quad (2.18)$$

$$0 \leq m(t) \leq m_{max} \quad \text{Bounds on management intensity} \quad (2.19)$$

When considering the boundary conditions, this optimization problem can be described through the following Lagrangian:

$$\begin{aligned} L(m, u, z, d, s, \lambda) = & e^{-rt} [pf(s(t), m(t), a(t)) - c_1 m(t) - c_2 z(t) - c_3 u(t) - c_4 d(t)] \\ & + \lambda(t) (k(s(t), m(t), u(t), d(t), z(t))) \\ & + \zeta m(t) + \varepsilon(m_{max} - m(t)) + \alpha z(t) + \beta(1 - z(t)) + \gamma u(t) + \delta(1 - u(t)) \\ & + \mu d(t) + \eta(d_{max} - d(t)) \end{aligned} \quad (2.20)$$

Case of the interior solution

Assuming an interior solution, that is, a solution where all decision variables take a value that is within the set of values delimited by the boundary conditions (*i.e.* $\zeta = \varepsilon = \alpha = \beta = \gamma = \delta = \mu = \eta = 0$), this optimization problem can be described through the

following Hamiltonian:

$$H(m, u, z, d, s, \lambda) = e^{-rt}[pf(s(t), m(t), a(t)) - c_1m(t) - c_2z(t) - c_3u(t) - c_4d(t)] \\ + \lambda(t)(k(s(t), m(t), u(t), d(t), z(t))) \quad (2.21)$$

According to the maximum principle, the optimal paths of m , u , z , d , s and λ satisfy ³¹:

$$H_m = e^{-rt}[pf_m - c_1] + \lambda k_m = 0 \Leftrightarrow e^{-rt}[pf_m - c_1] = -\lambda k_m \quad (2.22)$$

$$H_z = e^{-rt}(-c_2) + \lambda k_z = 0 \Leftrightarrow e^{-rt}c_2 = \lambda k_z \quad (2.23)$$

$$H_u = e^{-rt}(-c_3) + \lambda k_u = 0 \Leftrightarrow e^{-rt}c_3 = \lambda k_u \quad (2.24)$$

$$H_d = e^{-rt}(-c_4) + \lambda k_d = 0 \Leftrightarrow e^{-rt}c_4 = \lambda k_d \quad (2.25)$$

$$\dot{\lambda} = -H_s \Leftrightarrow \dot{\lambda} = -e^{-rt}[pf_s] - \lambda k_s \quad (2.26)$$

Condition (2.22) states that the foregone benefits of using more chemical inputs in terms of net revenues have to be balanced with the opportunity costs of using more chemical inputs in terms of soil quality marginal value. From condition (2.23), at the optimum, tillage intensity is such that the foregone costs of tillage are balanced with tillage benefits in terms of soil quality marginal value. Similarly, at optimum, the farmer adds legumes or green manure in his rotation such that the foregone costs associated with a more complex crop intensity are equal to its benefits in terms of soil quality marginal value (condition (2.24)). In addition, the farmer leaves crop residues on the parcel such that the foregone costs associated with crop residue management are balanced with the benefits from leaving crop residues in terms of soil quality marginal value (condition (2.25)). The costate equation (2.26) introduces the rate of change of the costate variable λ , the soil quality shadow price. It implies that changes in soil quality marginal value $\dot{\lambda}$ depend on the discount rate r , crop prices p , the influence of soil quality on crop yield f_s , the current value of the costate variable λ and the influence of current soil quality on soil quality (strength of recursion).

For long-term profit maximization, the first conditions imply that $pf_m - c_1 = -e^{rt}\lambda k_m$, $c_2 = e^{rt}\lambda k_z$, $c_3 = e^{rt}\lambda k_u$ and $c_4 = e^{rt}\lambda k_d$ with $\lambda > 0$ being the implicit price of

31. For simplicity and clarity, soil quality attributes are presented here as a single variable in the theoretical model. In the section describing the empirical control model, both production and soil quality functions are detailed.

soil quality. Consequently, the intertemporal change in net revenue can be written as:

$$\begin{aligned}\dot{\pi}(t) &= [-e^{rt}\lambda k_m]\dot{m}(t) + pf_s\dot{s}(t) - e^{rt}\lambda k_z\dot{z}(t) - e^{rt}\lambda k_u\dot{u}(t) - e^{rt}\lambda k_d\dot{d}(t) + pf_a\dot{a}(t) \\ &= -e^{rt}\lambda(k_m\dot{m} - k_z\dot{z} - k_u\dot{u} - k_d\dot{d}) + pf_s\dot{s} + pf_a\dot{a}\end{aligned}\quad (2.27)$$

According to this equation, it is possible for the farmer to have a sustainable system, that is, to have a constant or increasing net revenue ($\dot{\pi} > 0$), while soil quality deteriorates ($\dot{s} < 0$). Similarly, the model also allows the system to be sustainable with an increasing soil quality, provided the appropriate and corresponding farm management. The question addressed here is under which conditions and farm management is the profit of the farmer constant or increasing along an intertemporally efficient time path.

Although the complexity of our model does not allow us to characterize the optimal steady state or the optimal paths leading to it or even to establish if such an equilibrium exists, it is still possible to discuss the possibility of having corner solutions.

Corner solutions : intensive practices

Let us examine if the case where the farmer uses the maximum amount of chemical inputs m_{max} and the maximum tillage intensity ($z = 1$), while crop rotations are not diversified at all ($u = 0$) and crop residues are not left on the parcel ($d = 0$), is plausible with respect to the optimality conditions of our problem.

In this case, the current value Lagrangian of our problem can be written as:

$$\begin{aligned}L(m, u, z, d, s, \lambda) &= e^{-rt}[pf(s(t), m(t), a(t)) - c_1m(t) - c_2z(t) - c_3u(t) - c_4d(t)] \\ &\quad + \lambda(t)(k(s(t), m(t), u(t), d(t), z(t))) \\ &\quad + \varepsilon(m_{max} - m(t)) + \beta(1 - z(t)) + \gamma u(t) + \mu d(t)\end{aligned}\quad (2.28)$$

The first-order conditions can be written as:

$$L_m = [pf_m - c_1] + \lambda k_m - \varepsilon = 0 \Leftrightarrow [pf_m - c_1] + \lambda k_m = \varepsilon > 0 \quad (2.29)$$

$$L_z = (-c_2) + \lambda k_z - \beta = 0 \Leftrightarrow -c_2 + \lambda k_z = \beta > 0 \quad (2.30)$$

$$L_u = (-c_3) + \lambda k_u + \gamma = 0 \Leftrightarrow -c_3 + \lambda k_u = -\gamma < 0 \quad (2.31)$$

$$L_d = (-c_4) + \lambda k_d + \mu = 0 \Leftrightarrow -c_4 + \lambda k_d = -\mu < 0 \quad (2.32)$$

Such a case is plausible. According to condition (2.29), the maximum use of chemical inputs can occur in the situation where the benefits from using one additional unit of

chemical input in terms of revenue is higher than the possible negative impacts of the chemical input. Tillage intensity is at the maximum when the condition (2.30) is met, that is, when the cost of tillage is lower than the benefits in terms of soil quality marginal value (condition (2.30)). As can be expected, the situation where crop rotations are not diversified and crop residues are not used corresponds to the case where the costs of diversifying crop rotation and the costs associated with the use of crop residues are higher than the corresponding benefits of one additional unit of the variable considered, so that the farmer has no interest in using them (conditions (2.31) and (2.32)).

Since none of these conditions are contradictory, *a priori* such a situation could arise.

Corner solutions : conservation practices

Let us examine if the case where the farmer uses the minimum amount of chemical inputs ($m = 0$) and the minimum tillage intensity ($z = 0$), crop rotations are totally diversified ($u = 1$) and crop residues are all left on the parcel ($d = d_{max}$) is a plausible case with respect to the optimality conditions of our problem.

In this case, the current value Lagrangian of our problem can be written as:

$$\begin{aligned} L(m, u, z, d, s, \lambda) = & e^{-rt} [pf(s(t), m(t), a(t)) - c_1 m(t) - c_2 z(t) - c_3 u(t) - c_4 d(t)] \\ & + \lambda(t) (k(s(t), m(t), u(t), d(t), z(t))) \\ & + \eta m(t) + \alpha z(t) + \delta(1 - u(t)) + \eta(d_{max} - d(t)) \end{aligned} \quad (2.33)$$

The first-order conditions can be written as:

$$L_m = [pf_m - c_1] + \lambda k_m + \eta = 0 \Leftrightarrow [pf_m - c_1] + \lambda k_m = -\eta < 0 \quad (2.34)$$

$$L_z = (-c_2) + \lambda k_z + \alpha = 0 \Leftrightarrow -c_2 + \lambda k_z = -\alpha < 0 \quad (2.35)$$

$$L_u = (-c_3) + \lambda k_u - \delta = 0 \Leftrightarrow -c_3 + \lambda k_u = \delta > 0 \quad (2.36)$$

$$L_d = (-c_4) + \lambda k_d - \eta = 0 \Leftrightarrow -c_4 + \lambda k_d = \eta > 0 \quad (2.37)$$

Such a case is plausible. For the condition (2.34) to be verified, the minimum use of chemical inputs can occur in two situations: (1) when chemical inputs negatively impact soil quality ($k_m < 0$), and the benefits from using one additional unit of chemical inputs in terms of production (pf_m) cannot compensate for the cost of using chemical inputs (c_1) and the marginal cost of chemical inputs use in terms of soil quality marginal value (μk_m); or (2) when chemical inputs positively impact soil quality ($k_m > 0$), but nevertheless, the benefits of using one additional unit of a chemical input in terms of gross profit

(pf_m) and soil quality marginal value (μk_m) are still lower than the cost of one unit of chemical input (c_1). Tillage intensity is at a minimum when the cost of tillage is higher than its benefits in terms of soil quality marginal value or when tillage has a detrimental impact on soil quality (condition (2.35)). As can be expected, the situation where crop rotations are the most diversified and crop residues are the most used corresponds to the case where the costs of diversifying crop rotation and the cost associated with the use of crop residues are lower than the corresponding benefits of one additional unit of the variable considered, so that the farmer has an interest in using them (conditions (2.36) and (2.37)).

Since none of these conditions are contradictory, *a priori* such a situation could arise.

2.3.3 Land tenure and patrimonial value

In the previous setting, since the profit of the farmer is maximized over an infinite planning horizon, the terminal condition is not considered.

Let us now maximize the farmer's profit on a T -years planning horizon, so that in addition to the profit, the market value of the land at the end point in his planning horizon, $R\{h[s(T), a(T)]\}$, is also maximized.

The maximization problem can be written as:

$$\text{Max}_{u,z,m,d} \int_0^{T \rightarrow \infty} e^{-rt} [pf(s(t), m(t), a(t)) - c_1 m(t) - c_2 z(t) - c_3 u(t) - c_4 d(t)] dt \quad (2.38)$$

$$\text{subject to: } \dot{s}(t) = k(s(t), m(t), u(t), d(t), z(t), a(t)) \quad \text{Soil quality motion} \quad (2.39)$$

$$s(0) = s_0 \quad \text{Initial soil quality} \quad (2.40)$$

$$0 \leq z(t) \leq 1 \quad \text{Bounds on tillage intensity} \quad (2.41)$$

$$0 \leq u(t) \leq 1 \quad \text{Bounds on crop intensity} \quad (2.42)$$

$$0 \leq d(t) \leq d_{max} \quad \text{Bounds on crop residues} \quad (2.43)$$

$$0 \leq m(t) \leq m_{max} \quad \text{Bounds on management intensity} \quad (2.44)$$

The first-order conditions characterizing the optimal paths of m , u , z , d , s and λ are once

again (2.22), (2.23), (2.24), (2.25), with in addition the terminal condition, which is such that:

$$\lambda(T) = e^{-rT} \frac{\partial R\{h(s(T), a(T))\}}{\partial s(T)} \quad (2.45)$$

Equation (2.45) is the transversality condition according to which, in the final period T , the marginal value of soil quality corresponds to soil quality impact on land market value.

Land tenure and both land market and patrimonial values are likely to impact soil quality rate of change, through the planning horizon and investment incentives (McConnell, 1983).

Following McConnell (1983), by taking into account different lengths of planning horizon according to land tenure arrangements (owners or renters), the family farmer then maximizes:

$$\text{Max}_{u,z,m,d} \int_0^{T\theta} e^{-rt} [pf(s(t), m(t), a(t)) - c_1 m(t) - c_2 z(t)] dt + e^{-rT} \theta R\{h(s(T), a(T))\} \quad (2.46)$$

subject to constraints (2.39) to (2.44) and such that $\theta = 1$ for owners, and $\theta = 0$ for renters. The first-order conditions of this maximization problem are the same as for equations (2.22) to (2.26), except that:

$$\lambda(T_\theta) = e^{-rT\theta} \frac{\partial R\{h(s(T_\theta), a(T_\theta))\}}{\partial s(T_\theta)} \quad (2.47)$$

Hence, for the renter, soil quality changes are such that marginal value of soil quality or user cost of soil quality is zero in the last period. This suggests that soil quality has been used and has decreased during the previous periods. The only reason renters conserve soil is for its productive capacity. When renters do not perceive soil quality as having an impact on productivity, they ignore the soil quality motion equation.

The same reasoning could apply to owners when soil quality does not influence land market value, or inadequately. In these cases, for a given impact of soil quality on productivity, investment in soil conservation measures is lower than in the optimal case.

Considering the French case, where farmers can benefit from an unlimited rural lease that can be passed on to their close relatives, it can be interesting to distinguish between long-term and short-term renters. In such a case, the maximization problem can

be written such that:

$$\text{Max}_{u,z,m,d} \int_0^{T\theta} e^{-rt} [pf(s(t), m(t), a(t)) - c_1m(t) - c_2z(t)]dt + e^{-rT} \Theta R\{h(s(T), a(T))\} \quad (2.48)$$

subject to constraints (2.39) to (2.44), and such that $\theta = 1$ for owners and long-term renters, $\theta = 0$ for short-term renters, $\Theta = 1$ for owners, and $\Theta = 0$ for short-term and long-term renters.

Deeper theoretical analysis of the stationary equilibrium and its dynamics would require a simpler model, in which decision management variables that negatively and positively affect soil quality are grouped together. In such a simplified model, prices and policy effects could be more easily considered.

2.4 Conclusion

In the economic literature, farm-level bioeconomic models addressing soil resources management issues consider soil quality as an endogenous production factor, and most of the approaches reviewed are dynamic. Actually, soil dynamics involve slow processes and cumulative changes, and to take them into account, a dynamic approach is appropriate. Integrating a recursive feature in the model makes it possible to consider the resilience properties of soils. Here, models are considered as having a recursive feature, where at minimum, current soil quality depends on the previous quality of the soil.

The theoretical framework proposed here is based on the key elements found in the literature review, adapted to meet the objective of our model. The objective of the model is to determine whether EIA practices related to the maintenance or enhancement of soil quality, considered as an endogenous production factor, are relevant to achieve profitable, productive and sustainable agriculture at the farm level.

To do so, a normative mechanistic model has been proposed that is built upon the economic and agronomic literature. It is a dynamic model with a recursive feature that contains functional relationships between farming practices (chemical input use, crop rotation intensity, crop residue use and tillage intensity), soil quality characteristics, and crop yield functions. In this model, soil quality is considered as an endogenous production factor in the farmers' decision-making process and is not reduced to only one characteristic. Indeed, in economic models, soil quality is usually reduced to soil depth and soil degradation to soil erosion. The main elements to consider in an empirical

application of this model are present, and the discussion relative to the impacts of farming practices on soil quality shows how complex these relationships are, even when simplified.

Nonetheless, as simplified as it may be, the model accurately represents the substitution and complementary relationships between the various variables and, in particular, the cooperating relationship between soil quality and chemical inputs. Deeper and further theoretical analysis of the stationary equilibrium and its dynamics requires simpler models, in which decision management variables are grouped together whether they negatively and positively affect soil quality. In such a simplified model, prices and policy effects could be more easily considered through a qualitative analysis of the equilibrium situation. It also requires the cooperating inputs hypothesis to be simplified.

Thus far, we based our hypothesis on results from the agronomic and economic literature. In the following chapter, we investigate from a statistical point of view the relationships between soil quality dynamics, crop yields, and productive inputs for a specific region of France. The objective is to confront the literature review results with our statistical results in order to better choose and discuss how we can simplify the hypothesis of our theoretical framework, in particular regarding the productive cooperative relationship between soil quality and fertilizer inputs.

Chapter 3

Empirical relationships between soil quality, crop yield and farming practices: Evidence from the Grand Ouest of France

THIS chapter investigates the relationship between soil quality indicator dynamics and farming practices and the relationship between productive inputs, soil quality indicators and crop yield using a statistical approach. The objective is to compare the crucial relationships between farming practices, soil quality and crop yield described in the literature and in our theoretical framework with what can be observed from an actual data set. The results will be used to discuss the simplification of the hypothesis in our theoretical framework.

Actually, in order for our theoretical framework to be mathematically solvable, we have to simplify our hypothesis. This concerns the hypothesis relative to the cooperative relationships between productive inputs (such as fertilizers and crop protection products) and soil quality and those relative to the relationships between productive inputs and soil quality dynamics.

Through our literature review, it has been demonstrated that farming practices impact soil quality and soil quality impacts crop production. Here, we establish whether the relationships between farming practices and soil quality parameter dynamics described in the literature can be observed in our study area, the Grand Ouest, using statistical

tools. The Grand Ouest is defined here as the the western part of France that includes four administrative regions: Bretagne, Normandie (formally Basse Normandie and Haute Normandie), Pays de la Loire and Poitou-Charentes, now part of a larger region (see Figure 3.1).

To conduct our statistical analysis, we built a database combining soil quality data, farming practice data and crop yield data. These data have been aggregated from different databases and different geographic and time scales. As such, it is also a methodological reflection on the construction of a sound database from the aggregation of different geographic scale data in a context of constrained accessibility of data.

Actually, in order to capture statistically significant and meaningful correlations between soil quality parameters, farming practices and crop production, one interesting statistical analysis would have been to conduct time series analysis over a time period of a minimum of 3 years - to take into account rotation effects - at the scale of the parcel. Since such data are not available, we conducted our analysis using data from public French databases at the cantonal and regional scale. Farming practices data, relative to nitrogen and phosphorus fertilizers, as well as tillage practices, are collected from surveys conducted by the French office of statistics and forecasting. They are available online for the years 2001, 2006 and 2011 (DISAR platform, Agreste website). Crop yield data are obtained from the Annual Agricultural Statistics issued each year (DISAR platform, Agreste website). Soil indicator data are available online on the BDAT website at the cantonal level. Since data relative to farming practices are only available for the years 2001, 2006 and 2011, it did not seem relevant to conduct a time series analysis on three distant periods. Instead, we have used linear regression techniques.

In what follows, first, the characteristics of the study area are presented since the relationships between farming practices, soil quality and crop production are likely to vary with the climatic, geographic and geologic context. Then, a statistical analysis of the dynamics of soil quality parameters in our study area is proposed in order to establish whether significant changes in soil quality parameters can be observed throughout the time period considered. In a third part, we have estimated whether correlation can be observed between farming practices and changes in soil quality parameters in “reality” - that is, not in controlled situations. Changes in soil quality parameters are considered over a period of 10 to 15 years. Actually, we assume that long-lasting changes in soil quality parameters are the result of the accumulation of changes induced by crop practices. Finally, the same exercise is performed while examining the relationship between soil quality and crop yield in the Grand Ouest. For each statistical analysis, the methodology

and data are described.

3.1 Characteristics of the study area

In this part, the study area is defined and characterized through climatic, topographical and hydrologic criteria and soil typology. All of these parameters, together with intrinsic soil quality attributes, determine soil suitability to agriculture (Carter, 2002) and have an impact on the estimation of the relationships between soil quality and crop yield and management practices and soil quality (Knowler and Bardshaw, 2007; Verhulst et al, 2010).

Information provided here is illustrative: There is a relatively substantial diversity and variability in climate, topography and hydrology within regions, departments or even more local geographical units (see Cantat and Brunet, 2001). Nonetheless, such a description is interesting and represents information that could be included in our functions. Since EIA developed in the Grand Ouest and is promoted by three agricultural cooperative groups (Agrial, Terrena and Triskalia) established in this area, our study area is composed of the regions of the Grand Ouest (see the Agrial, Terrena and Triskalia websites)¹. In addition, the Grand Ouest represents an important agricultural production area, where in 2016 31 % of French cereals, 25 % of the oilseed crop, and 35 % of the protein crop were produced (DISAR web platform, agricultural annual statistics). It also represented 27 % of the French Agricultural Land Utilized in 2016 (DISAR web platform, agricultural annual statistics). Four administrative regions are considered: Bretagne, Basse Normandie, les Pays de la Loire and Poitou-Charentes (see Figure 3.1).

3.1.1 Climate

Our study area is characterized by an oceanic climate that can be differentiated into three types (Joly et al, 2010): (i) typical oceanic climate, with average and homothermic temperatures (few cold or warm days), a very low intra-annual variability in temperature and annually abundant precipitation (about 1000 mm); (ii) altered oceanic climate, which is a transition between a typical and modified oceanic climate, and (iii) modified oceanic climate, with intermediate temperatures (an annual average of about 11°C and 8 to 14 days of temperature lower than 5°C within a year), and low annual accumulated

1. The perimeter is larger than that of the cooperative groups mentioned: Since for agricultural farming practices we only have access to regional data, we include in our study area and dataset every region in which one or several departments are part of one of the three cooperative groups.

precipitation (less than 700 mm).

3.1.2 Topography

Most of Bretagne is less than 300 meters in altitude, with the highest point at 387 m. Bretagne can be decomposed into three main sections: a southern plateau, a northern plateau, which is higher and divided into a range of continuous massifs and an interior basin, and a large depression separating the two plateaus (Barbois, 1897) (see Figure 3.3).

Pays de la Loire is characterized by low elevations, from 0 to 416 m, with the Vendée Hills to the south and the Coevrons, the Alpes Mancelles and the Perche Hills to the north. Poitou-Charentes has a smooth topography, with low altitudes (100 to 200 meters on average) (Bry and Hoflack, 2004). Basse Normandie is characterized by a relatively uniform relief (about 0 to more than 431 m). However, at a more local scale, a variety of geological outcrops and erosion can be found, for instance, in Suisse Normande. Differences in topography within the same region lead to local differences in climate (Cantat and Brunet, 2001).

3.1.3 Hydrology

There is no large river in Bretagne, with the exception of the Vilaine, which occupies around 1/3 of the territory, and rather small watersheds in the North (Agrocampus Ouest, 2007). Most of the river system draining the Pays de la Loire comprises the Loire and its main affluents. Groundwater resources are hard to mobilize due to massive and impermeable rocks (*Profil environnemental des pays de la Loire* website). In Basse Normandie, due to steep slopes, rivers have a rapid surface flow, especially in the East of Calvados and the North-West littoral of Cotentin. However, surface flows are more limited in the plain of Caen and in the Bay of Mont St. Michel area (Guerin, 2003). In Poitou-Charentes, groundwater resources are important but located at low depths and hence vulnerable to climatic hazards and pollution (*Observatoire Régional de l'Environnement* website). The water regime is pluvial, characterized by high winter waters and low summer waters, with most waterways presenting floodplain with a progressive water rise and prolonged submersion. (*L'Eau en Poitou-Charentes* website).

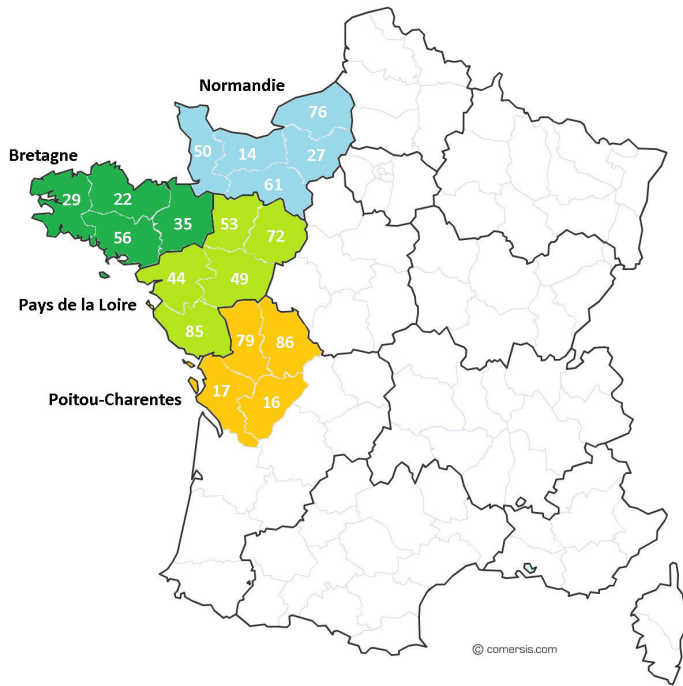


Figure 3.1 – Study area : Grand-Ouest, administrative regions and departments

Source: from the author

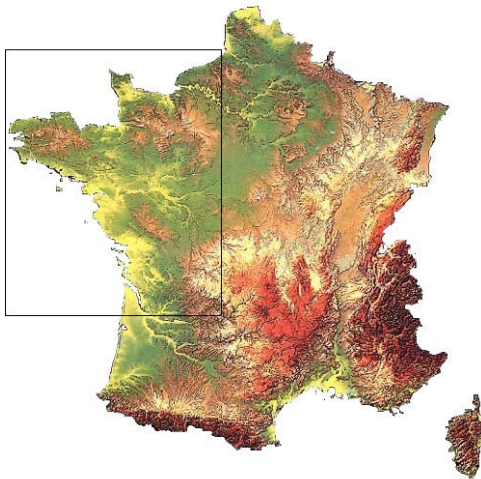


Figure 3.3 – France : Topography

Source: http://www.geowiki.fr/index.php?title=Carte_g%C3%A9ologique

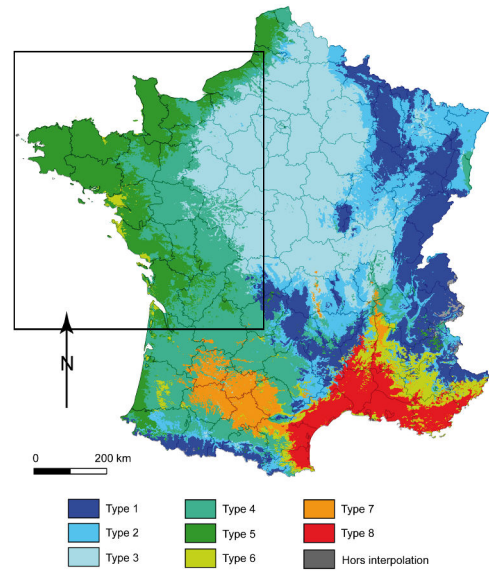


Figure 3.2 – The different climates in France

Type 1 = Mountain climate, Type 2 = Semi-continental climate and mountainous margin climate, Type 3 = Modified oceanic climate, Type 4 = Altered oceanic climate, Type 5 = Typical oceanic climate, Type 6 = Altered Mediterranean climate, Type 7 = South West basin climate, Type 8 = Typical Mediterranean climate

Source: Joly et al, 2010

Les stocks de carbone organique dans la partie superficielle du sol en France métropolitaine



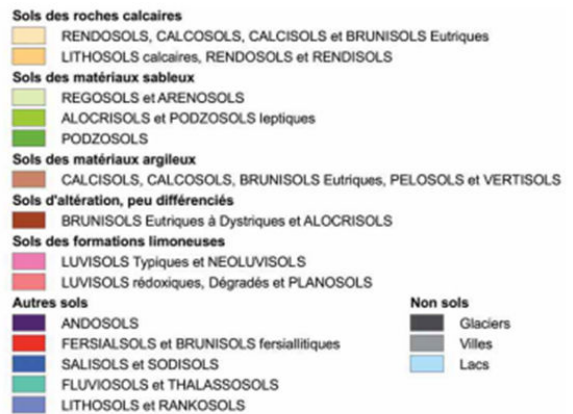
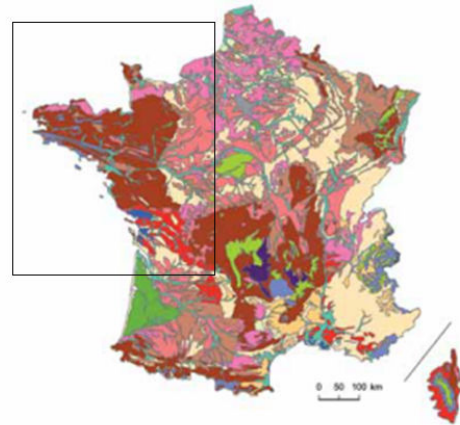
Source : Gis Sol, 2013 – d'après Meersmans et al., 2012. Traitements : SOeS, 2013.

Figure 3.4 – France : Organic carbon stocks in soil superficial layer

Source: Gissol, 2013

3.1.4 Soil typology

In this area, soils can for the most part be classified as Eutric to Dystric Brunisolic soils and Alocrisolic soils. These are weathering little differentiated soils (see Figure 3.5). One can also find soils from silty formation material (Luvisolic, Neoluvisolic and Planosolic soils), littoral soils from sandy formation material (Arenosolic, Alocrisolic and Podzosolic soils), and Fluviosolic and Thalassosolic soils, as well as Lithosolic and Rankosolic soils (Gissol, 201; Berthier, 2013). This large diversity in soil classes is accompanied by large diversity in soil endogenous and exogenous characteristics (differences in soil pH and SOM; see examples for Bretagne in Berthier, 2013 and Fig 3.4).



Source : Inra, Base de données Géographique des Soils de France à 1/1 000 000, 1996.

Figure 3.5 – The different soils in France

Source: Gissol, 2011

3.1.5 *Structure of farms*

3.1.5.1 *Size of farms*

Among the four administrative regions, the region Pays de la Loire has the highest surface of utilized agricultural land (2103393 ha in 2010, and 2092734 ha in 2013), while the highest number of farms is in Brittany (34453 farms in 2010 and 32349 farms in 2013). However, the region Basse Normandie has the smallest area of utilized agricultural land (1210808 ha in 2010 and 1229761 ha in 2013) and the smallest number of farms (23927 farms in 2010 and 21278 farms in 2013) (*Recensement agricole 2010; Enquête Structure 2013*).

In Basse Normandie, 40% of the farm area is less than 20 ha, and 56% is less than 50 ha. This region has the highest proportion of small farms. In Poitou Charentes, 29% of farm area is less than 20 ha, and 49% is less than 50 ha. In the region Pays de la Loire, 29% of the farms have an area less than 20 ha, and 45% have an area less than 50 ha. In Bretagne, 31% of the farms have an area less than 20 ha, and 54% have an area less than 50 ha. The highest proportion of farms with an area between 50 and 100 ha is in Bretagne (32% of farms). The proportion of farms with an area between 50 and 100 ha is 24% in Pays de la Loire, 21% in Basse Normandie, and 24% in Poitou-Charentes (*Enquête Structure 2013*). The highest proportion of farms with an area between 100 and 200 ha is in Poitou Charentes (22% of farms). The proportion of farms with area between 100 and 200 ha is 21% in Pays de la Loire, 18% in Basse Normandie, and 10% in Bretagne (*Enquête Structure 2007*). Farms with an area of 200ha or more are the minority: 3% of farms in Basse Normandie and Pays de la Loire, less than 1% of farms in Bretagne, and 5% of farms in Poitou-Charentes (*Recensement agricole 2010; Enquête Structure 2013*).

3.1.5.2 *Main technical economic types of farms*

In Basse Normandie, 27% of farms specialize in dairy farming, with 41% of the agricultural land allocated to this activity. 14% of farms specialize in meat livestock farming, representing 6% of agricultural land. 17% of farms specialize in other herbivores, and 11% specialize in multi-crop-livestock farming (*Enquête Structure 2013*).

In the region Pays de la Loire, the specialization is also dairy farming, which represented 18% of the farms in this region in 2013. 15% of farms specialize in crop cultures, 13% in meat production and 13% in multi-crop-livestock farming. 14% of farms special-

ized in granivores and 4% in viticulture in 2013 (*Enquête Structure* 2013).

In Bretagne, 30% of farms specialize in dairy farming. 11% of farms specialize in multi-crop-livestock farming, and 17% specialize in crop cultures. 21% of farms specialize in pork and poultry production (*Enquête Structure* 2013).

In Poitou-Charentes, 39% of farms specialize in crop cultures, representing 47% of agricultural areas. 17% of farms specialize in multi-crop-livestock farming. 16% of farms specialize in viticulture (*Enquête Structure* 2013).

3.1.6 Evolution of soil occupation in the Grand Ouest (1970-2010)

The evolution of soil occupation in the *Grand Ouest* of France is interesting to consider. It reflects the trajectories of the different departments in terms of production. Here, we use data from the Agricultural Census, from 1970 to 2010, relative to crop surface.

From Figure 3.6, we observe how the total Utilized Agricultural Land (UAL) has decreased over forty years. This is a known phenomenon due, among other reasons, to urbanization. Two of the departments whose decrease in UAL is higher than 15 % have an important city (Nantes and Rennes) located in their territory. The departments for which the decrease in UAL is less important (departments 86, 16, 17, 79 and 27) are also those that had a larger proportion of cereal crops in their UAL in 1970 (see Figure 3.7). For most of these departments, the proportion of cereals in their UAL increases over time.

Closer observation of the percentage of cereal crops within these agricultural areas reveals an overall increase in the percentage of cereal crops (see Figure 3.7). The almost inverse phenomenon can be observed for the proportion of forage and grasslands in UAL (see Figure 3.8): There is an overall decreasing proportion of these types of soil applications, except in departments 22, 29, 44, and 56, for which the proportion of lands allocated to forage and grasslands varies over time, with no clear trend.

In the departments and regions of the Grand Ouest considered here, the two main cereal crops are soft winter wheat and maize grain. In Figures 3.9 and 3.10, the evolution of the percentage of these crops in the total UAL are presented for each department. The evolution of the proportion of soft wheat is similar to the general trend observed for cereal crops. For each department, an increase in the percentage of soft wheat is observed

from 1970 to 2010 (see Figure 3.9).

The trends in the evolution of maize grain surfaces in the UAL are more heterogeneous among departments (see Figure 3.10). However, over a period of forty years, an overall increase in the proportion of maize grain surfaces can be observed. The increase is more or less substantial among departments, with substantial variations. The highest proportion of maize grain in the UAL can be historically found in Poitou Charentes, which suggests that their current main technical economic type is an inheritance of history.

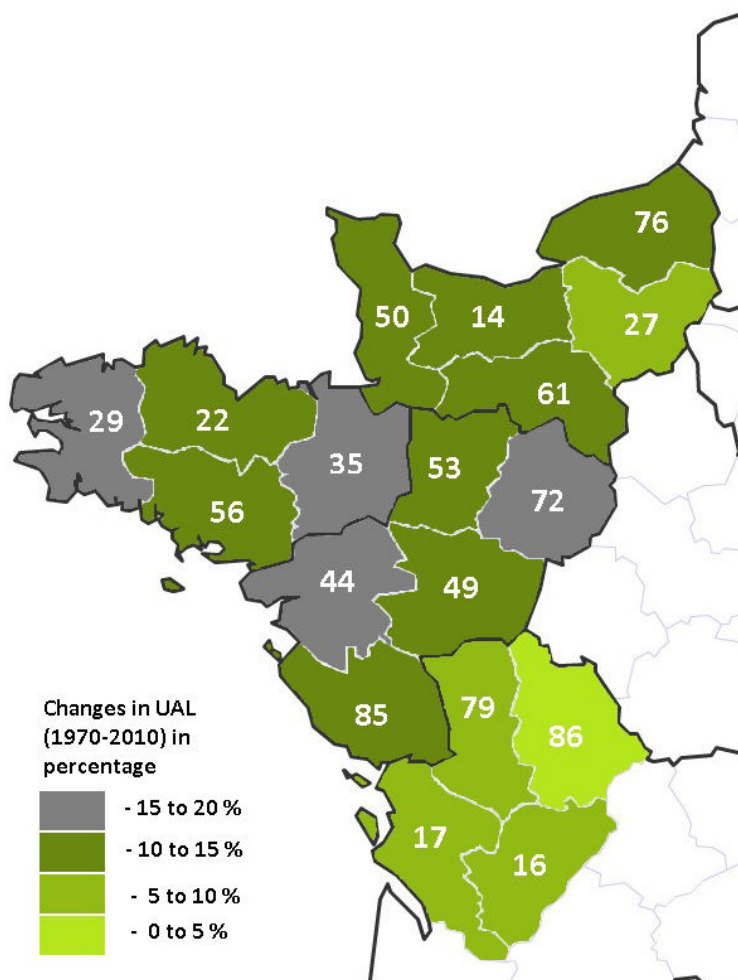


Figure 3.6 – Evolution of the total Utilized Agricultural Land (UAL) from 1970 to 2010, per department, in The Grand Ouest of France
(Source: using data from the Agricultural Census)

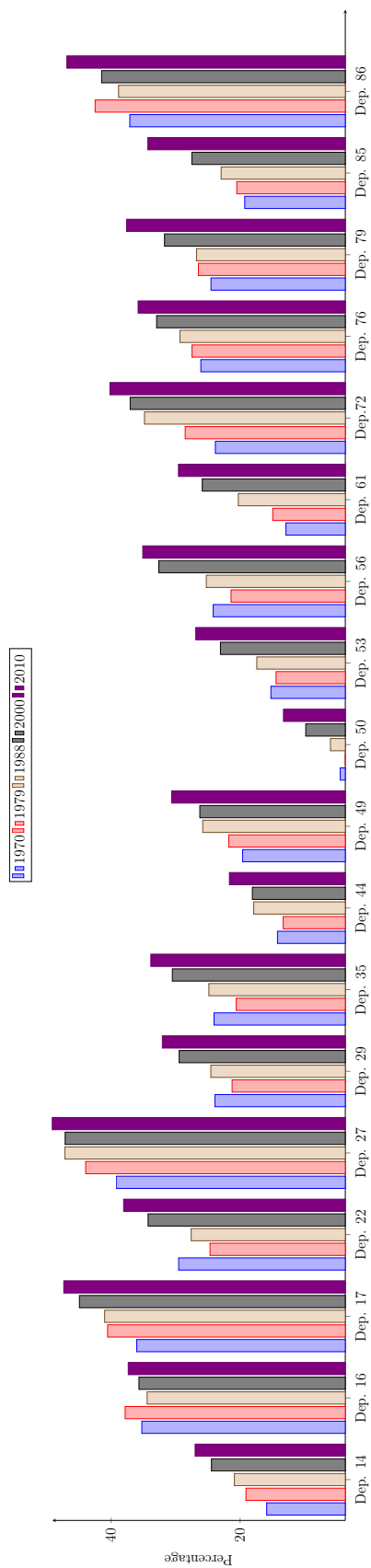


Figure 3.7 – Evolution of the cereal crops proportion in utilized agricultural land, from 1970 to 2010, per department, in The Grand Ouest of France

(Source: the author from the *Agricultural Census data*)

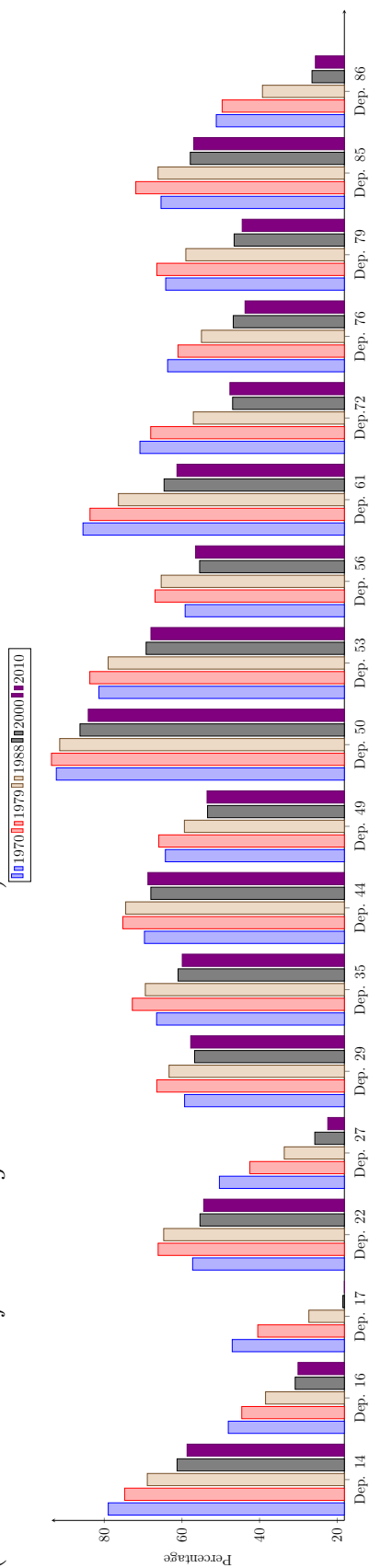


Figure 3.8 – Evolution of the proportion of forage and grasslands in utilized agricultural land, from 1970 to 2010, per department, in The Grand Ouest of France

(Source: the author from the *Agricultural Census data*)

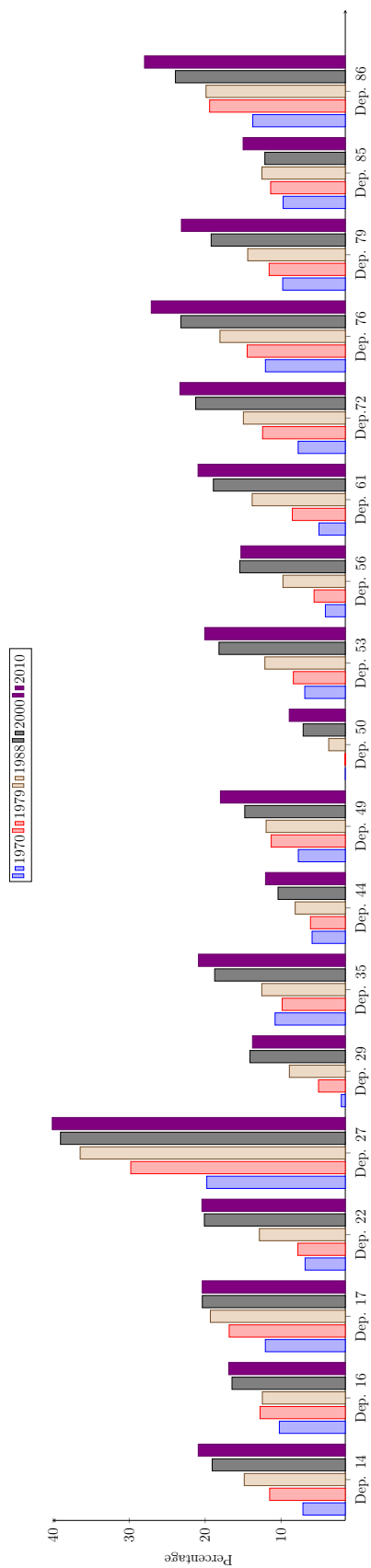


Figure 3.9 – Evolution of the proportion of soft wheat in utilized agricultural land, from 1970 to 2010, per department, in The Grand Ouest of France

(Source: the author from the *Agricultural Census data*)

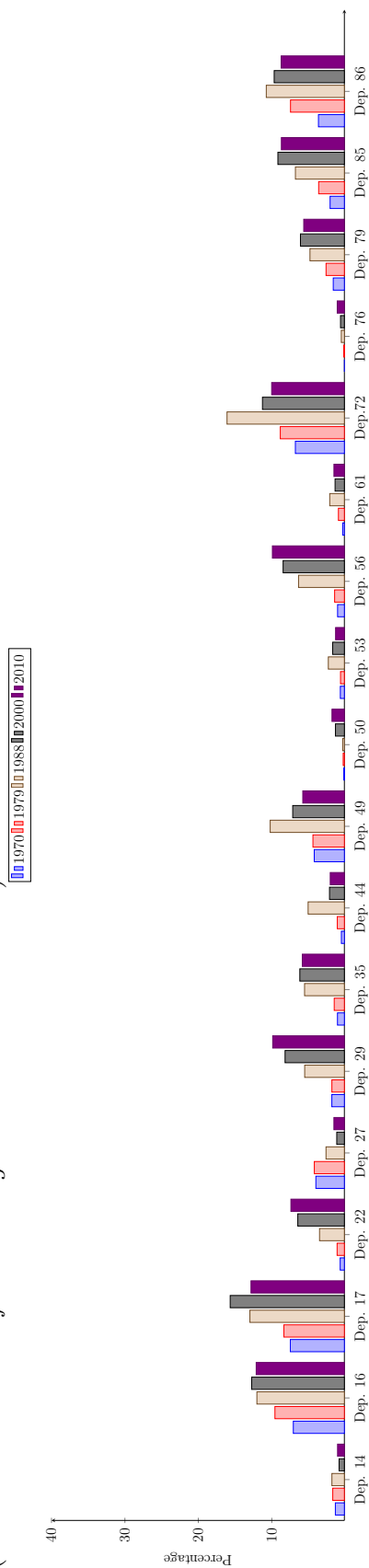


Figure 3.10 – Evolution of the proportion of maize grain in utilized agricultural land, from 1970 to 2010, per department, in The Grand Ouest of France

(Source: the author from the *Agricultural Census data*)

3.2 The dynamics of soil quality parameters in the Grand Ouest

Our objective is to establish whether statistically significant changes can be observed in different soil quality parameters through time. If there are changes, then they will be compared with data regarding farming practices to examine whether a correlation can be observed between farming practices and changes in soil quality parameters.

Here, three soil quality parameters have been chosen: soil total nitrogen, soil organic carbon and soil pH. These parameters are impacted by farming practices and impact soil quality (Miglierina et al, 2000 ; Shukla, Lal and Ebinger, 2006 ; Verhulst et al, 2010). In addition, It is fairly common to consider them when performing soil quality analysis.

Data regarding soil quality parameters are obtained from the BDAT (*Base de Données d'Analyse de la Terre*). This is a network of soil analysis measures provided voluntarily by soil analysis laboratories. Data are available on the cantonal scale and in five-year periods. Data are collected for a five-year period (for instance, from 2000 to 2004) and at the end of the last year (2004 in our example). For each parameter data, values are treated to obtain different statistical values: the minimum and maximum value, the deciles, quartiles, median and mean, and the amount of data collected for each canton and the standard deviation.

It is not possible to obtain data on a smaller scale than the canton, nor is it possible to know why or precisely where farmers conducted a soil analysis. Furthermore, it is most likely that for the same canton, from one period to another, different parcels are analyzed.

From the descriptive statistics of the soil quality parameters considered here (see Table 3.1), it appears that for the three periods considered, soil pH remains within the range of values between 6 and 7. Extreme values of pH are found from 5.5 to 8.34. The minimum observed value corresponds to a critical threshold of pH, under which aluminum becomes toxic and fertilizer elements can be blocked. The highest pH observed corresponds to a level where some nutritive components can be made unavailable for the plant. Actually, it is likely that crops are grown on soils with a pH favorable to agriculture. In addition, farmers can control for the pH of soil through the practice of liming. For soil organic carbon content, most soils have values between 13 and 20.77 g/kg of soil. Depending on the amount of clay in the soil, this can correspond to a low or a correct ratio of carbon. The minimum values observed are very low, regardless of the amount of clay in the soil. Similarly, high soil organic carbon content can also be observed. For most observations, soil total nitrogen values range from 1.2 to 2 g/kg of soil.

Soil quality parameter	Minimum	1st quartile	Median	3rd quartile	Maximum	Number of observations
pH (1995-1999)	5.540	6.025	6.300	6.935	8.260	706
pH (2000-2004)	5.7	6.1	6.4	7.132	8.340	720
pH (2005-2009)	5.6	6.2	6.4	7.1	8.3	650
Soil organic carbon (1995-1999) g/kg	7.13	13	15.7	20.77	40.3	710
Soil organic carbon (2000-2004) g/kg	6.5	12.39	15.66	19.65	40.12	722
Soil organic carbon (2005-2009) g/kg	8	13.04	16.3	19.72	45	592
Soil total nitrogen (1995-1999) g/kg	0.140	1.368	1.645	2.130	3.840	312
Soil total nitrogen (2000-2004) g/kg	0.190	1.260	1.610	2.00	3.810	509
Soil total nitrogen (2005-2009) g/kg	0.510	1.275	1.550	1.975	3.5	637

Note: Descriptive statistics of all sample data.

Table 3.1 – Descriptive statistics of the soil quality parameters in the Grand Ouest.
(Source: from the author)

	1995-1999 / 2000-2004	2000-2004 / 2005-2009	1995-1999 / 2005-2009
SOIL NITROGEN	non-significant	significant	significant
SOIL ORGANIC CARBON	significant	non-significant	significant
SOIL PH	significant	significant	significant

Table 3.2 – Results of the Wilcoxon test on BDAT data for the *Grand Ouest*.
(Source : from the author)

The Wilcoxon test for matched samples is used to test whether the cantonal medians between different sampling periods are statistically different (see Table 3.2). The null hypothesis of the test is that the cantonal medians for two different periods do not differ. The hypothesis is rejected if $p < 0.05$.

From these results, it appears that the most statistically significant differences for all soil quality parameters can be observed for the differences between the period (1995-1999) and the period (2005-2009). Hence, in the following section, the soil quality parameter

changes considered to estimate the relationship between farming practices and soil quality in the Grand Ouest are the changes occurring between these periods.

3.3 Farming practices and soil quality in the Grand Ouest

In the previous section, it was shown that there are significant changes in the selected soil quality parameters over time. Now, regression tools are used to establish whether correlations can be observed between these changes and farming practices.

First, the objective of the regressions and the hypothesis are presented. Then, the methodology is presented. In the third part, the data and the construction of the dataset as well as the resulting limitations are addressed. Finally, the results are displayed, and discussion follows.

3.3.1 Objective and hypothesis

The objective here is to examine whether farming practices impact soil quality changes using statistical tools. Three soil quality parameters are considered: soil organic carbon, soil pH and soil total nitrogen. Two farming practices are taken into account. These are practices for which comparable data are available on two dates (2001 and 2011) that match the time periods of our soil quality parameter data. These practices are the average amount of nitrogen fertilizer applied (in units/ha or kg/ha²) on the treated parcels and the percentage of surface of tilled parcels (*Enquêtes pratiques culturales 2001, 2011*, DISAR platform, Agreste website).

Farming practices impact the flow of soil organic carbon and soil nitrogen in the short term; however, this impact is punctually small. The repetition of these flows has a long term impact on stocks of soil organic carbon, soil pH and soil total nitrogen.

The following hypotheses are put forward:

— Soil organic carbon

Inputs of nitrogen fertilizer should increase at least the labile part of soil organic carbon (SOC) (Verhulst et al, 2010). This positive effect of nitrogen fertilizer on SOC is assumed to decrease as more fertilizer is applied (negative second order effect). Tillage practices are expected to decrease SOC (Blevins et al, 1983 ; Astier

2. Since one unit of a fertilizing element is equal to one kilogram of this element, the two measures are equivalent

et al, 2006). Similarly, a negative second-order effect is expected. It is expected that at extreme values (high or low organic content), the opposite variation is higher. However, there is also a saturation effect when soil organic carbon is high since a given soil can only stock a limited quantity of soil organic carbon.

— pH

Following Shukla, Lal and Ebinger (2006) and Verhulst et al (2010), it is expected that nitrogen fertilizer inputs decrease pH. It is also expected that this effect decreases with the quantity of inputs. From the literature, it is not possible to formulate a strong hypothesis regarding the impact of tillage on soil pH.

— Nitrogen

It is expected that soil nitrogen increases with nitrogen fertilizer inputs, although this positive effect decreases with the quantity of inputs. According to the literature review conducted by Verhulst et al (2010), zero-tillage may have a short-run negative effect on soil nitrogen content, although in the long run, it could reduce soil nitrogen losses.

Some interesting farming practices are not taken into account due to a lack of information. In particular for changes in pH, liming would have been interesting to consider; however, this information is not available in the farming practices survey (DISAR platform, Agreste website). Similarly, data regarding preceding crops are not available for the 2011 survey. As a consequence, we did not consider this variable in our regressions.

3.3.2 Methodology

To estimate the impacts of farming practices on soil quality changes, a multiple linear regression is performed using the software R.

Here, the explanatory variables are the change in SOC, the change in soil pH, and the change in soil total nitrogen between the period 1995-1999 and the period 2005-2009; they can be interpreted as flows.

The explanatory variables are the average amounts of nitrogen fertilizer applied in units/ha and in kg/ha on the parcels having been treated, the percentage of fertilized parcels (*NFERTI*) and the percentage of surface of tilled parcels (*TILL*). The amount of fertilizers applied and the intensity of tillage depend on the crops cultivated. Hence, the surfaces of land allocated to the main crops cultivated in the studied area are considered (soft wheat, rapeseed, maize grain and forage, sunflower and barley). Crop surfaces are considered according to the ratio of the surface allocated to a given crop for each canton

to the total utilized agricultural land of the canton. We also consider the initial stock of soil parameters.

Control variables are also used. From the French Agricultural Census (for the years 2000 and 2010), two pieces of data are used to control for cattle breeding (live-stock units, *LIVESTOCK*) and surfaces of land allocated to forage and grasslands (*RATIOGRASS*). The livestock units are used to control for additional inputs of organic carbon, through manure, for instance. In addition, taking into account forage and grasslands makes it possible to control for surfaces where there are few disturbing practices, which may explain some of the changes observed in soil quality parameters. Indeed, there is no indication in the BDAT of where the soil samples were taken within a canton. We also control for soil texture with variables such as the soil content of clay, silt and sand. The levels of clay, silt and sand remain constant throughout the years and condition soil ability to stock organic carbon and nitrogen as well as soil resilience.

Soil data and agricultural census data are available at the cantonal level, and farming practices data are available at the regional level.

Two regressions are conducted for each soil quality parameter:

— Regression 1

The first regression corresponds to the soil quality dynamics function of our theoretical model. This is a function used in an intertemporal model, where one-year changes depend on the past year practices. Since such data are not available from one year to another, the soil quality parameter data are considered for two periods, which corresponds to a difference of 10 to 15 years between samples. These soil quality parameter changes are compared against 2001 farming practices. Soil type is also considered as well as the initial level of the soil quality parameter considered. Taking organic carbon as an example, the regression is such that:

$$\begin{aligned}
SOC_{2005-2009} - SOC_{1995-1999} = & \alpha_0 + \alpha_1 SOC_{1995-1999} + \alpha_2 LIVESTOCK_{2000} \\
& + \alpha_3 RATIOGRASS_{2000} + \alpha_4 NFERTI_{2001} + \alpha_5 NFERTI_{2001}^2 + \alpha_6 TILL_{2001} + \alpha_7 TILL_{2001}^2 \\
& + \alpha_8 NFERTI_{2001} * TILL_{2001} + \alpha_9 CLAY + \alpha_{10} SILT + \alpha_{11} SAND \\
& + \alpha_{12} RATIOSOFTWHEAT_{2000} + \alpha_{13} RATIOCOLZA_{2000} + \alpha_{14} RATIOMAISGRAIN_{2000} \\
& + \alpha_{15} RATIOMAISFOR_{2000} + \alpha_{16} RATIOBARLEY_{2000}
\end{aligned} \tag{3.1}$$

Soil data are available at the cantonal level, while farming practices data (tillage and fertilization practices) are available at the regional level. The regional data

are matched to the cantonal data using soil occupation data from the agricultural census.

Hence, in our regression, N_{2001} and L_{2001} are such that:

$$\begin{aligned}
NFERTI_{2001} = & MEANNSWHEAT_{2001} * RATIOSWHEAT_{2000} * RATIOFERTINSWHEAT_{2001} \\
& + MEANNCOLZA_{2001} * RATIOCOLZA_{2000} * RATIOFERTINCOLZA_{2001} \\
& + MEANNMAIZEG_{2001} * RATIOMAIZEG_{2000} * RATIOFERTINMAIZEG_{2001} \\
& + MEANNMAIZEF_{2001} * RATIOMAIZEF_{2000} * RATIOFERTINMAIZEF_{2001} \\
& + MEANNSUNF_{2001} * RATIOSUNF_{2000} * RATIOFERTINSUNF_{2001} \\
& + MEANNBARL_{2001} * RATIOBARL_{2000} * RATIOFERTINBARL_{2001}
\end{aligned} \tag{3.2}$$

$$\begin{aligned}
TILL_{2001} = & MEANLSWHEAT_{2001} * RATIOSWHEAT_{2000} \\
& + MEANLCOLZA_{2001} * RATIOCOLZA_{2000} \\
& + MEANLMAIZEG_{2001} * RATIOMAIZEG_{2000} \\
& + MEANLMAIZEF_{2001} * RATIOMAIZEF_{2000} \\
& + MEANLSUNF_{2001} * RATIOSUNF_{2000} \\
& + MEANLBARL_{2001} * RATIOBARL_{2000}
\end{aligned} \tag{3.3}$$

where $MEANN'CROP'$ is the average amount of nitrogen fertilizer applied in units/ha for a given crop at the regional scale, $MEANL'CROP'$ is the average percentage of tilled surface for a given crop at the regional level, $RATIO'CROP'$ is the proportion of the considered crop in the cantonal total utilized agricultural land (UAL), and $RATIOFERTIN'CROP'$ is the percentage of fertilized crop at the regional level.

— Regression 2

The second regression is more suited to the available data. In this regression, the changes in soil quality parameters are explained by the changes ($DIFF$) in farming practices between 2001 and 2011. Taking organic carbon as an example,

the regression is such that:

$$\begin{aligned}
SOC_{2005-2009} - SOC_{1995-1999} = & \alpha_0 + \alpha_1 SOC_{1995-1999} + \alpha_2 LIVESTOCK_{2000} \\
& + \alpha_3 DIFFRATIOGRASS_{2010-2000} + \alpha_4 DIFF(NFERTI_{2011-2001}) \\
& + \alpha_5 DIFF(NFERTI_{2011-2001})^2 + \alpha_6 DIFF(TILL_{2011-2001}) + \alpha_7 DIFF(TILL_{2011-2001})^2 \\
& + \alpha_8 DIFF(NFERTI_{2011-2001}) * DIFF(TILL_{2011-2001}) + \alpha_9 CLAY + \alpha_{10} SILT + \alpha_{11} SAND \\
& + \alpha_{12} DIFFRATIOSOFTWHEAT_{2010-2000} + \alpha_{13} DIFFRATIOCOLZA_{2010-2000} \\
& + \alpha_{13} DIFFRATIOMAISGRAIN_{2010-2000} + \alpha_{14} DIFFRATIOMAISFOR_{2010-2000} \\
& + \alpha_{15} DIFFRATIOBARLEY_{2010-2000} \tag{3.4}
\end{aligned}$$

where farming practices data are computed following the same process as above, matching 2001 farming practices data with 2000 agricultural census data and 2011 farming practices data with 2010 agricultural census data.

In the next part, we detail the data used and the construction of our dataset.

3.3.3 Data used and construction of the dataset

Data for these regressions are collected from the BDAT (soil quality parameters and soil texture) and from the farming practices surveys performed by Agreste (for the years 2001 and 2011).

The farming practices considered are those for which the same indicators are used in 2001 and 2011 in the farming practices survey. Two farming practices have been selected: 1) the average amount of nitrogen fertilizer applied in units/ha or kg/ha on the parcels having been treated; and 2) the percentage of surface of tilled parcels. These values are available at the regional scale.

Hence, there are two different databases: one at the cantonal scale (soil information) and the other at the regional scale (farming practices information). To harmonize these two databases, a third one is used: data from the agricultural census. This database is exhaustive and available at the cantonal scale for the years 1988, 2000 and 2010.

The regressions have been conducted within the following variables:

- Exogenous soil parameters: clay, sand and silt

These parameters are used to describe the soil texture and granulometry. They do not change throughout the years, and these data are only available for the first

period 1995-1999 registered in the BDAT. These parameters are used to control the impact of the soil nature and texture on the dynamics of the endogenous soil quality parameters.

- Endogenous soil quality parameters: soil organic carbon, soil pH, soil total nitrogen
Data are directly available by canton. The data are from the period 1995-1999 and the period 2005-2009. Our hypothesis is that due to the slow dynamics of organic carbon, the aggregated median value of organic carbon for the period 1995-1999 is close to the level of organic carbon for the year 2001 and that the aggregated median value of organic carbon for the period 2005-2009 is close to the organic carbon level for year 2011.

A similar hypothesis is put forward for pH and soil total nitrogen.

- Farming practices parameters: the average amount of nitrogen fertilizer applied in kg/ha on the parcels having been treated and the percentage of surface of tilled parcels, harmonized at the cantonal level, for 5 crops (soft wheat, sunflower, rapeseed, barley, maize)

These parameters are available for the years 2001 and 2011. They are at the regional scale, but they are harmonized at the cantonal level using data from the agricultural census (years 2000 and 2010).

First, for each canton, the respective proportions of surfaces allocated to soft wheat, rapeseed, maize, sunflower and barley (and sturgeon) have been computed using the total utilized agricultural land area for each canton and the surfaces allocated to each of the crops mentioned above. Then, regional values of N fertilization are weighted by the ratio of surfaces allocated to each crop in each canton and the ratio of surfaces where nitrogen fertilizers have been applied. We used a similar approach for tillage. Thus, the farming practices data are at least adapted to the crops grown in each canton.

Liming practices are not provided in the farming practices survey. Similarly, information relative to preceding crops are not available for 2011.

Before displaying our results, let us first verify that our data respect the conditions for conducting a multiple linear regression. Two tests are performed: the non-constant variance test, and the Breusch-Godfrey test. The non-constant variance test verifies the condition of homoscedasticity. The Breusch-Godfrey test for higher-order serial correlation is used to estimate the correlation of the residues. These tests are performed on the linear regressions of the models described above. The regressions are obtained using the program “lm” of the statistical software R. The non-constant variance test is performed using the “ncvTest” program of the “car” package, and the Durbin-Watson test

is computed using the “bgtest” program of the “lmtest” package.

It appears that none of our regressions respect the homoscedasticity conditions. In addition, our residues are correlated (see Table 3.3 and Table 3.4). Hence, we cannot run a linear regression using the ordinary least squares (ols) estimator: Faced with heteroscedasticity and autocorrelated residues, our ols estimators would be biased. To overcome these issues, we use the generalized least square (gls) procedure, which makes it possible to have no biased estimates. This corresponds to the function “gls” of the “nlme” package on R. Actually, this function has the argument “correlation,” allowing us to take into account the form of the correlation observed - in our case, a first-order correlation.

	Regression 1	Regression 2
Non-constant variance test	$p = 3.001878e - 07$	$p = 1.582909e - 07$
<i>Interpretation</i>	<i>Since $p < 0.05$, the null hypothesis according to which variances are constant can be rejected. Our regressions do not respect the homoscedasticity condition.</i>	
Breusch-Godfrey test	$p = 1.12e - 05$, for serial correlation up to 1	$p = 0.02735$, for serial correlation up to 1
<i>Interpretation</i>	<i>Since $p < 0.05$, the null hypothesis according to which there is no serial correlation of any order up respectively to 49 and to 20 can be rejected. The residues of our regressions are autocorrelated. For both cases, a coefficient test (coeftest) has been performed to estimate the correlation lag of the residues. In each case, the most statistically significant correlation is of order 1</i>	

Table 3.3 – Tests on the organic carbon regressions: non-constant variance test and Breusch-Godfrey test.

(Source: from the author)

	Regression 1	Regression 2
Non-constant variance test	$p = 7.918257e - 23$	$p = 8.394953e - 09$
<i>Interpretation</i>	<i>When $p > 0.05$, the null hypothesis according to which variances are constant cannot be rejected. Our regressions do not respect the homoscedasticity condition.</i>	
Breusch-Godfrey test	$p = 0.0005405$	$p = 0.04596$
<i>Interpretation</i>	<i>Since $p < 0.05$, the null hypothesis according to which there is no serial correlation of any order up to 47 and correlation up to 25 can be rejected. The residues of our regressions are autocorrelated. For both cases, a coefficient test (coeftest) has been performed to estimate the correlation lag of the residues. In each case, the most statistically significant correlation is of order 1</i>	

Table 3.4 – Tests on the pH regressions: non-constant variance test and Breusch-Godfrey test.

(Source: from the author)

3.3.4 Results and Discussion

Regressions are performed for the median values and the first and third quartiles of soil organic carbon and soil pH. The median values of each canton are assumed to be representative at the cantonal scale. The first and third quartiles are considered to establish whether the impacts of farming practices are the same for lower or higher values of soil pH and soil organic carbon.

The results of regression 1 and then regression 2 are presented for soil organic carbon and soil pH. The results for soil total nitrogen are not displayed because they show no significance other than resilience. This may be due to the small size of the sample for nitrogen compared to soil pH and soil organic carbon. Let us note that the most significant relationships are observed for soil organic carbon regressions, which is the parameter with the highest number of observations.

In the first organic carbon regression, it appears that initial soil organic carbon has a negative impact on the variation of organic carbon. The latter confirms our hypothesis: The median value of soil organic carbon corresponds to a low or correct ratio of carbon in soils, far from the extremes. The more soil organic carbon approaches an average concentration in soils, the less variation is observed. Moreover, in the areas where soil organic carbon levels are high, the system appears to be stabilized (see Table 3.5). According to our results, there is a negative relationship between SOC changes and past nitrogen fertilizer inputs for all levels of soil organic carbon, with a negative second-order effect observed for the median values. The more the nitrogen fertilizer inputs, the lower is the amount of soil organic carbon, with a lesser effect as the inputs are more important. The second-order effect of the percentage of tilled surface is associated with a negative effect on soil organic carbon changes. These counter-intuitive results can be explained by missing information, regarding the rotation, for instance. For median values of soil organic carbon, the N fertilizers and tillage are cooperating: Simultaneous use of N fertilizers and tillage seems to have a positive impact on soil organic carbon variation. The relationship between N fertilizer inputs, tilled surface and SOM changes is represented graphically in Figure 3.11.

In terms of land allocation, the correlations appear to be different depending on the values of soil organic carbon considered. For median values, the ratio of grasslands in the canton, soft wheat and barley have a positive impact on soil organic carbon. For the first quartile values, soft wheat and barley surfaces have a positive impact, while maize forage surfaces seem to positively impact the third quartile values. One can also observe that

the more a crop is grown on an important surface, the more likely it is that the impact of this variable will be significant.

Most coefficients are statistically significant in the first regression on soil pH (see Table 3.6). Initial soil pH has a significant coefficient: the higher the soil pH is, the lower the variation in soil pH. On the contrary, N fertilizers have a positive impact on soil pH variation. This is not consistent with the studies of Shukla et al (2006) and Verhulst et al (2010). The second-order effect of this relationship is significantly positive for median values and first quartile values, suggesting that the higher the amount of N fertilizers applied, the higher the variation in soil pH observed. Tillage practice, however, has a significant negative impact on soil pH variation, suggesting an acidifying effect of tillage. The second-order effect is positive, suggesting that this impact is increasing. The interaction between N fertilizers and tillage is significantly negative: When both items are implemented, soil pH decreases (see Figure 3.12).

Actually, the results observed are for the most part not consistent with what the literature on the matter would predict. This can be explained by the strong assumption of our regressions that considers that the farming practices observed in 2001 are constant until 2009. The second series of regressions were conducted for this reason: to relate changes in soil parameters and changes in farming practices.

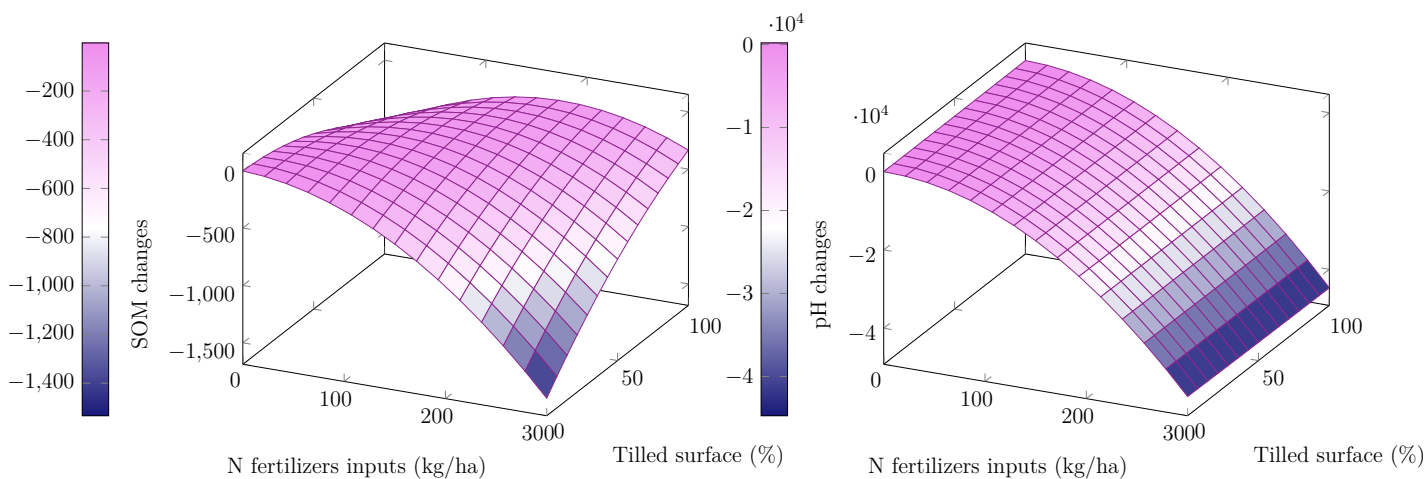


Figure 3.11 – SOM dynamics: N fertilizers and Tillage impact (median values).

(Source: from the author)

Figure 3.12 – Soil pH dynamics: N fertilizers and Tillage impact (median values).

(Source: from the author)

Explanatory variables	Explained variable: Changes in soil organic carbon, from 1995 to 2009					
	SOC Median value		SOC 1st quartile		SOC 3rd quartile	
	Estimate	$Pr(> z)$	Estimate	$Pr(> z)$	Estimate	$Pr(> z)$
(Intercept)	-2.5355e + 00	0.523175	-8.6729e-01	0.6877193	-1.4827e+00	0.709644
Soil clay content	-9.7969e - 04	0.853628	-1.5004e-03	0.6205147	9.8564e-03	0.084123 .
Soil silt content	1.9055e - 03	0.616475	2.1905e-03	0.2977796	1.4557e-03	0.708573
Soil sand content	4.4495e - 03	0.246703	1.3790e-03	0.5131729	5.0611e-04	0.896874
Initial soil organic carbon (1995-1999)	-1.1990e - 01	5.133e - 05***	-9.6486e-02	4.396e-06 ***	-2.0485e-01	1.724e-12 ***
Livestock (2000)	8.9360e - 06	0.326338	-1.1831e-06	0.8223299	-2.2528e-05	0.028274 *
Ratio of grasslands (2000)	2.8118e + 00	0.060730 .	2.4743e-01	0.7722925	4.2241e+00	0.008156 **
Total amount of N fertilizers applied (all crops, at <i>pro rata</i> of the surfaces allocated to each crop) (2001)	-4.0461e - 01	0.001726 **	-3.2462e-01	-4.4501 8.584e-06 ***	-7.9102e-01	9.383e-08 ***
Second order effect of the total amount of N fertilizers applied (2001)	-1.5668e - 02	0.006687 **	-3.3149e-03	0.3113904	-5.8694e-03	0.391489
Percentage of surface tilled (all crops, at <i>pro rata</i> of the surfaces allocated to each crop) (2001)	-5.3477e - 01	0.260318	-3.4859e-01	0.1922903	6.8773e-01	0.219917
Second order effect of percentage of surface tilled (2001)	-5.1974e - 02	0.005247 **	-1.9838e-02	0.0611745 .	-5.0912e-02	0.019077 *
Cross effect of the total amount of N fertilizers applied and the percentage of surface tilled (2001)	5.9091e - 02	0.004353 **	1.7531e-02	0.1351103	3.9369e-02	0.106019
Ratio of surfaces allocated to soft wheat (2000)	1.0898e + 02	0.029230 *	7.9049e+01	0.0047699 **	6.2339e+01	0.287960
Ratio of surfaces allocated to rapeseed (2000)	-3.3442e + 00	0.613756	3.1500e + 00	0.3890593	5.6207e+00	0.428279
Ratio of surfaces allocated to maize grain (2000)	9.2080e - 01	0.766267	2.2468e + 00	0.1893625	5.0396e-01	0.877596
Ratio of surfaces allocated to maize forage (2000)	-5.1841e + 00	0.151027	2.8987e + 00	0.1660923	7.1552e+00	0.070837 .
Ratio of surfaces allocated to barley (2000)	1.6030e + 01	0.006207 **	1.1901e+01	3.5996 0.0003187 ***	7.8407e+00	0.225454
	<i>Observations: 457</i>			<i>Observations: 530</i>		
	<i>Signif. codes: 0.001***, 0.01**, 0.05*, 0.1.</i>					

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Table 3.5 – Regression on soil organic carbon changes, at the cantonal level, for the *Grand Ouest*.
(Source: from the author)

	Explained variable: Changes in pH, from 1995 to 2009					
Explanatory variables	pH Median value		pH 1st quartile		pH 3rd quartile	
	Estimate	$Pr(> z)$	Estimate	$Pr(> z)$	Estimate	$Pr(> z)$
(Intercept)	4.2021e + 00	2.281e - 05 ***	2.8324e+00	1.708e-05 ***	3.1117e+00	9.051e-05 ***
Soil clay content	-6.1456e - 04	0.5386100	-5.3449e-04	0.4662410	-1.9011e-04	0.8030151
Soil silt content	-1.6575e - 03	0.0462780 *	-9.2517e-04	0.1123172	-4.8120e-04	0.4673544
Soil sand content	-7.7930e - 04	0.3357115	-4.5985e-04	0.4217682	6.5353e-06	0.9919124
Initial soil pH (1995-1999)	-3.3896e - 01	1.367e - 05 ***	-2.9126e-01	5.548e-09 ***	-2.9871e-01	2.383e-07 ***
Livestock (2000)	-2.6036e - 06	0.2071575	-1.2545e-06	0.3679141	-3.0500e-06	0.0615737 .
Ratio of grasslands (2000)	-3.4044e - 01	0.2838218	-3.8151e-01	0.0934631 .	-1.5518e-01	0.5181267
Total amount of N fertilizers applied (all crops, at <i>pro rata</i> of the surfaces allocated to each crop) (2001)	1.0471e - 01	0.0013539 **	3.5870e-02	0.0993445 .	9.6592e-02	0.0001808 ***
Second order effect of the total amount of N fertilizers applied (2001)	4.9264e - 03	0.0014047 **	2.8252e-03	0.0046628 **	1.1342e-03	0.3403935
Percentage of surface tilled (all crops, at <i>pro rata</i> of the surfaces allocated to each crop) (2001)	-2.7225e - 01	0.0195587 *	-1.4338e-01	0.0546934 .	-2.0611e-01	0.0233059 *
Second order effect of percentage of surface tilled (2001)	2.0489e - 02	2.336e - 05 ***	9.0997e-03	0.0043944 **	1.0820e-02	0.0039692 **
Cross effect of the total amount of N fertilizers applied and the percentage of surface tilled (2001)	-2.0073e - 02	0.0002349 ***	-1.0407e-02	0.0034260 **	-7.5188e-03	0.0742438 .
Ratio of surfaces allocated to soft wheat (2000)	4.8282e + 00	0.6877709	8.6036e+00	0.2657477	-2.2809e-01	0.9807706
Ratio of surfaces allocated to rapeseed (2000)	-1.5901e + 00	0.2920507	-3.4910e + 00	0.0005849 ***	-1.0575e+00	0.3636144
Ratio of surfaces allocated to maize grain (2000)	-2.8300e - 01	0.5868861	2.8801e - 01	0.4138422	-1.9386e-01	0.6462230
Ratio of surfaces allocated to maize forage (2000)	8.8865e - 01	0.2917599	-8.8018e - 02	0.8832886	-1.1208e-01	0.8696745
Ratio of surfaces allocated to sunflower (2000)	-2.8864e - 01	0.7536564	-1.1638e+00	0.0692579 .	2.6221e-01	0.7116384
Ratio of surfaces allocated to barley (2000)	-1.7966e + 00	0.1094890	-1.9129e - 02	0.9804924	-2.1523e+00	0.0157768 *
	Observations: 282 90			Observations: 306		
	Signif. codes: 0.001***, 0.01**, 0.05*, 0.1.					

Table 3.6 – Regression on soil pH changes, at the cantonal level, for the *Grand Ouest*.
(Source: from the author)

For the second soil carbon regression that considers the impacts of changes in farming practices on soil organic carbon changes, the results are consistent with our hypothesis and the literature (see Table 3.7), at least when the median values are considered. For the soil organic carbon first and third quartile values, farming practices do not seem to impact their evolution.

For the soil organic carbon median values regression, the impact of initial soil organic carbon is not significant. The parameters estimation shows a negative correlation between the changes in nitrogen fertilizers and the changes in soil organic carbon: the higher the increase in nitrogen fertilizer inputs, the lower the soil organic carbon from one period to another (and the reverse). This effect increases with the amplitude of the difference in nitrogen fertilizers. As for tillage, this regression indicates a positive correlation between the high proportion of tilled surfaces and soil organic carbon. This result can be explained by the complex impact tillage can have on soil quality changes: Indeed, its impact highly depends on other farming practices, such as crop rotation management. Actually, the interaction between tillage and fertilizer is negative, suggesting that these two practices have diverging impacts on soil organic carbon changes (see Figure 3.13). In addition, cattle (UGBTA) and the ratio of grasslands have a positive impact on organic carbon variation. In areas where a higher proportion of land is allocated to the soft wheat crop, soil organic carbon appears to increase. However, this is the inverse of the relationship observed with the ratio of surfaces allocated to maize forage.

For the pH regression, only the intercept and the initial soil pH have statistically significant coefficients for all soil pH ranks. Soil initial pH has a negative impact on soil pH variation (see Table 3.8). The descriptive statistics show that in our dataset, the level of pH in soil is already suitable for cropping and is probably maintained that way by farmers through liming. This farming practice is not available from the farming practices survey at our disposal. Soil texture has a significant impact on soil pH changes at least for pH median and first quartile values.

For the median values of soil pH and in contrast with our hypothesis, an increase in N fertilizers applied increases soil pH instead of having an acidifying effect (see Figure 3.14). On the other hand, the increase in the ratio of grasslands and soft wheat within the canton has an acidifying effect on soil.

Some of these results are quite interesting - either because they confirm what can be found in the literature or because they shed more light on the relationship between farming practices and soil quality changes. It would be interesting to evaluate these results using data obtained at the parcel scale.

Explanatory variables	Explained variable: Changes in soil organic carbon from 1995 to 2009					
	SOC Median value		SOC 1st quartile		SOC 3rd quartile	
	Estimate	$Pr(> z)$	Estimate	$Pr(> z)$	Estimate	$Pr(> z)$
(Intercept)	-1.2033e + 00	0.776403	9.0575e-01	0.764006	6.0519e+00	0.328763
Soil clay content	-5.5116e - 03	0.399834	-1.3228e-03	0.775490	-3.5800e-03	0.711210
Soil silt content	4.8462e - 03	0.245383	8.2453e-04	0.780467	2.8326e-04	0.962789
Soil sand content	3.8513e - 03	0.375235	-1.1914e-03	0.697843	-6.8453e-03	0.277823
Initial soil organic carbon (1995-1999)	-4.8312e - 02	0.105879	-3.6138e - 02	0.137945	-8.2496e-02	0.022352 *
Changes in ratio of grasslands (2000-2010)	1.8314e + 01	0.006275 **	1.1375e+01	0.008659 **	1.6935e+01	0.058027 .
Livestock (2010)	2.7897e - 05	0.003294 **	1.7522e-05	2.6666 0.007662 **	1.2886e-05	0.330401
Changes in total amount of N fertilizers applied (all crops, at <i>pro rata</i> of the surfaces allocated to each crop) (2001-2011)	-1.5698e + 00	2.728e - 05 * * *	-1.2867e-01	0.616840	6.5436e-01	0.216109
Second order effect of the changes in total amount of N fertilizers applied (2001-2011)	1.1598e - 01	0.000122 * * *	-5.4400e-03	0.793814	-4.7241e-02	0.269401
Changes in the percentage of surface tilled (all crops, at <i>pro rata</i> of the surfaces allocated to each crop) (2001-2011)	1.4796e + 00	6.312e - 05 * * *	3.6694e-01	0.156018	2.5609e-01	0.629970
Second order effect of the changes in percentage of surface tilled (2001-2011)	2.1046e - 01	2.929e - 05 * * *	3.0190e-02	0.392642	-3.0457e-02	0.674462
Cross effect of the changes in total amount of N fertilizers applied and in the percentage of surface tilled (2001-2011)	-3.2866e-01	3.584e-05 * * *	-6.0489e-03	0.912567	1.0664e-01	0.346061
Changes in ratio of surfaces allocated to soft wheat (2000-2010)	6.2977e+01	0.025302 *	1.0046e+00	0.956740	-7.0548e+01	0.067258 .
Changes in ratio of surfaces allocated to rape-seed (2000-2010)	1.7907e+01	0.170640	8.4869e+00	0.362854	3.1730e+01	0.099345 .
Changes in ratio of surfaces allocated to maize grain (2000-2010)	1.2806e+00	0.902825	-6.1636e+00	0.384110	-1.1814e+01	0.418201
Changes in ratio of surfaces allocated to maize forage (2000-2010)	-8.6462e+00	0.107030 .	-5.4182e+00	0.144963	-1.0111e+00	0.894913
Changes in ratio of surfaces allocated to barley (2000-2010)	4.7822e+00	0.623765	9.9922e+00	0.137468	3.7223e+01	0.006959 **
	Observations: 312			Observations: 336		
	Signif. codes: 0.001***, 0.01**, 0.05*, 0.1.					

Table 3.7 – Regression on soil organic carbon changes, at the cantonal level, for the *Grand Ouest* explained by farming practices changes.
(Source: from the author)

Explanatory variables	Explained variable: Changes in pH, from 1995 to 2009					
	pH Median value		pH 1st quartile		pH 3rd quartile	
	Estimate	$Pr(> z)$	Estimate	$Pr(> z)$	Estimate	$Pr(> z)$
(Intercept)	2.9864e + 00	2.845e - 06 ***	1.9461e+00	5.848e-07 ***	1.8746e+00	0.0004798 ***
Soil clay content	-1.6272e - 03	0.056590 .	-8.6748e-04	0.08305 .	-5.2903e-04	0.4622901
Soil silt content	-1.4030e - 03	0.011536 *	-2.0244e-04	0.53601	-4.6486e-04	0.3248185
Soil sand content	-8.4589e - 04	0.143796	9.3091e-05	0.78271	-1.9043e-04	0.6962592
Initial soil pH (1995-1999)	-2.4611e - 01	8.434e - 07 ***	-2.6599e-01	7.229e-16 ***	-1.8313e-01	4.747e-08 ***
Changes in ratio of grasslands (2000-2010)	-1.7302e + 00	0.037639 *	-1.5532e-01	0.74728	-3.1428e-01	0.6534219
Livestock (2010)	-8.1578e - 07	0.495170	-2.1088e-07	0.75385	-1.0493e-06	0.2959097
Changes in total amount of N fertilizers applied (all crops, at <i>pro rata</i> of the surfaces allocated to each crop) (2001-2011)	1.2473e - 01	0.013465*	-9.6202e-03	0.73728	-8.0129e-03	0.8481706
Second order effect of the changes in total amount of N fertilizers applied (2001-2011)	-5.5330e - 03	0.164299	2.4240e-03	0.29799	-7.5016e-05	0.9823228
Changes in the percentage of surface tilled (all crops, at <i>pro rata</i> of the surfaces allocated to each crop) (2001-2011)	-2.8371e - 02	0.577237	1.8705e-02	0.52423	6.5405e-02	0.1244865
Second order effect of the changes in percentage of surface tilled (2001-2011)	-5.3865e - 03	0.430026	4.4746e-03	0.25712	8.3962e-03	0.1452889
Cross effect of the changes in total amount of N fertilizers applied and in the percentage of surface tilled (2001-2011)	1.3349e - 02	0.207344	-6.9846e-03	0.25729	-4.1768e-03	0.6418576
Changes in ratio of surfaces allocated to soft wheat (2000-2010)	-1.1148e+01	0.002298 **	-1.3241e+00	0.51296	-6.2421e-01	0.8312299
Changes in ratio of surfaces allocated to rape-seed (2000-2010)	7.9225e-01	0.646567	4.0419e-01	0.69011	1.0566e+00	0.4709246
Changes in ratio of surfaces allocated to maize grain (2000-2010)	-1.3296e+00	0.316510	2.4599e-01	0.74636	6.7152e-03	0.9951598
Changes in ratio of surfaces allocated to maize forage (2000-2010)	2.1563e-01	0.757413	1.9340e-03	0.99624	-7.9390e-01	0.1825659
Changes in ratio of surfaces allocated to barley (2000-2010)	-1.0378e+00	0.416531	-7.0717e-01	0.33989	-1.1931e+00	0.2693667
	Observations: 325			Observations: 325		
	Signif. codes: 0.001***, 0.01**, 0.05*, 0.1.					

Table 3.8 – Regression on soil pH changes, at the cantonal level, for the *Grand Ouest* explained by farming practices changes.
(Source: from the author)

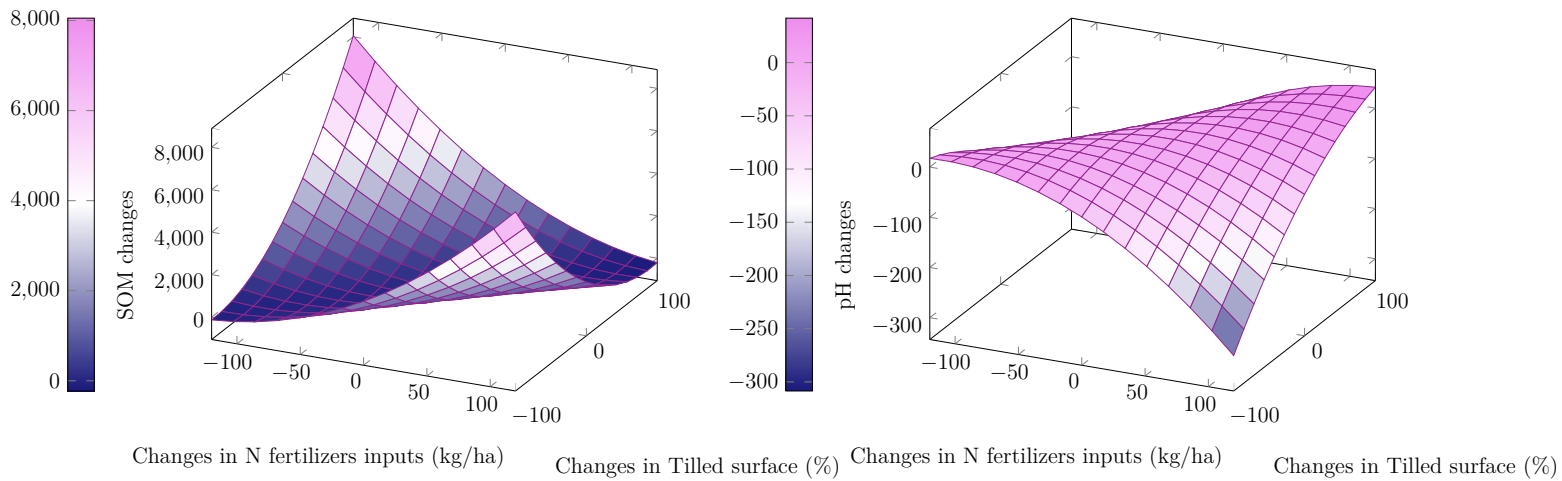


Figure 3.13 – SOM dynamics: Changes in N fertilizers and Tillage impacts (median values).
 Figure 3.14 – Soil pH dynamics: Changes in N fertilizers and Tillage impacts (median values).

(Source : from the author)

(Source: from the author)

3.4 Soil quality and crop production in the Grand Ouest

3.4.1 Objective and hypothesis

The objective is to examine the relative impact of production factors on crop production and also to study the effect of their interactions. Here, soil quality is considered as a production factor. In this statistical analysis, the productive inputs considered are nitrogen and phosphorus fertilizers, and the only soil quality parameter considered is soil organic carbon. We do not consider soil pH because based on previous regressions, it seems that it is maintained at a suitable level by the farmer - in an unobservable way for us given our dataset. The following hypotheses are put forward:

- Soil organic carbon

Soil organic carbon is expected to have a positive marginal effect on crop production. The second-order effect is expected to be negative, with a smaller marginal impact when the soil organic carbon level is higher. This also translates into relationship thresholds particularly since a given soil has a finite storage capacity.

- N and P fertilizers

N and P fertilizers are expected to have a positive marginal impact on crop production. The second-order effect is expected to be negative: the more that N or P fertilizers are applied, the lower their positive marginal effect on production. Following Smith et al. (2000), their interaction is expected to be positive.

— Interaction between fertilizers and soil organic carbon

Both fertilizers and soil organic carbon have positive marginal effects on crop production. Hence, we expect them to be cooperating: Their interaction should be positively signed.

3.4.2 Methodology

To estimate our crop production regressions, we performed a multiple linear regression *via* the software R. These regressions are performed for the two main crops grown in the Grand Ouest of France: soft wheat and maize grain.

The explained variable is the level of crop production in quintal per hectare (YIELD). The explanatory variables are soil organic carbon (COOH), nitrogen fertilizer (NFERTI), phosphorus fertilizers (PFERTI), the cumulative amount of rainfall during crop growth (RAIN), and the amount of soil clay, silt and sand. The preceding crops are considered (PC). Actually, for each region, we consider the percentage of surfaces for which the preceding crop is the same as the current one. It is assumed that this value is the same for the departments of the same region.

The proportions of soil clay, silt and sand are considered as constant. Data relative to nitrogen and phosphorus fertilizers are available for the years 2001 and 2006 but not for the year 2011. Since this is not enough to perform a time series analysis, we have proceeded to the regression for the years 2001 and 2006 together.

Following Smith et al (2000), the regressions proposed have a quadratic form. For crop production regression, it is such that:

$$\begin{aligned}
YIELD(CROP)_t = & \beta_0 + \beta_1 CLAY + \beta_2 SILT + \beta_3 SAND + \beta_4 COOH_t \\
& + \beta_5 NFERTI(CROP)_t + \beta_6 PFERTI(CROP)_t \\
& + \beta_7 RAIN(CROP)_t + \beta_8 NFERTI(CROP)_t * PFERTI(CROP)_t \\
& + \beta_9 COOH_t * NFERTI(CROP)_t + \beta_{10} COOH_t * PFERTI(CROP)_t \\
& + \beta_{11} PRECCROP(CROP)_t + \beta_{12} PC(CROP)_t
\end{aligned} \tag{3.5}$$

Data relative to crop yield (or crop production), nitrogen and phosphorus fertilizers, and accumulated rainfall are available for the years 2001 and 2006. These two years have not been expectational in terms of yields for soft wheat and maize grain crops. In 2001,

climatic conditions were not favorable to annual crops, with substantial rainfall in autumn and climatic irregularities in the spring. This has caused a decrease in crop yield, which is more important for cereals than maize grain (*Enquête sur les pratiques culturales 2001, 2004*). In 2006, soft wheat yields were 2% below the average yield of the past 5 years, while maize grain yields were 9 % lower than the good yields of 2002 and 2004. This is due to the hot and dry climatic conditions in the summer (*Enquête sur les pratiques culturales 2006, 2008*).

Data relative to soil are extracted from the same database used for the soil dynamics regressions (BDAT) and are available for the period 1995-1999 and the period 2000-2004. It is assumed that soil data for the period 1995-1999 and the period 2000-2004 can be matched to 2001 climate data and farming practices, respectively. This is the same database as the one used previously for soil dynamics regressions.

Crop yield data are found in the Annual Agricultural Statistics surveys for 2001 and 2006. Crop yield data are available at the departmental level. However, farming practices (N fertilization, P fertilization and preceding crop) are only available at the regional level. We assume that these regional data are representative of departmental data.

The accumulated amounts of rainfall during crop growth have been obtained using data from the the French website *Infoclimat*, which delivers the monthly climate in various observatories. It was not possible to have such data for each canton. Hence, we have chosen to consider rainfall data corresponding to the weather station of the prefecture of each department considered in our dataset - when data were available. The monthly accumulated amounts of rainfall have been extracted from March to July. For each crop, the cumulated amount of growth rainfall is calculated by adding up the monthly accumulated rainfall for the months where rain is considered a critical growth factor. For soft wheat, this corresponds to the months of March, April and May. For maize, this corresponds to the months of May, June and July. For maize grain, irrigation is also taken into account. To do so, we used data from a farming practices survey relative to the quantity of irrigation in mm and the proportion of surfaces irrigated (*Enquête sur les pratiques culturales, 2001, 2006*). These data are available at the regional scale.

From the farming practices survey (Agreste 2001, 2006), we obtain the average amount of nitrogen and phosphorus fertilizer applied to parcels that have been treated (NFERTIAPPLIED and PFERTIAPPLIED) and the percentage of surface that has been fertilized with nitrogen and phosphorus in each region. However, the average level of crop

yield encompasses both treated and non treated parcels. Hence, we have adjusted the amount of fertilizer with the ratio of parcels treated (FERTINSURF and FERTIPSURF), such that:

$$NFERTI(CROP)_t = NFERTIAPPLIED(CROP)_t * \frac{FERTINSURF(CROP)_t}{100} \quad (3.6)$$

$$PFERTI(CROP)_t = PFERTIAPPLIED(CROP)_t * \frac{FERTIPSURF(CROP)_t}{100} \quad (3.7)$$

Since these regressions are estimated for each crop, the amount of N fertilizer is considered for each crop. This is done for the years 2001 and 2006 for each crop. Data relative to the amount of fertilizer applied is available for the years 2001 and 2006; while the surface of fertilized data is only available for the year 2000.

We have performed a multiple linear regression using the program “lm” from the statistical software R. We performed two tests on these regressions to ensure that they verify the homoscedasticity condition and that there are no correlations between residues (see Table 3.9).

According to our results, our regressions respect the homoscedasticity condition, and they do not exhibit auto-correlation between residues.

Regressions		
	Soft wheat	Maize grain
Non-constant variance test	$p = 0.6915$	$p = 0.2799$
Breusch-Godfrey test	$p = 0.7376$	$p = 0.3972$
<i>Interpretation of the non-constant variance test</i>	<i>When $p > 0.05$, the null hypothesis according to which variances are constant cannot be rejected. Our regressions respect the homoscedasticity condition.</i>	
<i>Interpretation of the Breusch-Godfrey test</i>	<i>When $p < 0.05$, the null hypothesis according to which there is no serial correlation up to 1 can be rejected. The residues of our regressions are not autocorrelated.</i>	

Table 3.9 – Tests on the crop production regressions: non-constant variance test and Breusch-Godfrey test.

(Source: from the author)

3.4.3 Results and Discussion

The results of our regressions are displayed in Table 3.10. Due to the relatively small amount of observations for each regression, regressions are performed with the variables that best explain soft wheat or maize grain yields (using the R-squared value). This is why different explanatory variables are used for soft wheat yield and maize grain yield regressions.

As expected, soil organic carbon has a significant positive impact on crop yield for soft wheat. For maize grain yield, the impact is not statistically significant.

N fertilizers have a statistically significant positive impact on soft wheat and maize grain yields. This is consistent with our assumptions. However, P fertilizers seem to negatively impact soft wheat production. The cumulated amount of rainfall during crop growth has a positive impact on maize grain yield, which is consistent with the nature of this crop.

The cooperating relationship between N fertilizers and soil organic carbon is statistically significant and negative for both crops. As for the cooperation between P fertilizers and soil organic carbon, it exhibits a positive sign for maize grain.

These results are interesting when confronted with the hypothesis put forward in our theoretical models. In our soil quality investment models, we assume that productive inputs (including mineral fertilizers) may or may not be cooperating with soil quality, implying an undetermined sign of the cross derivative functions of soil quality and fertilizers on crop yield. Our empirical results reassure us of the necessity of considering both cases. In addition, the negative cooperation effect between soil quality and productive inputs implies that productive inputs no longer increase with the level of soil quality when optimality conditions are respected.

There is potential bias in the results presented due to the fact that farmers make choices: They are likely to choose to grow crops in high-quality soil. This may explain why crop yields are so positively correlated to soil quality: These crops are grown in lands characterized by high soil quality. However, we are using crop yield data for two different years and with a five-year gap. Since farmers have an interest in practicing crop rotations, even short ones, we are also likely to observe crop allocation that reflects this phenomenon, thus reducing this bias.

Another potential bias could be the impact of farmers' practices and choices on soil organic carbon - which is the hypothesis of our theoretical models. This would mean that soil organic carbon is endogenous in our regressions. However, here, we use soil quality parameter data from 1995 to 1999 and from 2000 to 2004, regressed on crop yield data from 2001 and 2006, respectively. Hence, soil quality data are not impacted by the farming practices or crop allocation of the years considered - although it is impacted by a succession of crop allocation choices and farming practices. As such, we can consider here that the soil quality parameters used in our regressions are not endogenous.

Another bias that is not addressed here is related to spatial autocorrelation. Neighboring cantons may have functional relationships between each other, for instance, due to a particular spatial organization of activities. For instance, a canton with a high proportion of maize grain is likely to also present a high proportion of cattle, with a relatively high amount of spreading that can impact neighboring parcels located in different cantons.

Explaining variables	Explained variables			
	Soft wheat yield		Maize grain yield	
	Estimate	p-value	Estimate	p-value
Intercept	42.19446	0.45087	-24.61	0.7409
Clay content in soil	-0.12235	0.06260 .	0.1666	0.1031
Silt content in soil	-0.12003	0.03649 *	0.1347	0.852
Sand content in soil	-0.15240	0.00974 **	0.05729	0.3864
Soil organic carbon (SOC)	6.95754	0.02296 *	-1.287	0.2108
N fertilizers inputs	1.48444	0.00966 **	0.7159	0.0102 *
P fertilizers inputs	-2.23053	0.02183 *	-1.583	0.091 .
Rain fall during growing season + irrigation	-	-	0.0945	0.0260 *
Percentage of surfaces where the preceding crop is the same than the current one	-0.41006	0.15677	-	-
Cross impact of N and P fertilizers inputs	-	-	0.000004654	0.9983
Cross impact of SOC and N fertilizers inputs	-0.06426	0.03089 *	-0.04114	0.0167 *
Cross impact of SOC and P fertilizers inputs	0.08291	0.10541	0.091	0.0397 *
<i>Number of observations</i>	36		26	
<i>Multiple R-squared</i>	0.76		0.71	
<i>Adjusted R-squared</i>	0.68		0.51	

*Signif. codes: 0.001***, 0.01**, 0.05*, 0.1.*

Table 3.10 – Crop production regressions results.

(Source: from the author)

3.5 Conclusion

The relationship between soil quality indicators, farming practices and crop yields has been investigated statistically. Through this exercise, three soil quality indicators have been selected based on their availability in soil analysis reports and their importance in the phenomena described. These indicators are soil organic carbon, soil pH and soil nitrogen. The farming practices considered are the use of N and P fertilizers and tillage

practices. These practices are known to impact soil organic carbon and pH, and statistical data are available for these practices. Other practices, such as liming and rotation, are not considered because either no data at all are available or no data are available for the time periods studied. The crops considered are those that are mainly grown in the Grand Ouest of France: soft wheat, maize grain, maize forage, barley, sunflower and rapeseed. However, due to a lack of data, crop production functions have been estimated on soft wheat and maize grain since they are the most common crops cultivated in our study area.

According to our results, farming practices such as tillage and N fertilization have a statistically significant impact on soil organic carbon dynamics (for both regressions) and on soil pH (one regression out of two) when considering the median values of soil quality parameters. However, the signs of these impacts are not always consistent with the literature. As for the relationships between crop yield, soil quality and farming practices, when statistically significant, they do not always conform with expectations. Our results have shown that the cooperation effect between fertilizers and soil organic carbon is not always positive. These results have interesting implications in terms of choices regarding farming practices, in particular when considering the balance between long-term soil quality investment and the immediate use of fertilizers. Our results confirm the interest of considering such relationships and the need for good quality data in order to pursue such investigations. However, we can still obtain interesting results when combining various databases operating at different geographic scales.

The results of our statistical analysis support the hypothesis regarding the soil quality dynamics function. Farming practices have both a positive and negative impact on soil quality depending on the parameters considered (here, SOC or soil pH). Regarding the crop production functions, the results we obtain confirm our theoretical assumptions. In some cases, productive inputs may or may not be cooperating with soil quality. In our case, it seems that SOC and N fertilizer inputs are not cooperating in terms of production, while SOC and P fertilizer inputs are.

In the next chapter, a simplified version of our theoretical framework is proposed. This theoretical model is a soil quality investment model where the farmer maximizes his profit while taking into account soil quality dynamics. As a consequence of our statistical results, we have specified a simplified soil quality dynamics function where soil quality is impacted both positively and negatively by farming practices. For the sake of simplicity, only two types of practices are taken into account. The farmer can use productive inputs that positively impact crop production and negatively impact soil quality dynamics. He

can also invest in soil quality through conservation practices that do not impact crop yield but impact soil quality positively. As for our production function and the cooperating relationship between soil quality and productive inputs, our statistical results show the necessity of considering both cases: when productive inputs and soil quality parameters are cooperating and when they are not. Ignoring one of these cases would lead to an incomplete analysis.

Chapter 4

Soil resource, and the profitability and sustainability of farms: Soil quality investment models

IN the preceding chapters, it was established that through their practices, farmers have an impact on the physical, biological and chemical qualities of their soil. However, in a tense economic context, farmers face a trade-off between short-term objectives of production and profitability and the long-term objective of soil resource conservation.

In this chapter, we investigate the conditions in which farmers have a private interest to preserve soil quality. We also characterize the optimal strategies of the management of soil quality dynamics. We use a simplified theoretical soil quality investment model, where farmers maximize revenue under a soil quality dynamics constraint. This simplified model and the assumptions are based on our theoretical framework, the agronomic and economic literature, and our statistical analysis results.

Here, we propose a soil quality investment model where soil quality dynamics are considered within a crop production system. Two kinds of practices are distinguished: productive practices and conservation practices. The former have a direct impact on production, and the latter indirectly impact production through a positive effect on soil quality. From this model, the equilibrium point and the dynamics of this equilibrium are extensively discussed (1) with respect to the optimal equilibrium and the optimal paths to attain it; and (2) with respect to the reaction of the system to changes in the environment (crop prices, time preferences, costs).

4.1 Objective and interest of the model

The objective of this simplified model is to determine the conditions under which farmers have a private interest in maintaining or increasing soil quality when they maximize their revenue under a soil quality dynamics constraint. To achieve this end, we propose a soil quality investment model where soil quality dynamics are considered within a crop production system.

To this end, we use a simplified theoretical soil quality investment model and its variants, where farmers maximize their revenues under a soil quality dynamics constraint. In the production function, following our statistical results, soil quality and productive inputs are considered in one case as cooperating factors and in the other case as non-cooperating factors. When considering productive inputs and soil quality as cooperative factors, two cases are distinguished: In one case, productive inputs do not impact soil quality dynamics, and in the second case, productive inputs have detrimental impacts on soil quality dynamics.

Given the objective and the results expected from the analysis of these soil quality investment models, the use of dynamic optimization seems more relevant than the use of static optimization.

4.2 Dynamic optimization versus static optimization

The choice of studying our optimal control problem in a dynamic framework is motivated by the following.

Such an approach is first due to the very nature of our problem: Resource management issues should be solved using a dynamic approach. Indeed, the slow processes characterizing soil quality dynamics as well as the importance of cumulative changes induced by management practices justify a dynamic approach (Saliba, 1985). In addition, we seek to determine the role of soil quality changes not only in the profitability of farms but also in their sustainability. Taking into account the sustainability issue requires a dynamic approach.

Moreover, when conducting dynamic analysis, the role of the discount rate is taken into account. This is a particularly interesting aspect to consider, in particular when attempting to analyze the short-term and long-term trade-offs that seem to condition the

farmers' decisions to adopt or forego soil conservation practices. Here, the discount rate is considered as the preference between immediate or future profits and the subsequent trade-offs. The discount rate is used to describe the farmer's time preference¹: The higher the discount rate is, the more that short-term gratifications are preferred. In our theoretical models, we assume that the discount rate converges toward the interest rate. The values of discount rate r range between 0 and 1. An r equal to 0 may correspond to the time preference of a selfless agent, for instance, a benevolent state for which future revenues are considered as valuable as current revenues. On the other hand, an r equal to 1 can correspond to the time preference of a selfish short-termist private agent who values only his present revenue.

In addition, dynamic optimization also makes it possible to consider and discuss the optimal (and non-optimal) strategies to attain (or not) the optimal and stable solution and to take into account the initial conditions.

4.3 Analytical tools used: of the interest and complementary of performing comparative statics, comparative dynamics and the phase diagram

Comparative statics is a method used to compare two equilibria with respect to changes in parameters (an increased price or cost for instance) (Léonard and Van Long, 2002). Comparative statics can be used to compare equilibria obtained from a dynamic maximisation, if such equilibria exist.

Whereas comparative statics makes it possible to determine how the steady state can be impacted by a change in parameter, local comparative dynamics provide information as to how the approach path is affected. The two approaches are complementary since steady state comparative statics appear in the local comparative dynamics for the level of the control variable (Caputo, 2005). However, comparative statics and comparative dynamics do not explain the adjustment process caused by a change in a given parameter. Nonetheless, this can be considered using a dynamic analysis of the problem (Feldere and Homburg, 1992).

The dynamic behavior of our optimal control model can be described using a phase diagram, which is a graphical representation of the optimal solution. Within the phase diagram, the phase space is divided into four regions in which variables either increase

1. Following the definition proposed by Frederick, Loewenstein and O'Donoghue (2002).

or decrease over time. Throughout the analysis, restrictions can be made on the shape of the trajectories leading to the optimal path. This is a tool that allows for detailed qualitative analysis (Léonard and Van Long, 2002).

4.4 Soil quality, agricultural practices and crop production

In the proposed soil quality investment model, farmers maximize their profit. Profit is equal to the crop yield multiplied by crop prices minus the costs of farming practices, subject to soil quality dynamics.

Two types of practices are distinguished: (1) productive inputs m (corresponding to chemical input use); and (2) conservation practices u , considered here as an investment in soil quality. Investments in soil quality correspond to the extra costs induced, for instance, by implementing green manure in the crop rotation, leaving crop residues, or adopting superficial tillage or no-tillage. The extra costs also encompass the costs induced by a more complex management of the system.

There are two production factors, soil quality q and productive inputs m . The crop production function is represented by $y = \phi(q, m)$. As in McConnell (1983), Barbier (1990) and Hediger (2003), soil quality q is composed of endogenous attributes s and exogenous attributes a . Exogenous attributes, such as soil type or other site-specific attributes, are fixed. Endogenous attributes, however, are impacted by farming practices. When the farmer invests in soil quality, he is investing in his soil endogenous quality. Contrary to McConnell (1983), Barbier (1990) and Hediger (2003), soil endogenous quality is considered here not only with respect to soil depth (physical dimension) but also with respect to the chemical and biological dimensions of soil quality, such as soil acidity or soil fauna and flora auxiliaries. These three soil characteristics are chosen as examples because all three have positive impacts on soil quality, are positively impacted by conservation practices u and are cooperating with productive inputs m .

In fact, there are numerous dimensions of soil quality (physical, chemical or biological) having positive or negative impacts on crop production. In addition, a single soil quality characteristic can be impacted positively by one practice and negatively by another practice if implemented at the same time. Hence, the relationships are complicated. This is a simple model, where the effects of so-called productive inputs and conservation inputs are simplified and exaggerated in order to focus on a qualitative discussion of the trade-offs faced by the farmer.

Crop production per hectare $y(t)$ depends on soil quality q and productive input intensity m , considered as having a direct impact on production. t denotes time. The production function is $C^{(2)}$ (twice continuously differentiable). Since soil quality exogenous attributes a are fixed, the crop production function can be written as:²

$$y(t) = \phi(q(s(t), a), m(t)) = f(s(t), m(t)) \quad (4.1)$$

$$f_s > 0, f_m > 0, f_{ss} < 0, f_{mm} < 0, \quad (4.2)$$

$$f_{sm} = f_{ms} \stackrel{\geq}{\leq} 0, f_{ss}f_{mm} - (f_{ms})^2 > 0 \quad (4.3)$$

It is assumed that crop production f increases with soil quality ($f_s > 0$) and productive inputs ($f_m > 0$). However, the higher the soil quality is, the slower the increase in production observed ($f_{ss} < 0$). In addition, the more that productive inputs are intensively used, the less is their positive impact ($f_{mm} < 0$). In our models, following our statistical results, we consider whether productive inputs and soil quality are positively cooperating ($f_{sm} \stackrel{\geq}{\leq} 0$). Cooperating inputs can be considered as inputs working as a team (Alchian and Demsetz, 1972). The output is yielded by this team, in our case, productive inputs m and soil quality s . Hence, stating that productive inputs and soil quality are cooperating means that the production f is not separable; that is, the production obtained is not the sum of the production yield based on the use of productive inputs and the benefits of soil quality. In the original framework of Alchian and Demsetz (1972), team production is used in the case where inputs produce a higher output together than separately and such that the increase in production covers the costs of organizing this cooperation. When production factors are negatively cooperating, we say for the sake of simplicity that they are not cooperating. However, it does not change the mathematical properties of the function f .

Two cases are distinguished: (1) in case one, productive inputs do not impact soil quality dynamics; and (2) in case two, productive inputs have detrimental impacts on soil quality dynamics.

4.4.1 Case 1: when farming practices only impact positively soil quality changes

Soil quality changes over time depend on a soil natural degradation factor δ and on a soil natural formation factor g . McConnell (1983) and Hediger (2003) also consider

2. For the sake of simplicity, soil quality endogenous attributes are referred to as soil quality in the rest of the chapter.

the two aspects of soil degradation and formation. However, McConnell (1983) reduces the soil degradation to soil loss, and Barbier (1990) and Hediger (2003) focus on the soil degradation rate, reduced to the soil erosion rate.

In this case, the effects of productive inputs on soil quality are ignored. Only the positive impacts of conservation practices on soil quality dynamics are considered. The soil quality dynamics function is $C^{(2)}$ and such that:

$$\dot{s}(t) = -\delta s(t) + g(u(t)) \quad (4.4)$$

$$g_u > 0, g_{uu} < 0 \quad (4.5)$$

It is assumed that the soil natural formation factor g depends positively on the conservation practices u , which increase soil quality ($g_u > 0$). For instance, leaving crop residues on the soil surface decreases erosion (Cutforth and McConkey, 1997; Malhi and Lemke, 2007) and increases the number of auxiliaries, while more complex crop rotation decreases the pest and disease pressures (Cook and Haglund, 1991). The more that conservation practices are implemented, the lower is their positive impact on soil quality ($g_{uu} < 0$).

Here, for simplification, the soil degradation factor δ is considered as constant. This implies that a high-quality soil will have the same degradation rate as a low-quality soil. The soil resilience effect is therefore ignored.

4.4.2 Case 2: When farming practices impact positively and negatively soil quality changes

In this case, the detrimental effects of productive inputs and the positive impacts of conservation practices on soil quality changes are both considered. The soil degradation factor δ is no longer exogenous but depends on the productive inputs m , which are also considered soil quality degrading practices. For instance, pesticides can have non-desirable detrimental effects on the auxiliaries, and fertilizers can increase soil acidity (Verhulst et al, 2010), thus decreasing soil productivity.

As indicated previously, the farmer can invest in soil quality through the adoption of conservation practices u , which have a positive impact on the soil regeneration factor

g. The soil quality dynamics function is $C^{(2)}$ and such that:

$$\dot{s}(t) = -\delta(m(t))s(t) + g(u(t)) \quad (4.6)$$

$$\delta_m > 0, \delta_{mm} > 0, g_u > 0, g_{uu} < 0 \quad (4.7)$$

Assumptions relative to the impact of soil conservation investment are the same as in case 1. It is assumed that conservation practices increase soil quality ($g_u > 0$). The more that conservation practices are implemented, the lower is their positive impact on soil quality ($g_{uu} < 0$). It is assumed that soil quality is all the more degraded as productive inputs are used ($\delta_m > 0$). In addition, this detrimental impact of productive inputs on soil quality is increasing with the use of productive inputs ($\delta_{mm} > 0$).

4.5 Optimal soil quality investments

The farmer, owner of his land, maximizes his profit. The profit depends on crop yield, crop prices and the costs of farming practices. The constant marginal cost of productive input use m is denoted by c_1 , and the constant marginal cost associated with conservation practices u is denoted by c_2 . The marginal costs encompass the labor cost and the energy cost associated with each activity. The price of the crop p is constant. Farmers' profit can be written as:

$$\pi(t) = pf(s(t), m(t)) - c_1m(t) - c_2u(t) \quad (4.8)$$

In addition, the farmer is constrained by the dynamics of his soil. Hence, he has the following optimization problem:

$$\text{Max}_{m,u} \int_0^{T \rightarrow \infty} e^{-rt} [pf(s(t), m(t)) - c_1m(t) - c_2u(t)] dt \quad (4.9)$$

$$\text{subject to: } \dot{s}(t) \quad (4.10)$$

The current value hamiltonian of this problem can be written as:

$$\tilde{H}(m, u, s, \mu) = pf(s(t), m(t)) - c_1m(t) - c_2u(t) + \mu\dot{s} \quad (4.11)$$

In the first case, according to the maximum principle, the optimal paths of m , u , s and μ satisfy:

$$\tilde{H}_m = pf_m - c_1 = 0 \quad (4.12)$$

$$\tilde{H}_u = -c_2 + \mu g_u = 0 \quad (4.13)$$

$$\dot{\mu} - r\mu = -\tilde{H}_s \Leftrightarrow \dot{\mu} = r\mu - pf_s + \delta\mu = \mu(r + \delta) - pf_s \quad (4.14)$$

In the second case, the optimal paths of m , u , s and μ satisfy:

$$\tilde{H}_m = pf_m - c_1 - \mu\delta_m s = 0 \quad (4.15)$$

$$\tilde{H}_u = -c_2 + \mu g_u = 0 \quad (4.16)$$

$$\dot{\mu} - r\mu = -\tilde{H}_s \Leftrightarrow \dot{\mu} = r\mu - pf_s + \delta(m)\mu = \mu(r + \delta(m)) - pf_s \quad (4.17)$$

In the first case, condition (4.12) indicates that for conventional inputs m , the value of the marginal product pf_m must be equal to the cost of the inputs c_1 . However, in case 2, the marginal revenues obtained from using more productive inputs must no longer be equal to zero; they must be balanced with their marginal damages on soil quality, expressed in soil quality marginal value (see condition (4.15)). Conditions (4.13) and (4.16) are the same for both cases. They state that conservation practices u should be implemented such that the costs of conservation inputs c_2 are equal to the additional benefits generated in terms of soil quality marginal value. The costate variable μ , which can be interpreted as the implicit value of soil quality, has a rate of change that depends on the interest rate r , the degradation rate δ , the current soil quality implicit value μ , the crop price p and the influence of soil quality on crop yield f_s (conditions (4.14) and (4.17)). The implicit value of soil quality grows at the rate of discount and degradation minus the contribution of soil quality to current profits. In addition, in this second case, the rate of change of the costate variable $\dot{\mu}$ also depends on productive inputs through their aggravating impact on the soil degradation rate.

The two conditions (4.12) and (4.13) in case 1 and (4.15) and (4.16) in case 2, related to productive inputs and conservation practices, respectively, are always true at equilibrium and on the optimal paths leading to the equilibrium (when both exist).

In case 2, when (4.15) and (4.16) are combined, they can be rewritten such that:

$$\frac{pf_m - c_1}{\delta_m s} = \frac{c_2}{g_u} = \mu \quad (4.18)$$

Equation (4.18) states that, at equilibrium and on the optimal paths, soil quality marginal value is equal to the ratio between the marginal revenues obtained from the use of productive inputs over their marginal damages on soil quality. This ratio must be equal to the ratio between soil conservation costs over the marginal restoration of soil quality.

Along the optimal time paths of the state and costate variables s and μ , productive input m use must continuously be adjusted to satisfy at any time the first-order condition (4.12) for case 1 and (4.15) for case 2. Similarly, soil quality investment u must satisfy (4.13) for case 1 and (4.16) for case 2.

Consequently, management intensity and soil quality investment must be represented as an implicit function of soil quality s and marginal soil rent μ :

For case 1, when the production factors are cooperating,

$$\frac{\partial m}{\partial s} = -\frac{\tilde{H}_{ms}}{\tilde{H}_{mm}} = -\frac{pf_{ms}}{pf_{mm}} = -\frac{f_{ms}}{f_{mm}} > 0 \quad (4.19)$$

$$\frac{\partial m}{\partial \mu} = -\frac{\tilde{H}_{m\mu}}{\tilde{H}_{mm}} = -\frac{0}{pf_{mm}} = 0 \quad (4.20)$$

$$\frac{\partial u}{\partial s} = -\frac{\tilde{H}_{us}}{\tilde{H}_{uu}} = -\frac{0}{\mu g_{uu}} = 0 \quad (4.21)$$

$$\frac{\partial u}{\partial \mu} = -\frac{\tilde{H}_{u\mu}}{\tilde{H}_{uu}} = -\frac{g_u}{\mu g_{uu}} > 0 \quad (4.22)$$

For case 1, when the production factors are *not* cooperating,

$$\frac{\partial m}{\partial s} = -\frac{\tilde{H}_{ms}}{\tilde{H}_{mm}} = -\frac{pf_{ms}}{pf_{mm}} = -\frac{f_{ms}}{f_{mm}} < 0 \quad (4.23)$$

$$\frac{\partial m}{\partial \mu} = -\frac{\tilde{H}_{m\mu}}{\tilde{H}_{mm}} = -\frac{0}{pf_{mm}} = 0 \quad (4.24)$$

$$\frac{\partial u}{\partial s} = -\frac{\tilde{H}_{us}}{\tilde{H}_{uu}} = -\frac{0}{\mu g_{uu}} = 0 \quad (4.25)$$

$$\frac{\partial u}{\partial \mu} = -\frac{\tilde{H}_{u\mu}}{\tilde{H}_{uu}} = -\frac{g_u}{\mu g_{uu}} > 0 \quad (4.26)$$

For case 2, when the production factors are cooperating,

$$\frac{\partial m}{\partial s} = -\frac{\tilde{H}_{ms}}{\tilde{H}_{mm}} = -\frac{pf_{ms} - \mu\delta_m}{pf_{mm} - \mu\delta_{mm}s} \begin{matrix} \geq 0 \\ < 0 \end{matrix} \quad (4.27)$$

$$\frac{\partial m}{\partial \mu} = -\frac{\tilde{H}_{m\mu}}{\tilde{H}_{mm}} = -\frac{-\delta_ms}{pf_{mm} - \mu\delta_{mm}s} < 0 \quad (4.28)$$

$$\frac{\partial u}{\partial s} = -\frac{\tilde{H}_{us}}{\tilde{H}_{uu}} = -\frac{0}{\mu g_{uu}} = 0 \quad (4.29)$$

$$\frac{\partial u}{\partial \mu} = -\frac{\tilde{H}_{u\mu}}{\tilde{H}_{uu}} = -\frac{g_u}{\mu g_{uu}} > 0 \quad (4.30)$$

For case 2, when the production factors are *not* cooperating,

$$\frac{\partial m}{\partial s} = -\frac{\tilde{H}_{ms}}{\tilde{H}_{mm}} = -\frac{pf_{ms} - \mu\delta_m}{pf_{mm} - \mu\delta_{mm}s} < 0 \quad (4.31)$$

$$\frac{\partial m}{\partial \mu} = -\frac{\tilde{H}_{m\mu}}{\tilde{H}_{mm}} = -\frac{-\delta_ms}{pf_{mm} - \mu\delta_{mm}s} < 0 \quad (4.32)$$

$$\frac{\partial u}{\partial s} = -\frac{\tilde{H}_{us}}{\tilde{H}_{uu}} = -\frac{0}{\mu g_{uu}} = 0 \quad (4.33)$$

$$\frac{\partial u}{\partial \mu} = -\frac{\tilde{H}_{u\mu}}{\tilde{H}_{uu}} = -\frac{g_u}{\mu g_{uu}} > 0 \quad (4.34)$$

The expression of soil conservation investment u as an implicit function of soil quality s and marginal soil rent μ is the same in cases 1 and 2 regardless of the cooperation relationship. Indeed, the impact of soil conservation measures on soil quality is the same in both cases. According to (4.26) and (4.34), soil conservation practice implementation increases with the marginal soil rent. However, a change in soil quality does not trigger a change in soil conservation practices ((4.25) and (4.33)).

On the contrary, the expression of production inputs m as an implicit function of soil quality s and marginal soil rent μ is different in cases 1 and 2. In case 1, when productive inputs do not impact soil quality, productive input use increases or decreases with soil quality ((4.23)) depending on the cooperation relationship between m and s and has no relation to marginal soil rent ((4.24)). In case 2, when productive inputs negatively impact soil quality, productive input use decreases with the marginal soil rent ((4.32)). When the production factors are not cooperating, productive input use decreases with soil quality. However, when production factors are cooperating, the sign of the relationship between productive input use and soil quality is ambiguous. Indeed, on one hand, productive inputs and soil quality are cooperating production factors, and

on the other hand, the use of productive inputs deteriorates soil quality ((4.31)) . Hence, the sign associated with the implicit function of m is undetermined. More specifically, it is the sign of $H_{ms} = pf_{ms} - \mu\delta_m$ that is ambiguous.

Two cases can be distinguished when productive inputs m and soil quality s are cooperating:

1. The case where $H_{ms} > 0$, which can be written as $pf_{ms} > \mu\delta_m$. This is the case where the use of productive inputs provides more benefits in terms of marginal production than losses in terms of soil quality marginal value.
2. The case where $H_{ms} < 0$, which can be written as $pf_{ms} < \mu\delta_m$. This is the opposite case. It corresponds to a situation where the marginal damages to soil quality caused by productive inputs are higher than the marginal benefits in terms of productivity.

In this second case, when deciding the amount of productive inputs to be used and soil quality to be restored, one has to consider the costs and benefits of organizing such cooperation. In the case where $H_{ms} > 0$, the situation is favorable to the cooperation between productive inputs and soil quality. This is a situation where $\frac{p}{\mu} > \frac{\delta_m}{f_{sm}}$, that is, where the ratio between crop price and soil quality value is higher than the ratio between the damages of m on soil quality and the cooperating effect in terms of production. However, in the opposite case, it is more difficult to make a conclusion. This is the case where $\frac{p}{\mu} < \frac{\delta_m}{f_{sm}}$.

In addition, H_{ms} can be rewritten using condition (4.15), such that:

$$pf_{ms} - \mu\delta_m \begin{matrix} \geq \\ \leq \end{matrix} 0 \quad (4.35)$$

$$pf_{ms} \begin{matrix} \geq \\ \leq \end{matrix} \mu\delta_m \quad (4.36)$$

$$pf_{ms} \begin{matrix} \geq \\ \leq \end{matrix} \frac{pf_m - c_1}{s} \quad (4.37)$$

$$\frac{\partial \Pi_m}{\partial s} \begin{matrix} \geq \\ \leq \end{matrix} \frac{\Pi_m}{s} \quad (4.38)$$

where Π_m/s is the marginal profit of productive inputs m per unit of soil quality and $\partial \Pi_m / \partial s$ is the marginal profit of productive inputs m for one additional unit of soil quality.

There can be a threshold value of soil quality, $s_{\#}$, below which soil quality is sufficiently low for the cooperating marginal productivity of m and s to exceed the marginal damages caused by m . However, above this threshold, marginal damages are greater

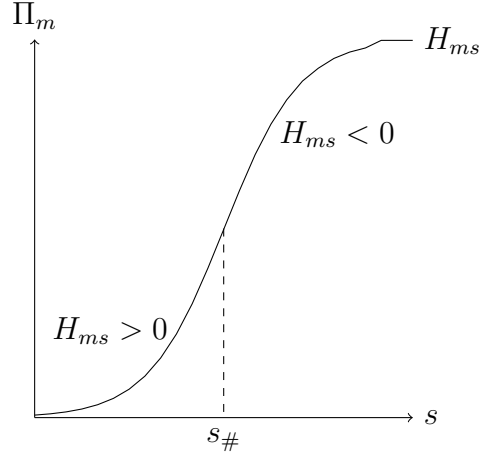


Figure 4.1 – Soil quality threshold and the marginal productivity of productive inputs.

(Source : from the author)

in value than marginal cooperative productivity. In this case, the shadow value of soil quality μ is higher than below the threshold $s\#$ (see Figure 4.1).

4.6 Phase diagram and stability properties of our problem

The long-run or steady state equilibrium of the optimal control problem is determined by the intersection of the ($\dot{\mu} = 0$) and ($\dot{s} = 0$) demarcation curves, which are such that:

$$A(s, \mu) = \dot{\mu} \begin{matrix} \geq \\ \leq \end{matrix} 0$$

$$\text{if } \mu(r + \delta) - pf_s(m(s, \mu), s) \begin{matrix} \geq \\ \leq \end{matrix} 0 \text{ for case 1} \quad (4.39)$$

$$\text{if } \mu(r + \delta(m(s, \mu))) - pf_s(m(s, \mu), s) \begin{matrix} \geq \\ \leq \end{matrix} 0 \text{ for case 2} \quad (4.40)$$

$$B(s, \mu) = \dot{s} \begin{matrix} \geq \\ \leq \end{matrix} 0$$

$$\text{if } -\delta s + g(u(s, \mu)) \begin{matrix} \geq \\ \leq \end{matrix} 0 \text{ for case 1} \quad (4.41)$$

$$\text{if } -\delta(m(s, \mu))s + g(u(s, \mu)) \begin{matrix} \geq \\ \leq \end{matrix} 0 \text{ for case 2} \quad (4.42)$$

The slopes of the stationary loci are given by:

$$\left. \frac{d\mu}{ds} \right|_{B=\dot{s}=0} = - \frac{\partial H_\mu / \partial s}{\partial H_\mu / \partial \mu} \quad (4.43)$$

$$\left. \frac{d\mu}{ds} \right|_{A=\dot{\mu}=0} = - \frac{\partial(\mu r - H_s) / \partial s}{\partial(\mu r - H_s) / \partial \mu}$$

— **In case 1:**

$$\left. \frac{d\mu}{ds} \right|_{B=\dot{s}=0} = -\frac{-\delta + g_u u_s}{g_u u_\mu} = -\frac{-\delta}{g_u u_\mu} > 0 \quad (4.44)$$

$$\begin{aligned} \left. \frac{d\mu}{ds} \right|_{A=\dot{\mu}=0} &= -\frac{\partial(\mu(r + \delta) - pf_s(s, m(s, \mu)))/\partial s}{\partial(\mu(r + \delta) - pf_s(s, m(s, \mu)))/\partial \mu} \\ &= -\frac{-pf_{ss} - pf_{sm}m_s}{r + \delta - pf_s m m_\mu} = -\frac{-f_{ss} - pf_{sm}(-\frac{f_{ms}}{f_{mm}})}{r + \delta - pf_s m \times 0} = -\frac{p(\frac{(f_{ms})^2}{f_{mm}} - f_{ss})}{r + \delta} \\ &= -\frac{p(\frac{(f_{ms})^2}{f_{mm}} - f_{ss})}{r + \delta} \times \frac{f_{mm}}{f_{mm}} = -\frac{p((f_{ms})^2 - f_{ss}f_{mm})}{(r + \delta)f_{mm}} < 0 \end{aligned} \quad (4.45)$$

Given the conditions (4.2) and (4.3), equations (4.23) to (4.26), and $p > 0$, $(r + \delta) > 0$ and $\mu > 0$, the gradient of the $(\dot{s} = 0)$ -line is positive. Actually, when $\dot{s} = 0$, $s^* = u^*/\delta$. Given these conditions, the gradient of the $(\dot{\mu} = 0)$ -curve is negative. This is true regardless of the cooperation between productive inputs.

— **In case 2:**

$$\left. \frac{d\mu}{ds} \right|_{B=\dot{s}=0} = -\frac{-\delta_m m_s s - \delta(m) + g_u u_s}{-\delta_m m_\mu s + g_u u_\mu} = -\frac{-\delta_m m_s s - \delta(m)}{-\delta_m m_\mu s + g_u u_\mu} \quad (4.46)$$

$$\left. \frac{d\mu}{ds} \right|_{A=\dot{\mu}=0} = -\frac{\partial(\mu(r + \delta(m(s, \mu))) - pf_s(s, m(s, \mu)))/\partial s}{\partial(\mu(r + \delta(m(s, \mu))) - pf_s(s, m(s, \mu)))/\partial \mu} = -\frac{\delta_m m_s \mu - pf_{ss} - pf_{sm}m_s}{r + \delta_m m_\mu \mu + \delta(m) - pf_{sm}m_\mu} \quad (4.47)$$

When H_{ms} is positive, the gradient of the $(\dot{s} = 0)$ -curve is positive, and the gradient of the $(\dot{\mu} = 0)$ -curve is negative. This is only the case when production factors are cooperating.

When production factors are non-cooperating, which corresponds to the case where H_{ms} is negative, the signs of the gradients of the curves cannot be determined.

In addition, the slope of the trajectories in the (s, μ) space are such that:

$$\frac{d\mu}{ds} = \left(\frac{d\mu}{dt} \right) \cdot \left(\frac{dt}{ds} \right) = \frac{\dot{\mu}}{\dot{s}} \quad (4.48)$$

Hence, when a trajectory goes through a locus where $\dot{\mu} = 0$, it has a slope zero, and when it goes through a locus where $\dot{s} = 0$, it has an infinite slope.

To determine the stability properties of our problem, i.e., whether all solutions

converge toward the steady state, one can evaluate the Jacobian matrix

$$J = \begin{bmatrix} \partial \dot{s} / \partial s & \partial \dot{s} / \partial \mu \\ \partial \dot{\mu} / \partial s & \partial \dot{\mu} / \partial \mu \end{bmatrix} = \begin{bmatrix} H_{\mu s} & H_{\mu \mu} \\ -H_{s s} & r - H_{s \mu} \end{bmatrix} \quad (4.49)$$

at the steady state (s^*, μ^*) . Computing the trace of the Jacobian matrix, it appears that:

$$\text{tr}[J] = r > 0 \quad (4.50)$$

Since the eigenvalues of the Jacobian matrix equal its trace, at least one eigenvalue is positive, which implies that the fixed point (here, the intersection point of the $(\dot{\mu} = 0)$ and $(\dot{s} = 0)$ demarcation curves) is not locally asymptotically stable (Caputo, 2005). If the determinant of the Jacobian matrix is negative, the steady state is a local saddle point (Hediger, 2003; Narain and Fisher, 2006). Otherwise, if the determinant of the Jacobian matrix is positive, the steady state is an unstable node or at the center of an unstable spiral (Caputo, 2005), so that the system is not converging toward the steady state.

— **In case 1:**

$$\begin{aligned} \det J &= \begin{vmatrix} H_{\mu s} & H_{\mu \mu} \\ -H_{s s} & r - H_{s \mu} \end{vmatrix} = H_{\mu s}(r - H_{s \mu}) - H_{\mu \mu}(-H_{s s}) \\ &= (-\delta)(r - pf_{sm}m_{\mu} + \delta) - (g_u u_{\mu})(-pf_{sm}m_s - pf_{ss}) \\ &= (-\delta)(r + \delta) - (g_u u_{\mu})(-pf_{sm}m_s - pf_{ss}) < 0 \end{aligned} \quad (4.51)$$

— **In case 2:**

When production factors are not cooperating and in the case where $H_{ms} > 0$, which corresponds to the case where the marginal benefits of using productive inputs in terms of revenues are higher than the damages in terms of soil quality marginal

value, there is a steady state equilibrium since the Jacobian matrix is such that:

$$\begin{aligned}
\det J &= \begin{vmatrix} H_{\mu s} & H_{\mu\mu} \\ -H_{ss} & r - H_{s\mu} \end{vmatrix} = H_{\mu s}(r - H_{s\mu}) - H_{\mu\mu}(-H_{ss}) \\
&= (-\delta_m m_s s - \delta(m) + u_s)(r + \delta_m m_\mu \mu + \delta(m) - p f_{sm} m_\mu) \\
&\quad - (-\delta_m m_\mu s + u_\mu g_u)(\delta_m m_s \mu - p f_{ss} - p f_{sm} m_s) \\
&= (-\delta_m m_s s - \delta(m))(r + m_\mu(-H_{sm}) + \delta(m)) - (-\delta_m m_\mu s + u_\mu g_u)(m_s(-H_{ms}) - p f_{ss}) \\
&= (-\delta_m m_s s - \delta(m))(r + m_\mu(-H_{sm}) + \delta(m)) \\
&\quad - (-\delta_m m_\mu s + u_\mu g_u) \left(\left(-\frac{H_{ms}}{H_{mm}} \right) (-H_{ms}) - p f_{ss} \right) \\
&= (-\delta_m m_s s - \delta(m))(r + m_\mu(-H_{sm}) + \delta(m)) - (-\delta_m m_\mu s + u_\mu g_u) \left(\frac{H_{ms}^2 - p f_{ss} H_{mm}}{H_{mm}} \right) \\
&= (-\delta_m m_s s - \delta(m))(r + m_\mu(-H_{sm}) + \delta(m)) \\
&\quad - (-\delta_m m_\mu s + u_\mu g_u) \left(\frac{p^2(f_{ms}^2 - f_{ss} f_{mm}) + \mu \delta_m (\mu \delta_m - 2p f_{sm}) + p f_{ss} \mu \delta_{mm} s}{H_{mm}} \right) \\
&< 0 \tag{4.52}
\end{aligned}$$

From conditions (4.2), (4.3) and (4.7) and equations (4.31) to (4.34), given r and p are positive and assuming that $H_{ms} > 0$, then $H_{\mu s} < 0$, $r - H_{s\mu} > 0$, $H_{\mu\mu} > 0$ and $H_{\mu\mu}(-H_{ss}) > 0$. From these results, the determinant of the Jacobian matrix is negative.

In addition, when $\dot{s} = 0$ and $\dot{\mu} = 0$, we have:

$$\left[\begin{array}{cc} \frac{\partial \dot{s}}{\partial s} & \frac{\partial \dot{\mu}}{\partial \mu} \\ \frac{\partial \dot{\mu}}{\partial s} & \frac{\partial \dot{s}}{\partial \mu} \end{array} \right] < 0 \Leftrightarrow \frac{-\partial \dot{s} / \partial s}{\partial \dot{s} / \partial \mu} > \frac{-\partial \dot{\mu} / \partial s}{\partial \dot{\mu} / \partial \mu} \tag{4.53}$$

from which one can conclude that the slope of the $\dot{s} = 0$ isocline is greater than the slope of the $\dot{\mu} = 0$ isocline in a neighborhood of the steady state. This is true if and only if the steady state is a local saddle point (Caputo, 2005).

Hence, the solution of our optimal control problems is characterized by a long-term optimum in case 1, when productive inputs are cooperating or not cooperating, and in case 2, only when $H_{ms} > 0$ and production factors are cooperating. The long-term equilibrium is represented in a phase diagram (see Figure 4.2 and Figure 4.3). This is a steady state, where $\dot{m} = \dot{u} = \dot{s} = \dot{\mu} = 0$. The steady state is attained through a stable transition path, departing from an initial state s_0 toward the steady state (s^*, μ^*) . The stability properties of the problems and the determination of the long-term equilibrium

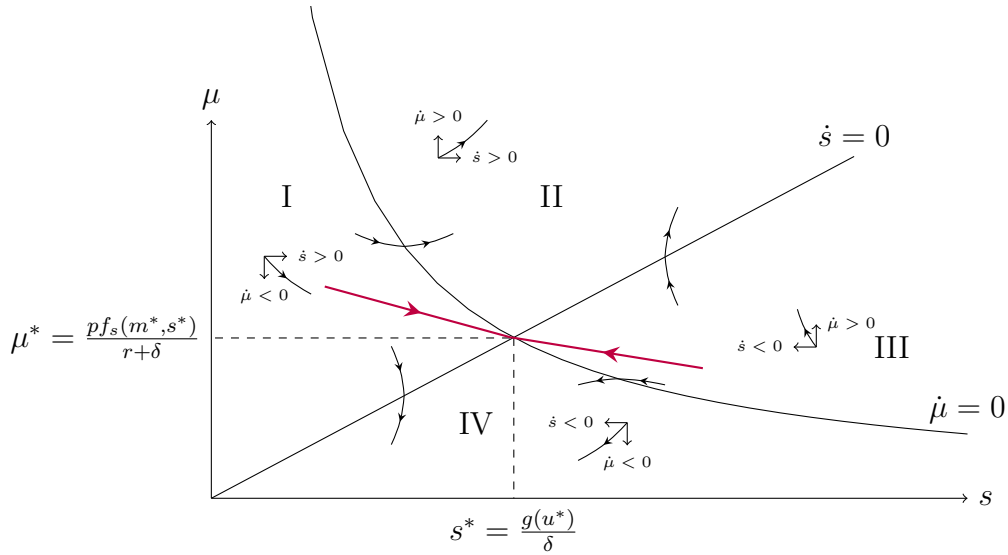


Figure 4.2 – Phase diagram: case 1

(Source : from the author)

are described in Annex 1.

The phase diagrams obtained for case 1 and case 2 when $H_{ms} > 0$ (see Figure 4.2 and 4.3) are similar qualitatively. However, the shapes of the curves are different. The phase diagram of case 1 is true for all values of s . In case 2, the phase diagram corresponds to the situation where soil quality is below some soil quality threshold $s_{\#}$. It corresponds only to the case where the damages caused by the use of productive inputs are overcompensated by its cooperating benefits with soil quality in terms of revenue (see Figure 4.1). For the case above the threshold $s_{\#}$, one cannot determine the existence of an equilibrium.

The steady state can only be achieved by pursuing one of the optimal trajectories. The optimal trajectories are represented in the phase diagrams by the two directed lines going toward the steady state (s^*, μ^*) (see Figure 4.2 and Figure 4.3).

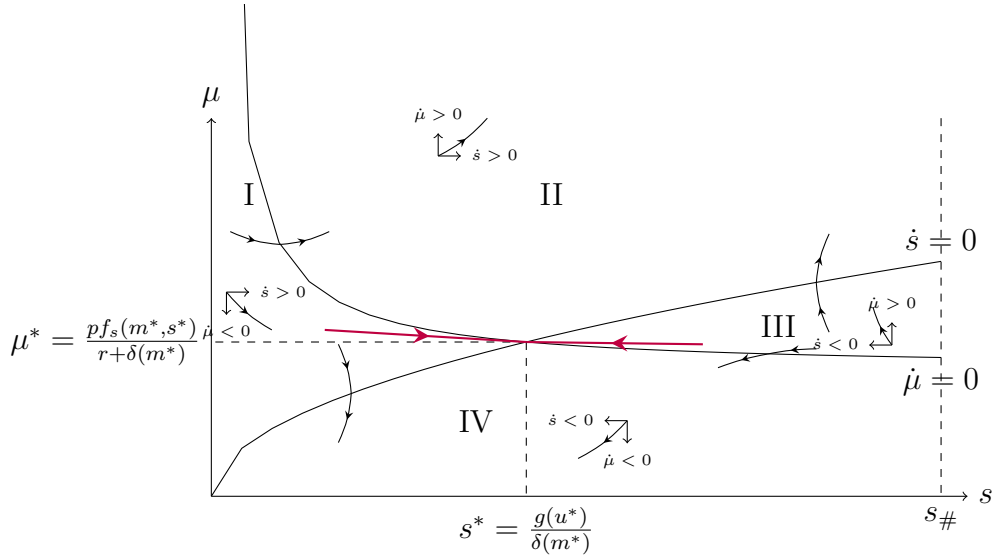


Figure 4.3 – Phase diagram: case 2

(Source : from the author)

When the initial soil quality is low ($s_0 < s^*$ for case 1, $s_0 < s^* < s_{\#}$ for case 2), the optimal trajectory is located in region I. On this path, soil quality increases, while the marginal soil quality value decreases. In addition, the productive inputs intensity increases with soil quality (from (4.23) and (4.31)) and conservation practices decrease with the soil quality marginal value (from (4.26) and (4.34)). Actually, this is a situation where soils show low productivity. To improve this situation, investments in soil conservation are made that diminish, while soil quality is improved, and its value decreases. Indeed, on this optimal path, the higher the soil quality is, the lower its marginal value, and the more effective conservation practices are. Thus, as soil quality increases, less investment in conservation practices is required to increase soil quality (see condition (4.13)). The farmer adjusts his productive inputs to the higher soil quality.

When the initial soil quality is high ($s_0 > s^*$ for case 1, $s^* < s_0 < s_{\#}$ for case 2), the optimal trajectory is located in region III. Along this path, soil quality decreases while the marginal soil quality value increases. Moreover, from (4.23), (4.31) and (4.26),(4.34), when soil quality decreases, the use of productive inputs decreases when production factors are cooperating and increases when production factors are not cooperating. When the marginal soil quality value increases, implementation of conservation practices increases. In this situation, initial soil quality is “too” high compared to

the equilibrium and exhibits high soil productivity. Hence, the optimal strategy for the farmer is to let his soil deteriorate until the equilibrium level of soil quality is reached. However, at some point, the impact of soil deterioration on productivity is such that soil quality investments become necessary to maintain soil quality at equilibrium.

Strategies that differ from these two optimal strategies will turn away from the steady state equilibrium.

For instance, initial conditions (s_0, μ_0) can be such that the farmer is initially located in region I, with a μ_0 placing him above the unique optimal path of region I. Let us remember that $\mu_0 = \frac{c_2}{g_u(u_0)}$. Hence, such a case may correspond to a situation where $g_u(u_0)$ is small and u_0 big. Since we are not on an optimal path, this is a case where $u_0 > u^*$, that is, where investments in soil conservation are higher than what the optimum would require. At first, the strategy followed by the farmer would be similar to the optimal one. However, at some point, the path followed by the farmer will cross the $\dot{\mu} = 0$ locus and will enter into region II. In region II, the trajectory followed is to increase both soil quality s and soil quality marginal value μ by investing increasingly in soil quality conservation practices u . Thus, in this region, the paths followed correspond to an over-investment in soil quality. Such a path may also lead to over-production when production factors are cooperating since the use of productive inputs will increase along with soil quality in this case.

Initial conditions (s_0, μ_0) can also be such that the farmer is in region I but with a small μ_0 . In this case, $g_u(u_0)$ is high; hence, u_0 is small and investment in soil conservation is lower than what the optimum would require ($u_0 < u^*$). Once again, at first, the strategy followed corresponds to the optimal one, except that when following this non-optimal path, the $\dot{s} = 0$ locus is crossed. The farmer is now located in region IV, where it is no longer optimal to maintain soil quality. In region IV, both soil quality and soil marginal quality decrease, along with soil quality investment. This corresponds to a situation of under-production, where soil quality is depleted until it is totally degraded.

A similar discussion is relevant to initial conditions placing the farmer in region III. Initial conditions can be such that the non-optimal path followed will cross the $\dot{s} = 0$ locus, thus leading into region II and its unsustainable over-production where investment in soil quality is higher than optimal. Initial conditions can also be such that the non-optimal path followed will cross the $\dot{\mu} = 0$ locus and enter region IV and its unsustainable under-production, where investment in soil quality is lower than optimal.

4.7 To consider or not to consider soil quality dynamics

When farmers do not consider soil quality dynamics, considering both cases, the first-order conditions of our problem can be rewritten as follows:

$$H_m = pf_m - c_1 = 0 \quad (4.54)$$

$$H_u = -c_2 = 0 \quad (4.55)$$

For case 1, the optimal use of productive inputs is the same regardless of whether farmers consider soil quality dynamics in their decision-making process. The marginal benefits in terms of using m must be balanced by the inputs costs.

For case 2, the conditions are different. Since the farmer does not consider soil quality dynamics or the detrimental impact of productive inputs on soil quality, he does not internalize the additional cost of using productive inputs in terms of soil quality marginal value. According to condition (4.55), the optimal use of conservation practices is such that the investment is equal to zero at any point in time. That is to say, when not considering the dynamics of soil quality, no soil conservation investment is made. Hence, we are always in a situation of under-investment in soil quality.

One can still expect soil quality to attain a long-term equilibrium (Smith et al, 2000), such that:

$$\dot{s} = -\delta s + g(u) = 0 \Leftrightarrow s^S = \frac{g(0)}{\delta} \quad \text{in case 1} \quad (4.56)$$

$$\dot{s} = -\delta(m)s + g(u) = 0 \Leftrightarrow s^S = \frac{g(0)}{\delta(m^S)} \quad \text{in case 2} \quad (4.57)$$

— For case 1,

When comparing the long-term soil quality equilibrium (s^S) when not considering soil quality dynamics and the optimum soil quality level (s^*) when considering soil quality dynamics, one obtains:

$$s^S = \frac{g(0)}{\delta} < s^* = \frac{g(u^*)}{\delta} \quad (4.58)$$

In addition, in case 1, regardless of whether the farmer considers soil quality, the optimal level of productive inputs, at any point in time and thus also when soil

quality attains a long-term equilibrium, must satisfy:

$$pf_m(m^*, s^*) - c_1 = 0 \quad \text{and} \quad pf_m(m^S, s^S) - c_1 = 0 \quad (4.59)$$

$$\Leftrightarrow pf_m(m^*, s^*) - c_1 = pf_m(m^S, s^S) - c_1 \quad (4.60)$$

$$\Leftrightarrow f_m(m^*, s^*) = f_m(m^S, s^S) \quad (4.61)$$

We know that $s^S < s^*$. From the assumptions of our model, we know that $f_{ms} > 0$ and $f_{mm} < 0$. Hence, for the equality to hold, $m^S < m^*$.

Compared to the situation where the farmer considers soil quality dynamics when optimizing his productive inputs use and soil conservation investments, the long-term level of soil quality is lower than the optimal one.

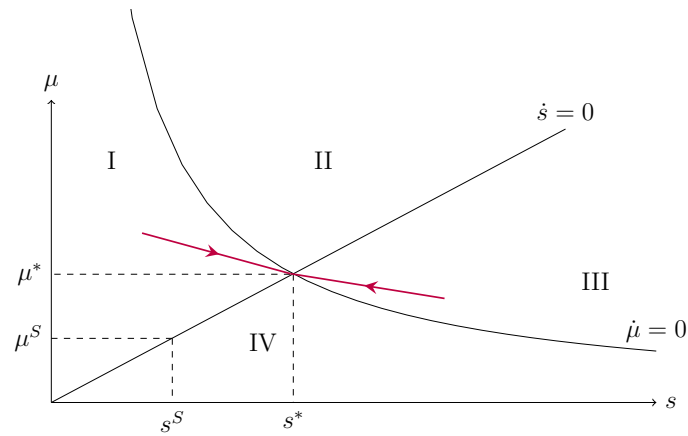


Figure 4.4 – Phase diagram/Not considering soil quality dynamics: case 1

(Source : from the author)

— For case 2

When comparing the long-term soil quality equilibrium (s^S) when not considering soil quality dynamics and the optimum soil quality level (s^*) when considering soil quality dynamics, one obtains:

$$s^S = \frac{g(0)}{\delta(m^S)} \quad \text{and} \quad s^* = \frac{g(u^*)}{\delta(m^*)} \quad (4.62)$$

In addition, from the conditions (4.12) and (4.54) of the two optimization problems, at any point in time, and in particular for the bundles (m^*, s^*) and (m^S, s^S) , we

have:

$$pf_m(m^*, s^*) - c_1 - \mu\delta_m(m^*)s^* = 0 \quad \text{and} \quad pf_m(m^S, s^S) - c_1 = 0 \quad (4.63)$$

$$\Leftrightarrow pf_m(m^*, s^*) - c_1 - \mu\delta_m(m^*)s^* = pf_m(m^S, s^S) - c_1 \quad (4.64)$$

$$\Leftrightarrow f_m(m^*, s^*) - \frac{\mu}{p}\delta_m(m^*)s^* = f_m(m^S, s^S) \quad (4.65)$$

In addition to the cooperation effect in terms of production, the detrimental impact of productive inputs on soil quality dynamics is to be considered. In this second case, several situations are plausible depending on the initial soil quality.

— $m^* < m^S$ and $s^* > s^S$

From the assumptions of our model:

$$m^* < m^S \Rightarrow \delta(m^*) < \delta(m^S) \quad (4.66)$$

$$g(u^*) > g(0) \Rightarrow \frac{g(u^*)}{\delta(m^*)} > \frac{g(0)}{\delta(s^S)} \quad (4.67)$$

$$s^* > s^S \quad (4.68)$$

— $m^* = m^S$ and $s^* > s^S$

From the assumptions of our model:

$$m^* = m^S \Rightarrow \delta(m^*) = \delta(m^S) \quad (4.69)$$

$$g(u^*) > g(0) \Rightarrow \frac{g(u^*)}{\delta(m^*)} > \frac{g(0)}{\delta(s^S)} \quad (4.70)$$

$$s^* > s^S \quad (4.71)$$

These two cases are consistent with (4.65). These are situations where when not considering soil quality dynamics, the farmer uses productive inputs without compensating for the damages caused to soil quality, thus degrading his soil quality below the optimum. There is an over-use of productive inputs and an under-use of soil quality investments.

— $m^* > m^S$

$$m^* > m^S \Rightarrow \delta(m^*) > \delta(m^S) \quad (4.72)$$

$$g(u^*) > g(0) \Rightarrow \frac{g(u^*)}{\delta(m^*)} \begin{matrix} \geq \\ < \end{matrix} \frac{g(0)}{\delta(s^S)} \quad (4.73)$$

$$s^* \begin{matrix} \geq \\ < \end{matrix} s^S \quad (4.74)$$

This can correspond to different situations. One is where initial soil quality is above

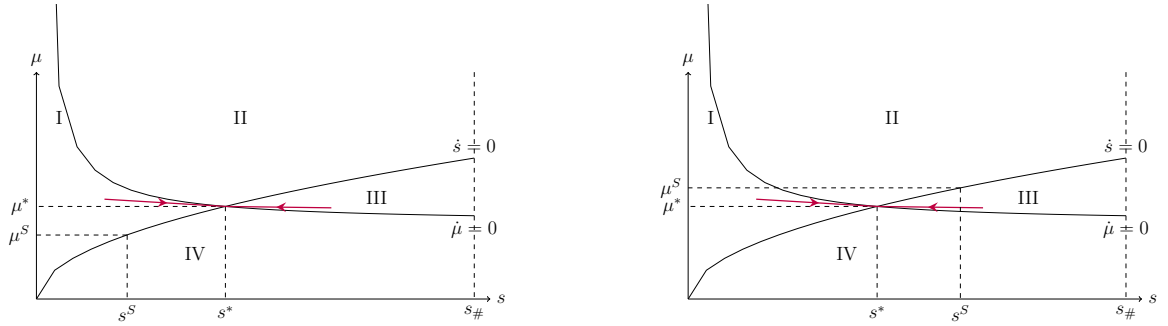


Figure 4.5 – Phase diagram/Not considering soil quality dynamics: case 2
 (Source : from the author)

the optimum and sufficiently high for long-term soil quality to stabilize above the optimum, even when the farmer does not compensate for the impact of productive inputs on his soil. This could be possible since the farmer also uses less productive inputs than optimum, thus causing less damage. The other is a situation where initial soil quality is not sufficiently high for less use of productive inputs to compensate for the lack of investment in soil quality.

In most cases, not considering soil quality dynamics leads to a long-term equilibrium level where soil quality is lower than the optimal. This can be observed when the farmer engages in over-use or under-use of productive inputs compared to the cases where the farmer considers soil quality. Indeed, in all cases, no investment is made in soil quality. The damages, whether natural or caused by the use of productive inputs, are not compensated for. In one of the situations described, a sufficiently high initial soil quality level can still lead to a long-term equilibrium of soil quality higher than the optimal. The problem is that in all cases, the long-term equilibrium of soil quality is not a stable one: These are situations that cross the $\dot{s} = 0$ locus, so that the strategies followed by the farmer remain non-optimal strategies with under-investment in soil quality leading to a depletion of the resource.

In the next sections, considering the cases where the farmer takes into account soil quality dynamics, we present the static and dynamics comparative of our problem. The objective of these sections is to study the changes in equilibrium and optimal strategies when there is a change in the economic environment of the farmer (changes in price, in costs) or a change in preference to time. The latter parameter can also explain why in similar external conditions, farmers that maximize their profit under a soil quality dynamics constraint may follow different strategies due to a personal preference for time.

4.8 Impacts of a change in parameters on the equilibrium

A comparative static analysis of this problem makes it possible to determine how the values of the endogenous variables of our model at the steady state equilibrium would differ with different values of exogenous parameters (Léonard and Van Long, 2002). In our case, endogenous variables that characterize the optimal steady state are productive inputs m , conservation practices u , soil quality s and soil quality implicit value μ . In what follows, we present the change in optimal values for a change in a given parameter, all other parameters remaining constant.

When production factors are cooperating, our comparative static analysis for case 1 and for case 2 when the damages caused by the use of productive inputs are over-compensated by its cooperating benefits with soil quality in terms of revenue ($H_{ms} > 0$) yields the same following results (see Annex 1 for the computations details):

$$m = m(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (4.75)$$

$$u = u(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (4.76)$$

$$\mu = \mu(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (4.77)$$

$$s = s(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (4.78)$$

The comparative statics for case 1 when production factors are *not* cooperating yields different results:

$$m = m(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (4.79)$$

$$u = u(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (4.80)$$

$$\mu = \mu(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (4.81)$$

$$s = s(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (4.82)$$

We do not compute the comparative static analysis for case 2 when production factors are not cooperating since we cannot establish the existence of an equilibrium in this case.

An increase in the cost associated with productive inputs, c_1 , leads to an expected decrease in productive inputs and a decrease in soil marginal value at equilibrium. When production factors are cooperating, soil quality decreases with production input use, and there is less investment in soil quality. However, when production factors are not cooperating, soil quality increases, as well as soil investment u .

An increase in the cost associated with soil conservation and non-productive practices, c_2 , decreases the investment in soil conservation, which can be expected. As a consequence, soil quality at optimum is lower, and the marginal value associated increases. When productive inputs and soil quality are cooperating, the use of productive inputs associated with a lower soil quality is smaller than in our original equilibrium. When production factors are not cooperating, the use of productive inputs is higher.

An increase in the crop yield price p , leads to an increase in soil quality and productive inputs when production factors are cooperating. Indeed, the farmer has the opportunity to increase his production to attain an equilibrium where the marginal benefits of using more productive inputs are equal to the costs of these practices. Due to the cooperation between the two variables, soil quality at equilibrium also increases. To maintain this level of soil quality, the investment in soil conservation techniques is higher in this equilibrium. With a higher price and a higher productivity of soil quality at this optimum, the marginal soil quality is also higher. However, when production factors are not cooperating, it is not possible to determine the impact of crop yield price on the equilibrium. This impact will depend on the weights of soil quality or productive inputs in the crop production function.

An increase in the discount rate r can correspond to a higher preference for the present. Hence, in his maximisation problem, the farmer values more present revenue than future revenue. As a consequence, soil quality will be either more depleted or less restored by the farmer, who will be less willing to invest in soil conservation measures, regardless of whether production factors are cooperating. When production factors are cooperating, the level of productive inputs also decreases: The loss in soil productivity seems to be compensated by lesser expenses in productive inputs. When production factors are not cooperating, the contrary is observed.

Figure 4.6 is a graphical representation of how the steady state can be modified by an increase in crop price for case 1. The $\dot{s} = 0$ isocline is independent of p , so that a change in p does not change the $\dot{s} = 0$ isocline. Hence, it is the $\dot{\mu} = 0$ isocline that shifts when p increases. Indeed, the $\dot{\mu} = 0$ isocline explicitly depends on the price p . In addition to the changes described previously, such a change also has an impact on the optimal and non-optimal strategies.

In our example (see Figure 4.6), the former optimal path, which was located in region III, is now in region IV. While in the previous situation, a farmer located on this path would have attained the steady state, this farmer is now in a situation of

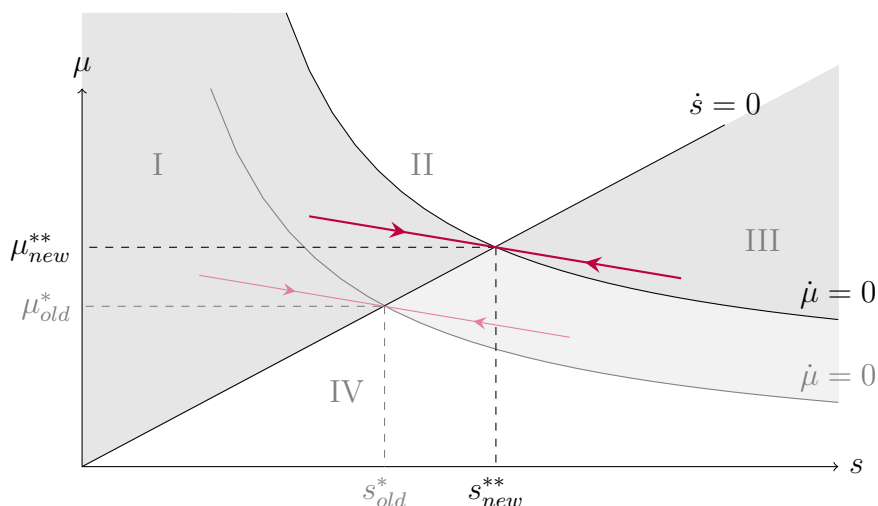


Figure 4.6 – Phase diagram and static comparatives: case 1 and an increase in crop price p , when production factors are cooperating

(Source : from the author)

under-production with a total depletion of his soil quality. Conversely, farmers that in the previous situation were located in region II, characterized by non-sustainable over-production, may be either on the optimal path or on the path not leading immediately to a situation of over- or under-production.

Figure 4.7 is a graphical representation of how the steady-state equilibrium can be modified by an increase in the cost c_1 of productive inputs in case 2 when production factors are cooperating. In this example, the former optimal path, which was located in region I, is now in region II: While in the previous situation a farmer located on this path would have attained the steady state, this farmer is now in a situation of over-production with a total depletion of his soil quality. Conversely, farmers that in the previous situation were located in region IV, characterized by non-sustainable under-production, may be either on the optimal path or on the path not leading immediately to a situation of over- or under-production.

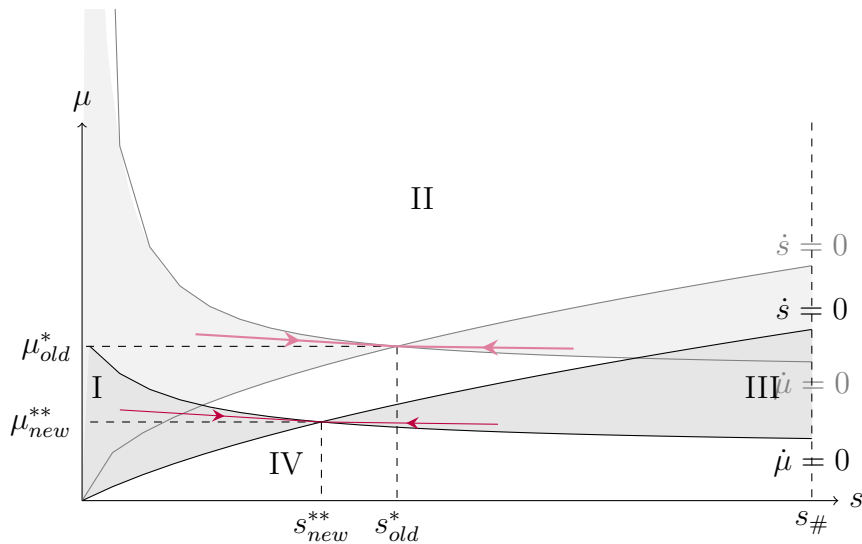


Figure 4.7 – Phase diagram and static comparatives: case 2 and an increase in the cost of productive inputs c_1 when production factors are cooperating

(Source : from the author)

Based on the comparative statics, the change in steady state as a response to a change in a given parameter has been investigated (see Figure 4.6 and Figure 4.7). Making use of the steady state comparative statics results and the phase diagram, it is possible to find the local comparative dynamics of the increase in the crop price.

4.9 Moving from one equilibrium to another: transition paths

The local comparative dynamics illustrate the transition path from the old steady state to the new one, which was not discussed in the previous section. When considering local comparative dynamics, it is assumed that the economy observed is at rest at the old steady state. The local comparative dynamics, through the optimal transition path, describe how the economy comes to rest at the new steady state (Caputo, 2005) (see Figure 4.8 and Figure 4.9).

Usually in an optimal control model, the state variable is considered as given at any moment in the planning horizon (Caputo, 2005). Hence, considering the old steady state as the initial condition, when a parameter of the model initially changes, the state variable will not change at first. Nevertheless, it will eventually change. In the example for case 1 (see Figure 4.8) considering an increase in crop price, it is the marginal value of soil

quality that initially changes. It could go downwards or upwards. However, downward movement would lead to zone IV, where trajectories are non-optimal and go further from the steady state. Thus, going upward, in zone I, an optimal strategy leading to the new steady state can be reached. Reaching this new steady state leads to an increase in soil quality.

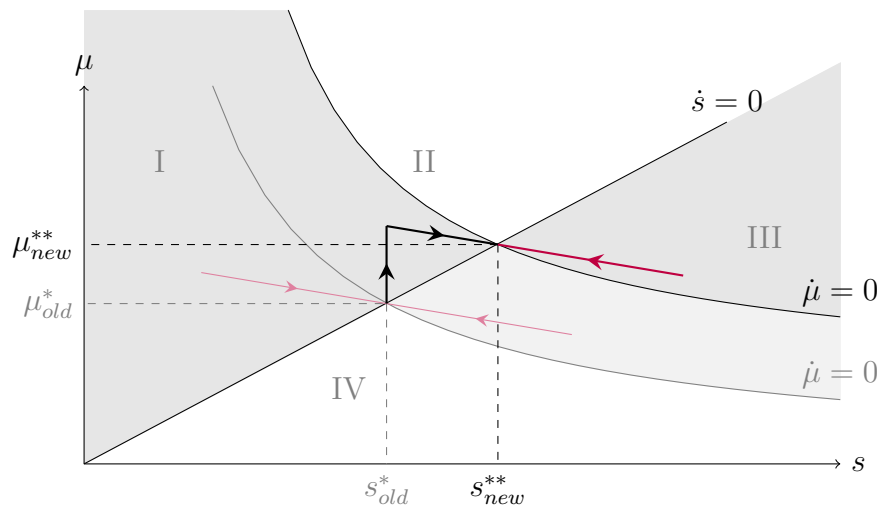


Figure 4.8 – Static and local dynamics comparatives: case 1 and the optimal transition path resulting from an increase in crop price (when production factors are cooperating)

(Source : from the author)

Similarly, in case 2, considering an increase in productive inputs cost, it is the marginal value of soil quality that initially changes vertically. Since an upward movement would lead to zone II, where trajectories are non-optimal and go further from the steady state, the marginal value of soil quality is going downward in zone III, where an optimal strategy leading to the new steady state can be reached (see Figure 4.9). Following this optimal strategy, soil quality decreases.

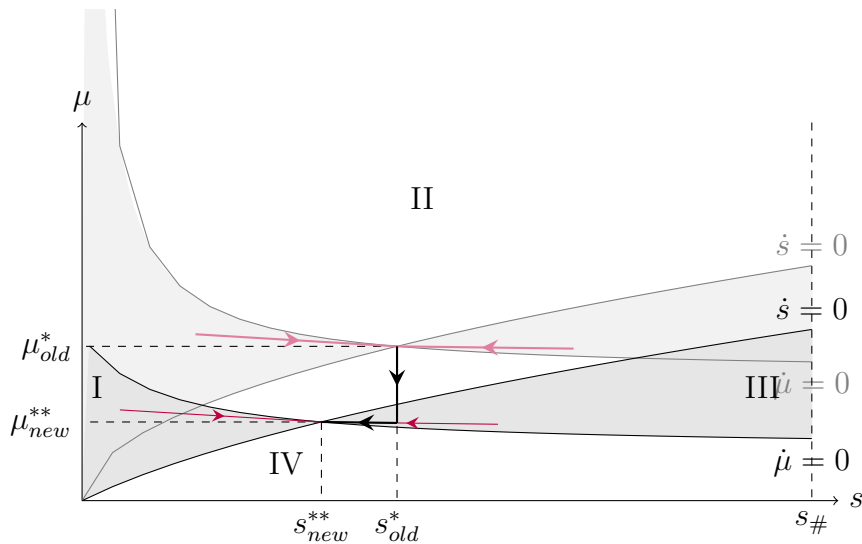


Figure 4.9 – Phase diagram and local dynamic comparatives: case 2, an increase in the cost of productive inputs and the adjustment process (when production factors are cooperating)

(Source : from the author)

In addition to comparative statics and local comparative dynamics, comparative dynamics also provide interesting economic information as to how the cumulative discounted functions of our model can be impacted by changes in a given parameter (Caputo, 2005).

4.10 The impact of a change in parameters on the optimal paths

To conduct our comparative dynamics, we used the methodology proposed by Caputo (2005) *via* envelope methods. This is a general method of comparative dynamics that can be applicable to any sufficiently smooth optimal control problem using a primal-dual approach (see Annex 1 for computations).

The primal form of our soil quality investment model is such that:

$$V(\alpha) \equiv \max_{m(\cdot), u(\cdot)} J[m(\cdot), u(\cdot), s(\cdot)] \equiv \max_{m(\cdot), u(\cdot)} \int_0^T e^{-rt} [pf(s(t), m(t)) - c_1 m(t) - c_2 u(t)] dt \quad (4.83)$$

$$\text{s.t. } \dot{s}(t) = k(s(t), u(t)) = -\delta s(t) + g(u(t)) \text{ for case 1,} \quad (4.84)$$

$$\dot{s}(t) = k(s(t), u(t)) = -\delta(m(t))s(t) + g(u(t)) \text{ for case 2,} \quad (4.85)$$

$$s(0) = s_0, s(T) = s_T \quad (4.86)$$

where $\alpha \equiv (p, c_1, c_2, r)$ is the vector of time-independent parameters. We denote $z(t; \alpha)$, $v(t; \alpha)$ and $w(t; \alpha)$ the optimal paths of soil quality, productive inputs, and investments in soil conservation practices, respectively. The comparative dynamics analysis is conducted on the vector $\alpha \equiv (p, c_1, c_2, r)$ of parameters.

Applying Theorem 11.1 yields for both cases:

$$V_p(\alpha) \equiv \int_0^T y(t; \alpha) e^{-rt} dt > 0 \quad (4.87)$$

$$V_{c_1}(\alpha) \equiv - \int_0^T v(t; \alpha) e^{-rt} dt < 0 \quad (4.88)$$

$$V_{c_2}(\alpha) \equiv - \int_0^T w(t; \alpha) e^{-rt} dt < 0 \quad (4.89)$$

$$V_r(\alpha) \equiv - \int_0^T t\pi(t; \alpha) e^{-rt} dt \leq 0 \quad (4.90)$$

where $y(t; \alpha) \equiv f(z(t; \alpha), v(t; \alpha))$ is the value of the production function of the farm, and $\pi(t; \alpha) \equiv pf(z(t; \alpha), v(t; \alpha)) - c_1 v(t; \alpha) - c_2 w(t; \alpha)$ is the instantaneous profits along the optimal path.

Information obtained from the dynamic envelope theorem is relative to the cumulative discounted profit and production functions. Equations (4.87), (4.88) and (4.89) are unambiguously signed: According to the assumptions of our model, the production function cannot be negative nor can the productive inputs or the investment in soil quality conservation practices. However, equation (4.90) is ambiguously signed. Indeed, although $V(\alpha) > 0$ must hold for the farm to be able to thrive in the market, it may be possible that instantaneous profits along the optimal path may be positive or negative at any given point. This could be the case where important investments in soil quality are made that do not yield productivity gains instantaneously. However, one could add a constraint whereby instantaneous profit has to be positive, in which case $V_r(\alpha) < 0$.

In our model, the integrand function of the soil quality investment model is linear in $\gamma \equiv (p, c_1, c_2)$. Thus, the model satisfies the conditions of Corollary 11.2³ (Caputo, 2005). This implies that the optimal value function $V(\cdot)$ is locally convex in γ . Hence, when differentiating equation (4.87) from (4.89), one can use the convexity of $V(\cdot)$ to determine the signs of the second partial derivatives and infer from those signs the own-price effects:

$$V_{pp}(\alpha) \equiv \frac{\partial}{\partial p} \int_0^T y(t; \alpha) e^{-rt} dt = \int_0^T \frac{\partial y}{\partial p}(t; \alpha) e^{-rt} dt \geq 0 \quad (4.91)$$

$$V_{c_1 c_1}(\alpha) \equiv -\frac{\partial}{\partial c_1} \int_0^T v(t; \alpha) e^{-rt} dt = -\int_0^T \frac{\partial v}{\partial c_1}(t; \alpha) e^{-rt} dt \geq 0 \quad (4.92)$$

$$V_{c_2 c_2}(\alpha) \equiv -\frac{\partial}{\partial c_2} \int_0^T w(t; \alpha) e^{-rt} dt = -\int_0^T \frac{\partial w}{\partial c_2}(t; \alpha) e^{-rt} dt \geq 0 \quad (4.93)$$

Equation (4.91) shows that the cumulative discounted crop production is not decreasing in the crop price. One can note that it is the discounted production function slope, integrated over the entire planning horizon, that is not decreasing. For a given and finite period of time, crop production could be decreasing while the crop price has increased. Actually, while in the short-term such behavior could appear irrational, as long as over the entire planning horizon equation (4.91) is verified, such behavior would be somehow rational. Similar reasoning can be applied to the respective impacts of an increase in the cost of productive inputs and in the cost of conservation practices. Equations (4.92) and (4.93) demonstrate that the cumulative discounted use of productive inputs and the cumulative discounted investment in conservation practices are non-increasing in their own prices.

The comparative dynamics of the discount rate r cannot be derived through the use of Corollary 11.2 since the integrand function $F(\cdot)$ of our soil quality investment model is not convex in the discount rate r :

$$F(t, m, u, s; \alpha) \equiv [pf(s, m) - c_1 m - c_2 u] e^{-rt} \quad (4.94)$$

Hence, to conduct the comparative dynamics of the discount rate, we rely on Theorem 11.2 (see Annex 1). From Theorem 11.2, with $\alpha \equiv (p, c_1, c_2, r)$, so that the discount rate r is the fourth element of the parameter vector α , and since $L_{\alpha\alpha}(\beta)$ is a negative

3. Corollary 11.2 (Convexity of the Optimal Value Function): For control problem (P), with assumptions (A.1) through (A.4) holding, if (i) $g_\alpha(t, x, u; \alpha) \equiv 0_{N \times A}$ and (ii) $f(\cdot)$ is convex in α for all $\beta \in B(\beta^\circ; \delta)$, then $V(\cdot)$ is convex in α for all $\beta \in B(\beta^\circ; \delta)$. (Caputo, 2005 - page 297)

semi-definite matrix, we have:

$$L_{rr}(\beta) = - \int_0^T [F_{rs}(t, z(t; \alpha), v(t; \alpha); \alpha) \frac{\partial z}{\partial r}(t; \alpha) + F_{rm}(t, z(t; \alpha), v(t; \alpha); \alpha) \frac{\partial v}{\partial r}(t; \alpha) + F_{ru}(t, z(t; \alpha), v(t; \alpha); \alpha) \frac{\partial w}{\partial r}(t; \alpha)] dt \quad (4.95)$$

$$= - \int_0^T [pf_s(t, z(t; \alpha), v(t; \alpha)) \frac{\partial z}{\partial r}(t; \alpha) + [pf_m(z(t; \alpha), v(t; \alpha)) \frac{\partial v}{\partial r}(t; \alpha) - c_1] - c_2 \frac{\partial w}{\partial r}(t; \alpha)] te^{-rt} dt \leq 0 \quad (4.96)$$

Equation (4.96) describes the impact of a change in the discount rate on the soil quality investment model over the entire planning horizon. However, the comparative dynamics of the discount rate are not easy to interpret, contrary to the comparative dynamics of the crop price and the costs of productive inputs and soil conservation practices.

4.11 What about when the marginal cooperating benefits in terms of productivity are lower than the marginal damages on soil quality ? Same as when production factors are not cooperating.

As stated previously, the existence of a stable steady-state equilibrium when $H_{ms} < 0$ - that is, when the cooperating benefits of productive inputs and soil quality are lower than the marginal damages of productive input use on soil quality - cannot be stated since the determinant of the Jacobian matrix is ambiguously signed.

Actually, some observations can be made with respect to such a situation. Irrespective of the value of H_{ms} , the trace of the Jacobian matrix of our problem is positive. Hence, for a saddle point to exist, the determinant of the matrix has to be negative. In addition, the slope of the curves is likely to be of similar sign, irrespective of the value of H_{ms} . The conditions under which such a situation can occur do not contradict themselves. Thus, it is possible to conclude that a stable steady state equilibrium point can exist when $H_{ms} < 0$. However, such conditions are arithmetic and do not really allow for an economic interpretation.

This is also the case when production factors are not cooperating, and the conclusion is the same. This does not necessarily mean that such an equilibrium does not exist but that the existence of a stable steady-state equilibrium point depends on the crop production and soil quality dynamics function specification and calibration. In other words, it is a situation that requires empirical analysis to determine whether an equilibrium exists for a given situation.

4.12 Conclusion

This chapter examines whether farmers have a private interest in maintaining or increasing soil quality. It explores and discusses the different optimal strategies to achieve a long-term equilibrium. In addition, the dynamics elements of the soil resource management problem have been characterized. The importance of the cooperation relationship between soil quality and productive inputs is also demonstrated.

The investment models proposed highlight some of the favorable situations for the maintenance and enhancement of soil quality. In the first one, productive inputs are assumed to have no impact on soil quality dynamics and, in the second one, to have detrimental impacts on soil quality dynamics. Conservation practices are used as a lever to increase soil quality and maintain it at the optimum level. The model of case 2 shows the importance of the cooperation between the two production factors (soil quality and productive inputs). When production factors are cooperating *and* the marginal cooperative productivity is higher than the marginal damages of productive inputs on soil quality, there exists a long-term optimal equilibrium with optimal strategies that can be followed by the farmer to reach the optimum. However, when the marginal productivity of the cooperating inputs is lower than the marginal and detrimental impact of productive inputs on soil quality *or* when production factors are not cooperating, one cannot come to a conclusion about the existence of an equilibrium. This addresses situations where the increase in production does not cover the costs of organizing this cooperation in terms of soil quality shadow value.

The cooperation between the production factors can also impact the efficiency of public policies. Let us imagine that a subsidy is put in place to encourage farmers to invest in their soil. If the production factors are cooperating, productive input use will increase along with soil quality, which might not be desirable. Such a policy would have a negative feed-back effect. On the contrary, if production factors are not cooperating, then productive input use would decrease, while soil quality would increase. In this situation, we have a positive snowball effect.

These ambiguities show that we are indeed facing empirical questions that depend on technical interactions that are difficult to know and control. Furthermore, such simplified theoretical models offer interesting analysis and diagnostic perspectives for farm advisory services. With these theoretical models, interesting qualitative analysis can be provided. In addition, empirical modelling would make it possible to provide both qualitative and quantitative analysis.

In fact, the different theoretical models proposed here are an introduction to the empirical modelling of the optimal investment in soil quality. The theoretical models have been used to preside over the first investigations into the relationships between soil quality, agricultural practices and farm profitability.

In the next chapter, an empirical modelling is proposed. The objective is to provide both qualitative and quantitative analysis of the trade-offs faced by farmers between short-term objectives of profitability and productivity and the long-term objective of soil resource conservation. The empirical bioeconomic model and the various price scenarios proposed in the following chapters are based on the literature review previously presented as well as our theoretical and statistical results.

Chapter 5

Application of the optimal control model: A case study

THIS chapter is dedicated to the empirical application of the theoretical framework presented previously. The empirical model has a twofold objective: (1) address our general question regarding the relevance of the EIA approach in achieving productive, profitable and sustainable agriculture, and (2) provide diagnostics and advice to farmers with respect to strategies regarding farming practice choices and implementation in response to economic changes.

EIA is a long-term approach that consists in producing more with less. In such an approach, agricultural productivity is based on the intensive use of ecosystem services, many of which are closely linked to soil resources (food, feed, elemental cycling, for instance) (Lal, 2015). When considering soil resources, the EIA approach corresponds to a strategy of maintenance or an increase in the quality of this resource. The techniques relative to such a strategy include conservation agriculture practices, which are the practices considered in our study. Actually, inappropriate farming practices can trigger an ever-increasing downward spiral of soil degradation that leads to a decrease in ecosystem services, soil use efficiency and soil resilience. Such a negative process can be mitigated by the adoption of soil conservation practices (Lal, 2015). However, the implementation of suitable practices is site specific, in both the environmental and economic context. Indeed, the farmer faces a trade-off between a short-term objective of productivity and profitability and a long-term objective of sustainability - which includes soil sustainability.

To investigate such a trade-off, dynamic bioeconomic modeling is a suitable tool,

as it makes it possible to consider both the socio-economic and biophysical conditions necessary to the farmer's decision making process. Through such models, it is also possible to study the interlinks between economical objectives and the existing biological dynamics and constraints. They also make it possible to evaluate changes in the economic context and assess changes in policy. Holden *et al* (2005), Louhichi *et al* (1999 and 2010) used dynamic bioeconomic models to assess the impacts of existing or alternative policies. Smith *et al* (2000) used bioeconomic modeling to determine the optimal cropping systems in a specific agricultural region of Canada.

The previously mentioned models take into account soil dynamics: soil erosion in Louhichi *et al* (1999), soil erosion and soil nutrients (soil nitrogen stocks) in Holden *et al* (2005), and soil erosion and soil organic carbon in Smith *et al* (2000). In all models, different scenarios of farming practices are simulated to evaluate their impact on the indicators of soil quality considered, among other objectives. These models are context and site specific. Holden *et al* (2005) study the case of a farming household in Ethiopia, incorporating specific soil, climatic and economic conditions. Similarly, the soil context of the Dark Brown Chernozem (Typic Boroll) soils of the Canadian plains in Smith *et al* (2000) is very different from the soil context of the Grand Ouest of France. The results as well as the crop production functions and soil quality parameter dynamics cannot be transferred to our case. We address this limitation here.

We propose an empirical model adapted to the climatic and soil conditions of the Grand Ouest of France, with crop production functions and soil quality dynamics functions calibrated and estimated from a farm representative of crops grown in the Grand Ouest.

Most of the features of the model proposed by Smith *et al* (2000) are close to those of our model. They consider soil organic carbon (SOC) as a production factor. However, in Smith *et al* (2000), changes in SOC are considered through a biological long-term equilibrium of SOC. This long-term equilibrium depends on cropping intensity, the use of fertilizers (1 or 0) and the use of tillage (1 or 0). This function is used to determine the SOC target level attained for each simulated combination of these farming practices. Hence, SOC end value is not determined endogenously during the optimization process. In our model, we also consider SOC (expressed as soil organic matter (SOM)) since it is a reliable indicator of changes in soil quality in addition to being frequently studied and present in most soil analysis. Hence, it is an indicator for which there are data and which is simulated by several biophysical modeling systems. However, contrary to Smith *et al* (2000), we consider SOC as an endogenous production factor in our model, wherein the

SOC end value is determined endogenously through the optimization process.

The bioeconomic model proposed here is an intertemporal model. It takes into account the long-term dynamics of soil quality characteristics, as well as their cumulative changes. The intertemporal setting of our problem allows for environmental feedback of soil quality changes. In addition, these changes are taken into account in the farmer's decision-making process. We introduce soil organic matter dynamics as a production constraint that the farmer takes into account when maximizing his revenue. During the optimization process, the intensity of farming practices is endogenously determined. We address the conflict between the short-term objective of profitability and productivity and the long-term objective of sustainability, placing emphasis on soil resource sustainability. Actually, since soil is both a production support and a production factor, the question of its conservation is of great importance. Soil erosion is not taken into account since it is not a primary concern in our region. In addition, since soil quality investments usually involve low tillage intensity, such measures also reduce soil erosion.

This is an empirical bioeconomic intertemporal model applied to the case of a French crop farm located in the Grand Ouest (Vienne department). The farmer has been involved in soil conservation issues since the 1990s. Thus, we have had access to a fair amount of data relative to his farming practices and soil quality analysis over time. The model is used to determine which farming practices (tillage intensity, N fertilizer inputs, crop rotations, residue use) are best suited to profit maximization when taking soil quality dynamics into account. This model is also used to identify the incentives or impediments to the adoption of soil conservation practices.

First, our case study as well as the characteristics of the study area are presented. Then, the empirical bioeconomic model is described, along with its different components. It is a dynamic intertemporal optimal control model that directly incorporates the soil quality dynamics function and the crop production function. The model is implemented on GAMS. In a third part, the soil quality indicator dynamics function and the crop yield functions are presented in more detail. These functions are estimated using the biological simulation model CropSyst in order to capture the specific effects of N fertilizer inputs, tillage and crop residue use on soil quality in addition to the effects of N fertilizers and soil quality on crop yields. Following the previous chapter, the soil quality indicator is soil organic carbon. We present the calibration and validation of the model. We briefly present the software and solver used to run our simulations as well as the main limits of our empirical model. Finally, the results of our simulations are presented and discussed.

5.1 Description of the case study area

5.1.1 *Our case study: A cereal farm of the Grand Ouest of France*

The case study our empirical model is based on is a 194 ha cereal farm located in the southern part of the Grand Ouest in the Vienne department (86).

In terms of crop activities, it can be considered a representative cereal farm, where most of the crops cultivated in the Grand Ouest are grown. However, the farmer has a specific approach. Since the 1990s, he has made radical changes, incorporating soil conservation practices under the guidance of a soil counselor from the cooperative Terrena.

Nine types of crops are cultivated on this farm: winter soft wheat, winter durum wheat, sunflower, rapeseed, winter barley, oats, and alfalfa, as well as flax since the 2016/2017 season. When climatic conditions are suitable, the farmer also includes inter-cropping. Hence, inter-cropping is not systematic, although he practices it whenever possible.

In the model presented in the following sections, inter-cropping, oats and flax are not considered in the crop rotations. Flax is not considered because it only represents one parcel of the farm. In addition, it does not seem to be a recurrent feature of crop rotation according to the historic data regarding his parcels. Similarly, we do not consider oats production other than in the descriptive context of the farm. Indeed, oats are cultivated only on one parcel as feed for horses. The parcels on which oats are grown are the low-quality parcels. Hence, the implantation of this crop is utilitarian for the horses and is not part of a strategic rotation. As for inter-cropping, their presence depends on climatic events variability, which we do not simulate in our models.

Three main types of soils can be found on the farm: (1) loam soils, (2) clay-limestone soils and (3) clay-silt soils. Based on the farm fertilization plan for 2016/2017 and the soil characterization presented by the cooperative, we have estimated the proportion of farm parcels belonging to each of these soil types. 38 pedological profiles are identified by the cooperative on its territory, and 14 pedological profiles are identified on the farm. To classify the farm soil types, we took into account both the soil type (surface texture) and the subsoil type, describing the names of the pedological profiles used in the decision-support tools of the cooperative. Loam soils represent 11% of the UAS, with mainly permanent meadows. Clay-limestone soils represent 45% of the UAS and clay-silt soils 41%, and the range of crops grown on the farm can be found in these two soils.

5.2 The empirical bioeconomic control model

5.2.1 Maximisation program: the objective function

It is assumed that the farmer's objective is to maximize his expected revenue. The objective function of the model is the expected present value of returns over a T time period:

$$\text{Max}_{Z,N,D} U = \sum_{t=1}^T (1+r)^{-t} \mathbb{E}(\pi_t) \quad (5.1)$$

subject to: $OM_{c,s,t} = OM_{c,s,t-1} + h(OM_{c,s,t-1}, N_{c,s,t-1}, Z_{c,s,t-1}, D_{c,s,t-1})$ Soil organic matter motion (5.2)

$$0 \leq OM_{c,s,t} \leq OM_{max} \quad \text{Bounds on soil organic matter levels} \quad (5.3)$$

$$OM(0) = OM_0 \quad \text{Initial soil quality} \quad (5.4)$$

$$0 \leq Z_t \leq 1 \quad \text{Bounds on tillage intensity} \quad (5.5)$$

$$\text{Cropland constraint, rotation constraint, cropland accounting} \quad (5.6)$$

$$\text{Labour constraint} \quad (5.7)$$

$$\text{Liquidity constraint} \quad (5.8)$$

$$0 \leq D_t \leq 1 \quad \text{Bounds on crop residues} \quad (5.9)$$

$$0 \leq N_t \leq N_{max} \quad \text{Bounds on N fertilizers inputs} \quad (5.10)$$

$$(5.11)$$

where:

c = crop,

Z = tillage intensity,

N = nitrogen fertilizers,

D = crop residues,

s = soil type,

OM = soil organic matter,

r = discount rate,

π = profit,

T = terminal year in the planning horizon

5.2.2 Profit function

The profit of the farmer is composed of the following:

1. **The amount of money received for the total crop yields sold**, which corresponds to the current price of a culture multiplied by the crop yield as determined by the production function f_C , which depends on fertilizer inputs, soil endogenous quality and exogenous determinants for each activity level area. The activity level area X , expressed in ha, is characterized by the preceding crop pc , the current crop C and the soil type s .

$$\sum_{pc} \sum_c \sum_s (P_{c,t} f_{s,c,t}(N_{c,s,t}, OM_{c,s,t})) X_{pc,c,s,t} \quad (5.12)$$

2. **The costs associated to the different inputs used on each activity level area (variable costs), and the fixed costs associated.** For crop production, variable costs correspond to seeds, fertilizers, soil conditioner products, crop protection products (phytosanitary products) and petroleum products (heating and motor fuels, lubricants). Fixed costs correspond to land costs, comprising land rental prices and the interest on loans contracted to buy land, depreciation on machinery and equipment, and other costs and services such as taxes and interest incurred for other than land-related reasons, i.e., building, plantation and land improvement depreciation, machinery and building repair, insurance costs, and other various goods and services (contract work, car expenses, electricity, water..) (Desbois and Legris, 2007).

$$\sum_i C_i M_{i,pc,c} X_{pc,c,s,t} + FC \times X_{pc,c,s,t} \quad (5.13)$$

3. **The CAP aids**, composed of the coupled premium for each crop multiplied by the corresponding activity level area, the Basic Payment Scheme BPS , the Green Direct Payment GDP , redistributive payment RP and contracted agri-environmental measures AEM .

The BPS , GDP and RP are decoupled aids. The BPS is provided depending on the surfaces held by farmers. The GDP complements the BPS and is provided to any farmer that respects tree criteria that benefit the environment: (i) contributions to the regional maintenance of a given ratio of permanent grassland ; (ii) crop diversification (at least different tree cultures on one's arable lands); (iii) 5% of land designated as an ecological focus area. The RP is provided to smaller farmers

as redistributive support for the first hectares (the first 52 hectares in France).

$$\sum_{pc} \sum_c \sum_l X_{pc,c,s,t} Pr_{c,t} + BPS_t + GDP_t + RP_t + AEM_t \quad (5.14)$$

Thus, the profit function is such that:

$$\begin{aligned} \pi_t = & \sum_{pc} \sum_c \sum_s (P_c f_{c,s,t}(N_{c,s,t}, OM_{c,s,t})) X_{pc,C,s,t} - \sum_i C_i M_{i,pc,c} X_{pc,c,s,t} - FC \times X_{pc,c,s,t} \\ & + \sum_{pc} \sum_c \sum_s X_{pc,c,s,t} Pr_{c,t} + BPS_t + GDP_t + RP_t + AEM_t \end{aligned} \quad (5.15)$$

where:

pc = preceding crop,

c = crop,

s = soil type,

P = price,

f = production function,

X = activity level area,

C = cost,

i = input index,

OM = soil organic matter,

N = N fertilizers,

M = inputs,

FC = fixed costs,

Pr = coupled premium,

BPS = Basic Payment Scheme,

GDP = Green Direct Payment,

RP = Redistributive Payment,

AEM = Agri-Environmental Measure.

5.2.3 Crop production functions and soil quality dynamics functions

These two types of functions were estimated for each crop and each soil type using the biological simulation software CropSyst. Details of the methodology are provided in the Methodology section of this chapter.

5.2.4 Constraints

5.2.4.1 Cropland constraint

This constraint considers the limited availability of cropland on a farm:

$$\sum_{pc,c} CROPAREA_{pc,c,s,t} \leq LANDAV_{s,t} \quad (5.16)$$

$CROPAREA$ is activity level area, defined by the present crop C , the previous crop pc , and the soil type s , at time t . The sum of all activity level areas must not exceed the total land available on the farm for each soil type.

5.2.4.2 Rotation constraints

Rotation choices are such that, for each soil type, the total area allocated to each crop this year cannot exceed the total area allocated the previous year to the preceding crops matching the current crop considered.

$$CROPAREA_{pc,c,s,t} \leq \sum_c CROPAREA_{pc,c,s,t-1} \quad (5.17)$$

5.2.4.3 Labor constraint

There is a pre-determined amount of work time available per year on the farm ($TTIMAVAIL$), corresponding to two full-time jobs over the year, with two part-time jobs during the months of July and August. The constraint states that the actual yearly working time ($WTIME$) shall not exceed this available working time (which corresponds to the farmer's work time as well as that of potential employees):

$$\sum_{c,s} WTIME(c, s, t) \leq TTIMAVAIL \quad (5.18)$$

5.2.4.4 Liquidity constraint

This constraint expresses the necessity for the farmer to be able to pay his rent and his fixed and variable charges at the end of each exercise. This constraint may be relaxed.

$$\mathbb{E}(\pi_t) \geq 0 \quad (5.19)$$

5.3 Methodology

5.3.1 Data used in our empirical bioeconomic control model

To proceed to the calibration of the bioeconomic model and perform simulations, data are required at the cooperative scale, farm scale and crop scale. These are data relative to farming practices, soil characteristics, and input and output prices. Data used to construct our model are mostly from the farmer's documentation on his practices (phytosanitary register, definitive or forecast fertilization books, mineral inputs supply plans, manure plans) and from estimates given by the farmer or his farming counselor. When necessary, other sources of information have been used, such as technical reports and documentation from the Chambers of Agriculture and the Agreste website (French agricultural statistics, evaluation and forecasting) as well as data from a previous case study applied to this same cereal farm (in Ghali, 2013).

— Data at the cooperative or farm scale

- Seed price (euros/kg)
- Fertilizers price (N, NP, PK, NPK) (euros/kg)
- Crop protection products price (herbicides, fungicides, pesticides) (euros/kg)
- Petroleum products prices (heating and fuel) (euros/L)

Source : farmer's information and Ghali (2013)

— Data at the farm scale

- Total surface of cultivated land (ha)

Source : farmer's documentation - cropping pattern of the farm in 2016 and 2017

- Crops (number, name, and surface (ha))

Source : farmer's documentation - cropping pattern of the farm in 2016 and 2017

- Types of soil, and their characteristics (soil organic carbon, soil nitrogen)

- Source : farmer's documentation - Soil analysis of three representative parcels
 - Bournais parcel, silt soil, soil analysis of 2008 and 2015
 - Laimée parcel, soil, clay-silt soil analysis of 2008 and 2014
 - Closures parcel, clay-limestone soil, soil analysis of 2010 and 2015
- Labor needed per crop and per year (hours/ha) for different farming practices (tillage, soil loosening, seeding, fertilization, harvesting...)
 - Source : farmer's information and Ghali (2013)
- Intermediary consumption
 - Expenses linked to electricity (euros/kWh) and water (euros/m³)
 - No available source.
- Perennial production factors
 - Rental price of land (and interest of the outstanding loans) (euros)
 - Source : Ghali (2013)
 - Equipment and machinery (annual costs): owned equipment value, annual membership at the CUMA (machinery sharing cooperative), annual costs of agricultural firms services, and renting expenses (euros)
 - Source : Ghali (2013) and CUMA website
 - Insurance costs
 - Contractual work (salary and employer contribution) (euros)
 - Source : Ghali (2013)
 - Car expenses (euros)
 - Source : Ghali (2013)
- Basic payment (euros)
 - Source : Farmer's information
- Data at the crop scale
 - Preceding crop
 - Source : Farmer's documentation - Advised manure plans for 2016 yield, 2015 yield, 2014 yield, 2013 yield, and 2012 yield
 - Tillage intensity (superficial tillage, plow-down tillage, direct seeding)
 - Source : Farmer's and farming counselor's information
 - Nitrogen, Phosphorus and Potassium fertilizers and Magnesium applied (units/ha and number of application)

Source : Farmer's and farming counselor's information and farmer's documentation (definitive fertilization book of 2016 yield, forecast fertilization books of 2016 yield, 2015 yield, 2014 yield, 2013 yield and 2012 yield, mineral inputs supply plans of 2014 yield, 2013 yield, 2012 yield)

- Crop protection products (number of applications)

Source : Farmer's 2016 phytosanitary register

Apart from particular climatic conditions that caused low yields, the cultural year was normal in terms of pests and disease pressures (farmer's counselor information)

- Crop residues use

Source : Farmer's and farming counselor's information

- Yield (hundredweight/ha)

Source : Farmer's documentation (Nitrogen fertilization plan for 2017 yield, where the 2016 yields are indicated)

- Coupled CAP aid (euros/ha)

Source : Farmer's information

- Agri-environmental measures (type and amount in euros)

Source : Farmer's information

Not enough data were available to estimate soil quality dynamics functions and crop production functions. Hence, the functions have been estimated using the biological simulation software CropSyst.

CropSyst provides agronomic and environmental outputs and allows long-term simulations as well as rotation simulation (Stöckle et al, 2003). In addition, Stöckle, Cabelguenne and Debaeke (1997) have shown that the performance of CropSyst is suitable for applications in France. In addition, CropSyst is a simulation model that does not require a great deal of soil data in order to provide consistent simulations. Actually, while we have access to soil analysis for three representative parcels for our case study, it does not represent a very precise or exhaustive description of soil characteristics, unlike those found in other biological simulation models.

With CropSyst, it is possible to take into account the geographic and climatic characteristics of our study area by filling in information relative to altitude, latitude, longitude and average climatic data. For altitude, latitude and longitude data, we used the coordinates of the village residence of the farmer, Usseau. This corresponds to a latitude of $46,87^\circ$, a longitude of 0.50944° and an altitude of 80 meters. For climatic data, CropSyst requires mean, maximum and minimum temperatures per month. The data of the closest climatic station, Poitiers, are used here.

For the soil quality dynamics functions and the crop production functions, three representative soil types are distinguished. Soil analysis for the parcels representative of these soil types are used to describe their composition:

- **Loam soils:** 60,2 % of sands, 11.5 % of clay, 28.4 % of silts
- **Clay-limestone soils:** 30.8 % of sands, 20.1 % of clay, 35.0 % of silts
- **Clay-silt soils:** 26.8 % of sands, 27.2 % of clay, 45 % of silts

The specific methods used for the estimation of the crop production functions and soil quality dynamics functions are described below.

5.3.2 Estimation of the soil quality dynamics function

5.3.2.1 Functional form

The role of soil quality in the profitability and sustainability of farms can be modeled through its attributes or characteristics. They can be used as such or integrated into an index (Wienhold et al, 2009). A soil quality index can be useful for normalizing soil indicator data, and it also makes it possible to compare various management practices or assess management-induced changes (Wienhold, Andrews and Karlen, 2004). However, modelling soil quality attributes directly rather than through a quality index arguably prevents the use of a soil quality index. Indeed, the various and complex interactions between soil quality attributes make it difficult to aggregate soil quality indicators in a unique soil quality index (Letey et al, 2003).

To overcome this issue, the approach used by Smith et al (2000) can be adopted, which consists in taking into account soil quality based on the relationship between soil quality attributes and crop yield. With this approach, soil quality is considered with respect to a specific use (here, agricultural goods production).

Here, soil quality dynamics are considered through soil organic carbon. The soil organic carbon pool is a reliable indicator of soil quality changes (Lal, 2005). Furthermore, soil organic carbon is an important factor in sustainability (Lal, 2015). Actually, the biological software CropSyst considers soil organic matter instead of soil organic carbon. However, this does not change anything according to our reasoning: In soil analysis, the organic carbon is measured, and the result that appears in the soil analysis is organic matter, according to the commonly accepted factor of 1.72.

In order to be consistent with the results of our statistical analysis, it would have been interesting to consider soil pH dynamics as well; however, the biological software does not allow such simulation. Similarly, soil total nitrogen dynamics would have been an interesting factor to consider, but CropSyst does not allow soil total nitrogen to be taken into account. CropSyst addresses the dynamics of mineral nitrogen through the mineralization, nitrification and denitrification processes. The dynamics of mineral nitrogen and soil total nitrogen are very different: The former is fast with important variations through time, while the latter is slow with less variation.

To capture the impact of farming practices on SOM dynamics, one can consider the

following functional form:

$$\begin{aligned}
OM(c, s, t) = & OM(c, s, t - 1) + (\alpha_0 + \alpha_1 OM(c, s, t - 1) + \alpha_2 OM(c, s, t - 1)^2 + \alpha_3 N(c, s, t - 1) \\
& + \alpha_4 N(c, s, t - 1)^2 + \alpha_5 Z(c, s, t - 1) + \alpha_6 Z(c, s, t - 1)^2 \\
& + \alpha_7 D(c, s, t - 1) + \alpha_8 D(c, s, t - 1)^2 + \alpha_9 N(c, s, t - 1)Z(c, s, t - 1) \\
& + \alpha_{10} N(c, s, t - 1)D(c, s, t - 1) + \alpha_{11} Z(c, s, t - 1)D(c, s, t - 1) \\
& + \alpha_{12} OM(c, s, t - 1)N(c, s, t - 1) + \alpha_{13} OM(c, s, t - 1)D(c, s, t - 1) \\
& + \alpha_{14} OM(c, s, t - 1)Z(c, s, t - 1) + \varepsilon
\end{aligned} \tag{5.20}$$

(5.21)

where

OM = soil organic matter

s = soil type

c = crop cultivated

D = crop residues left and buried

N = amount of N fertilizer used

Z = tillage (superficial or profound)

ε = error term

Hence, we consider that the level of SOM of a given parcel at time t is the initial value of SOM in the previous period $t - 1$, to which we add the variation caused by the practices implemented and the crop grown throughout the year $t - 1$ on this parcel. This is why we have estimated SOM dynamics functions that are specific to each crop to take into account the preceding crop effect.

5.3.2.2 Scenarii tested and parameters estimations

In order to estimate the soil organic matter (SOM) function, a database was built based on CropSyst simulations. A particular set of techniques was simulated for the same soil type and crop during a period of thirty years. The objective was to be able to simulate the significant and lasting impacts of these practices on SOM dynamics.

Simulations are performed for three soil types and seven crops. For each soil type/crop bundle, the same set of simulations is run. Each simulation had a differ-

Inorganic nitrogen inputs level	Durum wheat	Soft wheat	Barley	Maize	Sunflower	Rapeseed	Alfalfa
N0	0	0	0	0	0	0	0
N1	215	180	140	150	60	180	50
N2	300	300	250	300	120	300	100

Table 5.1 – The different levels of nitrogen fertilizers applied, per crop.
(Source: from the author)

ent combination of N inputs (three different values; see Table 5.1), OM initial stock (three different values; see Table 5.2), tillage practices (simplified or not), and residue use (shredded and incorporated at the surface, or not). It corresponds to 36 simulations per crop and per soil type.

The various values of nitrogen fertilizer inputs and OM soil content are determined by the farmer’s practices and soil analysis as a benchmark. For nitrogen fertilizer input levels, three levels are distinguished for OM dynamics simulation:

- Level 0 N_0 , which corresponds to no nitrogen applied
- Level 1 N_1 , the average level of nitrogen inputs as usually applied by the farmer (except for alfalfa, for which the farmer usually does not apply any N fertilizer)
- Level 2 N_2 , a high level of nitrogen inputs: twice the usual amount applied by the farmer

OM soil level (g/kg)	S1 (Loam soils)	S2 (Clay-limestone soils)	S3 (Clay-silt soils)
OM 1		11.6	
OM 2		22.8	
OM 3		40	

Table 5.2 – The different levels of initial soil OM.
(Source: from the author)

N fertilizer application is fractioned. The planning of fertilization operations followed in CropSyst is the same as the one observed in our case study (see plannings below). For instance, for sunflower, we consider one passage of 100 % N fertilizers inputs per cultural year, at $J + 40$ after planting.

		Till scenario		Superficial till scenario
	Residue use	Activity - tool used	CropSyst Activities	Activity - tool used
Step 1	Residue left	Shredder	RESIDUE (FLAIL, CHOP, BUST)	Shredder
	Residue removed	Shredder	-	Shredder
Step 2	Residue left	<i>Cover crop</i> - shallow stubble cultivation	15 - PRIMARY DISC PLOW SHALLOW	<i>Cover crop</i> - shallow stubble cultivation
	Residue removed	-	-	-
Step 3		Till, deep	19 - PRIMARY MOLD-BOARD 15 - PRIMARY DISC PLOW SHALLOW	<i>Cover crop</i>
Step 4		Superficial secondary tillage - <i>Outil à dents</i>	35 - SPRING TOOTH CULTIVATOR	Superficial secondary tillage - <i>Outil à dents</i>
Step 5		Seeding (<i>semoir à dents</i>)	52 - HOE DRILL	Seeding (<i>semoir à dents</i>)

Table 5.3 – Two tillage crop managements: Till (T1) and No-Till (T0).
(Source: from the author)

$$\begin{aligned}
 \text{Durum wheat} &= \begin{cases} J + 120 & 22 \% \text{ N inputs} \\ J + 160 & 26 \% \text{ N inputs} \\ J + 180 & 19 \% \text{ N inputs} \\ J + 210 & 33 \% \text{ N inputs} \end{cases} & \text{Soft wheat} &= \begin{cases} J + 120 & 20 \% \text{ N inputs} \\ J + 150 & 40 \% \text{ N inputs} \\ J + 175 & 20 \% \text{ N inputs} \\ J + 200 & 20 \% \text{ N inputs} \end{cases} \\
 \\
 \text{Rapeseed} &= \begin{cases} J + 69 & 28 \% \text{ N inputs} \\ J + 99 & 44 \% \text{ N inputs} \\ J + 120 & 28 \% \text{ N inputs} \end{cases} & \text{Barley} &= \begin{cases} J + 106 & 36 \% \text{ N inputs} \\ J + 131 & 32 \% \text{ N inputs} \\ J + 156 & 32 \% \text{ N inputs} \end{cases} \\
 \\
 \text{Maize} &= \begin{cases} J + 30 & 30 \% \text{ N inputs} \\ J + 70 & 70 \% \text{ N inputs} \end{cases} & \text{Sunflower} &= \begin{cases} J + 40 & 100 \% \text{ N inputs} \end{cases}
 \end{aligned}$$

Two sets of tillage practices are designed: one under conventional tillage and one with superficial till (see Table 5.3). These two scenarios are based on the statements of the farmer (for the superficial till scenario) and on two technical documents from the Chambers of Agriculture of *Languedoc Rousillon* (2009) and *Nouvelle-Calédonie* (undated) as well as statements by the farmer’s counselor (for the conventional till scenario). The different initial levels of soil organic matter are also defined using the soil analysis of the three representative parcels provided by the farmer. Actually, in the soil analysis, the

desirable content of organic matter is indicated for each soil type (see Table 5.2).

5.3.2.3 Calibration

The SOM dynamics functions are calibrated using soil analysis provided by the farmer and using information relative to his tillage practice, residue use and N fertilization practice.

Soil analysis is performed on three different parcels, representative of the three different rough types of soil that can be found on the farm. These soil analyses are available for two dates each (respectively 2008 and 2014, 2008 and 2015, 2010 and 2015).

Our farmer usually does not plow his soil. When soil is compacted, he relies on superficial tillage. The main tillage/soil preparation practices used by the farmer are: (1) harvest, (2) disk arrow (when residues are left) at 3-4 cm, (3) other disk arrow, (4) cultivator as a seedbed preparation ; and (5) tine seed drill. This is the set of tillage practices considered for calibration (see the scenario No-Till of Table 5.3). Crop residues are shredded and left incorporated near the surface. As such, they are also used as soil cover. There is one exception to this crop residue management: No wheat residues are left before rapeseed. As for nitrogen fertilizer inputs, we used actual inputs over the period covering the soil analysis in the corresponding parcels.

The rotation and N fertilizer applications reproduced for the three soil types are displayed in the Table 5.4.

The results of the calibrations are provided in Table 5.5. We were not able to better parametrize CropSyst for the S2 parcel SOM simulated end value.

Crops succession on the Bournais parcel - S1 soil type						
Cultural year	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	2015/2016
Crop	Sunflower	Soft wheat	Sunflower	Soft wheat	Maize grain	
Planting date	15/04	12/10	15/04	20/10	20/10	
N fertilizers inputs and application date relative to planting	J+46 / 60 N	J+118 / 45 N J+148 / 54 N J+176 / 67 N	J+46 / 60 N	J+120 / 45 N J+150 / 81 N J+175 / 50 N J+205 / 34 N	J-4 / 53 N J+21 / 100 N	
Crops succession on the Closures parcel - S2 soil type						
Cultural year	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	2015/2016
Crop	Sunflower	Durum wheat	Maize grain	Soft wheat	rapeseed	Durum wheat
Planting date	14/04	21/10	10/04	20/10	01/12	23/10
N fertilizers inputs and application date relative to planting	J+47 / 50 N	J+114 / 45 N J+144 / 54 N J+169 / 67 N J+194 / 50 N	J-170 / 44 N J0 / 57 N J+51 / 57 N	J+120 / 45 N J+150 / 81 N J+175 / 44 N J+200 / 34 N	J+69 / 50 N J+99 / 77 N J+120 / 50 N	J+113 / 45 N J+150 / 68 N J+170 / 40 N J+197 / 80 N
Crops succession on the Laimée parcel - S3 soil type						
Cultural year	2010/2011	2011/2012	2012/2013	2013/2014	2014/2015	2015/2016
Crop	Soft wheat	rapeseed	Soft wheat	Soft wheat	Durum wheat	
Planting date	15/10	21/08	15/10	20/10	30/10	
N fertilizers inputs and application date relative to planting	J+120 / 45 N J+150 / 41 N J+120 / 34 N	J-11 / 29 N J+160 / 50 N J+207 / 40 N	J+120 / 45 N J+150 / 41 N J+120 / 34 N	J+120 / 45 N J+150 / 68 N J+175 / 17 N J+200 / 34 N	J+110 / 45 N J+140 / 54 N J+160 / 40 N J+190 / 68 N	

Table 5.4 – Crop rotations and N fertilizer inputs simulated in the CropSyst calibration of the SOM dynamics.

(Source: from the author)

	Initial SOM (2008)	Observed SOM (2015)	Simulated SOM (2015)
S1 parcel	1.26%	1.16 %	1.11%
	Initial SOM (2010)	Observed SOM (2015)	Simulated SOM (2015)
S2 parcel	2.42 %	2.7 %	2.12 %
	Initial SOM (2008)	Observed SOM (2015)	Simulated SOM (2015)
S3 parcel	2.62%	2.28 %	2.14 %

Table 5.5 – Results of the CropSyst calibration of the SOM dynamics.
(Source: the author from CropSyst simulations)

5.3.2.4 *Parameters estimations of the OM dynamics functions*

We then proceeded to the simulations. The results of the simulations are used to estimate the different crop production functions for each soil type. We use the software R and the *lm* function. All regressions respect the homoscedasticity condition, and there are no correlations between residues. Results of the regressions are displayed in the following tables (see Tables 5.6, 5.7, 5.8, 5.9, 5.10, 5.11, 5.12).

One interesting result of our simulations is relative to the impact of tillage. The impact of tillage on SOM dynamics is statistically significant for durum wheat on soil type S3, for barley on all soil types, for rapeseed on all soil types and sunflower on all soil types. For rapeseed and sunflower, profound tillage has a positive impact on SOM variation for all soil types. For barley, as expected, profound tillage has a negative impact on SOM variation for all soil types. For durum wheat on soil type S3, profound tillage also has a negative impact on SOM variation.

Hence, depending on the crop considered, all practices, and especially tillage, do not yield the same results in terms of SOM variation. This supports the decision to consider the impact of crop rotation choices on the SOM dynamics.

Explaining variables	Explained variable					
	SOM variation when growing soft wheat					
	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-1.080e-02	8.18e-07 ***	3.520e-02	5.54e-05 ***	-0.014191882	0.0054 **
N fertilizers inputs	1.243e-04	9.68e-15 ***	-1.113e-04	0.00179 **	0.000126129	< 2e-16 ***
N fertilizers inputs second order effect	-2.327e-07	1.03e-11 ***	4.198e-08	0.61532	-0.000000204	0.0001 ***
Initial soil organic matter	-1.693e-02	< 2e-16 ***	-1.895e-02	< 2e-16 ***	-0.020102221	< 2e-16 ***
Initial soil organic matter second order effect	3.708e-06	0.105	3.842e-06	0.69553	0.000005783	0.3983
Tillage intensity	-2.887e-04	0.799	-2.400e-17	1.000	0.001569264	0.2375
Residue use (left or not)	5.835e-03	2.80e-05 ***	-2.605e-02	2.41e-05 ***	0.008270744	0.0001 ***
Cross effect of soil organic matter and N fertilizers inputs	-8.708e-07	2.03e-06 ***	1.494e-06	0.02253 **	-0.000001081	0.0099**
Cross effect of N fertilizers inputs and tillage intensity	-1.049e-06	0.748	6.243e-20	1.000	0.000000322	0.9379
Cross effect of N fertilizers inputs and residue use	5.494e-06	0.103	1.106e-04	7.35e-08 ***	0.000005526	0.3946
Cross effect of tillage intensity and residue use	-8.519e-04	0.293	-1.496e-17	1.00	-0.001099151	0.3320
Cross effect of soil organic matter and residue use	-2.556e-04	1.17e-07 ***	-6.458e-05	0.67012	-0.000347168	< 2e-16 ***
Cross effect of soil organic matter and tillage intensity	1.799e-05	0.601	6.251e-19	1.000	-0.000021166	0.5721
<i>Number of observations</i>	36		36		36	
<i>Multiple R-squared</i>	1		0.9996			
<i>Adjusted R-squared</i>	1		0.9994			
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.6 – CropSyst Simulations - Soft wheat soil OM dynamics regressions results.
(Source: the author from CropSyst simulations)

Explaining variables	Explained variable					
	SOM variation when growing durum wheat					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-1.268e-02	1.62e-07 ***	-0.005051624	0.8194	-6.198e-03	0.47708
N fertilizers inputs	1.122e-04	2.06e-12 ***	0.000164898	0.0094**	1.430e-04	0.00223 **
N fertilizers inputs second order effect	-1.702e-07	5.07e-07 ***	-0.000000140	0.4694	-2.293e-07	0.07630 .
Initial soil organic matter	-1.683e-02	< 2e-16 ***	-0.020478200	< 2e-16 ***	-2.087e-02	< 2e-16 ***
Initial soil organic matter second order effect	2.749e-06	0.24249	0.000043604	0.1542	1.933e-05	0.10493
Tillage intensity	-7.513e-04	0.53541	-0.003598741	0.3566	-1.023e-02	0.09988 .
Residue use (left or not)	9.095e-03	9.85e-08 ***	0.008425523	0.1559	1.485e-02	0.02056 *
Cross effect of soil organic matter and N fertilizers inputs	-1.181e-06	1.72e-08 ***	-0.000003549	0.0289 *	-1.242e-06	0.08929 .
Cross effect of N fertilizers inputs and tillage intensity	-1.379e-06	0.67723	-0.000019962	0.1040 .	2.151e-05	0.20143
Cross effect of N fertilizers inputs and residue use	1.109e-05	0.00253 **	-0.000010192	0.6148	-1.114e-05	0.50274
Cross effect of tillage intensity and residue use	-9.877e-04	0.24405	0.004841112	0.1293	3.543e-03	0.39973
Cross effect of soil organic matter and residue use	-2.414e-04	5.84e-07 ***	-0.000134727	0.4320	-3.453e-04	0.06303 .
Cross effect of soil organic matter and tillage intensity	4.134e-05	0.25441	0.000290453	0.0128 **	1.189e-04	0.50787
<i>Number of observations</i>	36		36		36	
<i>Multiple R-squared</i>	1				0.9996	
<i>Adjusted R-squared</i>	1				0.9993	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.7 – CropSyst Simulations - Durum wheat soil OM dynamics regressions results. (Source: the author from CropSyst simulations)

Explaining variables	Explained variable					
	SOM variation when growing barley					
	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-1.391e-02	0.00951 **	-1.238e-02	0.062027 .	-1.242e-02	0.042402 *
N fertilizers inputs	2.085e-04	3.71e-08 ***	2.235e-04	7.11e-07 ***	2.117e-04	4.17e-07 ***
N fertilizers inputs second order effect	-4.359e-07	2.38e-05 ***	-4.713e-07	0.000187 ***	-4.486e-07	0.000121 ***
Initial soil organic matter	-1.676e-02	< 2e-16 ***	-1.900e-02	< 2e-16 ***	-2.003e-02	< 2e-16 ***
Initial soil organic matter second order effect	2.960e-06	0.65996	4.733e-06	0.584088	3.264e-06	0.679657
Tillage intensity	-6.338e-03	0.07613 .	-1.202e-02	0.011566 *	-1.022e-02	0.018009 *
Residue use (left or not)	2.024e-02	4.80e-06 ***	2.000e-02	0.000137 ***	2.098e-02	2.64e-05 ***
Cross effect of soil organic matter and N fertilizers inputs	-2.058e-06	0.00043 ***	-2.064e-06	0.003884 **	-2.004e-06	0.002442 **
Cross effect of N fertilizers inputs and tillage intensity	-6.428e-07	0.95667	5.408e-06	0.722096	3.132e-06	0.821905
Cross effect of N fertilizers inputs and residue use	3.152e-05	0.01297 *	2.653e-05	0.090587 .	2.899e-05	0.046185 *
Cross effect of tillage intensity and residue use	4.259e-03	0.08854 .	1.123e-02	0.001318 **	8.543e-03	0.005877 **
Cross effect of soil organic matter and residue use	-3.789e-04	0.00119 **	-5.851e-04	0.000185 ***	-5.209e-04	0.000251 ***
Cross effect of soil organic matter and tillage intensity	2.609e-04	0.01809 *	4.582e-04	0.002011 **	4.005e-04	0.002953 **
<i>Number of observations</i>	36		36		36	
<i>Multiple R-squared</i>	0.9998		1		0.9996	
<i>Adjusted R-squared</i>	0.9997		0.9999		0.9993	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.8 – CropSyst Simulations - Barley soil OM dynamics regression results.
(Source: the author from CropSyst simulations)

Explaining variables	Explained variable					
	SOM variation when growing maize grain					
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-1.019e-02	0.001153 **	-1.051e-02	0.000810 ***	-1.004e-02	0.001030 **
N fertilizers inputs	1.296e-04	2.12e-10 ***	1.405e-04	3.91e-11 ***	1.286e-04	1.47e-10 ***
N fertilizers inputs second order effect	-2.488e-07	5.93e-08 ***	-2.765e-07	8.38e-09 ***	-2.535e-07	2.70e-08 ***
Initial soil organic matter	-1.634e-02	< 2e-16 ***	-1.856e-02	< 2e-16 ***	-1.959e-02	< 2e-16 ***
Initial soil organic matter second order effect	2.624e-06	0.488710	2.823e-06	0.453943	1.556e-06	0.672063
Tillage intensity	8.607e-04	0.655229	8.204e-07	0.999658	5.758e-04	0.758645
Residue use (left or not)	1.471e-02	7.62e-08 ***	1.520e-02	3.93e-08 ***	1.580e-02	1.39e-08 ***
Cross effect of soil organic matter and N fertilizers inputs	-1.012e-06	0.000261 ***	-9.578e-07	0.000437 ***	-8.723e-07	0.000892 ***
Cross effect of N fertilizers inputs and tillage intensity	-5.247e-06	0.349086	-4.444e-06	0.423586	-4.691e-06	0.388998
Cross effect of N fertilizers inputs and residue use	3.080e-05	1.04e-05 ***	3.086e-05	9.27e-06 ***	3.049e-05	8.22e-06 ***
Cross effect of tillage intensity and residue use	-3.086e-03	0.031161 *	-1.617e-03	0.238444	-2.778e-03	0.044781 *
Cross effect of soil organic matter and residue use	-5.497e-04	1.81e-09 ***	-6.399e-04	8.85e-11 ***	-6.060e-04	1.70e-10 ***
Cross effect of soil organic matter and tillage intensity	1.014e-06	0.986103	3.033e-05	0.600990	9.140e-06	0.871833
<i>Number of observations</i>	36		36		36	
<i>Multiple R-squared</i>	0.9999		0.9999		1	
<i>Adjusted R-squared</i>	0.9999		0.9999		0.9999	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.9 – CropSyst Simulations - Maize grain soil OM dynamics regression results.
(Source: the author from CropSyst simulations)

Explaining variables	Explained variable					
	SOM variation when growing sunflower					
	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-2.287e-02	4.10e-06 ***	-2.041e-02	2.18e-05 ***	-1.959e-02	4.47e-05 ***
N fertilizers inputs	2.928e-04	4.35e-07 ***	2.515e-04	4.86e-06 ***	2.335e-04	1.67e-05 ***
N fertilizers inputs second order effect	-8.719e-07	0.00429 **	-7.034e-07	0.01848 *	-6.481e-07	0.03079 *
Initial soil organic matter	-1.549e-02	< 2e-16 ***	-1.784e-02	< 2e-16 ***	-1.889e-02	< 2e-16 ***
Initial soil organic matter second order effect	-8.510e-07	0.87096	1.092e-06	0.83623	-3.453e-07	0.94865
Tillage intensity	7.259e-03	0.01150 *	7.029e-03	0.01470 *	7.455e-03	0.01126 *
Residue use (left or not)	2.111e-02	4.43e-08 ***	2.231e-02	1.94e-08 ***	2.299e-02	1.51e-08 ***
Cross effect of soil organic matter and N fertilizers inputs	-3.933e-06	7.30e-05 ***	-2.937e-06	0.00162 **	-2.948e-06	0.00180 **
Cross effect of N fertilizers inputs and tillage intensity	-2.346e-05	0.23101	-2.330e-05	0.23766	-2.377e-05	0.23565
Cross effect of N fertilizers inputs and residue use	1.043e-04	1.46e-05 ***	1.085e-04	9.57e-06 ***	1.080e-04	1.25e-05 ***
Cross effect of tillage intensity and residue use	-1.286e-02	5.07e-07 ***	-1.302e-02	4.74e-07 ***	-1.402e-02	1.84e-07 ***
Cross effect of soil organic matter and residue use	4.255e-05	0.59975	1.855e-05	0.82003	2.548e-05	0.75835
Cross effect of soil organic matter and tillage intensity	-2.345e-04	0.00749 **	-2.251e-04	0.01036 *	-2.416e-04	0.00715 **
<i>Number of observations</i>	36		36		36	
<i>Multiple R-squared</i>	0.9999		0.9999		0.9999	
<i>Adjusted R-squared</i>	0.9998		0.9998		0.9998	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.10 – CropSyst Simulations - Sunflower soil OM dynamics regression results.
(Source: the author from CropSyst simulations)

Explaining variables	Explained variable					
	SOM variation when growing rapeseed					
	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-1.811e-02	7.32e-05 ***	-1.660e-02	2.14e-05 ***	-1.499e-02	8.16e-05 ***
N fertilizers inputs	1.164e-04	3.67e-07 ***	1.019e-04	1.83e-07 ***	9.169e-05	9.22e-07 ***
N fertilizers inputs second order effect	-1.857e-07	0.000418 ***	-1.536e-07	0.00048 ***	-1.406e-07	0.00109 **
Initial soil organic matter	-1.555e-02	< 2e-16 ***	-1.752e-02	< 2e-16 ***	-1.872e-02	< 2e-16 ***
Initial soil organic matter second order effect	-3.155e-06	0.538932	-2.841e-06	0.50974	-2.827e-06	0.51017
Tillage intensity	6.437e-03	0.021559 *	5.338e-03	0.02287 *	5.732e-03	0.01502 *
Residue use (left or not)	2.421e-02	3.10e-09 ***	2.666e-02	1.65e-11 ***	2.706e-02	1.13e-11 ***
Cross effect of soil organic matter and N fertilizers inputs	-1.519e-06	7.74e-05 ***	-1.445e-06	1.57e-05 ***	-1.306e-06	5.45e-05 ***
Cross effect of N fertilizers inputs and tillage intensity	-8.382e-06	0.268848	-6.205e-06	0.32752	-6.222e-06	0.32451
Cross effect of N fertilizers inputs and residue use	2.887e-05	0.000717 ***	2.251e-05	0.00140 **	2.229e-05	0.00149 **
Cross effect of tillage intensity and residue use	-1.428e-02	6.18e-08 ***	-1.365e-02	6.21e-09 ***	-1.457e-02	1.77e-09 ***
Cross effect of soil organic matter and residue use	-2.207e-04	0.009565 **	-3.340e-04	3.63e-05 ***	-3.105e-04	8.46e-05 ***
Cross effect of soil organic matter and tillage intensity	-2.050e-04	0.015137 *	-1.737e-04	0.01421 *	-1.895e-04	0.00798 **
<i>Number of observations</i>	36		36		36	
<i>Multiple R-squared</i>	0.9999		0.9999		0.9999	
<i>Adjusted R-squared</i>	0.9998		0.9998		0.9999	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.11 – CropSyst Simulations - Rapeseed soil OM dynamics regression results.
(Source: the author from CropSyst simulations)

Explaining variables	Explained variable					
Soil type	SOM variation when growing alfalfa					
	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	3.137e-02	0.000452 ***	3.520e-02	5.54e-05 ***	3.451e-02	6.82e-05 ***
N fertilizers inputs	-4.353e-04	0.000277 ***	-3.338e-04	0.00179 **	-3.945e-04	0.000356 ***
N fertilizers inputs second order effect	1.207e-06	0.143384	3.778e-07	0.61532	8.222e-07	0.277687
Initial soil organic matter	-1.629e-02	< 2e-16 ***	-1.895e-02	< 2e-16 ***	-1.989e-02	< 2e-16 ***
Initial soil organic matter second order effect	-6.395e-06	0.545404	3.842e-06	0.69553	1.694e-06	0.862461
Tillage intensity	-4.096e-19	1.0000	-2.713e-17	1.000	-3.474e-17	1.000
Residue use (left or not)	-2.754e-02	32.98e-05 ***	-2.605e-02	2.41e-05 ***	-2.611e-02	2.26e-05 ***
Cross effect of soil organic matter and N fertilizers inputs	2.843e-06	0.162321	4.483e-06	0.02253 *	4.423e-06	0.023812 *
Cross effect of N fertilizers inputs and tillage intensity	7.249e-20	1.000	2.347e-19	1.00	2.166e-19	1.0000
Cross effect of N fertilizers inputs and residue use	3.659e-04	4.75e-08 ***	3.319e-04	7.35e-08 ***	3.274e-04	8.80e-08 ***
Cross effect of tillage intensity and residue use	-1.294e-17	1.0000	-1.951e-17	1.0000	2.054e-18	1.00
Cross effect of soil organic matter and residue use	-1.192e-04	0.466083	-6.458e-05	0.67012	-4.753e-05	0.752993
Cross effect of soil organic matter and tillage intensity	8.588e-20	1.000	7.266e-19	1.000	6.567e-19	1.000000
<i>Number of observations</i>	36		36		36	
<i>Multiple R-squared</i>	0.9995		0.9996		0.9997	
<i>Adjusted R-squared</i>	0.9992		0.9994		0.9995	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.12 – CropSyst Simulations - Alfalfa soil OM dynamics regressions results.
(Source: the author from CropSyst simulations)

5.3.3 Estimation of the crop production functions

5.3.3.1 Functional form

According to Yirga and Hassan (2010) the functional forms widely used in empirical studies of production relationships are the Cobb-Douglas and translog functions (see, for example, Kim et al, 2000, 2001; Yirga and Hassan, 2010 and Baudron et al, 2012), although Smith et al (2000) use a quadratic yield function.

The Cobb-Douglas functional form is convenient for estimating and interpreting parameter estimates (Yirga et al, 2000), where translog functions are less so. On the other hand, both quadratic and translog functions are flexible in terms of restrictions on the substitutability of the variables (Kim et al, 2001) and allow for testing the second-order effects of some variables of interest. According to Bureau, Butault and Rousselle (1989), flexible functional forms are usually a better approximation of reality than linear or Cobb-Douglas functions. However, it is difficult to choose between existing flexible functional forms (Bureau et al, 1989; Reynès and Tamsamani, 2009) since there are no general rules stating that a translog function should be preferred to a generalized quadratic function.

Here, the production function is specified as a quadratic crop-yield function, similarly to Smith et al (2000). This allows us to consider the second-order effect of the production factors as well as their cooperation relationship.

As in our simplified investment models, we consider two production factors. Productive inputs are represented by the amount of inorganic nitrogen (N) applied in addition to the soil mineral nitrogen present in the soil surface. We only consider inorganic nitrogen fertilizers since for many years now, the farmer in our study case has only applied inorganic nitrogen. The other production factor is SOM.

Hence, the crop-yield function is specified as:

$$\begin{aligned} y(c, s, t) = & \beta_0 + \beta_1 N(c, s, t) + \beta_2 N(c, s, t)^2 + \beta_3 OM(c, s, t) + \beta_4 OM(c, s, t)^2 \\ & + \beta_5 N(c, s, t)OM(c, s, t) + \varepsilon \end{aligned} \quad (5.22)$$

where

y = yield

s = soil type

c = crop

N = applied nitrogen (kg/ha)

OM = soil organic matter concentration (g OM/kg soil)

β = parameters to be estimated

ε = error term

The coefficients of N and SOM are expected to be positive. Interactions among N and OC represent complementarity and substitutability among soil quality and chemical input intensity (or management intensity) and are of undetermined sign. The second-order effects are supposed to be negative.

5.3.3.2 Scenarii tested

Once again, in order to estimate the crop yield functions, a database was constructed based on simulations. A particular set of techniques and soil conditions was simulated for the same soil type and each crop during a period of twenty years. The objective was to be able to simulate significant and lasting impacts of these parameters on crop production.

Simulations are performed for three soil types and six crops. For each soil type/crop bundle, the same set of simulations are run. These simulations had a different combination of N inputs (five different values) and OC soil (three different values). This corresponds to 15 combinations per soil type/crop bundle.

No production function is estimated for alfalfa. Actually, it is not possible to calibrate forage crops in CropSyst. In addition, alfalfa is not primarily grown by our farmer as a forage crop but as a seed crop. There are only two harvests, or clippings, for alfalfa: 1) a pre-harvest in May that the farmer can use as a “bonus” for his personal consumption and 2) the final harvest for seeds, once the alfalfa has grown seeds. Hence, CropSyst is not suited to simulating this kind of production. Furthermore, the crop production functions are used to simulate the impacts of applied nitrogen, while it is not necessary to apply any with alfalfa. In our model, we use the mean alfalfa yield observed by the farmer, that is, a yield of 0.7 t/ha.

Inorganic nitrogen inputs level	Durum wheat	Soft wheat	Barley	Maize	Sunflower	rapeseed
N0	0	0	0	0	0	0
N1	50	45	35	35	15	45
N2	107	90	70	75	30	90
N3	215	180	140	150	60	180
N4	300	300	250	300	120	300

Table 5.13 – The different levels of nitrogen fertilizers applied per crop.
(Source: from the author)

The various values of nitrogen fertilizer inputs and OM soil content are determined using the farmer’s practices and soil analysis as a benchmark. With respect to nitrogen fertilizer input levels, five levels are distinguished (see Table 5.13):

- Level 0 N_0 , which corresponds to no nitrogen applied
- Level 1 N_1 , very low level of nitrogen inputs: corresponds to the low amount of N fertilizers applied by the farmer, divided by 2
- Level 2 N_2 , low level of nitrogen inputs: corresponds to the usual amount of N fertilizers applied by the farmer, divided by 2
- Level 3 N_3 , average level of nitrogen inputs as usually applied by the farmer
- Level 4 N_4 , high level of nitrogen inputs: twice the usual amount applied by the farmer

The planning of fertilization operations is the same as the one observed in our case study and described in the SOM dynamics simulations.

Phosphorus and potassium inputs are considered as fixed in our model. Actually, CropSyst only considers the lack of phosphorus and does not allow precise monitoring of the amount of phosphorus applied to each crop. Thus, the quantities of phosphorus and potassium applied are determined based on the mean values used on each crop, as indicated by the agricultural adviser of the farmer and in accordance with the fertilization plan reviews of the farm from 2012 to 2014. Precipitation is not taken explicitly into account. The characteristic climatic conditions of the study area are taken into account within CropSyst.

5.3.3.3 Calibration

The crop functions are calibrated using actual crop yield data for each crop on the farm and incorporated into CropSyst for each of the three main soil types identified. N

Crop (soil type)	Crop yield observed	Estimated crop yield	Unstressed Harvest Index
Winter durum wheat (S3)	8.5 t/ha	8.516 t/ha	0.53
Winter soft wheat (S1)	8.0 t/ha	8.061 t/ha	0.96
Winter soft wheat (S2)	8.0 t/ha	8.016 t/ha	0.90
Winter soft wheat (S3)	8.0 t/ha	8.014 t/ha	0.91
Sunflower (S2)	3.5 t/ha	3.48 t/ha	0.39
Maize grain (S2)	8.0 t/ha	8.025 t/ha	0.76
Barley (S1)	5.4 t/ha	5.435 t/ha	0.69
Rapeseed (S2)	3.235 t/ha	3.238 t/ha	0.44

Table 5.14 – Crop yields calibration with CropSyst.
(Source: the author from CropSyst simulations)

fertilizer inputs are taken from actual data shared by our farmer. The crop production functions are calibrated for the year 2015 or 2014 for the representative parcels considered. For the crop file specifications, most files are directly parameterized in CropSyst, except for rapeseed, for which we use data from Donatelli et al (2015). To calibrate CropSyst in order to obtain a close estimation of the crop yield observed, we have modified the unstressed harvest index (see Figure 5.14).

5.3.3.4 Parameters estimations of the crop production functions

The results of the simulations are used to estimate the different crop production functions for each soil type. We use the software R and the *lm function*. All data respect the homoscedasticity condition, and there is no correlation between residues. Results of the regressions are displayed in the following tables (see Tables 5.15, 5.16, 5.17, 5.18, 5.19, 5.20).

We note that the signs of the different parameters are consistent with our statistical findings, in particular with respect to the non-cooperating relationship between soil organic matter and N fertilizer inputs. In addition, this non-cooperation is always statistically significant. As expected, N fertilizers and soil organic matter have a positive first-order effect and a negative second order effect, respectively.

Explaining variables			Explained variable			
Crop			Soft Wheat yield			
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	1.030e+01	0.061735 .	1.105e+01	0.020984 *	8.745e+00	0.0722 .
N fertilizers inputs	4.868e-01	< 2e-16 ***	4.837e-01	< 2e-16 ***	4.651e-01	< 2e-16 ***
N fertilizers inputs second order effect	-8.436e-04	1.07e-12 ***	-8.228e-04	2.36e-14 ***	-7.686e-04	4.45e-13 ***
Soil organic matter	1.740e+00	0.000353 ***	1.505e+00	0.000321 ***	1.833e+00	3.60e-05 ***
Soil organic matter second order effect	-1.056e-02	0.208656	-6.048e-03	0.398329	-1.151e-02	0.1229
Cross effect of soil or- ganic matter and N fertilizers inputs	-4.839e-03	6.96e-10 ***	-4.771e-03	1.86e-11 ***	-4.897e-03	2.08e-11 ***
<i>Number of observa- tions</i>	47		47		47	
<i>Multiple R-squared</i>	0.9284		0.948		0.9424	
<i>Adjusted R-squared</i>	0.9192		0.9413		0.935	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.15 – CropSyst Simulations - Soft wheat production regression results.
(Source: the author from CropSyst simulations)

Explaining variables			Explained variable			
Crop			Durum Wheat yield			
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	9.864e+00	0.03124 *	12.4465642	0.01413 *	1.344e+01	0.00951 **
N fertilizers inputs	4.013e-01	< 2e-16 ***	3.695e-01	7.19e-16 ***	0.3594484	7.79e-16 ***
N fertilizers inputs second order effect	-5.521e-04	9.67e-10 ***	-5.031e-04	6.78e-08 ***	-0.0004924	1.51e-07 ***
Soil organic matter	2.516e+00	2.81e-08 ***	2.693e+00	4.83e-08 ***	2.7424617	4.70e-08 ***
Soil organic matter second order effect	-1.972e-02	0.00572 **	-2.451e-02	0.00201 **	-0.0262222	0.00124 **
Cross effect of soil or- ganic matter and N fertilizers inputs	-5.879e-03	.61e-15 ***	-5.643e-03	2.71e-13 ***	-0.0054962	9.60e-13 ***
<i>Number of observa- tions</i>	47		47		47	
<i>Multiple R-squared</i>	0.9437		0.922		0.9149	
<i>Adjusted R-squared</i>	0.9365		0.912		0.904	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.16 – CropSyst Simulations - Durum wheat production regression results.
(Source: the author from CropSyst simulations)

Explaining variables			Explained variable			
Crop			Barley yield			
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	3.084e+00	0.3347	3.6573376	0.2274	4.174e+00	0.1627
N fertilizers inputs	4.219e-01	< 2e-16 ***	0.4254657	< 2e-16 ***	4.225e-01	< 2e-16 ***
N fertilizers inputs second order effect	-8.156e-04	2.69e-14 ***	-0.0008025	7.65e-15 ***	-7.984e-04	5.37e-15 ***
Soil organic matter	1.408e+00	4.11e-06 ***	1.4633330	7.39e-07 ***	1.453e+00	6.16e-07 ***
Soil organic matter second order effect	-8.661e-03	0.0843 .	-0.0092884	0.0513 .	-8.831e-03	0.0591 .
Cross effect of soil organic matter and N fertilizers inputs	-4.474e-03	6.32e-13 ***	-0.0044866	1.08e-13 ***	-4.574e-03	3.66e-14 ***
<i>Number of observations</i>	47		47		47	
<i>Multiple R-squared</i>	0.9565		0.9638		0.9638	
<i>Adjusted R-squared</i>	0.9509		0.9591		0.9592	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.17 – CropSyst Simulations - Barley production regression results.
(Source: the author from CropSyst simulations)

Explaining variables			Explained variable			
Crop			Maize grain yield			
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	0.7660063	0.924725	-7.5628559	0.3220	-4.5769782	0.57518
N fertilizers inputs	0.2748838	6.7e-07 ***	4.515e-01	8.65e-13 ***	0.3913730	2.94e-10 ***
N fertilizers inputs second order effect	-0.0004844	0.000468 ***	-7.201e-04	4.21e-07 ***	-0.0006346	1.35e-05 ***
Soil organic matter	2.7314102	0.000241 ***	3.236e+00	8.66e-06 ***	3.2825044	2.12e-05 ***
Soil organic matter second order effect	-0.0330194	0.012302 *	-2.969e-02	0.0159 *	-0.0348813	0.00879 **
Cross effect of soil organic matter and N fertilizers inputs	-0.0048194	5.1e-06 ***	-7.017e-03	4.84e-10 ***	-0.0064554	1.89e-08 ***
<i>Number of observations</i>	47		47		47	
<i>Multiple R-squared</i>	0.6482		0.8589		0.7919	
<i>Adjusted R-squared</i>	0.6031		0.8408		0.7652	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.18 – CropSyst Simulations - Maize grain production regression results.
(Source: the author from CropSyst simulations)

Explaining variables		Explained variable				
Crop		Sunflower yield				
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	-2.6665614	0.10050	-2.8446621	0.09763 .	-3.1801918	0.03736 *
N fertilizers inputs	0.2967300	1.03e-15 ***	0.3034878	2.96e-15 ***	0.2876380	2.81e-16 ***
N fertilizers inputs second order effect	-0.0005683	0.00078 ***	-0.0003711	0.03012 *	-0.0004955	0.00151 **
Soil organic matter	1.2419849	1.64e-11 ***	1.2831703	3.07e-11 ***	1.4298219	3.54e-14 ***
Soil organic matter second order effect	-0.0113055	4.74e-05 ***	-0.0091572	0.00117 **	-0.0144318	2.16e-07 ***
Cross effect of soil or- ganic matter and N fertilizers inputs	-0.0059480	5.30e-16 ***	-0.0060637	1.70e-15 ***	-0.0058711	< 2e-16 ***
<i>Number of observa- tions</i>	47		47		47	
<i>Multiple R-squared</i>	0.9553		0.9695		0.9641	
<i>Adjusted R-squared</i>	0.9495		0.9656		0.9595	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.19 – CropSyst Simulations - Sunflower production regression results.
(Source: the author from CropSyst simulations)

Explaining variables		Explained variable				
Crop		rapeseed yield				
Soil type	S1		S2		S3	
	Est.	p.value	Est.	p.value	Est.	p.value
Intercept	4.822e+00	0.17134	4.420e+00	0.0652 .	5.518e+00	0.0281 *
N fertilizers inputs	9.518e-02	1.55e-05 ***	1.609e-01	4.22e-15 ***	1.546e-01	4.67e-14 ***
N fertilizers inputs second order effect	-1.596e-04	0.00447 **	-2.474e-04	2.50e-08 ***	-2.405e-04	1.03e-07 ***
Soil organic matter	9.301e-01	0.00247 **	9.581e-01	1.45e-05 ***	9.357e-01	3.65e-05 ***
Soil organic matter second order effect	-1.080e-02	0.04977 *	-8.577e-03	0.0219 *	-8.634e-03	0.0260 *
Cross effect of soil or- ganic matter and N fertilizers inputs	-1.703e-03	7.88e-05 ***	-2.102e-03	7.24e-10 ***	-2.002e-03	5.73e-09 ***
<i>Number of observa- tions</i>	47		47		47	
<i>Multiple R-squared</i>	0.5483		0.8916		0.8738	
<i>Adjusted R-squared</i>	0.4904		0.8777		0.8576	
<i>Signif. codes : 0.001***, 0.01**, 0.05*, 0.1.</i>						

Table 5.20 – CropSyst Simulations - rapeseed production regression results.
(Source: the author from CropSyst simulations)

5.3.3.5 Concavity of the crop production functions estimated

We have verified the concavity of the crop production functions estimated in order to ensure the concavity of our maximization problem.

In order to determine the convexity or concavity of a function of several variables, the Hessian of the function is used, which is the square matrix of the second partial derivatives. In our case, the Hessian associated to our production functions is $H = \begin{bmatrix} y_{NN} & y_{NOC} \\ y_{OCN} & y_{OCOC} \end{bmatrix}$.

The function is strictly concave over \mathbb{R}^n if the leading principal minors (mpp) of the Hessian alternate in signs, such that $mpp_1(H) < 0$, $mpp_2(H) > 0$, $mpp_3(H) < 0, \dots$ for each $x \in \mathbb{R}^n$, where mpp_k is the determinant of the k th order leading principal submatrix of H , obtained by deleting the last $n - k$ columns and rows from the $n \times n$ matrix H .

Over the 18 crop production functions estimated, 4 are not strictly concave: the soft wheat production function for soil type S2 and sunflower production functions for all soil types. Hence, for these crop production functions, we chose to set the parameter of the cross order effect to 0.

5.4 Model validation

Here, the model validation consists in the computation of yields and OM dynamics with the functions estimated while using the practices actually implemented by the farmer, and these computations are then compared with the observed yield (see Tables 5.21 and 5.22). The computations are performed in the same conditions as the calibration simulations, which are the situations for which we have data relative to farming practices and soil analysis.

The results are satisfactory for crop yield function estimations. For the SOM dynamics functions, the computed SOM corresponds to what is observed for the S1 parcel and S3 parcel. However, the S2 parcel computed 2015 SOM does not correspond to what is observed in the soil analysis. Since all crop yield functions are valid and the other SOM computations are consistent with reality, we assume that there is an unobserved and unknown factor that has a sufficiently high impact on S2 parcel SOM dynamics to trigger an increase in SOM instead of a decrease. Indeed, we could not simulate all farming practices performed by the farmer on his lands, and we did not consider other soil

Crop (soil type)	Observed yield	Simulated yield (CropSyst)	Computed yield
Winter durum wheat (S3)	8.5 t/ha	8.516 t/ha	8.968 t/ha
Winter soft wheat (S1)	8.0 t/ha	8.061 t/ha	8.184 t/ha
Winter soft wheat (S2)	8.0 t/ha	8.016 t/ha	8.543 t/ha
Winter soft wheat (S3)	8.0 t/ha	8.014 t/ha	8.231 t/ha
Sunflower (S2)	3.5 t/ha	3.48 t/ha	3.121 t/ha
Maize grain (S2)	8.0 t/ha	8.025 t/ha	8.165 t/ha
Barley (S1)	5.4 t/ha	5.435 t/ha	5.175 t/ha
Rapeseed (S2)	3.235 t/ha	3.238 t/ha	3.471 t/ha

Table 5.21 – Crop yields functions validation.

(Source: the author from CropSyst simulations)

	Initial SOM (2008)	Observed SOM (2015)	Computed SOM (2015)
S1 parcel	1.26%	1.16 %	1.16 %
	Initial SOM (2010)	Observed SOM (2015)	Computed SOM (2015)
S2 parcel	2.42 %	2.7 %	2.21 %
	Initial SOM (2008)	Observed SOM (2015)	Computed SOM (2015)
S3 parcel	2.62%	2.28 %	2.37 %

Table 5.22 – SOM dynamics functions validation.

(Source: the author from CropSyst simulations)

quality parameters that impact and are impacted by SOM due to a lack of data.

5.5 Scenarii tested and planning horizon

In this section, the tested scenarios are presented (see Table 5.23). Scenarios are run for a 50-year planning horizon. We chose not to impose any terminal conditions. This allows extreme situations at the end of the planning horizon (with no profit for instance). This is why we consider in our results and discussions the outcomes obtained from period 1 to period 30. Indeed, in period 30, we are in an intermediate situation, where the farmer is still in a production stage: Either the land is passed on to his heir, or it is sold. In both cases, the land continues to serve a crop production purpose.

We chose to set up our model as an inter-temporal model. Hence, in our simulations, the farmer optimizes his objective function over the whole time period. This allows the intertemporal environmental feedback of SOM changes throughout the planning horizon. Actually, from one year to another, SOM changes can be neglected, in particular at average levels. It is the cumulative and continuous changes in SOM that are relevant (Saliba, 1985). In addition, this feature allows for nonlinearities in constraints as in the

<i>Parameters</i>	N fertilizers costs (€/kg)	Fuel costs (€/L)	Carbon price (€/TeqCO ₂)	Discount rate	Coupled premium (alfalfa)
<i>Scenario</i>					
Baseline scenario	1.22	0.5	0	5%	300
Dynamic costs scenario	1.22 at T1 with an annual increase in 1.5 %	0.5 at T1, with an annual increase in 2%	0	5 %	300
Dynamic costs scenario + carbon premium (CP)	1.22 at T1 with an annual increase in 1.5 %	0.5 at T1, with an annual increase in 2%	30.5 at T1, with an annual increase in 4.7 %	5 %	300
Dynamic costs scenario + CP + Alfalfa premium	1.22 at T1 with an annual increase in 1.5 %	0.5 at T1, with an annual increase in 2%	30.5 at T1, with an annual increase in 4.7 %	5 %	600
<i>This set of scenarii is simulated over a planning horizon of 50 years.</i>					
<i>These scenarii are also simulated with a discount rate of 1 % ; and with a planning horizon of 5 years.</i>					

Table 5.23 – Scenarii and base model.

(Source: the author)

objective function (Holden et al, 2005), which is the case here.

The base scenario is created from the 2017 situation. Crop prices considered for the base scenario are mean prices over a 7-year period in constant prices. Hence, this mean price encompasses price volatility. In this scenario, prices and costs remain constant throughout the planning horizon.

In the dynamic costs scenario, changes in N fertilizer costs and fuel price are introduced gradually (Table 5.23). This reflects the expected increase in N fertilizers and energy prices induced by the scarcity of fossil energy (prospects from the French Energy and Raw Materials Division, as quoted in the professional press). The rate at which each value increases is set in order to reach the end values of 2.44 €/kg for N inputs costs and 1 €/L for fuel costs.

In the dynamic costs and carbon premium scenario, a carbon price is introduced, and both input prices and carbon values increase throughout the planning horizon. The rate at which each value increases is set in order to reach the end values of 2.44 €/kg for N inputs costs, 1 €/L for fuel costs and 200 €/TeqCO₂ for carbon prices. Here, the carbon price is attached to the variation in SOM concentration in the farmer's soil. When SOM increases, the farmer is paid proportionally, and the reverse. The farmer is rewarded for increasing his soil quality and pays to deplete his SOM stock. This corresponds to the

polluter-payer principle¹. The initial carbon price considered is the current carbon price as planned in French law for a value of 30.5 €/T eq CO₂. The end value carbon price is an expected carbon price value for 2050. Since in 2030 the carbon price is expected to be around 100 €/T eq CO₂, we extrapolated in our 2050 horizon scenario a carbon price valued at 200 €/T eq CO₂ (*Ministère de l'Environnement, de l'Énergie et de la Mer*, 2016).

In the last scenario (Dynamic costs scenario+CP+alfalfa premium), in addition to carbon price, we doubled the coupled premium associated with alfalfa. This is a way to simulate a Common Agricultural Policy (CAP) incentive in favor of leguminous crops allowing carbon sequestration (Arrouays et al, 2002).

Two types of rotations are taken into account: long non-intensive rotations and short intensive rotations. The long rotations are based on the following pattern, with the possibility of including the alfalfa crop after sunflower:

STRAW → RAPESEED → STRAW → SUNFLOWER or MAIZE GRAIN → STRAW

In the simulations, the farmer can choose the crops to grow in each period as long as his choice respects the preceding crop constraint.

However, in the intensive rotation case, the farmer cannot choose to implement any crops other than rapeseed and soft wheat. The intensive crop rotation is based on the following pattern:

SOFT WHEAT → RAPESEED → SOFT WHEAT

Two discount rates are tested in order to evaluate the impact of the farmer's time preference on his optimal strategies and final outcomes: a discount rate of 5% and a discount rate of 1%. The discount rate r is equal to 5% since it is the risk-free rate for medium-term horizons (between 50 and 100 years) recommended by Gollier (2002) in the case of France². We used this discount rate since uncertainty is not taken into account in our model. We also simulate our scenario with a discount rate equal to 1%. In this case,

1. The difference in SOM content is expressed in g/kg of soil. First, we convert SOM in SOC, applying the conventional conversion factor ($SOC = SOM * 0.58$). Then, we convert from g/kg of soil to T/ha ($SOCT/ha = SOCg/kg * 0.003$). Given a value of a ton of carbon per hectare and carbon prices, which are in fact the price applied to TCO₂eq, we convert the tons of carbon into tons of CO₂ eq ($tCO_2eq/ha = 3.666tC/ha$).

2. Assuming that the private discount rate r equals the social discount rate.

the time preference for the present is less important than with a discount rate of 5 %. In fact, with a discount rate of 0 %, the farmer would value present and future outcomes equally.

We also evaluate our scenario based on a short planning horizon of 5 years, which corresponds to a more realistic planning horizon when considering the choices made by a farmer at the beginning of a cultural year. In this case, the discount rate is equal to 5 %.

5.6 Software and solver used to run our simulations: GAMS/MINOS

The GAMS (General Algebraic Modeling System) has been developed in close cooperation with mathematical economists. The GAMS makes it possible to describe and solve optimization problems using a fairly simple programming language (GAMS documentation, website - see Annex 2 for some extracts of our bioeconomic model code on GAMS).

MINOS is one of the numerous solvers that can be used within GAMS. GAMS/MINOS is a general purpose nonlinear programming solver. It is designed to find solutions that are locally optimal. There is no general procedure we could use to verify whether a given local optimum is global. It solves problems where nonlinear functions are smooth (GAMS documentation, website). Smith et al (2000), who solve a similar optimization problem, have also used GAMS/MINOS solver.

The MINOS solution procedure requires properly setting the initial values of our problem in order to obtain a solution that is both feasible and optimal. We use as initial values for our different variables the data obtained from the farmer and his farming adviser related to the farmer's farming practices, initial SOM and current crop rotation. We have performed simulations of our scenario with different sets of initial values to check whether the solutions followed the same trends, indicating solution robustness (Smith et al, 2000). We also tested important changes in SOM initial values to check whether the model reacted to such variations.

To further consolidate our simulations results, we could have used the solver CONOPT in addition to MINOS. Indeed, these two solvers do not use the same algorithms to solve models and are complementary (GAMS documentation). Since we do not have these two solvers on the computer used to perform the simulations, we could not proceed to this verification.

5.7 Main limits of our empirical model

The biophysical software used to estimate SOM dynamics functions and crop yield functions, CropSyst, has been chosen for its ability to perform long-term simulations and rotation simulations with respect to France. However, it only dynamically simulates SOM values through time. Other physical indicators are not taken into account.

This model has been calibrated on an interesting but particular farm that has engaged in conservation agriculture since the 1990s. Given the number of farming practices implemented on this farm, not all of them could be properly considered and simulated here. While we consider the main farming practices impacting soil quality dynamics, there are still numerous practices that are likely to impact soil quality and that are not taken into account in large part because of the limitations of CropSyst. As mentioned previously, this can explain the decrease in SOM computed and simulated for the S2 soil type while an increase is observed in field data. It would have been interesting and complementary to calibrate and validate our model on at least another farm not involved in the agriculture of conservation. Unfortunately, we did not have access to another study case that could have provided us with quality data.

In addition, in our model, decision rules are proposed for crop rotation choices. These rules have been established based on the past choices of farmers and the suggestions of a farming adviser. Nonetheless, the choices simulated in our model are constrained and thus limited by the rules imposed.

These omissions reduce the levers of action and the possible strategies of the farmer. As a consequence, the model is quite insensitive to changes in prices and costs. Actually, we have tested extreme values of crop price increases (10 % each year) with a negative discount rate (-10%) to simulate a situation where the farmer greatly favors future generations and future revenues with a gross margin that is increasing throughout time. In this case, the farmer has an interest in maintaining and preserving soil quality in the long run since he values more the forthcoming higher revenue. Nonetheless, even under extreme scenarios that favor soil conservation, the SOM dynamics trends observed are similar to our more realistic and conservative scenarios. Although the farmer takes advantage of his crop rotation management, it seems that the decision variables in our model are not sufficiently contrasted to allow the farmer to invest efficiently in soil quality (that is, with significantly higher SOM values compared to the conservative scenario).

Another important limit of our model is that it does not take into account risk and

uncertainty.

Risk related to sustainable practices as well as market and climate risks should have been included in the analysis in order to have a more realistic model. Apart from inter-annual climate risk, risks induced by climate change could also be considered. Indeed, crop-yield and SOM dynamics functions are sensitive to climatic conditions. Actually, climate change and the associated increase in temperature might negatively impact SOC content, even on non-agricultural lands, and could even cancel the positive impact of conservation practices on SOC content and carbon storage (Métay et al, 2009). Although through CropSyst we take into account average climatic conditions, risk and uncertainty linked to climatic conditions and their impact on crop yields are not considered.

The choice of an inter-temporal model can also be discussed. Actually, another approach could have been to use a dynamic recursive model, where for instance, at time t , the farmer optimizes his objective value inter-temporally over a 5-year planning horizon. The optimal strategy of the farmer at time t is the result of anticipation over 5 years. At $t+1$, state conditions are actualized, and once again, the farmer maximizes his profit over 5 years, and so on until the end of the planning horizon, for instance, 50 years. This is a more realistic way to model the farmer's decision making process while considering SOM cumulative changes over a significant period of time. For simplicity and due to a lack of time to complete the model, we present here the results of simulations run inter-temporally.

5.8 Results and Discussion

Results of the simulations are presented in Table 5.24 and Table 5.25 for long non-intensive crop rotations and in Table 5.29 and Table 5.27 for short intensive crop rotations. In these tables are presented the annualized objective function, the changes in endogenous practices of the farmer and the evolution of SOM stock for each scenario.

OB1 (€/ha/year) ³		Tillage intensity			N inputs (kg/ha)					⁵ SOM (g/kg) ⁶		Crop area ⁷
Mean residue use ⁴		S. wheat	D. wheat	Barley	Repeseed	Maize grain	Stunflower					
Base scenario 5% 347.80	S1	1	0	180 → 190 → 180	215 → 215 → 215	140 → 140 → 140	180 → 180 → 180	150 → 150 → 150	80 → 80 → 80	11.6 → 10.86 → 7.37	3.4	
	S2	0.732 → 0.7 → 0.662	0	190 → 190 → 190	150 → 215 → 215	126 → 140 → 140	124 → 180 → 180	120 → 150 → 150	80 → 80 → 27 → 25.09	15.81	82.06	
	S3	0.861 → 1 → 1	0	171 → 176 → 190	170 → 215 → 226	140 → 140 → 150	138 → 180 → 180	150 → 150 → 150	80 → 80 → 22.8 → 21.07 → 12.87	62.36		
Dynamic costs scenario (5 %) 330.83	S1	1 → 1 → 1	0 → 1 → 1	0 → 187 → 162	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	0 → 0 → 0	80 → 60 → 11.6 → 10.85 → 7.2	3.4 → 2.764 → 71 → 714 → 730	3.4	
	S2	0.617 → 0.658 → 1	0 → 0.915 → 1	190 → 190 → 0	150 → 0 → 0	126 → 0 → 0	124 → 180 → 162	120 → 160 → 142	80 → 80 → 27 → 25.08 → 15.93	82.06 → 65.753 → 71 → 726 → 730	82.06	
	S3	0.861 → 1 → 1	0 → 0.920 → 1	171 → 173 → 0	171 → 0 → 0	0 → 0 → 0	138 → 180 → 162	0 → 0 → 0	80 → 80 → 22.8 → 21.06 → 13.08	62.36 → 51.087 → 71 → 730		
Dynamic costs scenario + carbon 330.26 price (5 %)	S1	1 → 1 → 1	0 → 1 → 1	0 → 190 → 0	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	0 → 0 → 0	80 → 80 → 11.6 → 10.85 → 7.32	3.4 → 2.9 → 71 → 717 → 730	3.4	
	S2	0.732 → 0.686 → 0.473	0 → 0.859 → 1	190 → 190 → 0	150 → 236 → 0	126 → 150 → 0	124 → 180 → 0	120 → 0 → 145	80 → 80 → 27 → 25.08 → 15.9	82.06 → 74.782 → 71 → 728 → 730	82.06	
	S3	0.861 → 1 → 1	0 → 1 → 1	171 → 173 → 0	171 → 0 → 0	0 → 0 → 0	138 → 180 → 162	0 → 0 → 0	80 → 80 → 22.8 → 21.05 → 13.11	62.36 → 54.108 → 71 → 728 → 730	62.36	
Dynamic costs scenario + carbon 360.79 price + alfafa premium (5 %)	S1	1 → 1 → 1	0 → 1 → 1	0 → 190 → 162	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	0 → 0 → 0	80 → 0 → 0 → 11.6 → 10.85 → 7.12	3.4 → 2.9 → 71 → 717 → 730	3.4	
	S2	0.732 → 0.827 → 0.596	0 → 1 → 1	190 → 190 → 162	150 → 0 → 167	126 → 0 → 0	124 → 180 → 162	120 → 160 → 0	80 → 80 → 27 → 25.08 → 15.92	82.06		
	S3	0.861 → 1 → 0.812	0 → 0.92 → 1	171 → 173 → 162	170 → 0 → 0	0 → 0 → 0	138 → 180 → 162	0 → 0 → 0	80 → 80 → 22.8 → 21.06 → 12.96	62.36		

Table 5.24 – GAMS simulations results - Long non-intensive rotations (1/2).
(Source: the author from GAMS simulations)

3. It corresponds to the objective function value expressed as an annuity.
4. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1, 3 and 5 respectively.
5. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1, 3 and 5 respectively.
6. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1 and 5 respectively.
7. The arrows (→) indicate a change during the time horizon. We specify after the value at which time period significant changes occur.

OBI (€/ha/year) ⁸		Non-intensive rotations										Crop area ¹²
		Mean residue use ⁹	Tillage intensity	S. wheat	D. wheat	Barley	Rapeseed	Maize grain	Sunflower	N inputs (kg/ha) ¹¹		
Base scenario (1%)	S1	1	0	180 → 190 → 190	215 → 215 → 215	140 → 140 → 140	180 → 180 → 180	150 → 150 → 150	80 → 60 → 80	11.6 → 10.86 → 7.37	11.6 → 10.86 → 7.37	3.4
	S2	0.732 → 0.666 → 0.802	0	190 → 190 → 190	150 → 215 → 215	127 → 140 → 140	125 → 180 → 180	120 → 150 → 150	80 → 80 → 27	27 → 25.09 → 16.05	27 → 25.09 → 16.05	82.06
	S3	0.861 → 1 → 1	0	171 → 176 → 190	170 → 215 → 215	140 → 140 → 140	138 → 0 → 180	150 → 160 → 150	80 → 80 → 80	22.8 → 21.07 → 13.01	22.8 → 21.07 → 13.01	62.36
Dynamic costs scenario (1%)	S1	1 → 1 → 1	0 → 1 → 1	0 → 190 → 162	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	0 → 0 → 0	80 → 60 → 80	11.6 → 10.85 → 7.38	11.6 → 10.85 → 7.38	3.4 → 2.779 → 71 → 71 → 730
	S2	0.617 → 0.678 → 0.296	0 → 1 → 0.852	190 → 190 → 0	150 → 176 → 0	126 → 0 → 0	124 → 180 → 162	120 → 160 → 142	80 → 80 → 27	27 → 25.08 → 15.83	27 → 25.08 → 15.83	82.06
	S3	0.861 → 1 → 1	0 → 1 → 0.813	171 → 173 → 162	170 → 178 → 0	0 → 0 → 0	138 → 180 → 162	0 → 0 → 0	80 → 80 → 80	22.8 → 21.05 → 12.97	22.8 → 21.05 → 12.97	62.36
Dynamic costs scenario + carbon price (1%)	S1	1 → 1 → 1	0 → 1 → 0.652	0 → 190 → 162	0 → 0 → 0	0 → 150 → 0	180 → 0 → 0	0 → 0 → 0	80 → 0 → 80	11.6 → 10.85 → 7.2	11.6 → 10.85 → 7.2	3.4 → 2.926 → 71 → 71 → 730
	S2	0.732 → 0.863 → 0.662	0 → 1 → 1	190 → 190 → 162	149 → 0 → 0	126 → 0 → 0	126 → 0 → 0	120 → 0 → 0	80 → 80 → 27	27 → 25.06 → 15.84	27 → 25.06 → 15.84	82.06 → 74.782 → 82.06
	S3	0.861 → 1 → 1	0 → 0.92 → 0.8	171 → 173 → 162	171 → 0 → 0	0 → 0 → 0	136 → 0 → 0	0 → 0 → 0	80 → 80 → 80	22.8 → 21.05 → 12.97	22.8 → 21.05 → 12.97	62.36
Dynamic costs scenario + carbon price + alfalfa premium (1%)	S1	1 → 1 → 1	0 → 1 → 1	0 → 190 → 162	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	0 → 0 → 0	80 → 0 → 80	11.6 → 10.85 → 7.29	11.6 → 10.85 → 7.29	3.4
	S2	0.372 → 0.827 → 0.199	0 → 0.827 → 1	190 → 190 → 162	150 → 0 → 0	126 → 0 → 0	126 → 0 → 162	120 → 160 → 0	80 → 80 → 27	25.08 → 15.95	25.08 → 15.95	82.06
	S3	0.861 → 0.316 → 1	0 → 0.920 → 1	171 → 173 → 162	170 → 0 → 0	0 → 0 → 0	138 → 180 → 162	0 → 0 → 160	80 → 80 → 80	22.8 → 21.14 → 13.25	22.8 → 21.14 → 13.25	62.36
Base scenario (5T)	S1	1	0	180 → 190	215 → 215	140 → 140	180 → 180	150 → 150	80 → 60	11.6 → 10.86	11.6 → 10.86	3.4
	S2	0.732 → 0.588 → 1	0	190 → 190	150 → 215	126 → 140	124 → 132	120 → 150	80 → 80	27 → 25.07	27 → 25.07	82.06
	S3	0.861 → 1 → 1	0	171 → 176	170 → 180	140 → 140	138 → 180	150 → 160	80 → 80	22.8 → 21.05	22.8 → 21.05	62.36
Dynamic costs scenario (5T)	S1	1 → 0 → 0	0	0 → 0	0 → 0	0 → 0	180 → 180	0 → 0	80 → 60	11.6 → 11.39	11.6 → 11.39	3.4 → 0 → 0 ₀₇₁₋₇₇₃₋₇₇₅
	S2	0.732 → 0.588 → 1	0 → 1 → 1	190 → 190	150 → 240	127 → 0	121 → 180	120 → 160	60 → 80	27 → 25.07	27 → 25.07	82.06
	S3	0.861 → 1 → 1	0 → 1 → 1	171 → 173	171 → 176	0 → 0	138 → 156	0 → 0	80 → 60	22.8 → 21.05	22.8 → 21.05	62.36
Dynamic costs scenario + carbon price (5T)	S1	1 → 0 → 0	0	0 → 0	0 → 0	0 → 0	180 → 180	0 → 0	80 → 60	11.6 → 11.39	11.6 → 11.39	3.4 → 0 → 0 ₀₇₁₋₇₇₃₋₇₇₅
	S2	0.732 → 0.588 → 1	0 → 1 → 1	190 → 190	150 → 240	125 → 0	125 → 180	120 → 0	60 → 80	27 → 25.07	27 → 25.07	82.06
	S3	0.861 → 1 → 1	0 → 1 → 1	171 → 173	170 → 174	0 → 0	138 → 180	0 → 0	80 → 60	22.8 → 21.05	22.8 → 21.05	62.36
Dynamic costs scenario + carbon price + alfalfa premium (5T)	S1	1 → 0 → 0	0	0 → 0	0 → 0	0 → 0	180 → 180	0 → 0	80 → 60	11.6 → 11.39	11.6 → 11.39	3.4 → 0 → 0 ₀₇₁₋₇₇₃₋₇₇₅
	S2	0.732 → 0.588 → 1	0 → 1 → 1	190 → 190	150 → 158	127 → 0	124 → 180	121 → 160	60 → 80	27 → 25.07	27 → 25.07	82.06
	S3	0.861 → 1 → 1	0 → 1 → 1	171 → 172	171 → 172	0 → 0	138 → 98	0 → 160	80 → 60	22.8 → 21.05	22.8 → 21.05	62.36

Table 5.25 – GAMS simulations results - Long non-intensive rotations (2/2).

(Source: the author from GAMS simulations)

8. It corresponds to the objective function value expressed as an annuity.
9. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1, 3 and 5 respectively.
10. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1, 3 and 5 respectively.
11. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1 and 5 respectively.
12. The arrows (→) indicate a change during the time horizon. We specify after the value at which time period significant changes occur.

Short intensive rotations										
OBJ (€/ha/)	Mean residue use ¹⁴	Tillage intensity			S. wheat		N inputs (kg/ha)		SOM (g/kg) ¹⁶	Crop area ¹⁷
		1 → 0 → 1	1 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	180 → 180 → 180		
Base scenario (5%)	S1	1 → 0 → 1	1 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	180 → 180 → 180	180 → 180 → 180	11.6 → 11.39 → 11.39	3.4 → 0 → 0
	S2	0.580 → 0.672 → 1	1 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 180 → 180	0 → 180 → 180	27 → 25.06 → 22.33	82.06 → 26.9 → 0
	S3	0.587 → 0.389 → 0.611	1 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 180 → 180	0 → 180 → 180	22.8 → 21.04 → 12.64	82.06 → 26.9 → 0
Dynamic costs scenario (5%)	S1	1 → 0 → 1	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	180 → 180 → 162	11.6 → 11.39 → 11.39	3.4 → 0 → 0
	S2	0.732 → 0 → 1	0 → 1 → 0	190 → 190 → 0	125 → 127 → 162	190 → 190 → 0	125 → 127 → 162	125 → 127 → 162	27 → 25.1 → 19.01	82.06 → 26.9 → 0
	S3	0.861 → 0.106 → 1	0 → 1 → 0	171 → 174 → 0	139 → 140 → 162	171 → 174 → 0	139 → 140 → 162	139 → 140 → 162	22.8 → 21.09 → 16.74	82.06 → 26.9 → 0
Dynamic costs scenario + carbon price (5%)	S1	1 → 0 → 1	1 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	180 → 180 → 0	180 → 180 → 0	11.6 → 11.39 → 11.39	3.4 → 0 → 0
	S2	0.372 → 0 → 1	0.939 → 0.355 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	27 → 25.39 → 24.02	82.06 → 50.7 → 0
	S3	0.587 → 0 → 1	0.861 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 180 → 0	0 → 180 → 0	22.8 → 21.7 → 19.9	82.06 → 25.07 → 0
Dynamic costs scenario + carbon price + alfafa premium (5%)	S1	1 → 0 → 1	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	180 → 180 → 162	11.6 → 11.39 → 11.39	3.4 → 0 → 0
	S2	0.372 → 0 → 0	0 → 1 → 1	190 → 190 → 162	126 → 127 → 162	190 → 190 → 162	126 → 127 → 162	126 → 127 → 162	27 → 25.1 → 16.15	82.06 → 64.19 → 64.19
	S3	0.861 → 0.102 → 1	0 → 1 → 1	171 → 174 → 162	139 → 140 → 162	171 → 174 → 162	139 → 140 → 162	139 → 140 → 162	22.8 → 21.09 → 12.67	82.06 → 64.19 → 64.19

Table 5.26 – GAMS simulations results - Short intensive rotations. (1/2)
 (Source: the author from GAMS simulations)

13. It corresponds to the objective function value expressed as an annuity.
14. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1, 3 and 5 respectively.
15. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1, 3 and 5 respectively.
16. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1 and 5 respectively.
17. The arrows (→) indicate a change during the time horizon. We specify after the value at which time period significant changes occur.

Short intensive rotations									
OBJ (€/ha/)	Mean residue use ¹⁹	Tillage intensity	S. wheat		N inputs (kg/ha)		SOM (g/kg) ²¹	Crop area ²²	
			Repeaced	Repeaced	Repeaced	Repeaced			
Base scenario (1%)	S1	1 → 0 → 1	0 → 0 → 0	190 → 190 → 190	180 → 180 → 180	11.6 → 10.87 → 7.2	3.4		
	S2	0.732 → 0 → 1	0 → 0 → 0	190 → 190 → 190	127 → 133 → 172	27 → 25.1 → 15.96	82.06		
	S3	0.861 → 0.79 → 0.21	0 → 0 → 0	171 → 176 → 190	139 → 146 → 179	22.8 → 21.04 → 12.94	62.36		
Dynamic costs scenario (1%)	S1	1 → 0 → 1	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	11.6 → 11.39 → 11.39	3.4 → 0 → 0	71 → 73 → 730	
	S2	0.487 → 0 → 0	0 → 1 → 0	190 → 190 → 0	126 → 128 → 162	27 → 25.1 → 18.55	82.06 → 55.16 → 0	71 → 72 → 723	
	S3	0.861 → 0.102 → 1	0 → 1 → 0	171 → 174 → 0	139 → 140 → 162	22.8 → 21.09 → 15.49	62.36 → 55.97 → 0	71 → 719 → 722	
Dynamic costs scenario + carbon price (1%)	S1	1 → 0 → 1	0 → 0 → 0	0 → 0 → 0	0 → 0 → 0	11.6 → 11.39 → 11.39	3.4 → 0 → 0	71 → 73 → 730	
	S2	0.732 → 0 → 1	0 → 1 → 0	190 → 190 → 0	126 → 127 → 0	27 → 25.1 → 21.02	82.06 → 64.19 → 0	71 → 715 → 716	
	S3	0.861 → 0.79 → 1	0 → 1 → 0	171 → 173 → 0	138 → 140 → 0	22.8 → 21.04 → 17.78	62.36 → 49.26 → 0	71 → 713 → 725	
Dynamic costs scenario + carbon price + alfalfa premium (1%)	S1	1 → 0 → 1	0 → 0 → 0	0 → 0 → 0	180 → 180 → 162	11.6 → 11.39 → 11.39	3.4 → 0 → 0	71 → 73 → 730	
	S2	0.487 → 0 → 1	0 → 1 → 0	190 → 190 → 0	126 → 128 → 162	27 → 25.1 → 18.88	82.06 → 56.747 → 0	71 → 721 → 722	
	S3	0.861 → 0.790 → 1	0 → 1 → 0	171 → 173 → 0	139 → 140 → 162	22.8 → 21.07 → 15.81	62.36 → 49.26 → 0	71 → 720 → 721	
Base scenario (5T)	S1	1 → 0 → 0	0 → 0 → 0	147 → 0	180 → 180	11.6 → 11.4	3.4 → 0 → 0	71 → 73 → 75	
	S2	0.732 → 0 → 0.372	0 → 0 → 0	190 → 190	125 → 132	27 → 25.1	82.06		
	S3	0.861 → 0.790 → 0	0 → 0 → 0	171 → 176	138 → 145	22.8 → 21.05	62.36		
Dynamic costs scenario (5T)	S1	1 → 0 → 0	0 → 0 → 0	0 → 0	180 → 180	11.6 → 11.39	3.4 → 0 → 0	71 → 73 → 75	
	S2	0.732 → 0 → 0.672	0 → 1 → 1	190 → 190	125 → 127	27 → 25.1	82.06		
	S3	0.861 → 0.790 → 0.790	0 → 1 → 1	171 → 173	138 → 140	22.8 → 21.04	62.36		
Dynamic costs scenario + carbon price (5T)	S1	1 → 0 → 0	0 → 0 → 0	0 → 0	180 → 180	11.6 → 11.39	3.4 → 0 → 0	71 → 73 → 75	
	S2	0.732 → 0 → 0.672	0 → 1 → 1	190 → 190	125 → 128	27 → 25.1	82.06		
	S3	0.861 → 0.790 → 0.790	0 → 1 → 1	171 → 173	139 → 140	22.8 → 21.04	62.36		
Dynamic costs scenario + carbon price (5T)	S1	1 → 0 → 0	0 → 0 → 0	0 → 0	180 → 180	11.6 → 11.39	3.4 → 0 → 0	71 → 73 → 75	
	S2	0.695 → 0.193 → 0	0 → 0.39 → 0.50	190 → 0	124 → 180	27 → 25.35	82.06 → 79.552 → 37.298	71 → 73 → 75	
	S3	0.587 → 0.649 → 0	0.024 → 0.458 → 0	171 → 0	138 → 180	22.8 → 21.9	62.36 → 37.36 → 3.53	71 → 73 → 75	

Table 5.27 – GAMS simulations results - Short intensive rotations. (2/2)
(Source: the author from GAMS simulations)

18. It corresponds to the objective function value expressed as an annuity.
19. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1, 3 and 5 respectively.
20. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1, 3 and 5 respectively.
21. The arrows (→) indicate a change in the time horizon. Here, the values are for period 1, 5 and 30 or 1 and 5 respectively.
22. The arrows (→) indicate a change during the time horizon. We specify after the value at which time period significant changes occur.

5.8.1 *Non-intensive rotations*

5.8.1.1 *Changes in SOM dynamics in the different scenarii*

In our simulations, the evolutions of SOM values are similar. For the S1 parcel, in all scenarios, SOM end values range between 7.12 g/kg and 7.38 g/kg at year 30. SOM end values in the S2 parcel range between 15.81 g/kg and 16.05 g/kg, while in the S3 parcel, they are between 12.87 g/kg and 13.11 g/kg.

Graphically, SOM dynamics appear to be similar across scenarios (see Figures 5.1, 5.2, 5.3 and Figures 5.4, 5.5, 5.6, 5.7, 5.8, 5.9). In all scenarios, we observe a decrease in SOM that cannot be efficiently mitigated by the economic instruments tested.

— **Planning horizon 50 years, results at 30 years + discount rate of 5 %**

In the baseline case, at the end of the time horizon, the stocks of SOM have decreased in all soil types. For soil type 1, SOM has decreased by 36.4 %, and by 41.4 % and 43.55 % for soil type 2 and 3, respectively. It seems that the economic instruments simulated here do not favor SOM conservation (Table ?? and Figures 5.1, 5.2, 5.3).

It is in parcel S1 that more fluctuations can be observed in SOM dynamics. This is due to the changes in area cultivated for S1, which fluctuates earlier in the planning horizon for S1 than for the other soil types. As a result, SOM dynamics are less linear than for the other parcels.

A significant difference in SOM dynamics appears between year 12 and 19 for the S2 parcel (see Figure 5.2) in favor of the baseline scenario. This is explained by crop rotation choices. Actually, alfalfa is grown abundantly on this parcel during the previous years, leading to a temporarily higher level of SOM in the baseline scenario.

— **Planning horizon 50 years, results at 30 years + discount rate of 1 %**

When the farmer's preference for time changes, the overall dynamics of SOM do not change: We observe similar decreases in SOM end values and similar evolutions (see Tables 5.24 and 5.25 and Figures 5.4, 5.5, 5.6). We can, however, note a smoother evolution in SOM content for parcel S1 and S2 compared to their 5 % discount rate counterpart.

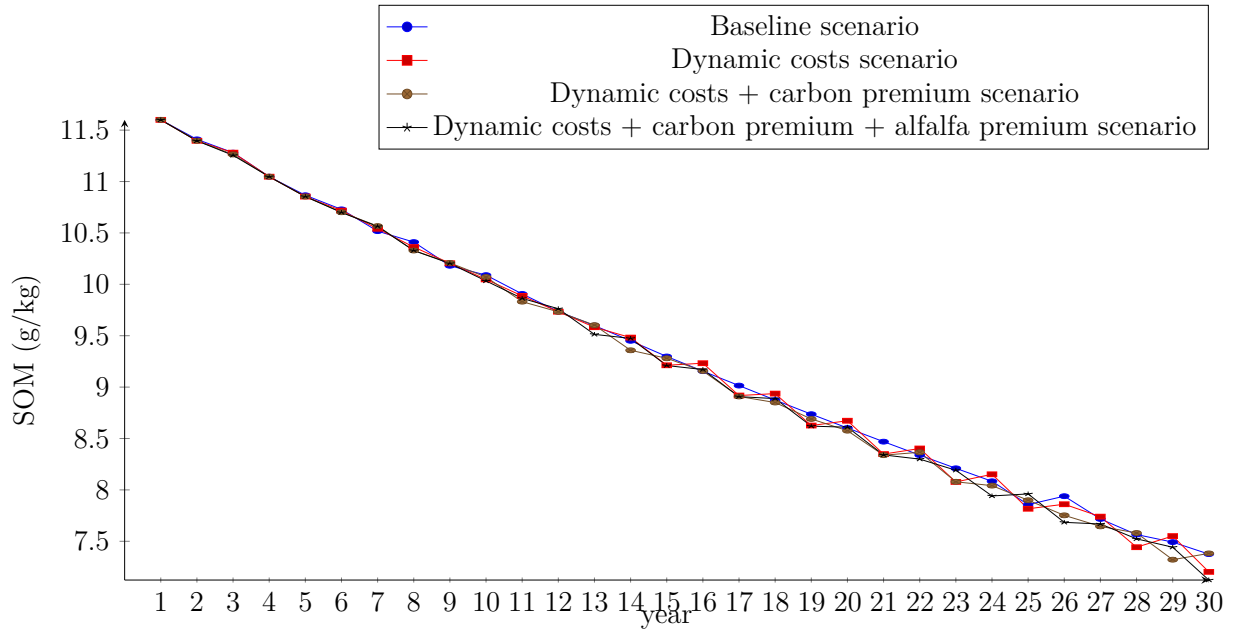


Figure 5.1 – SOM dynamics in parcel S1 for the different scenario (Long-term optimization and discount rate 5 %) (Source: the author from GAMS simulations)

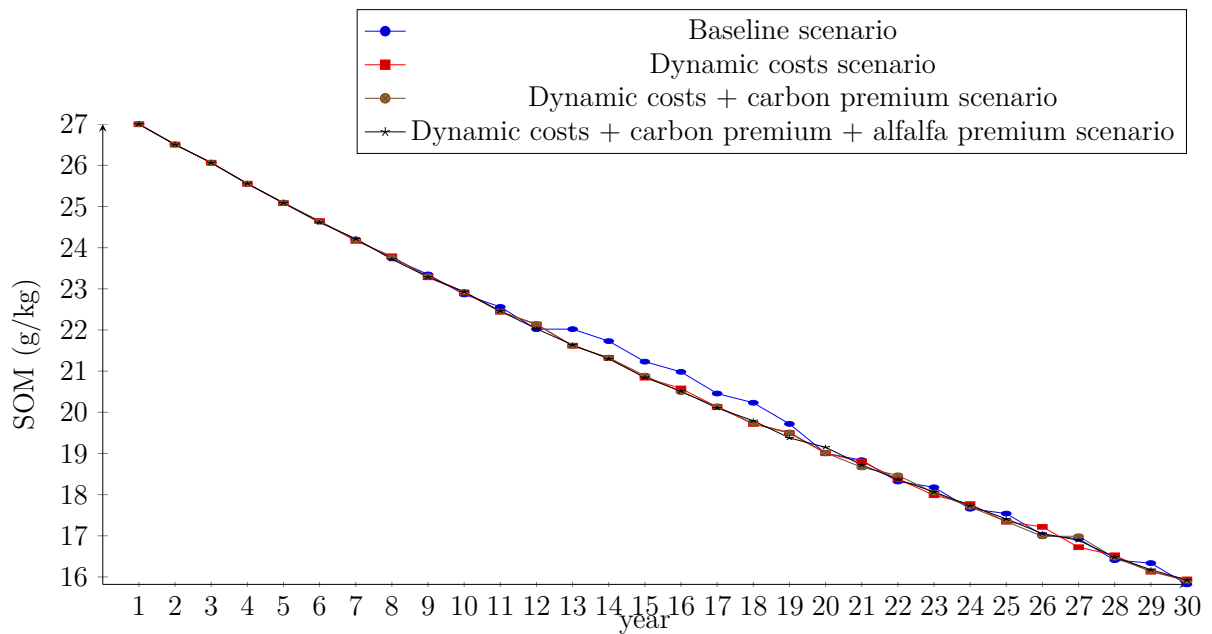


Figure 5.2 – SOM dynamics in parcel S2 for the different scenarios (Long-term optimization and discount rate 5 %) (Source: the author from GAMS simulations)

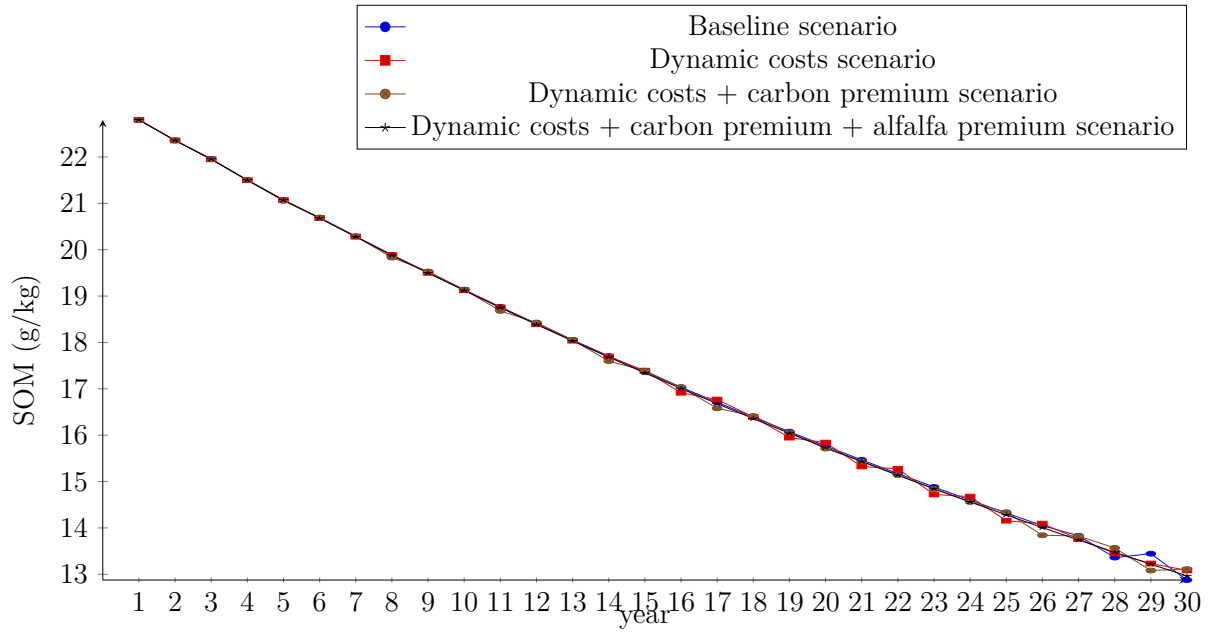


Figure 5.3 – SOM dynamics in parcel S3 for the different scenarios (Long-term optimization and discount rate 5 %) (Source: the author from GAMS simulations)

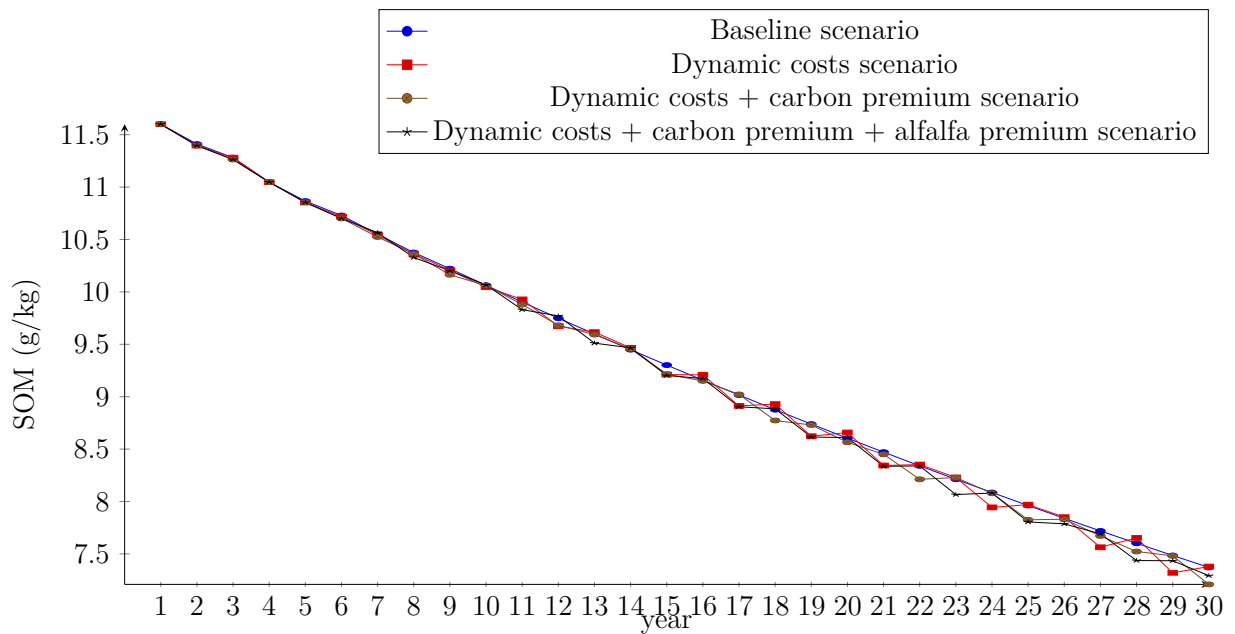


Figure 5.4 – SOM dynamics in parcel S1 for the different scenarios (Long-term optimization and discount rate 1 %) (Source: the author from GAMS simulations)

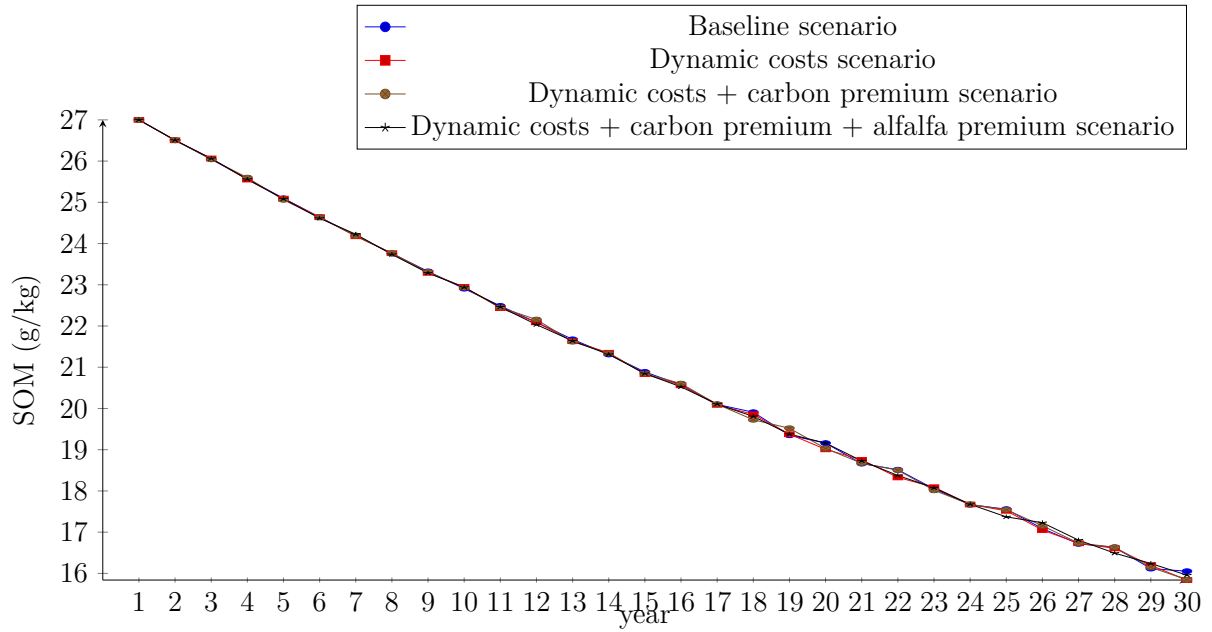


Figure 5.5 – SOM dynamics in parcel S2 for the different scenarios (Long-term optimization and discount rate 1 %)
 (Source: the author from GAMS simulations)

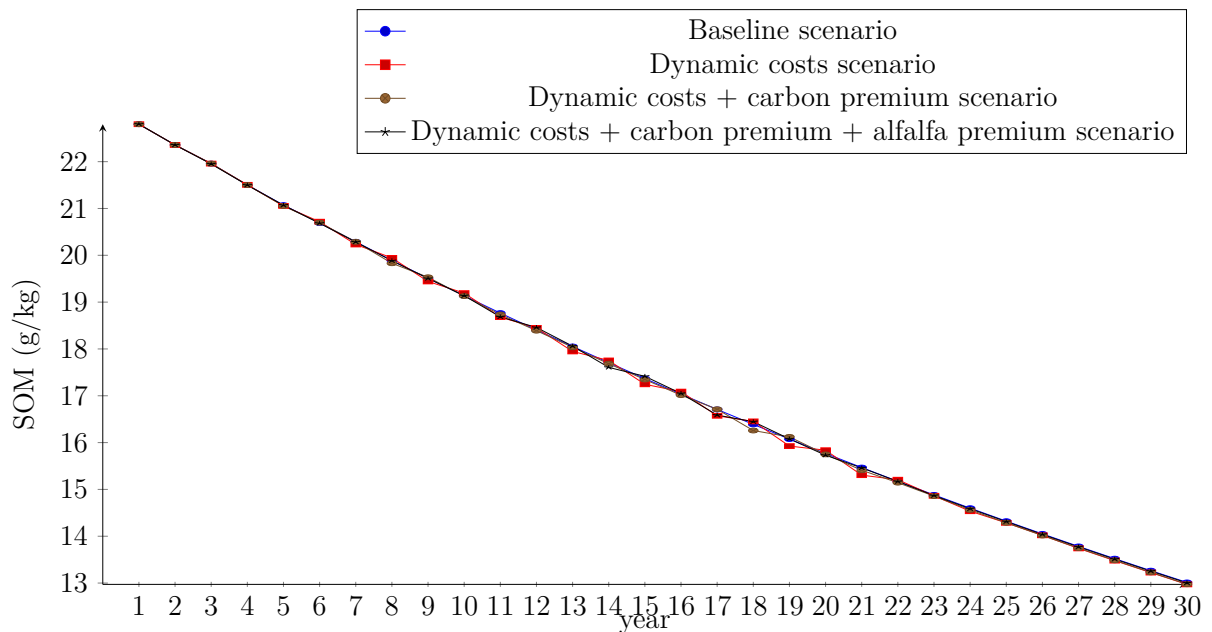


Figure 5.6 – SOM dynamics in parcel S3 for the different scenarios (Long-term optimization and discount rate 1 %)
 (Source: the author from GAMS simulations)

— Planning horizon 5 years, results at 5 years + discount rate of 5 %

For S2 and S3 parcels, the SOM end values at year 5 are the same as in all other scenarios for the same period (see Tables 5.24 and 5.25). Evolutions of SOM in the S2 and S3 parcels are similar regardless of the scenario (Figures 5.8 and 5.9): The increase in input prices and the introduction of carbon premium or alfalfa premium have no impact on SOM evolution in these two parcels. However, they have an impact on S1 parcel SOM evolution (Figure 5.7). Actually, we observe a stabilization of SOM from period 2 in all dynamic scenarios for this parcel. This is due to the end of cropping activities on this parcel, which is the less productive and the smallest (3.4 hectares).

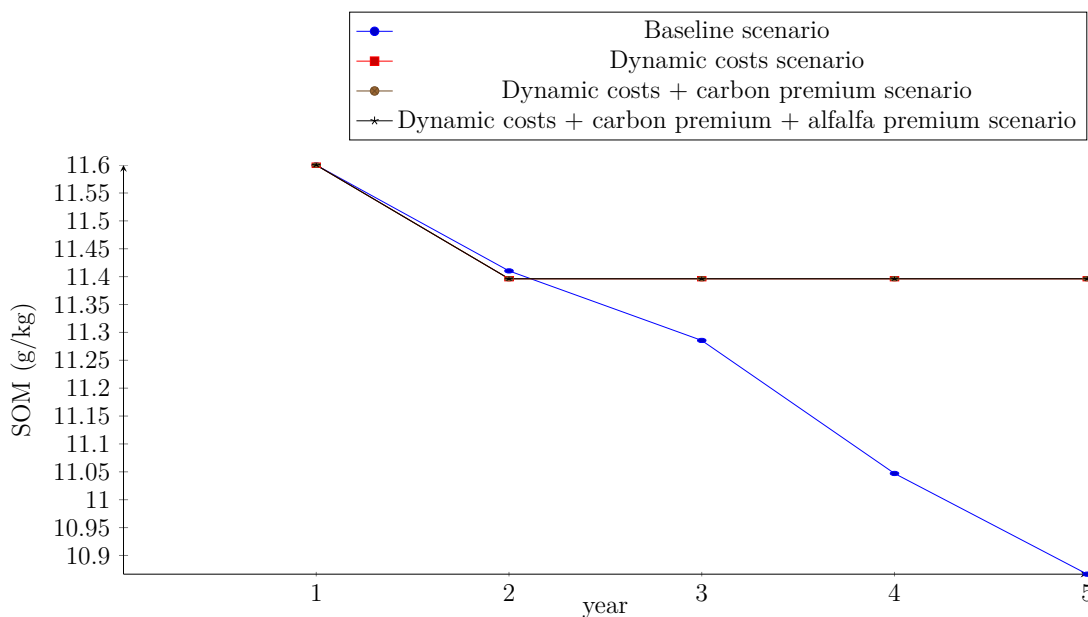


Figure 5.7 – SOM dynamics in parcel S1 for the different scenarios (Short-term optimization and discount rate 5 %)

(Source: the author from GAMS simulations)

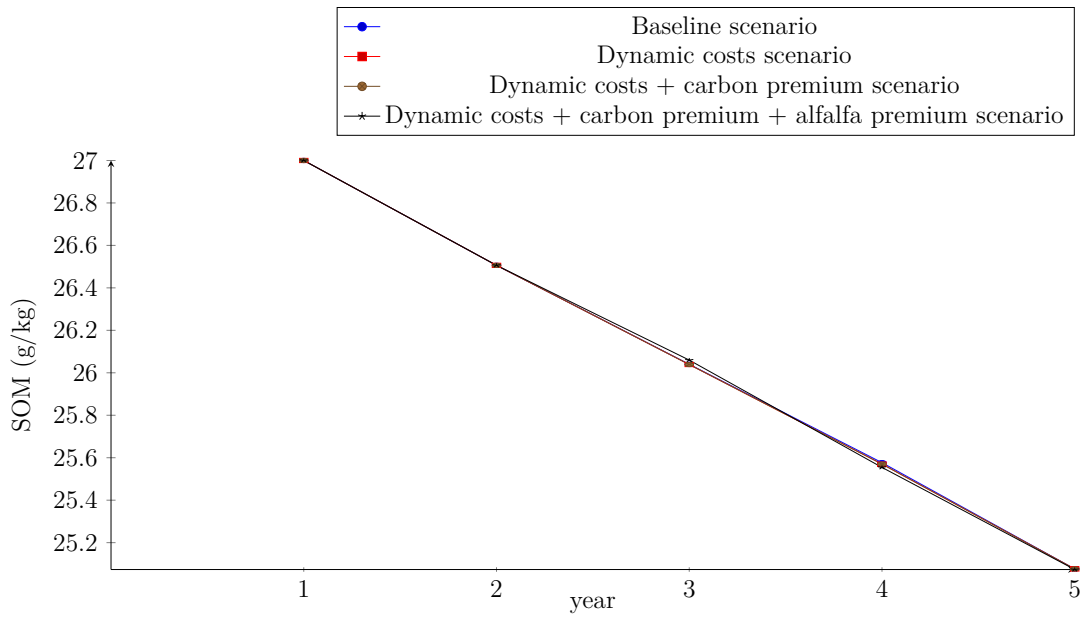


Figure 5.8 – SOM dynamics in parcel S2 for the different scenarios (Short-term optimization and discount rate 5 %)
 (Source: the author from GAMS simulations)

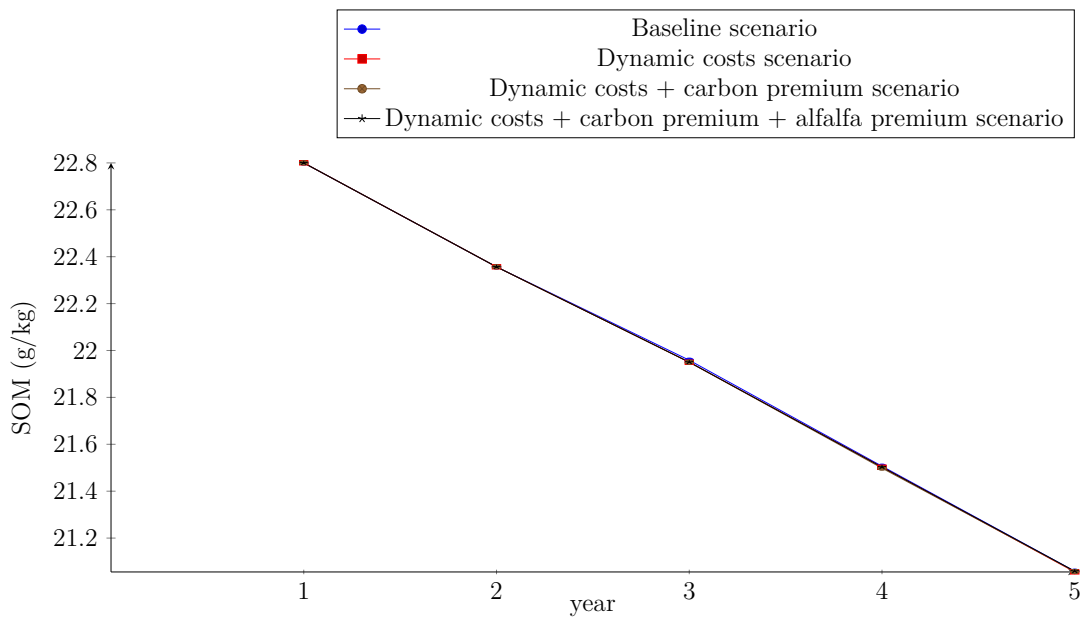


Figure 5.9 – SOM dynamics in parcel S3 for the different scenarios (Short-term optimization and discount rate 5 %)
 (Source: the author from GAMS simulations)

5.8.1.2 *Changes in farming practices in the different scenarii*

— **Planning horizon 50 years, results at 30 years + discount rate of 5 %**

The base scenario simulation has for a starting point what corresponds to the actual farming practices implemented in our study case. The annualized objective value for this scenario is 347.8 €/ha (see Table 5.24). Throughout the temporal horizon, we can observe substantial use of crop residues. For this scenario, a regular level of N fertilizer inputs is used: 180 kg/ha for soft wheat and 215 kg/ha for durum wheat, for instance (Figures 5.10, 5.13, 5.16, 5.19, 5.22, 5.25). In addition, the entire crop area is cultivated throughout the time horizon.

When introducing a dynamic and progressive increase in N fertilizers and fuel prices, we observe as expected from our theoretical models an average decrease in N fertilizer use for most crops (see Table 5.28), which is also observable in the N fertilization strategy depicted in Table 5.24 for years 1, 5 and 30. Actually, it seems to be part of the fertilization strategy to not apply fertilization to some crops in some periods, and there is more heterogeneity in fertilization planning over time (Figures 5.10, 5.13, 5.16, 5.19, 5.22, 5.25). One explanation is that the farmer has no interest in fertilizing some crops, in particular crops that are rarely cultivated and for which the economic ratio between the fertilizer expense and crop yield price is less favorable. In this scenario, residue use is similar to that in the baseline case. However, tillage intensity increases. It is not systematic, but deep tillage is quite widespread. We also observe a decrease in the annualized objective value of 5% with respect to the baseline scenario.

Introducing the carbon premium does not greatly change the annualized objective value (-0.1 %). The N fertilization strategy is slightly different than that in the simpler dynamic scenario, with lower levels of N fertilization. N fertilization levels are lower than in the baseline scenario for most crops. Residue use and tillage intensity are comparable to what is obtained for the previous dynamic scenario (Figures 5.10, 5.13, 5.16, 5.19, 5.22, 5.25). The management of cultivated crop areas is slightly different than in the previous case; however, the areas dedicated to each crop are very similar in the dynamic scenario with or without the carbon premium (Figure 5.28).

The scenario where the alfalfa premium is introduced has unexpected consequences: The total crop area where alfalfa is grown is lower in this scenario than in all previous scenarios (see Figure 5.28). In addition, this is the dynamic scenario where almost all cropping area is cultivated compared to the others. Residue use, tillage intensity and

fertilization strategies are similar in this scenario to those in the other dynamics scenarios.

— **Planning horizon 50 years, results at 30 years + discount rate of 1 %**

In this baseline scenario, crop areas and crop residue use, tillage intensity and fertilization strategy are roughly the same as in the baseline scenario with a discount rate of 5 % (see Tables 5.24 and 5.25 and Figures 5.11, 5.14, 5.17, 5.20, 5.23, 5.26). Crop rotation choices are slightly different, with less rapeseed and barley grown in favor of soft wheat, sunflower and alfalfa, where soft wheat and sunflower precede and follow, respectively, alfalfa (see Figure 5.29).

In the dynamic prices scenario, all S2 and S3 crop areas are cultivated throughout the time period considered. Cultivated S1 crop area decreases. We observe similar changes in practice to the 5 % discount rate scenario between the baseline scenario and the dynamic prices scenario (see Table 5.25 and Figures 5.11, 5.14, 5.17, 5.20, 5.23, 5.26).

In the scenario where a carbon premium is introduced, the N fertilization strategy is slightly different: Less N fertilizer is used for rapeseed, maize grain, durum wheat and barley, but the levels of N fertilizer for soft wheat is higher (Figures 5.11, 5.14, 5.17, 5.20, 5.23, 5.26). More of the S1 parcel area is cultivated throughout the planning horizon.

In the scenario where the alfalfa premium is introduced, the cultivated area allocated to alfalfa is not greater than in the other dynamic scenarios (Figure 5.29). The fertilization strategy is slightly more important than in the previous scenario (with carbon price) for rapeseed and maize grain (with a higher amplitude) (Figures 5.20, 5.26). Residue use is less important in this scenario than in the other scenarios.

In the case where the farmer gives almost equal importance to present and future revenues, the crop area cultivated is likely to be higher throughout the planning horizon compared to simulations with a higher discount rate.

— **Planning horizon 5 years, results at 5 years + discount rate of 5 %**

The results of the baseline scenario in this case are very similar to those of the other baseline scenarios with a longer planning horizon. However, the fertilization strategy is not as linear as in the other baseline scenarios: We can observe a decrease in fertilization for some soil types and crops (Figures 5.12, 5.15, 5.18, 5.21, 5.24, 5.27). At the end of the 5 years, SOM end values are practically the same (Table 5.25). The dynamic scenarios

yield very similar results in terms of crop residue use, tillage intensity, fertilization strategy and crop area cultivated (see Table 5.25 and Figures 5.12, 5.15, 5.18, 5.21, 5.24, 5.27 and 5.30).

Hence, it appears that in the short term, the farmer reacts to the increase in fuel prices and N fertilizer prices by reducing N fertilizer. However, the introduction of the carbon price and alfalfa premium has no impact on the practices or SOM dynamics.

— **To conclude about the impacts of our simulations on farming practices changes**

Changes in scenario do not impact crop residue use, which is consistently widespread across time and scenarios. When introducing an increase in input prices, deep tillage is practiced, which is not the case when input prices are constant. The increase in input prices triggers a global decrease in N fertilization strategy (see Tables 5.24, 5.25 and 5.28); however, the crops for which N fertilizer use remain at a relatively high level are also more cultivated, namely, soft wheat and sunflower (Tables 5.24, 5.25 and 5.28 and Figures 5.28, 5.29, 5.30). As a consequence, the overall amount of N fertilizers applied may not be that much diminished between the baseline scenario and the other scenarios. Overall, the N fertilization strategies are similar across the different dynamic scenarios compared to the baseline ones.

Including the baseline scenario, the principal crop rotation used in our scenario is the rotation “*soft wheat x1 - alfalfa x3 - sunflower x1*”. This may be explained by the attractiveness of alfalfa in our model: It requires no N fertilization, and it has a constant yield, in addition to a coupled premium (as currently set in the common agricultural policy). Hence, with alfalfa, the farmer secures a constant revenue per hectare of 1371 €²³, while this value changes for other crops.

Hence, crop rotation strategies are very similar among scenarios, while it seems to be an important lever in SOM depletion mitigation, which may explain why all SOM dynamics are very similar in our simulations (see Figures 5.1, 5.2, 5.3).

23. With a constant alfalfa yield price of 174.5 €/qt, a coupled premium of 150 €/ha and a constant yield of 7 qt/ha, with no N fertilization costs, without considering other charges and costs

	Baseline scenario			Dynamic costs scenario			Dynamic costs + carbon premium scenario			Dynamic costs + carbon premium scenario + alfalfa premium		
	r=5% and T=30	r=1% and T=30	r=5% and T=5	r=5% and T=30	r=1% and T=30	r=5% and T=5	r=5% and T=30	r=1% and T=30	r=5% and T=5	r=5% and T=30	r=1% and T=30	r=5% and T=5
Soft wheat S1	183	189	184	117	116	38	116	135	38	110	109	38
Soft wheat S2	190	183	190	161	154	190	167	148	190	152	147	190
Soft wheat S3	184	185	176	139	121	137	127	156	172	173	150	175
Durum wheat S1	215	215	215	0	0	0	0	8	0	12	0	0
Durum wheat S2	210	208	178	35	70	170	53	22	157	34	15	159
Durum wheat S3	212	211	138	57	25	187	23	25	173	43	41	187
Sunflower S1	76	78	72	72	73	64	53	53	64	48	45	64
Sunflower S2	79	80	80	77	80	72	72	80	72	77	80	72
Sunflower S3	78	80	80	77	80	76	74	80	76	80	80	76
Rapeseed S1	180	180	180	177	177	180	177	0	180	177	177	180
Rapeseed S2	146	162	138	167	140	139	161	13	152	162	143	122
Rapeseed S3	159	165	156	172	169	116	167	9	162	167	145	136
Barley S1	140	140	140	0	0	0	0	5	0	0	0	0
Barley S2	140	126	134	13	43	76	18	8	50	13	13	50
Barley S3	136	135	114	5	0	0	0	0	0	0	0	0
Maize grain S1	150	150	150	0	5	0	0	0	0	5	2	0
Maize grain S2	148	148	138	91	83	112	64	37	112	51	57	144
Maize grain S3	150	150	152	47	43	32	42	29	58	58	42	32

Table 5.28 – GAMS simulation results - Mean N fertilization dose applied over the planning horizon for long rotations (g/kg), per crop and soil type.

(Source: the author from GAMS simulations)

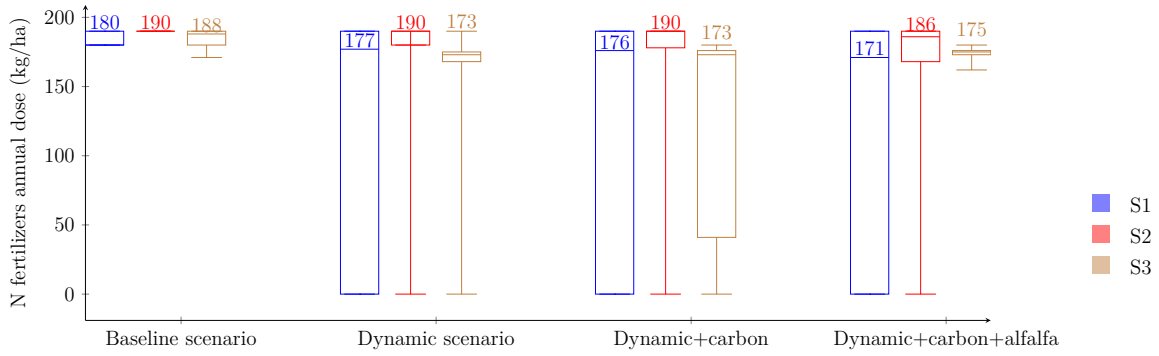


Figure 5.10 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for soft wheat (kg/ha) - for $r=5\%$ and $T=30$. (Source: the author from GAMS simulations)

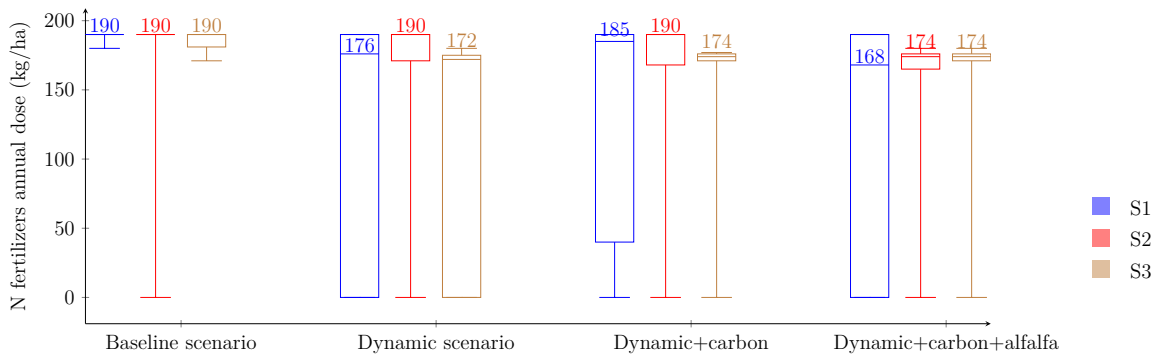


Figure 5.11 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for soft wheat (kg/ha) - for $r=1\%$ and $T=30$. (Source: the author from GAMS simulations)

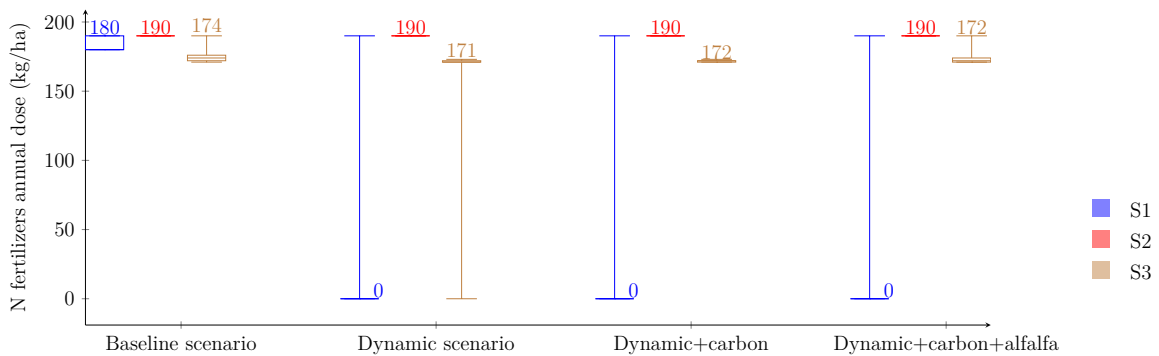


Figure 5.12 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for soft wheat (kg/ha) - for $r=5\%$ and $T=5$. (Source: the author from GAMS simulations)

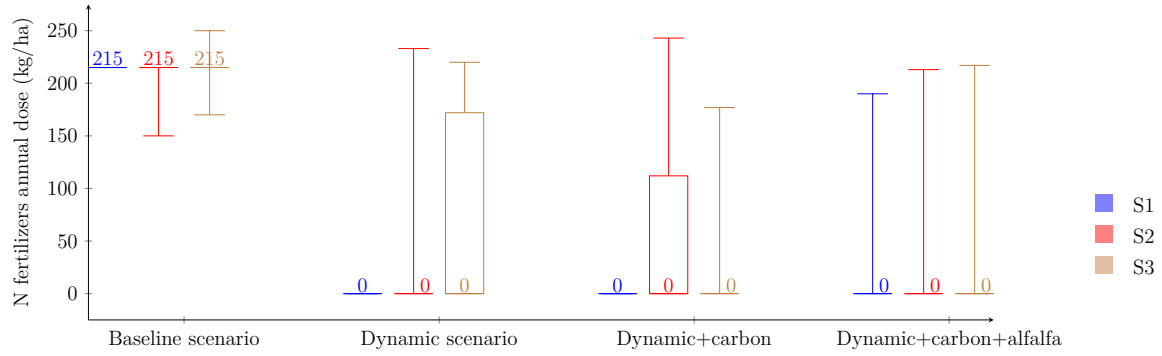


Figure 5.13 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for dur. wheat (kg/ha) - for $r=5\%$ and $T=30$.

(Source: the author from GAMS simulations)

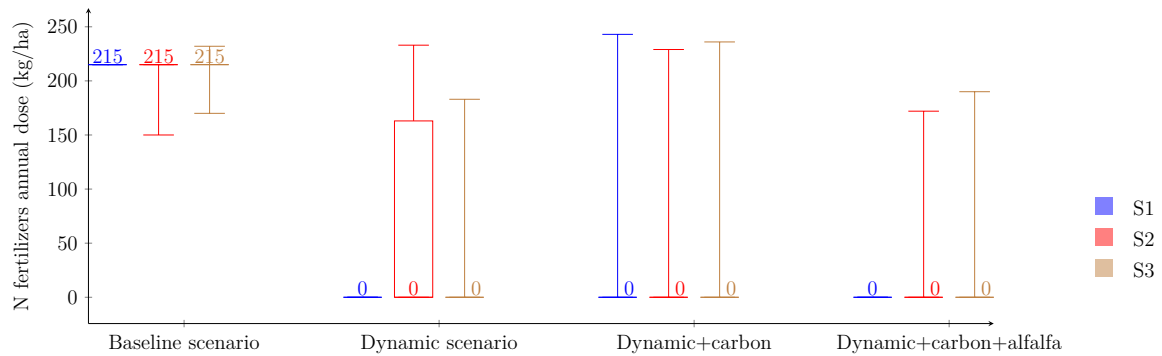


Figure 5.14 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for dur. wheat (kg/ha) - for $r=1\%$ and $T=30$.

(Source: the author from GAMS simulations)

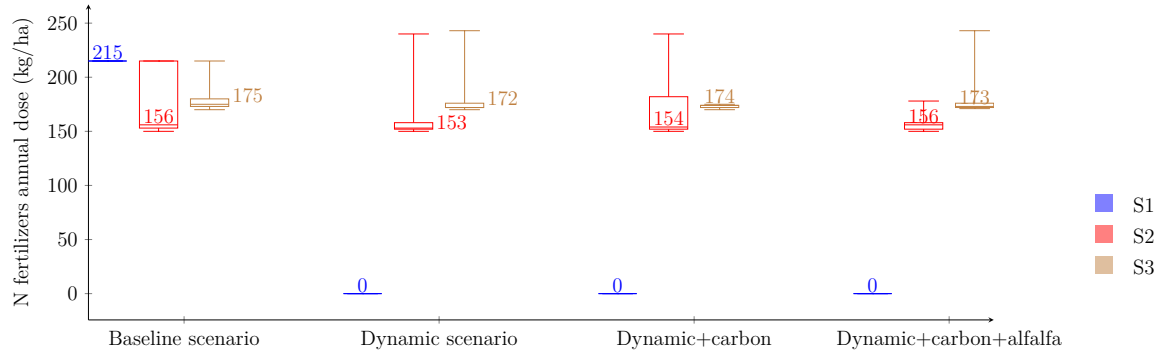


Figure 5.15 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for dur. wheat (kg/ha) - for $r=5\%$ and $T=5$. (Source: the author from GAMS simulations)

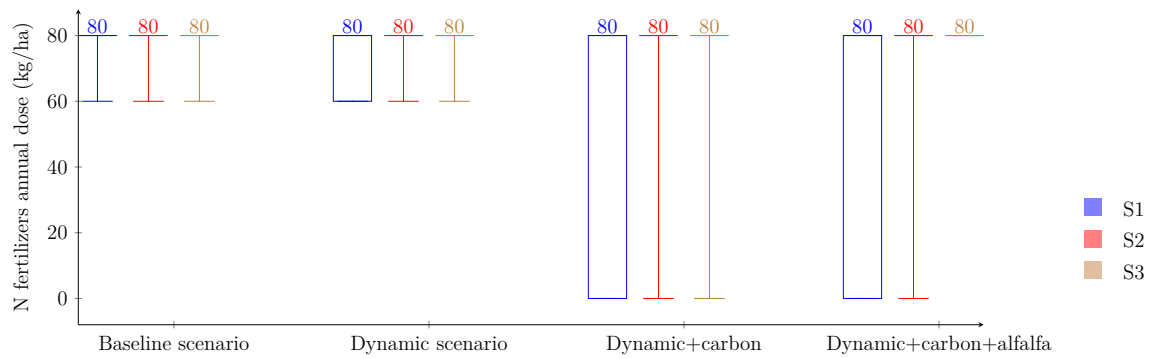


Figure 5.16 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for sunflower (kg/ha) - for $r=5\%$ and $T=30$. (Source: the author from GAMS simulations)

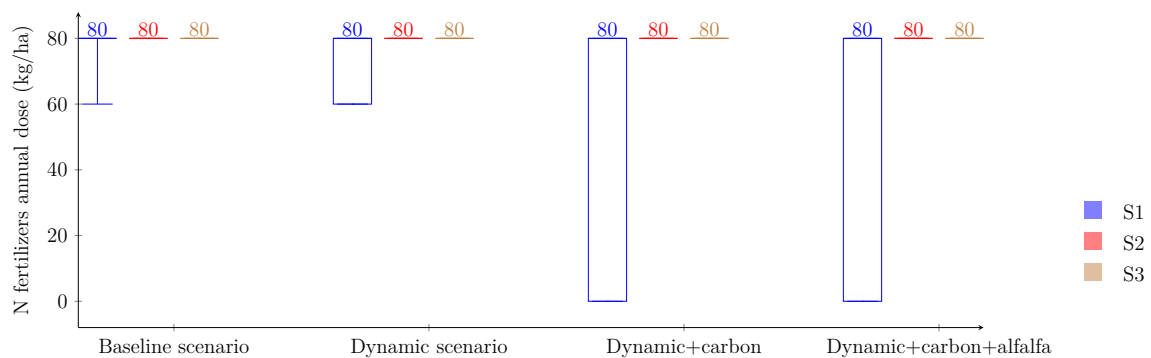


Figure 5.17 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for sunflower (kg/ha) - for $r=1\%$ and $T=30$. (Source: the author from GAMS simulations)

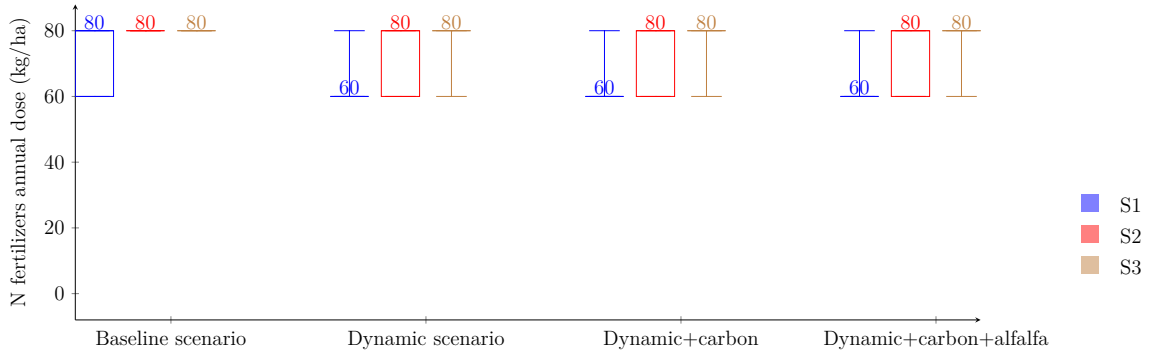


Figure 5.18 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for sunflower (kg/ha) - for $r=5\%$ and $T=5$. (Source: the author from GAMS simulations)

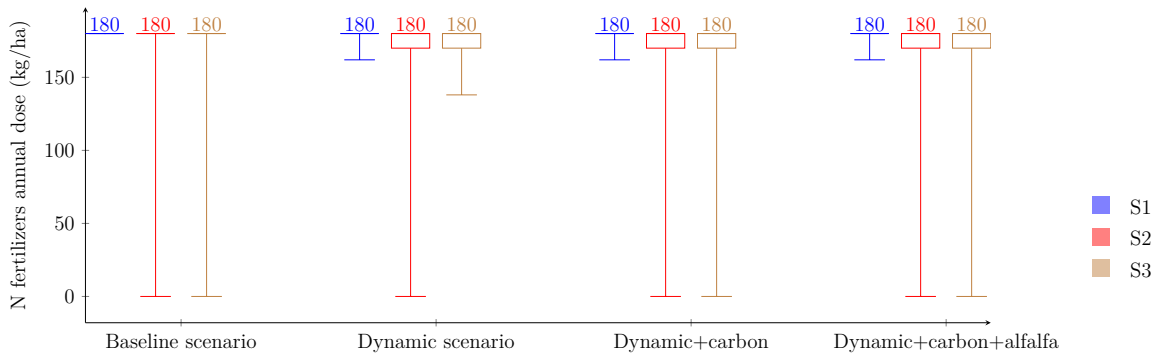


Figure 5.19 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for rapeseed (kg/ha) - for $r=5\%$ and $T=30$. (Source: the author from GAMS simulations)

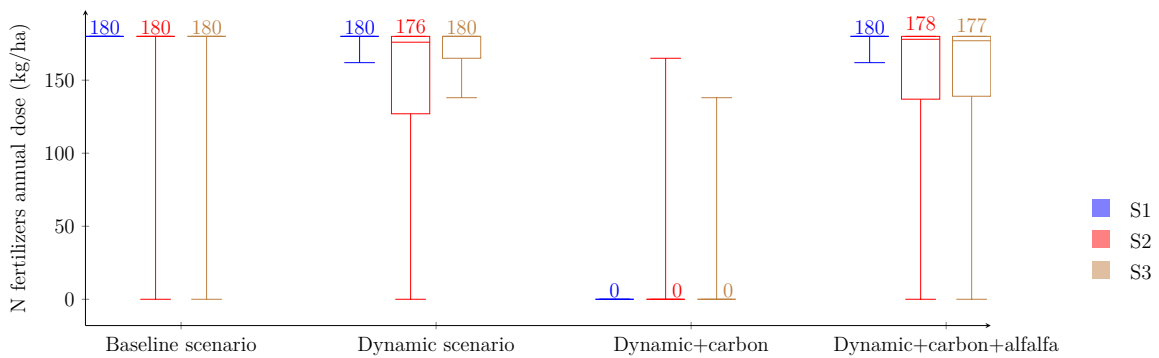


Figure 5.20 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for rapeseed (kg/ha) - for $r=1\%$ and $T=30$. (Source: the author from GAMS simulations)

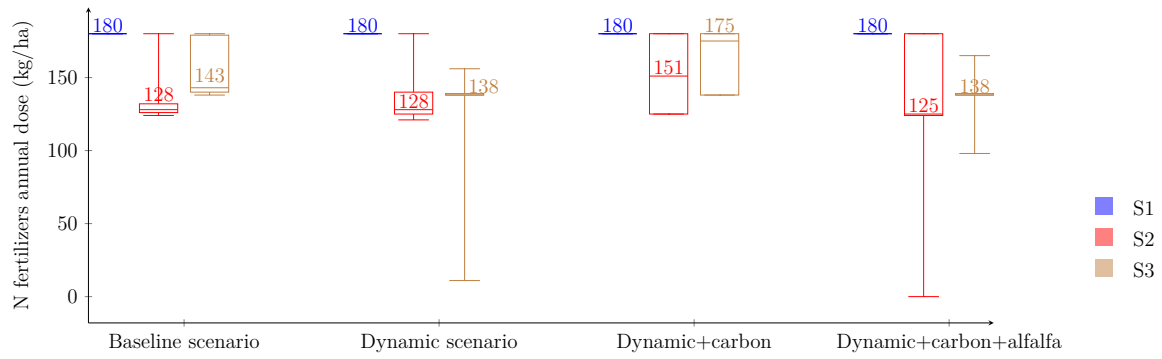


Figure 5.21 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for rapeseed (kg/ha) - for $r=5\%$ and $T=5$. (Source: the author from GAMS simulations)

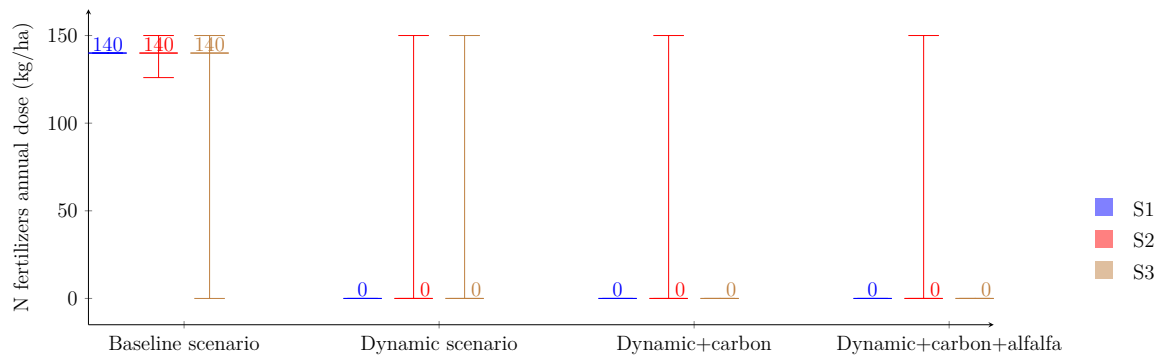


Figure 5.22 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for barley (kg/ha) - for $r=5\%$ and $T=30$. (Source: the author from GAMS simulations)

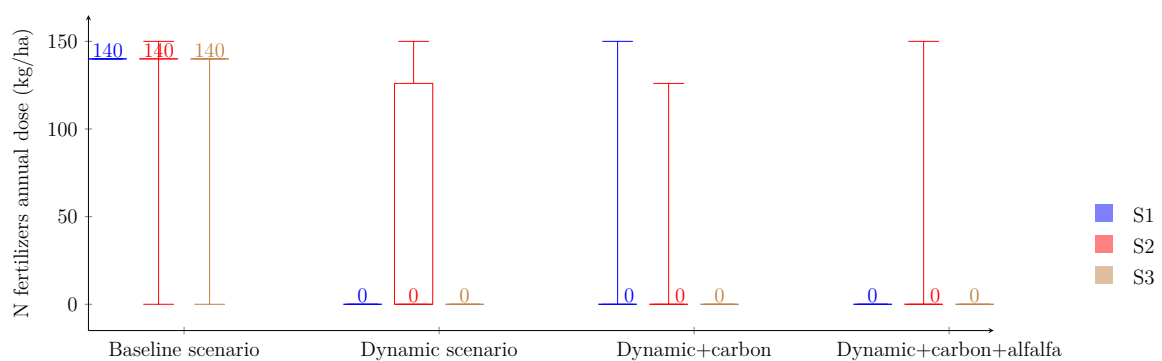


Figure 5.23 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for barley (kg/ha) - for $r=1\%$ and $T=30$. (Source: the author from GAMS simulations)

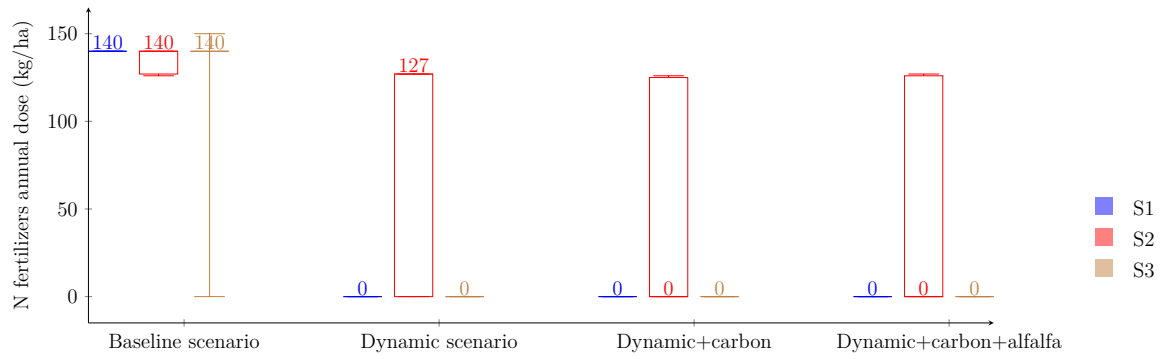


Figure 5.24 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for barley (kg/ha) - for $r=5\%$ and $T=5$. (Source: the author from GAMS simulations)

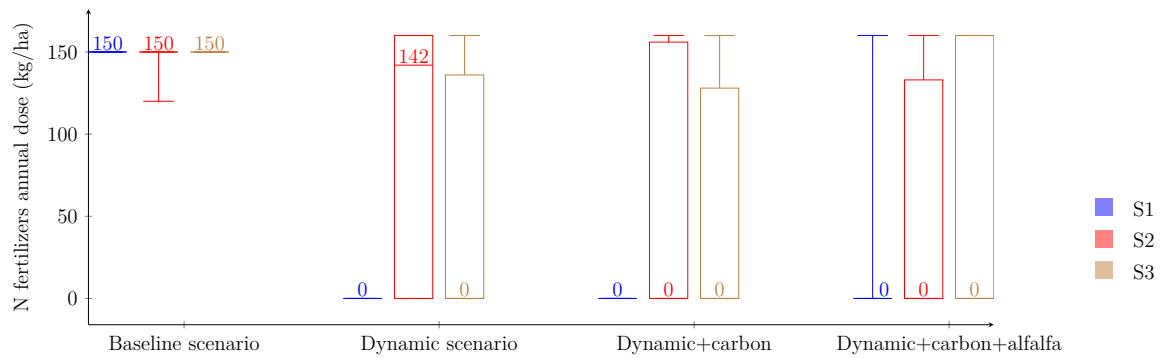


Figure 5.25 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for maize grain (kg/ha) - for $r=5\%$ and $T=30$. (Source: the author from GAMS simulations)

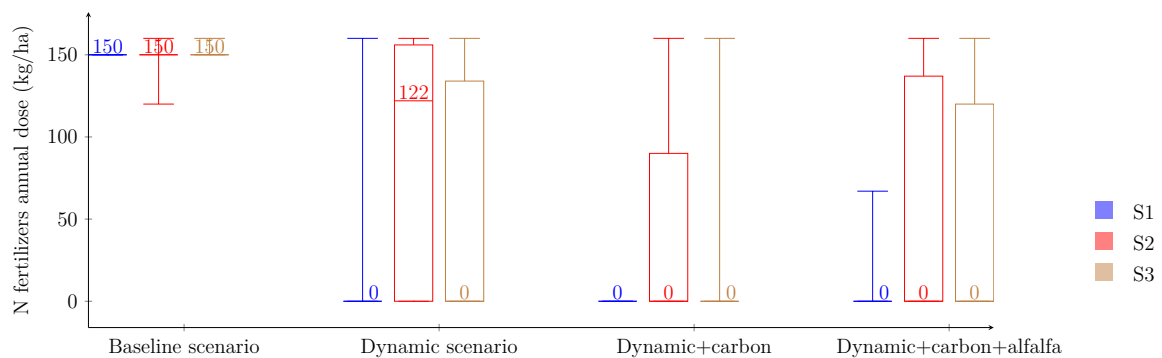


Figure 5.26 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for maize grain (kg/ha) - for $r=1\%$ and $T=30$. (Source: the author from GAMS simulations)

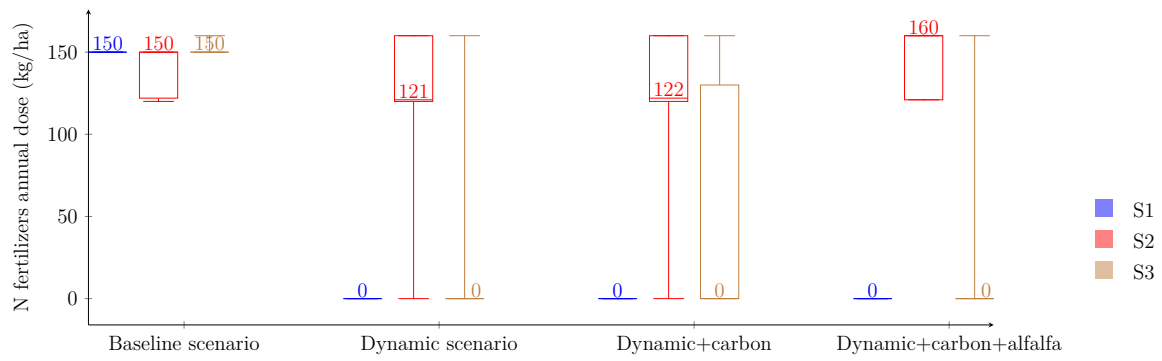


Figure 5.27 – GAMS simulation results - Boxplot and median of the N fertilization optimal strategy over the planning horizon for maize grain (kg/ha) - for $r=5\%$ and $T=5$. (Source: the author from GAMS simulations)

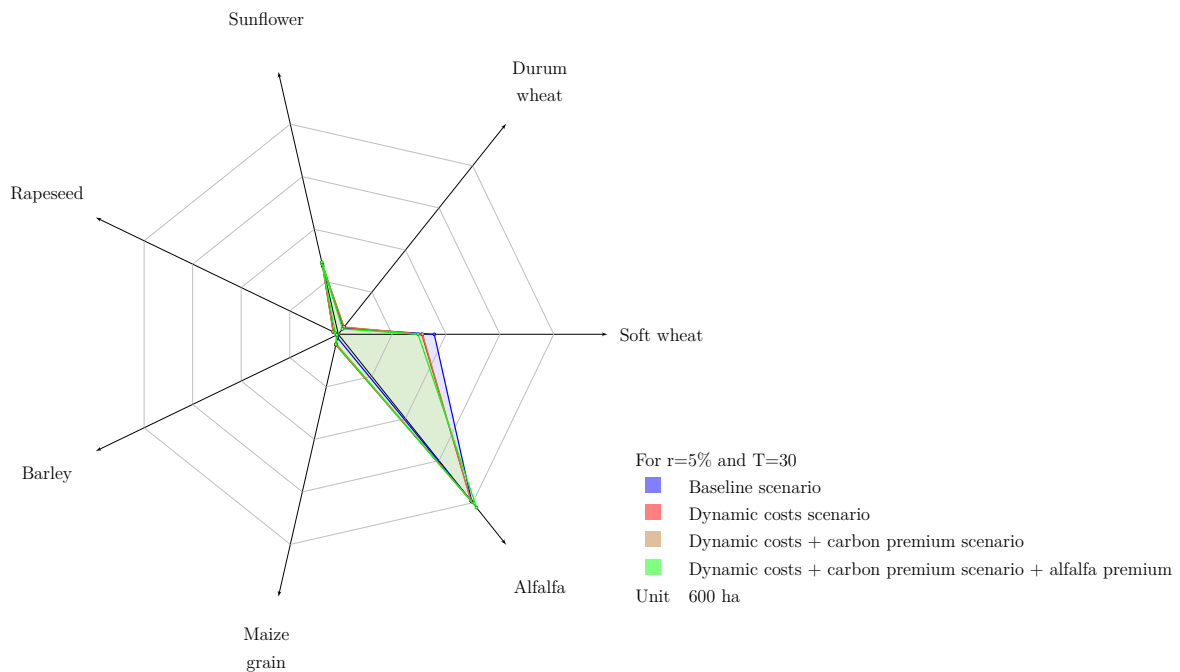


Figure 5.28 – GAMS simulation results - Accumulated surface cultivated for each crop over the planning horizon (ha) - for $r=5\%$ and $T=30$. (Source: the author from GAMS simulations)

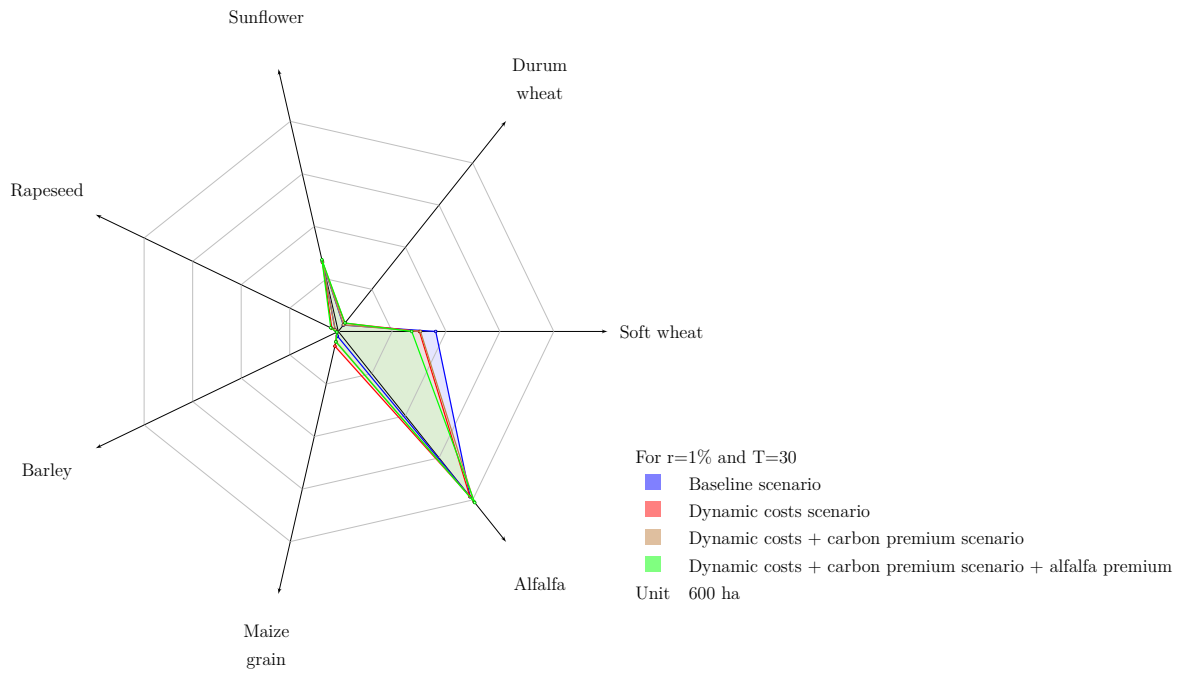


Figure 5.29 – GAMS simulation results - Accumulated surface cultivated for each crop over the planning horizon (ha) - for $r=1\%$ and $T=30$.
(Source: the author from GAMS simulations)

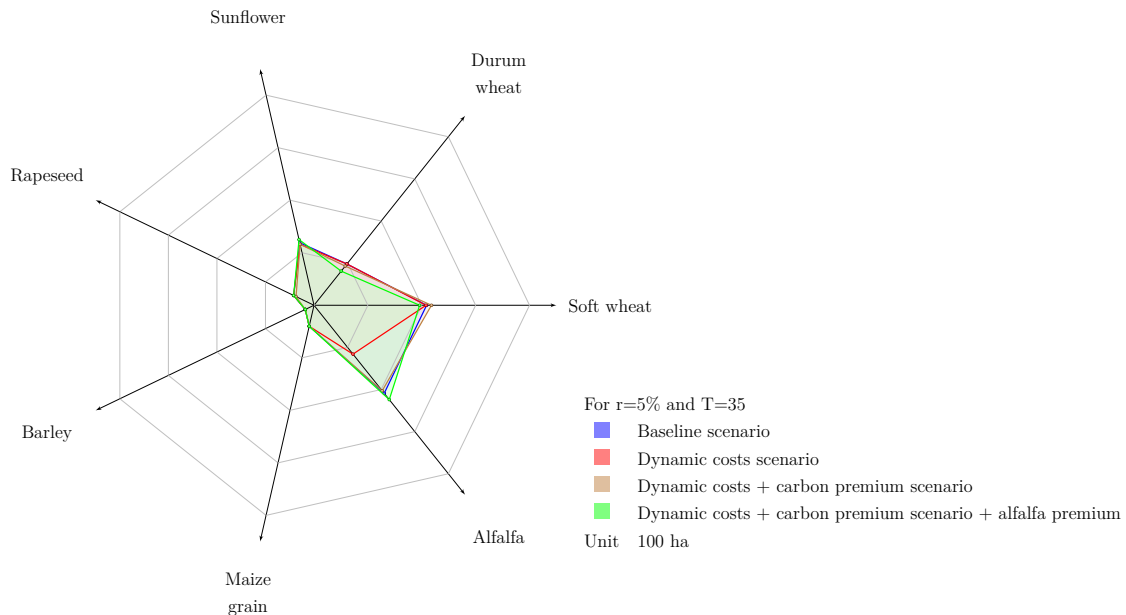


Figure 5.30 – GAMS simulation results - Accumulated surface cultivated for each crop over the planning horizon (ha) - for $r=5\%$ and $T=5$.
(Source: the author from GAMS simulations)

5.8.1.3 Impacts on crop yields

Table 5.29 presents the changes in crop yields throughout the time horizon. It is noticeable that crop yield evolutions are mostly the same in all scenarios. These results are explained by the similar N input strategies and the fairly similar amounts of SOM at the end period of all our scenarios. Actually, the impact of SOM on crop yields is most apparent in the difference between first-period and end-period yields in the same scenario (provided that the level of N fertilization does not vary too much) than in the difference between end-period yields of scenarios having the same N inputs (see Tables 5.24 and 5.25).

From Table 5.29, it appears that the decrease in SOM has a negative impact that differs among crops and soil type. For instance, in the case of soft wheat, for similar (in S1 and S2) and higher (in S3) N fertilization, crop yield decreases by 3.7% in S1, 12.8 % in S2 and 4.8 % in S3. When the decrease in SOM is coupled with a decrease or an absence in N fertilizer, the decrease in crop yield is substantial. However, the decrease in crop yield due to a lack of N fertilization is far more substantial than that caused by a decrease in SOM.

Long rotations scenarii										
scenarii	Soil type	Soft wheat yield (qt/ha) ²⁴	Durum wheat yield (qt/ha)	Barley yield (qt/ha)	Rapeseed yield (qt/ha)	Maize grain yield (qt/ha)	Sunflower yield (qt/ha)			
Base scenario (5%)	S1	79 → 80 → 76	82 → 81 → 78	54 → 53 → 51	22 → 22 → 20	49 → 49 → 44	30 → 25 → 26			
	S2	109 → 106 → 95	88 → 90 → 85	61 → 62 → 58	33 → 23 → 32	79 → 80 → 71	46 → 45 → 32			
	S3	82 → 82 → 78	87 → 89 → 84	61 → 60 → 58	32 → 33 → 31	74 → 73 → 64	41 → 40 → 29			
Dynamic costs scenario (5%)	S1	29 → 79 → 73	36 → 34 → 26	18 → 17 → 12	22 → 22 → 20	28 → 26 → 18	30 → 25 → 22			
	S2	109 → 107 → 33	88 → 64 → 47	62 → 34 → 24	33 → 34 → 31	79 → 80 → 69	46 → 45 → 37			
	S3	82 → 81 → 30	87 → 59 → 43	32 → 30 → 21	32 → 33 → 30	52 → 49 → 31	41 → 40 → 33			
Dynamic costs scenario + carbon price (5%)	S1	29 → 79 → 22	36 → 34 → 26	18 → 17 → 12	22 → 22 → 20	28 → 26 → 18	30 → 9 → 26			
	S2	109 → 107 → 33	88 → 64 → 48	62 → 34 → 24	33 → 34 → 17	79 → 80 → 70	46 → 45 → 37			
	S3	82 → 81 → 30	87 → 59 → 43	32 → 30 → 21	32 → 33 → 30	52 → 49 → 31	41 → 40 → 33			
Dynamic costs scenario + carbon price + alfafa	S1	29 → 79 → 73	36 → 34 → 26	18 → 17 → 12	22 → 22 → 20	28 → 26 → 18	30 → 9 → 6			
	S2	109 → 107 → 90	88 → 64 → 81	62 → 34 → 23	33 → 34 → 31	79 → 80 → 35	46 → 45 → 37			
	S3	82 → 81 → 75	87 → 59 → 43	32 → 30 → 20	32 → 33 → 30	52 → 49 → 31	41 → 40 → 33			
Base scenario (1%)	S1	79 → 80 → 77	82 → 81 → 78	54 → 53 → 51	22 → 22 → 20	49 → 49 → 44	30 → 25 → 26			
	S2	109 → 107 → 95	88 → 90 → 85	61 → 62 → 58	33 → 34 → 32	79 → 80 → 71	46 → 45 → 37			
	S3	82 → 82 → 78	87 → 89 → 83	61 → 60 → 56	32 → 21 → 31	74 → 73 → 65	41 → 40 → 33			
Dynamic costs scenario (1%)	S1	29 → 79 → 73	36 → 34 → 26	18 → 17 → 12	22 → 22 → 20	28 → 26 → 18	30 → 25 → 26			
	S2	109 → 107 → 33	88 → 89 → 48	62 → 34 → 24	33 → 34 → 31	79 → 80 → 69	46 → 45 → 37			
	S3	82 → 81 → 75	87 → 87 → 43	32 → 30 → 21	32 → 33 → 30	52 → 49 → 31	41 → 40 → 33			
Dynamic costs scenario + carbon price (1%)	S1	29 → 79 → 73	36 → 34 → 26	18 → 54 → 12	14 → 13 → 10	28 → 26 → 18	30 → 9 → 6			
	S2	109 → 107 → 90	88 → 64 → 48	62 → 34 → 24	33 → 23 → 17	79 → 54 → 35	46 → 45 → 37			
	S3	82 → 81 → 75	87 → 59 → 43	32 → 30 → 21	32 → 21 → 16	52 → 49 → 31	41 → 40 → 33			
Dynamic costs scenario + carbon price + alfafa	S1	29 → 79 → 73	36 → 34 → 26	18 → 17 → 12	22 → 22 → 20	28 → 26 → 18	30 → 9 → 26			
	S2	109 → 107 → 90	88 → 64 → 47	62 → 34 → 23	33 → 23 → 31	79 → 80 → 35	46 → 45 → 37			
	S3	82 → 81 → 75	87 → 59 → 43	32 → 30 → 20	32 → 33 → 30	52 → 49 → 64	41 → 40 → 33			
Base scenario (5T)	S1	79 → 80	82 → 81	54 → 53	22 → 22	49 → 49	30 → 25			
	S2	109 → 107	88 → 90	62 → 62	33 → 33	79 → 80	46 → 45			
	S3	82 → 82	87 → 87	61 → 60	32 → 33	74 → 73	41 → 40			
Dynamic costs scenario (5T)	S1	29 → 27	36 → 34	18 → 17	22 → 22	28 → 26	30 → 25			
	S2	109 → 107	88 → 90	62 → 34	33 → 34	79 → 80	41 → 45			
	S3	82 → 81	87 → 87	32 → 30	32 → 33	52 → 49	41 → 36			
Dynamic costs scenario + carbon price (5T)	S1	29 → 27	36 → 34	18 → 17	22 → 22	28 → 26	30 → 25			
	S2	109 → 107	88 → 90	61 → 34	33 → 34	79 → 54	41 → 45			
	S3	82 → 81	87 → 87	32 → 30	32 → 33	52 → 71	41 → 36			
Dynamic costs scenario + carbon price + alfafa premium (5T)	S1	29 → 27	36 → 34	18 → 17	22 → 22	28 → 26	30 → 25			
	S2	109 → 107	88 → 87	62 → 34	33 → 34	79 → 80	41 → 45			
	S3	82 → 81	87 → 87	32 → 30	32 → 30	52 → 73	41 → 36			

Table 5.29 – GAMS simulation results - Crop yields at the beginning and at the end of the planning horizon (Long rotations).

(Source: the author from GAMS simulations)

5.8.1.4 Changes in profitability in the different scenarii

The evolution of expected profit throughout the planning horizon is not linear (see Figures 5.31, 5.32, 5.33). These fluctuations are mainly due to crop rotation choices and changes in the total area cultivated. We can observe less variation in long-term optimization with a discount rate of 1 % compared to the one with a discount rate of 5 %, which is expected.

23. The arrows (→) indicate a change in the horizon time. Here, the values are for period 1, 5 and 30 respectively.

Consistent with the annualized objective values per hectare of Tables 5.24 and 5.25, the expected profit curves of the baseline scenario and the alfalfa premium scenario are overall higher than the curves of the other two scenarios. The alfalfa premium more than compensates for the increase in prices, while having no significant impact on farming practices or alfalfa surfaces. This is an illustration of the dead-weight effect.

Actually, the expected profits do not decrease much throughout the planning horizon, and the fluctuation in profits cannot be explained by the linear decreasing SOM curves. Actually, the impact of SOM on crop yields is much lower than the impact of N fertilizers. Hence, the impact of SOM on crop yield is advantageously compensated for by the use of N fertilizers for the most grown crops, as shown by the relatively constant expected profits through time. Actually the fairly constant expected profits across time and scenarios suggest that the increase in input prices as simulated here, following current projections, does not jeopardize the farmer's revenue.

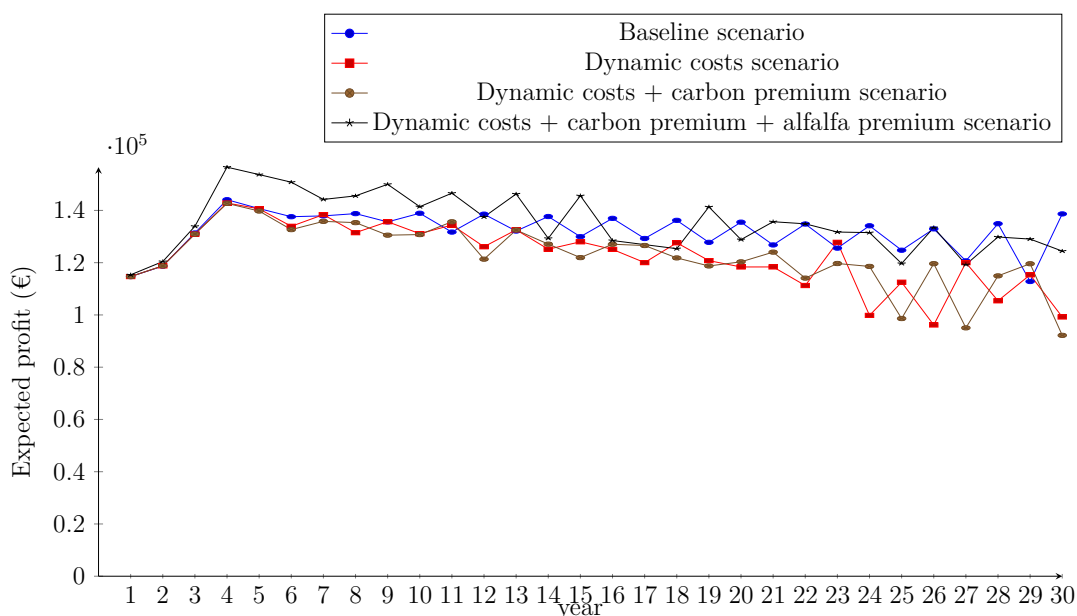


Figure 5.31 – Evolution of expected profits for the different scenarios (Long-term optimization and discount rate 5 %)

(Source: the author from GAMS simulations)

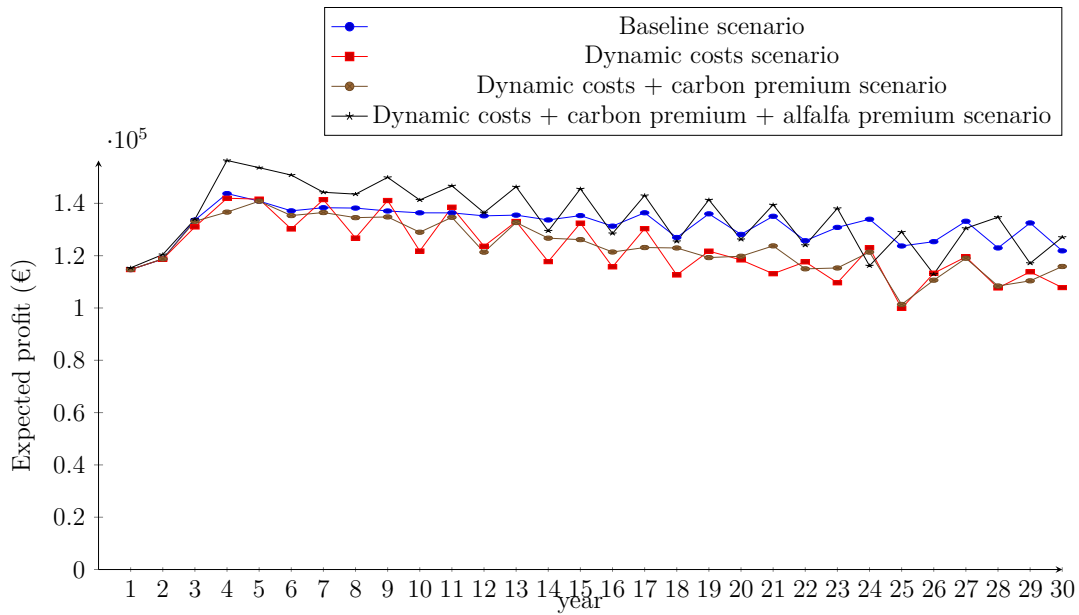


Figure 5.32 – Evolution of expected profits for the different scenarios (Long-term optimization and discount rate 1 %)
 (Source: the author from GAMS simulations)

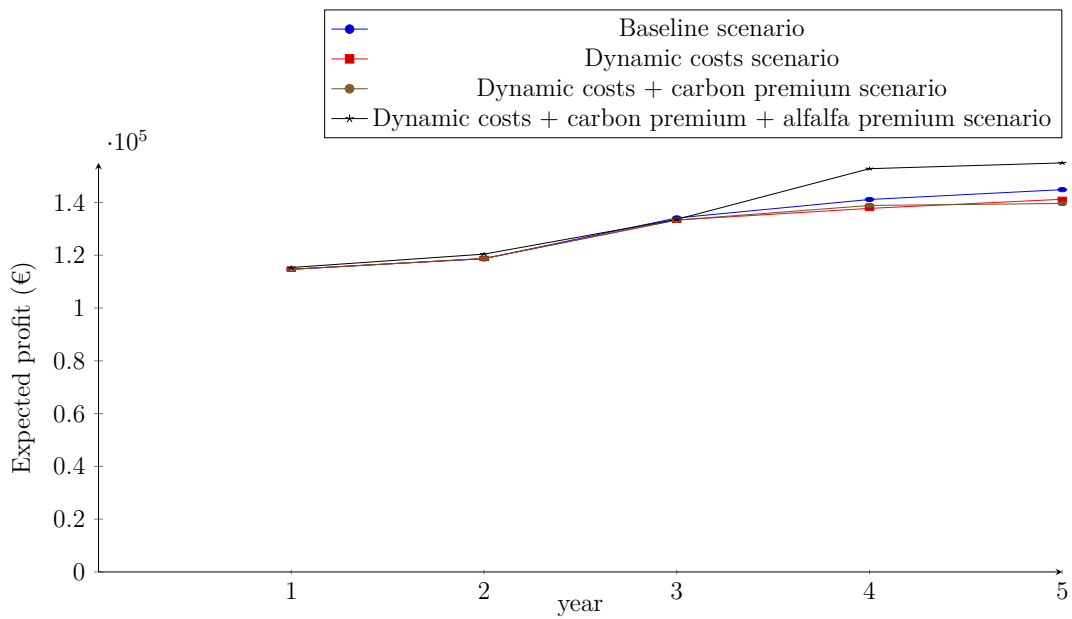


Figure 5.33 – Evolution of expected profits for the different scenarii (Short-term optimization and discount rate 5 %)
 (Source: the author from GAMS simulations)

5.8.2 Tillage intensity choices in the dynamic scenarios: deep tillage in optimal strategies, a counter-intuitive result ?

In all our dynamic scenarios, which have in common a continuous increase in fuel and N fertilizer prices, we observe an important use of deep tillage in the optimal strategies of the farmer. However, one of our hypothesis is that deep tillage is detrimental to numerous aspects of soil quality (auxiliaries, soil structure disturbance). On the contrary, a shallow tillage associated with sound crop residue use and crop rotation is beneficial to soil quality.

Nonetheless, deep tillage is favored in our dynamic scenarios. There are some explanations for what is observed. First, tillage impact on soil quality, in our case SOM, differs depending on soil type and crop. Actually, when looking at our SOM dynamics functions estimated from CropSyst simulations, it appears that depending on soil type and crop, deep tillage can have a positive impact on SOM dynamics. This is the case for soft wheat on S3, and for maize grain, sunflower and rapeseed. In addition, in all our dynamic scenarios, we observe on average a significant decrease in N fertilizers as a reaction to the anticipated increase in N fertilizer prices. Since for numerous crops and soil type N fertilizers and tillage intensity are not cooperating in terms of SOM dynamics, the decrease in N fertilizers can trigger an increase in tillage intensity, in particular in cases where tillage intensity has a small yet positive impact on SOM dynamics.

Hence, in our dynamic scenarios, the farmer invests in his soil quality through tillage, which otherwise only represents an extra cost. Nonetheless, we observe a linear decrease in SOM content in our simulations. One explanation is that the levers in terms of farming practices placed at the disposal of the farmer in our model are not sufficiently efficient in terms of SOM depletion mitigation to trigger an inversion of the SOM dynamics curves, regardless of the scenario considered.

5.8.3 Intensive rotations

In this series of scenarios, there are more changes in the amount of surfaces cropped than in the long rotations counterpart. As a consequence, differences in SOM values are more apparent across scenarios (see Tables 5.29 and 5.27). For instance, SOM content end values for S1 vary from 7.2 g/kg to 11.39 g/kg. For S2, these values range from 15.96 to 24.02 g/kg and for S3 from 12.67 g/kg to 19.9 g/kg. However, changes in SOM concentration at year 30 are due to the decrease in cultivated surfaces. As a consequence, the enhancement in SOM end values compared to the long rotation scenarios

is accompanied by lower profitability.

Actually, with short intensive rotations, the annualized objective value is always lower than for long rotation counterparts. N fertilizer use strategies are similar, although in the baseline case, N fertilizer use is lower than for the long rotations counterpart (the optimal strategies of the farmer imply 0 fertilization). Hence, with short rotation, in the baseline scenario, end amounts of SOM are higher than with less intensive rotations (+ 54.5 %, +41.2 % for S1 and S2, respectively). This is explained by the cropping choice of the farmer. In this scenario, the farmer does not cultivate crops on S1 from period T3 and from period T13 for S2. For parcel S3, which is cultivated entirely throughout the 30 years, the SOM end value in the baseline scenario is similar to that in the long rotation counterpart. In addition, he does not benefit from the variety of revenues induced by the variety of crops grown.

With the increase in input costs, N fertilizer use decreases for rapeseed. In addition, the farmer stops cultivating his S1, S2 and S3 parcels early in the planning horizon in all long-term scenarios compared to the long-rotation counterparts. This explains both high levels of SOM end values and the low annualized objective value. Hence, this is a situation where the farmer no longer cultivates anything and his revenues are derived from the Basic Payment Scheme and avoidance of the carbon tax. Actually, when the carbon price is introduced, the most important change in behavior is in the area cultivated, which decreases earlier than in the other dynamic scenarios.

When the discount rate is equal to 1%, since the farmer values present and future revenues almost equally, the area cultivated decreases less than in the scenarios with a 5 % discount rate. As a consequence, SOM end values are lower in the 1 % discount rate scenarios, except for the alfalfa premium scenario. In addition, N fertilizer use for soft wheat increases, while the N fertilization strategy for rapeseed is more similar between the 1 and 5 % discount rate scenarios.

Actually, it is intriguing that the farmer reacts to the introduction of the alfalfa premium while not having the opportunity to cultivate this crop.

In the short-term scenario, the farmer does not cultivate the S1 parcel, which explains the low fertilization on soft wheat for this soil type. Otherwise, the N fertilization strategy is the same for all scenarios, as is crop residue use and tillage intensity, except for the last alfalfa premium scenario. This explains why SOM end values are the same for the other three scenarios. SOM end values are slightly higher for the S3 soil type in

the alfalfa premium scenario. Actually, in this scenario, the farmer reduces the area of crop cultivated in these parcels.

Short rotations scenarii			
scenarii	Soil type	Soft wheat yield (qt/ha)	Rapeseed yield (qt/ha)
Base scenario (5%)	S1	29 → 27 → 77	22 → 22 → 20
	S2	47 → 44 → 33	24 → 34 → 32
	S3	44 → 42 → 29	22 → 33 → 31
Dynamic costs scenario (5%)	S1	29 → 27 → 21	22 → 22 → 20
	S2	109 → 107 → 33	33 → 32 → 31
	S3	82 → 81 → 29	32 → 32 → 30
Dynamic costs scenario + carbon price (5%)	S1	29 → 27 → 21	22 → 22 → 20
	S2	47 → 45 → 33	24 → 23 → 31
	S3	44 → 42 → 29	22 → 33 → 30
Dynamic costs scenario + carbon price + alfalfa premium (5%)	S1	29 → 27 → 21	22 → 22 → 20
	S2	109 → 107 → 90	33 → 32 → 31
	S3	82 → 81 → 75	32 → 32 → 30
Base scenario (1%)	S1	80 → 80 → 77	22 → 20 → 30
	S2	109 → 107 → 95	33 → 33 → 32
	S3	82 → 82 → 78	32 → 32 → 31
Dynamic costs scenario (1%)	S1	29 → 27 → 21	22 → 22 → 20
	S2	109 → 107 → 33	33 → 32 → 31
	S3	82 → 81 → 30	32 → 32 → 30
Dynamic costs scenario + carbon price (1%)	S1	29 → 27 → 21	14 → 13 → 10
	S2	109 → 107 → 33	33 → 32 → 31
	S3	82 → 81 → 29	32 → 32 → 16
Dynamic costs scenario + carbon price + alfalfa premium (1%)	S1	29 → 27 → 21	22 → 22 → 20
	S2	109 → 107 → 33	33 → 32 → 31
	S3	82 → 81 → 30	32 → 32 → 30
Base scenario (5T)	S1	79 → 27	22 → 22
	S2	109 → 107	33 → 33
	S3	82 → 82	32 → 32
Dynamic costs scenario (5T)	S1	29 → 27	22 → 22
	S2	109 → 107	33 → 32
	S3	82 → 81	32 → 32
Dynamic costs scenario + carbon price (5T)	S1	29 → 27	22 → 22
	S2	109 → 107	33 → 32
	S3	82 → 81	32 → 32
Dynamic costs scenario + carbon price + alfalfa premium (5T)	S1	29 → 27	22 → 22
	S2	109 → 44	33 → 34
	S3	82 → 42	32 → 33

Table 5.30 – GAMS simulations results - Crop yields at the beginning and at the end of the planning horizon (Short rotations).

(Source: the author from GAMS simulations)

5.9 Conclusion

The objective of this chapter was to build an empirical model in order to establish whether adopting an EIA decision making process enables farmers to achieve productive, profitable and sustainable agriculture in a context where fertilizers and energy prices are rising.

22. The arrows (→) indicate a change in the horizon time. Here, the values are for period 1, 5 and 30 respectively.

The case study approach has made it possible to collect a sufficient amount of data to estimate a production function for the main crops grown on the farm and to estimate soil organic matter dynamics functions specific to each of these crops and the main soil types of the farm.

Once the model is designed, different scenarios are proposed in order to test the hypothesis put forward based on the literature review and our theoretical framework and to compare the empirical results with our theoretical results. The baseline scenario is established from the current economic situation, with constant prices and costs applied throughout the planning horizon. The other scenarios are variations of this baseline scenario, with changes in energy price and N fertilizer price, as well as the introduction of a carbon price and an extra alfalfa premium.

Our results show that the use of long rotations and lower levels of N fertilizer as well as residues in most periods leads to an optimum in the dynamic scenarios, where the most common crops are soft wheat, alfalfa and sunflower. The farmer invests in his soil quality through the use of tillage. The different scenarios also have an impact on the cultivated area, which can dramatically decrease, jeopardizing the farmer's revenue. Based on our results, it appears that economic incentives to increase SOM have no significant impact on SOM dynamics and even less in the short term (5 years).

However, SOM stocks decrease linearly in all scenarios, reaching SOM end values for each soil type that are fairly close in all scenarios. This suggests that one cannot hope to significantly increase soil quality by monitoring only N fertilizers, tillage intensity and crop residue use. Such practices do have a role but must be integrated into a larger set of practices to be efficient and thus increase SOM content in soil. Actually, as mentioned earlier in this chapter, the farmer in our case study uses a more effective set of practices to monitor his soil quality. In addition, the economic context is still favorable to the use of N fertilizers as a substitute for SOM in terms of crop production.

In the next chapter, the main results obtained from our theoretical and empirical models are summarized with respect to insights regarding the role of farming practices and soil quality in the profitability, sustainability and productivity of farms. Then, limits, biases and opportunities for further research are provided. In a third part, the role of cooperatives and public policies in orienting farmers toward specific farming practices and encouraging soil carbon sequestration is also discussed, as well as the relevance of such a role.

Chapter 6

Discussion

IN this chapter, we discuss the results, limitations, biases and necessary improvements as well as the implications regarding the public and private incentives for farmers to preserve the quality of their soil. The objective of our discussion is to answer our research question based on the theoretical, statistical and simulation results regarding whether the EIA approach and soil conservation practices are optimal when the farmer maximizes his profit while taking into account soil quality dynamics; the objective is to achieve productive, profitable and sustainable agriculture. We enlarge upon the discussion by developing the role public policies and cooperatives may have in favoring practices that are favorable to both farmers' private interests and the public interest.

To conduct this discussion, first, we restate the purpose of this research, and we show that our results tend to confirm the need to adopt soil conservation practices in order to achieve profitable, sustainable and productive agriculture within a competitive economic context. Then, we present the limitations and bias of our work, and we provide suggestions to improve our study. In the third part, the possible implications of our results in terms of public policy are proposed, and questions are raised relative to the role that cooperatives can play in terms of private incentives that influence farmers' soil quality management.

6.1 Of the interest of adopting an EIA decision making process: theoretical and empirical evidence

In a tense economic context, where agriculture faces both an expected increase in food production demand and food production costs due to an increase in energy prices, it would be reasonable to speculate how French farms would position themselves. The challenge would be to achieve a productive, profitable and sustainable agricultural practice in addition to meeting increasing food demand in a difficult economic context.

The Ecologically Intensive Agriculture (EIA) concept proposes productive and sustainable agriculture based on the use of ecosystem functionalities, such as soil and soil quality (physical, chemical and biological). Soil and soil quality are beneficial factors in crop production. In addition, the use and preservation of soil are private concerns that fall within the sphere of public interest; at the same time, these practices are for the most part privately managed. Thus, soil and soil quality are the focus of this work. Applied to soil resources, the EIA concept and decision-making process can be translated into terms of soil conservation practices.

The objective of this thesis is to determine whether the EIA decision-making process and induced soil conservation practices are part of the optimal strategy of a farmer seeking to maximize his profits while taking into account the dynamics of his soil.

To answer this question, we have applied theoretical, statistical and simulation tools; the results are summarized in the following sections.

6.1.1 Our theoretical results show the importance of the cooperative relationship between soil quality and productive inputs in the farmer soil management choices,...

Our theoretical framework is based on the works of McConnell (1983), Saliba (1985), Smith et al (2000), Hediger (2003) and Yirga and Hassan (2010). The objective of this framework is to present a comprehensive theoretical bioeconomic model where conservation practices are used as decision variables. Endogenous and exogenous soil quality attributes are considered. The impact of soil quality in terms of soil productivity is captured through the relationships between soil attributes and crop yields. Soil quality and management intensity, such as chemical input use, are the two direct crop production factors. We also consider the trade-offs and inter-dependencies between conservation and

productive practices.

In this theoretical framework, where the farmer maximizes his profits under his soil quality dynamics constraint, the sign of the cooperation relationship between soil quality and productive or chemical inputs is undetermined. In some cases, chemical inputs and soil quality are cooperating when the latter is low or in transition from conventional to conservation practices (Smith et al, 2000; Mekuria and Waddington, 2002). Soil quality and chemical inputs can also be non-cooperating when the marginal use of both production factors is no longer beneficial to the farmer. This can also correspond to a situation where soil quality and chemical inputs are substitutes, that is, when soil quality is sufficiently high for the marginal productivity of chemical inputs to be decreasing.

Similarly, the hypothesis for soil quality dynamics is extensively discussed since one practice can have contradictory effects depending on its implementation or the initial soil quality. For instance, tillage is assumed to have both positive and negative impacts on soil quality: Depending on climatic conditions, the season or the initial soil structure, tillage may be recommended (Heddadj et al, 2005), and some systems may require controlled tillage to function (Verhulst et al, 2010), while a high level of organic matter is favored by no or superficial tillage (Barthès et al, 1998).

The complexity of the relationships described in our theoretical framework allows for discussion of the conditions leading to an optimum or to corner solutions. However, the existence of an equilibrium cannot be determined or discussed.

For this reason, soil quality investment models are proposed. In these simplified models, there are two production factors: a productive input and soil quality. Conservation measures are encompassed in a single variable that represents investments in soil quality. We consider two cases: one where the productive input does not impact soil quality dynamics and one where the productive input impacts soil quality dynamics negatively. We chose not to simplify the hypothesis regarding the cooperation relationship between productive inputs and soil quality. We explore both the hypothesis of cooperating inputs and the hypothesis of non-cooperating inputs.

We show that when productive inputs do not impact soil quality, there always exists an equilibrium. Depending on the initial soil quality, the farmer may have to increase or decrease his soil quality to maintain it at an optimal level and to avoid over- or under-investment in soil quality. Hence, even when ignoring the detrimental impacts of his practices on soil quality, the farmer has private incentives to maintain soil quality at a

level where he can sustain his crop production activity at a stable level. However, when not considering the impact of productive inputs on soil quality, the farmer over-estimates his soil quality level, and his optimal level of investment is actually an under-investment in soil quality.

The mis-evaluation of the detrimental impacts of productive inputs on soil quality by the farmer can be addressed by corrective public policies. From our comparative statics, several instruments may be used to increase optimal soil quality level depending on the cooperation relationship between production factors. When soil quality and productive inputs are cooperating, the public authorities can, for instance, subsidize the investment in soil quality to increase optimal soil quality. However, it would also increase the use of productive inputs, which may have negative externalities such as diffuse pollution. In the case where production factors are not cooperating, two public instruments could be coupled to increase the soil quality optimal level: a tax on productive inputs and a subsidy for soil quality investment. Since these two instruments would trigger the same effect, that is, an increase in soil quality and a decrease in productive input use, one can expect that when implementing both instruments, a positive snow-ball effect could be triggered.

In the more complex and realistic case, the farmer acknowledges in his maximization problem that productive inputs negatively impact soil quality. Here, we show the importance of considering the cooperation relationship between soil quality and productive inputs in the determination of the equilibrium. An equilibrium can be analytically found when soil quality and productive inputs are cooperating *and* when the marginal cooperating productivity of these two inputs is higher than the marginal damages of productive inputs on soil quality. In this case, the optimal strategies are similar to the simpler case. Otherwise, one cannot come to a conclusion about the existence of an equilibrium. Either a stable (steady-state) equilibrium is reached, or the optimal strategies depart from an unstable node or from the center of an unstable spiral, so that the system is not converging toward the steady state.

The unstable path can correspond to a situation where the price ratio is such that there is a total depletion of soil quality. The soil resource being both a support to and a factor in agricultural production, it is an unsustainable path. It can also correspond to an infinite increase in crop production with no chemical inputs. Although an infinite increase is unrealistic, this trajectory can be interpreted as a transition toward permaculture, which corresponds to a sustainable path. Furthermore, the unstable equilibrium can also be considered as a limit case between trajectories that converge toward stable equilibria.

Hence, the cooperation relationship between productive inputs and soil quality has an impact on the existence of an equilibrium and on how the equilibrium may change with changes in crop prices and production factor costs. However, whether production factors are cooperating is an empirical issue. It depends on various conditions, such as initial soil quality or climatic conditions. To determine the nature of the relationship between crop production factors, we use statistical analysis tools applied to the specific case of the Grand Ouest.

6.1.2 ... relationship that can differ depending on productive inputs and crops, as demonstrated in our statistical results.

The objective of this statistical analysis is to establish the situation of crop production in the Grand Ouest with respect to the cooperation relationship between soil quality and productive inputs. In addition, we also attempt to evaluate the hypothesis of our theoretical framework relative to the impact of farming practices on soil quality dynamics with empirical data.

To achieve this goal, we have used different public databases related to soil quality, farming practices and crop yields. Due to data availability, we had to limit the farming practices to mineral nitrogen and phosphorus fertilizer inputs as well as tillage practices. Soil quality dynamics is captured through soil pH, soil total nitrogen and soil organic carbon (SOC). For crop production function regressions, two crops grown in the Grand Ouest of France are considered: soft wheat and maize grain.

The productive input considered in the SOC changes regression is N fertilizer use. Consistent with our theoretical investment model, an increase in N fertilizers has a significant negative impact on SOC changes. Unexpectedly, at the cantonal level, an increase in the proportion of tilled surface is positively and significantly correlated with an increase in the cantonal median level of SOC. It may be the case that the tilled surfaces were once meadows and have been brought back into crop rotation, which would explain the positive correlation.

Regression results regarding pH dynamics are less significant since farming practices likely to have a substantial impact on soil pH, such as liming, are not considered.

Results obtained for crop yield regressions at the regional level are interesting when investigating the cooperation relationship between production factors. For soft wheat, as expected, SOC and N fertilizer inputs have a positive and significant impact on crop

yield. However, the cross impact of SOC and N fertilizer inputs is significantly negative: N fertilizer inputs and SOC are not cooperating. The impact of SOC on maize grain yield is not significant, while N inputs have a positive significant impact on yield. In this case as well, SOC and N fertilizers are not cooperating in terms of production.

Although N fertilizer inputs (productive inputs in our theoretical model) negatively impact SOC, they are not cooperating with SOC in terms of crop production. According to the theoretical results of our comparative statics, the expected increase in fertilizer prices would lead to a decrease in N fertilizer use and an increase in investment in soil quality, thus increasing soil quality.

In such a case, the expected increase in inputs price is favorable to climate change mitigation: Actually, two groups of actions leading to a decrease in GHG emissions are relative to the decrease in mineral N fertilizers and carbon sequestration (Pellerin et al, 2013). Even if the optimal level of SOM from a private perspective does not match the socially desirable level defined in the “4/1000” initiative, we have seen from our theoretical comparative statics that policies aiming at encouraging investment in soil quality or discouraging mineral N fertilizer use trigger a positive snowball effect whereby the increase in soil quality (here SOM) leads to a decrease in N fertilizer use.

Such results set favorable conditions for the adoption of the EIA decision-making process. Increased use of N fertilizer inputs negatively impacts SOC dynamics. In addition, these two production factors are not cooperating. Hence, substituting soil quality and SOC for N fertilizers, that is, substituting ecosystemic functionalities for chemical inputs, appears to be a means of coping with the expected increase in energy and fertilizer prices. However, here, we do not consider the investment costs in soil quality.

We further propose empirical dynamic bioeconomic modelling based on a study case located in the Grand Ouest (Vienne department). From this model, we simulate different economic scenarios in order to determine the impact of energy and fuel prices on farming practice choices, soil quality investment and soil quality dynamics. The objective is to determine whether the EIA decision-making process is part of the optimal strategy of a profit-maximizing farmer in a realistic scenario.

6.1.3 These theoretical and statistical results are tempered in our simulations

We propose an empirical bioeconomic model based on the theoretical framework and informed by the statistical results regarding the elements to take into account in the analysis of trade-offs between the short-term objective of profitability and productivity and the long-term objective of sustainability.

The inter-temporal model allows us to simulate long-term strategy in terms of farming practice choices when the farmer maximizes his profits in the long-term while taking into account the dynamics of his soil quality. The objective is to determine whether this long-term strategy corresponds to the EIA concept, that is, a strategy where the farmer copes with increases in the price of fertilizers and energy by investing in his soil ecosystem functionalities, here captured by the SOC content.

Our empirical model has all the features of a comprehensive farm-level soil quality model, as suggested by Saliba (1985): It is a dynamic model with recursive features that takes into account the impact of farm management choices (regarding chemical inputs, tillage intensity, crop rotation and crop residue) on soil quality characteristics (SOC) and includes a crop yield function incorporating soil attributes and determinants (SOC in an explicit manner and climate characteristics implicitly), substitution possibilities (between fertilizer inputs and SOC) and management variables (fertilizer inputs).

The model is calibrated on a crop farm located in the southern part of the Grand Ouest region in the Vienne department. The farmer has been involved in conservation practices since the 1990s. We used his fertilization records and his statements and those of his farming counselor in order to reproduce his farming practices in CropSyst, a biological simulation model. We also had access to a soil analysis of three parcels, representative of the three main soil types present in the farm. We use CropSyst to simulate and estimate crop production functions and soil organic matter dynamics function, which are specific to each soil type and the main crops grown on the farm. CropSyst parameters are calibrated using the real data of the farmer. The functions obtained from the regressions of the simulations on CropSyst are validated using the real data of the farmer.

Four scenarios are simulated: (1) a baseline scenario where prices and costs are constant throughout the planning horizon; (2) a dynamic cost scenario where N fertilizers and fuel prices increase annually by 1.5 % and 2 %, respectively; (3) a dynamic cost scenario where, in addition to the increase in N fertilizer and fuel prices, a carbon

bonus/malus is introduced in the first period, indexed on the variation in SOM between years with an annual increase; (4) a dynamic cost scenario based on the same assumptions as in the third scenario in addition to a doubled premium in alfalfa surfaces. These scenarios are based on different situations (long term, short term (5 years), 5% and 1 % discount rates, long rotations or short rotations).

The functions simulated on CropSyst show similar features to our statistical results: Soil organic matter and N fertilizers are non-cooperative production factors, and tillage intensity has an impact on SOC changes that can be positive or negative according to crops and soil type. Hence, according to our theoretical results, our dynamic scenarios present a favorable situation for decreased use of N fertilizers and increased investment in soil quality. Hopefully, such an increase in soil quality investment should allow the farmer to attain and maintain an optimal level of SOC.

As expected, a dynamic increase in fertilizers and energy prices leads to a decrease in the N fertilization use strategy of the farmer. In addition, the farmer invests in the quality of his soil through the implementation of deep tillage. However, in every scenario, we observe the same decreasing trend in SOM content throughout the planning horizon. This SOM depletion is not impacted by the farmer's changes in practice. Public policy instruments such as the carbon premium or the alfalfa premium fail to mitigate the decrease in SOM content. Our simulation results suggest that it is optimal for the farmer to invest in soil quality, which corresponds to what is advocated by EIA. However, in our case, when considering the farming practice options available to the farmer, such investment is simply not enough to maintain SOC content, which linearly decreases. Although the farmer is able to maintain his profits at a 30-year horizon, such a continuous decrease in SOM does not seem sustainable over the longer term.

Actually, our empirical model seems to provide fewer insights into optimal strategies or changes in equilibrium due to changes in the economic context than our theoretical model does. It may be that in our empirical model, we investigate the existence of an equilibrium and optimal strategies in the specific case where productive inputs negatively impact soil quality dynamics while not cooperating with soil quality in terms of crop production. Hence, our empirical model illustrates one of the many cases discussed theoretically. In this case, given the particular features of our empirical model, the locally optimal equilibrium found leads to low levels of SOM in spite of the investment made by the farmer.

In fact, it might illustrate a case where the farmer, although acknowledging the

impacts of his farming practices on soil quality, does not manage to increase his soil quality because he does not master the necessary farming practices. Indeed, conservation practices involve a complex articulation of various farming practices that have to be adapted to the climatic and soil context of each parcel. This can also explain why in such a case economic instruments do not impact the farmer's strategy.

In the sensitivity analysis of our model, based on extreme scenarios where the economic features of the model are highly favorable to high levels of SOM, the levels of SOM always exhibit a decreasing trend. This could be due to the lack of terminal conditions in our intertemporal setting: In this case, the farmer would have an interest in using all his soil quality productivity potential within the planning horizon. However, using a negative discount rate - that is, end-value profits are more important in the maximization program than current profits - does not shift SOM end values upward, while the strategy in terms of tillage intensity and residue use is similar throughout the dynamic scenario. This suggests that a limitation of our model is the calibration of an exemplary farm and farming practices are modeled that are not sufficiently contrasted with regards to their impact on SOM dynamics.

Hence, from our empirical modeling, it seems that the issue at stake is not to give the farmer incentives to change his practices and invest in his soil but rather to make him more efficient in his investment in soil quality, for instance, by integrating practices more favorable to soil quality than those modeled here. Hence, it is the quality of the learning and technical support offered to the farmers that seems to be at stake here.

Although there are some limitations and biases in our study, which are presented in the next part, such results prompt interesting discussions of how private and public interest may converge in terms of soil organic matter management and, more generally, soil quality management. These discussions are presented in more detail in the third part of this chapter.

6.2 A theoretical framework and a dynamic study case that clarify the main issues, with a lot of leads to pursue

Our theoretical and empirical models make it possible to clarify and study the role of the soil resource in the profitability and sustainability of farms. We have shown that investment in soil quality is theoretically a lever with which the farmer is able to react and adapt to economic changes such as fertilizer price and fuel price increases. However,

empirically, investments in SOM are not sufficient to mitigate the diminution of SOM in soil. However, our model has certain limitations, which are the subject of this section.

Further analysis would require taking into account other important issues, such as the integration of a wider range of farming practices and soil quality indicators in addition to risk and uncertainty as well as technical change. Another limitation is the analysis scale. The analysis is made from the farmer's point of view, without taking into account group effects and their consequences in the economic context. We also discuss the extent to which our model and the results are transferable.

6.2.1 Of the difficulty of considering the multiple aspects of soil quality and the variety of farming practices, ...

In our theoretical model, soil quality is represented by a unique variable that encompasses the physical, chemical and biological aspects of soil quality. However, a unique indicator of soil quality is used in an empirical model at the risk of not being able to disentangle the impacts of the respective farming practices on specific elements of soil quality (such as soil fauna and flora, microbiological activity, SOM, and structure).

When investigating from a statistical standpoint the relationship between farming practices, soil quality and crop yield, we have been confronted by limitations in the data. While our financial partners may have been able to grant access to a comprehensive database on various farming practice, economic, production and soil analysis data, this is not possible at this point. As a consequence, we used public databases that were not uniform in terms of time scale or geographic scale, such as BDAT, which offers soil data at the regional, departmental and cantonal scale over a 5-year period of time; annual agricultural statistics, which offer production data at the departmental scale for each year; and farming practice surveys, which are conducted every 5 years. Using secondary data also reduces the number of farming practices considered as well as the number of soil quality parameters studied.

We faced the same limitations in our empirical model. The soil analysis performed by the farmers in our study case is typical soil analysis, from which we have obtained data related to soil texture, SOM, soil pH and total N soil. These are quite well-known indicators of the physical qualities of a soil. The biophysical software used to estimate the production functions and SOM dynamics functions limited the farming practices considered to crop rotation, N fertilizer inputs, tillage intensity and residue use. It is

likely that the insensitivity of our model to changes in prices and costs in terms of SOM dynamics is due to the restrained range of the impacts of farming practices in our model. The use of at least one additional farm with a low level of SOM to calibrate and simulate our SOM dynamics functions may have reduced this bias.

The lack of access to specific data is an issue that is recurrently faced in empirical economic studies related to soil resource management (Barbier, 1998), as in the case of Magrath and Arens, 1989; Bandara et al, 2001; Schreinemachers, 2006; and Yirga and Hassan, 2010. In some cases, the data are unavailable because they have not been collected in the first place. In other cases, the data exist but are not shared (see Annex 3 and 4). Actually, while data are increasingly captured and stored through the use of decision-support tools, captors, and other numerical tools, specific data are not readily shared by the organizations that own the data. Of course, the data we are interested in must be geographical and attached to an individual, while data related to farming practices, soil quality parameters and economic indicators and such must be processed carefully. Actually, the value of such data is well acknowledged by private and commercial companies (Terrier, 2011), and most data are considered strategic. Even in the case of a multi-partner research project, sharing data might not be perceived as strategic - it can be costly in terms of data extraction and compilation - when the other partners do not seem willing to share their data as well.

In the current context, the use of other soil quality indicators, such as biological ones, would require either existing long-term field data or a specific protocol designed to obtain such data. This would have been unnecessarily time consuming and would have required the expertise of biologists or soil specialists, which is beyond the scope of this study. This calls for future collaboration between different disciplines in order to respond more precisely to the issues faced. For instance, there is a software that models worm population dynamics named WORMDYN. It is still subject to certain improvements and does not directly link farming practices to worm population dynamics (Pelosi et al, 2008). However, we can imagine a protocol where we first determine the impact of tillage and crop residue use on soil temperature and humidity, two factors that impact worm population dynamics (Pelosi et al, 2008). This software is designed for ecologists, agronomists and biologists.

In addition, our simulations are performed for a crop production system where additions are either vegetal (crop residues) or mineral (mineral N fertilizers). An extension to this work would be to consider organic inputs, for example, livestock manure, which is recognized by CropSyst. Since this is not part of the current fertilization strategy of

the farmer in our study case, we did not consider it in the present simulations.

A more general limit of the soil quality function proposed here is related to the use of continuous variables, when discrete variables would be more consistent with actual practice, in particular with respect to tillage. Although the use of continuous variables is required when considering a continuous optimal control model, such simplifications do not accurately reflect tillage practices and their impacts (Smith et al, 2000).

6.2.2 ... where other aspects of the problem would also be important to take into account: risk and uncertainty...

The theoretical and empirical models presented and discussed previously are deterministic models, where risk and uncertainty are not considered. This omission allows us to focus on the trade-offs and relationships between farming practices, soil quality and crop yields in a soil optimal control framework (Issanchou, 2014). It would have been very interesting to include it at least in our empirical model, which due to time constraints we were not able to do.

However, uncertainty plays a particularly important role in agriculture (Boussard, 1987; Moschini and Hennessy, 2001). For the agricultural producer, four sources of uncertainty can be enumerated: (1) production uncertainty, as the production function depends on uncontrollable elements such as weather conditions (Boussard, 1987; Moschini and Hennessy, 2001), and this takes place over relatively long production lags (Moschini and Hennessy, 2001); (2) price uncertainty due to time lags between production decisions, final product realization and the actual price paid for this product, to which must be added the inherent volatility of agricultural markets, which is an issue particularly relevant for outputs destined for the export market (Boussard, 1987; Moschini and Hennessy, 2001); (3) technological uncertainty, which is relative to the evolution of production techniques that can make obsolete quasi-fixed past investments and is a process carried out not by farmers but by other players in the sector; thus, farmers can be seen as captive players in the process (Moschini and Hennessy, 2001) - although technology can also be a source of yield growth (Smith et al, 2000); and (4) policy uncertainty, in the sense that policy can impact taxes, interest rates, exchange rates, and regulations, and is likely to change, in particular in areas where agricultural support is both strong and subject to criticism, as is the case in the European Union (Moschini and Hennessy, 2001).

Typically, risk and uncertainty are distinguished (Issanchou, 2014). Risk refers to

the law of probability of different outcomes of a given action. On the contrary, uncertainty refers to a situation where the information available is so scarce that it is not possible to assign probability to the possible results (Boussard, 1987). As noted by Boussard (1987), it is difficult to estimate probability in most cases; however, without the possibility of approximating uncertainty using probabilities, the possibilities for economic investigation are drastically reduced. As a consequence, numerous uncertain situations are treated as risky situations.

There are three main methods that make it possible to include risk in an agent decision-making process (Boussard, 1987; Li, Qian and Fu, 2003; Zhou, 2003; Ziemba and Vickson, 2014): the expected utility approach, the mean-variance approach and the safety-first approach. We would have used the mean-variance approach, which explicitly describes the trade-off between expected revenue and risk. With this approach, the economic agent maximizes his revenues minus a measure of risk, which is multiplied by a risk aversion coefficient.

Hence, it appears that risk and uncertainty are also important aspects to take into account when analyzing best management practices (Saliba, 1985). When considering changes in agricultural practices, risk is also related to variation in benefits or costs and the effectiveness of the practice as well as the uncertainty regarding when the benefits might be realized (Reimer, Weinkauff and Prokopy, 2012). It is a risk linked to a given practice, not the farmer's risk attitude, which does not seem to have a significant impact on technology adoption (Baumgart-Getz, Prokopy and Floress, 2012).

6.2.3 ... but also technical change...

Technical change is an important aspect of the analysis of the relationship between farming practices and soil quality dynamics (Issanchou, 2014). Indeed, technical change and progress is an important feature of agriculture: It is at the source of what is referred to as conventional agriculture and plays a consequent role in terms of competitiveness (Chevassus-au-Louis and Griffon, 2008). In addition, according to Taylor and Young (1985), technical progress strengthens the long-run payoff of conservation tillage. However, one could consider that if technical progress has a positive impact on yield, it can mitigate a decrease in soil quality. It thus appears to be a particularly interesting aspect of our analysis. Technical change is taken into account in McConnell (1990) and Smith et al (2000). In McConnell (1990), technical change is considered neutral with respect to soil quality, although it is observed that technical change is likely to have a positive

impact on soil erosion. Similarly, Smith et al (2000) include a technology yield growth rate, capturing the effect of new technologies on productivity.

Moreover, the role of technical change and innovation is important in the adoption of conservation agriculture: According to Lahmar (2010), the lack of dynamic and effective innovation systems in Europe is a source of socio-economical risk for European farmers when considering a change in practices.

6.2.4 ... in addition to an approach that only considers the optimal choices of one farmer for which transferability ?

The approach chosen in this study is at the farmer level and is based on a microeconomic approach. In fact, it is the farmer's decision-making process that is studied here, in addition to the levers that can be used by the farmer to manage soil quality. The objective here is to determine whether soil conservation practices are the farming practices implemented by a farmer when he maximizes his profit over time while taking into account soil quality dynamics.

Although consistent with the issue addressed, the microeconomic approach we propose assumes that the farmer's choices do not have an impact on the economic context, which is true at this scale. However, such optimal behavior would likely be adopted by all farmers since it allows them to maximize their profit.

However, in our model, agent interactions and their impact on the economic environment are not taken into account. Considering such interactions may change the optimal strategies, such as crop choices, through the likely impact on crop prices. For instance, in most of our dynamic scenarios, rather early in the planning horizon, there are three crops present in the rotation, soft wheat, sunflower and alfalfa. If all farmers were to only cultivate these crops, the prices of the other crops would rise, making them more attractive and prompting a change in the farmer's crop rotation strategy.

Agent-based simulation (ABS) models could be considered in order to address such issues. The ABS model "is a computerized simulation of a number of decision-makers (agents) and institutions, which interact through prescribed rules" (Farmer and Foley, 2009). In such models, a microeconomic approach can be used while allowing agents to interact within a dynamic environment and change their behavior in response to the changes of others (An, 2012).

In our empirical model, the crop production functions and SOM dynamics functions are estimated from data specific to our study case. Nonetheless, the functions used and the results obtained in our model in terms of fertilization are not as precise as the short-term simulation tools used by farming advisors. For now, the objective of the model is not designed to provide personalized and precise recommendations in terms of fertilization strategy but rather to establish optimal long-term strategies or to simulate individual reactions to changes in public policies.

Hence, the results obtained are transferable to every farm where common crops are grown, with soil types that are similar to those studied here (loam soils, clay-limestone soils and clay-silt soils). Although based on a crop farm, the reasoning can be applied to any farm where agricultural surfaces are allocated to crops.

In this part, we have discussed the main limits and bias of our theoretical and empirical works and provided possibilities for future improvements. In the next part, the results of our theoretical and empirical model are discussed in terms of private and public incentives that might be designed to induce farmers to conserve their soil quality, provided that it is socially desirable.

6.3 Private and public interest in terms of soil quality management can be converging...

Although soil quality management is studied in this thesis from a private farmer-agent perspective, soil quality conservation issues are also of public interest. Therefore, we simulated three policy options in our dynamic empirical scenario: laissez-faire, the polluter-payer principle and subsidization.

In this part, we discuss the possible implications of our theoretical and empirical results in terms of public policies and farming counseling, whether this counseling is provided by public or private entities. First, we review the extent to which soil can be related to public good issues, the justification for public policies and the role counseling may have in such issues. Then, we discuss the relevance of the different public policy options tested in our simulations and the implications in terms of policy instrument implementation. Finally, we discuss the advisory role cooperatives can play in the conservation of soil resources.

6.3.1 Soil, a common resource mainly managed by private agents: the role of public policies and counseling

Soil quality changes can be related to public good issues, as they represent the negative externalities or off-site impacts (McConnell, 1983; Barbier, 1998). Soil degradation can have downstream and off-site impacts such as reservoir sedimentation, losses to navigation, and irregular flow of irrigation and can impact agricultural, fishing and industrial production, water supply and drought and flood cycles (Barbier, 1998). Indeed, there is an important connection between soil and water quality (McConnell, 1983; Letey et al, 2003), and in some definitions of soil quality, the role of soil in maintaining or enhancing water quality is noted (Letey et al, 2003).

Hence, there can be a justification for public policy that addresses soil degradation issues in cases where soil degradation leads to significant pollution externalities (in particular with respect to water quality). This explains why McConnell (1983) studies the possible difference between social and private paths of erosion. The study conducted by Louhichi et al (1999) regarding the impact of water and soil conservation policies should also be mentioned.

In addition, the soil resource has a potential role in climate change mitigation in a context where 20% of GHG emissions are of agricultural origin. It explains the growing public interest in the soil resource, as illustrated by the 4/1000 Initiative. However, it is mainly managed by private agents such as farmers. The EIA concept can be a way to reconcile agricultural profitability and productivity and environmental preservation, as shown throughout this report. We have shown that farmers have a private interest in investing in soil quality when facing an expected increase in fertilizer and energy prices, although this investment is not enough to maintain SOM, the proxy of soil quality used, at a steady level.

However, the analysis of the adoption of EIA practices and the changes in farming practices they imply can hardly be reduced to a perfect information profit maximizing criterion. They are also related to social and anthropological aspects (Jansenn and van Ittersum, 2007), in particular regarding the learning process (Anastasiadis, 2013). Saliba (1985) mentions the importance of farmers' perceptions and beliefs regarding the decision to adopt soil conservation measures based on their perception of soil erosion impacts on crop yield. These beliefs and perceptions can be influenced by social and public awareness (Hanna, Mullainathan and Schwartzstein, 2014).

According to Hanna et al (2014), when using a (new) technology, farmers may fail to learn because of a failure to notice the important features of the data at their disposal. Actually, there are such a large number of dimensions to take into account (in particular, technical aspects) that some of them are ignored by farmers, so that they fail to optimize them (Hanna et al, 2014). Hence, observed behavior can be different than the behavior predicted in a perfect information setting (Issanchou, 2014).

Farm counseling can play a role in the adoption of new concepts and technologies, for instance, by communicating successful examples of soil conservation practices implementation in the case we are interested in or by organizing training programs. Such initiatives already exist, but they could be expanded and have a more strategic and targeted purpose. This can be placed in the context of a more general political orientation that combines public policy instruments and more pedagogical initiatives in public or private farm counseling entities.

6.3.2 Policy instruments simulations results: what consequences for public incentives and policies in the management of this common resources ?

The simulation results reflect three different policy instruments applied to our dynamic scenario: laissez-faire, polluter-payer (carbon bonus/malus) and subsidy (alfalfa doubled premium). Among these three scenarios, there is no significant difference between end values of SOM in the three soil types. The annualized objective value is similar between the laissez-faire and the polluter payer scenario and slightly higher for the third scenario (polluter-payer and alfalfa subsidy scenario). In addition, the strategies in terms of crop rotation and N fertilization are not significantly impacted by the different scenarios. Hence, in our simulations, policy instruments are inefficient.

In the polluter-payer scenario, the carbon price attributed to the changes in SOM in g/kg of soil is based on the current carbon price and the evolution of carbon prices as planned in the French law. In our model, at its maximum price (around 200€ t eq CO₂), the farmer pays a penalty of 50€ over a year, for all farms and surfaces considered. The cost of SOM loss is negligible compared to the annualized objective value per hectare of the farmer. In addition, we only consider one aspect of GHG emissions mitigation, which is carbon sequestration. This can explain the inefficiency of this measure. This result calls into question the position and integration of farms and agriculture in the carbon market, in particular regarding carbon sequestration.

Currently, this carbon price is applied to specific sectors, such as the electric and energy sectors, and carbon taxation is used to target CO₂ emissions rather than rewarding carbon sequestration. Furthermore, the agricultural sector is excluded from this carbon taxation (Elbeze and de Perthuis, 2011).

One of the difficulties of setting a carbon tax in the agricultural sector is the diffuse nature of CO₂ emissions (Elbeze and de Perthuis, 2011) and the difficulty of controlling the farmers (De Cara and Vermont, 2014). However, there is the potential for GHG attenuation in the agricultural sector through carbon sequestration and N fertilizer use (Pellerin, Bamière et al., 2013; De Cara and Vermont, 2014).

The polluter-payer principle can be coupled with subsidies to encourage mitigation practices. This is simulated in our third scenario, where the carbon bonus/malus is coupled with an alfalfa premium. In our simulations, it is an inefficient measure because alfalfa is already largely grown in the laissez-faire scenario.

In the current application of the Common Agricultural Policy (CAP) 2014/2020, virtuous practices are encouraged through climatic and agro-environmental measures (C-AEM). The climatic AEM corresponding to our case consists in encouraging a lasting change in practices on the farm and increasing the environmental performance of the farm in the long run with a set of actions that are gradually implemented over the 5 years of the AEM (Ministry of agriculture and alimentation website). The measures included in these AEM are aimed at increasing crop diversity on farms, monitoring N fertilization, limiting crop protection product use and maintaining tree zones. These measures are part of the actions to mitigate GHG emissions. However, they do not include an obligation of results in terms of climate change mitigation. In addition, there still exists the risk of opportunistic behavior as well as dead-weight effects, such as those observed in our simulations.

On the contrary, the appeal of having a polluter-payer system based on an indicator of both soil quality changes and carbon sequestration is that in this case, the farmer does not have an obligation of means but an obligation of results. One could also think of an AEM where the contract also contains an obligation of results. In practice, the technical difficulty of having an obligation of results lies in the difficulty of having a reliable and accurate measure of SOM content in the representative samples of a farm. According to Johannes et al (2017), a relevant indicator could be the ratio SOM/clay. Such a ratio takes into account the texture of the soil. Actually, depending on the percentage of clay in a soil, a given level of SOM can be considered as high or low, and the farming practices

leading to a high level of SOM may also vary (Johannes et al , 2017). Hence, Johannes et al (2017) consider these two indicators complementary. The costs of such a control should be evaluated, and the strategic behavior of the farmer could lead to an over-estimation of SOM content.

We can imagine a system where control costs are delegated to counseling and advisory entities, which could have a twofold role: a pedagogical role by moving farming practices toward approaches that are sustainable both environmentally and economically; and a controlling role that assesses these changes in practices.

6.3.3 Cooperatives can have a determinant advisory role to play in the conservation of soil resource in the private long-term interest of their farmers.

Del Corso, Nguyen and Képhaliacos (2014) demonstrated the role played by a private cooperative in the relative success of a territorialized AEM. This particular AEM is original in the sense that it is conducted by a private actor, an agricultural cooperative. The advisory service provided by the cooperative in this context was paid by the farmer, but this cost was absorbed by the subsidy received when applying to the AEM.

The success of this particular setting was due to the interactions between the cooperative and its adherents. The AEM were traduced in terms of practice strategies that are mastered by the cooperative advisors. The technical expertise of the advisors is recognized by the farmers. In addition to their own expertise, farming advisors are also able to mobilize the knowledge of other farmers that have developed alternative techniques and contribute to the sharing of knowledge and experimentation between the members of the cooperative. Hence, the climate of trust between the advisors and the farmers is an accelerator of technical change (Del Corso et al, 2014).

In addition, a change in practices represents a risk for the farmer. This risk is perceived as shared by the cooperative since the cooperative also bears the risk of having the crop production collection diminished, thus reducing the revenues from which cooperative advisors are paid. Both actors have an interest in the success of the contracted AEM (Del Corso et al, 2014).

In the case studied by Del Corso et al (2014), the cooperative is characterized by a dynamic of experimentation, innovation and anticipation that makes collective learning easier. Hanna et al (2014) showed the importance of social and public awareness

in the beliefs and perceptions of farmers when deciding to adopt conservation practices. Such social and public awareness can be successfully inculcated by cooperatives, as illustrated in Del Corso et al (2014). This is facilitated when the techniques proposed are in phase with the farmers' conception of their profession and the social norms they view as legitimate (Plumecocq, Del Corso and Kephaliacos, 2015).

The collaboration of the cooperative and other public actors in addition to the exchanges whereby the AEM is tailored to the objectives of each actor make it possible to reach a compromise, based on which the actors are able to work more efficiently (Del Corso et al, 2014). After studying five case studies of agro-environmental schemes with different levels of collaboration among governmental and other actors, Westerink et al (2017) consider it essential for adaptive agro-environmental governance arrangements to adopt an interdisciplinary and participatory strategy. It is an encouraging example of the combination of public and private interests leading to sustainable changes in practices, with persisting positive externalities.

One inquiry of the cooperative in the initial negotiations regarded practices that did not negatively impact the farmer's revenues (Del Corso et al, 2014). Thus, we have an example where the private interest of farmers is defended by the cooperative, while the cooperative advises the voluntary farmers to change their farming practices in accordance with the initial environmental objectives. The advantage for the cooperative is that, in this case, it has permitted experimentation with new approaches in terms of anticipating the future and global concerns.

It is indeed an advantage for the cooperative to be able to anticipate future regulations with respect to climate change mitigation, for instance, developing strategies for farmers and helping them to adopt new practices. Collaboration and communication between private and public actors can help in the design and implementation of changes to practices and awareness. For the government, it is an opportunity to use the organization and structure of the cooperative to guide farmers toward the objectives of the CAP or national agricultural policies.

Some of the actions presented in Pellerin et al (2013) could be integrated into the climate AEM designed by the French government and then tailored to the actors in the territory considered. In the case of soil conservation, such proceedings can be relevant since soil dynamics depend on climate and topography conditions. Counseling entities, such as cooperatives, which have a strong presence in the field and have developed a detailed cartography of these soils as well as technical expertise, would be interesting

partners in the design and implementation of local measures.

Conclusion

THE objective of this research was to determine whether considering soil quality as an endogenous production factor in addition to the impacts of farming practices on soil quality dynamics leads to investment in soil quality, thereby achieving a profitable and sustainable agriculture practice. This behavior corresponds to the concept of an Ecologically Intensive Agriculture, that is, agriculture that no longer relies on intensive use of chemical inputs but on the intensive use, in economic terms, of the ecosystem functionalities of natural resources. Through this concept, EIA proposes a way to reconcile environmental and agricultural productivity. This issue is not only relevant to the private interest of the farmer in the context of an expected increase in fertilizer and energy prices but also the public interest. Although soil resources are for the most part privately managed, soil quality management triggers positive and negative externalities. In addition, the soil resource can have a role in climate mitigation through carbon sequestration.

To answer our research question, it was necessary to model the interactions between soil quality, soil productivity and farm profitability and then determine whether, in a given context and set of constraints, farming practices aiming at maintaining or enhancing soil quality can ensure both the profitability and sustainability of the farm system when soil quality is explicitly considered as an endogenous production factor. In our research, we have focused on the case of a cereal farmer.

Using theoretical, statistical and empirical modeling tools, we have shown the importance of considering the cooperation relationship between soil quality and farming practices in the crop production function when determining the optimal levels of soil quality and investment in soil quality.

Theoretically, when soil quality and productive inputs (such as fertilizers) are cooperating in terms of crop production, a negative feedback effect can be triggered when implementing a policy aimed at decreasing fertilizer use, e.g., an increase in fertilizer

prices: While fertilizer use will theoretically decrease, soil quality will decrease as well. However, when soil quality and productive inputs are not cooperating, such a negative feedback effect is no longer expected. Based on our statistical results, it appears that N fertilizers and SOM have a positive significant impact on soft wheat crop yield, while they are non-cooperating production factors. Hence, the statistical relationship at the regional scale between N fertilizers, SOM and soft wheat yield suggests that a policy favoring higher levels of SOM or discouraging the use of N fertilizers would not have a negative feedback effect and would indeed lead in both cases to an increase in investment in soil quality and a decrease in the use of N fertilizers. Here, SOM is used as a reliable indicator of soil quality and soil quality changes.

In our empirical model, the crop production functions are estimated with the biological simulation software CropSyst and calibrated on the data of a study case. In all the production functions estimated, N fertilizers and SOM are also non-cooperating. Crop production functions and SOM dynamics functions are estimated and calibrated for three soil types that are representative of those found at the farm in our study case. One of our scenarios simulates a constant increase in N fertilizer prices and fuel prices. In this case, we observe a decrease in N fertilizer optimal use in the farmer's strategy and an investment in soil quality through the costly use of deep tillage in comparison with the baseline case. In fact, in the SOM dynamics functions estimated by CropSyst, for some crops and soil types, deep tillage may have a positive impact on SOM; and the crops concerned are the most commonly used in the crop rotations of the farmer, which explains his use of deep tillage. However, we also observe a constant decrease in SOM: The farmer's investments are not sufficient to maintain SOM at a steady level. Simulating the introduction of a carbon bonus/malus associated with the increase or decrease in SOM from one year to another does not change the results of the previous scenario. Hence, in a third scenario, in addition to the carbon bonus/malus, we also introduced a doubled premium for alfalfa: This does not significantly impact either the strategy of the farmer or the final levels of SOM.

Nonetheless, our empirical results suggest that, indeed, when faced with an increase in chemical input prices, it is part of the farmer's optimal strategy to decrease the use of N fertilizers and to invest in soil quality, although the outcomes in terms of the SOM end levels are not those expected.

The results obtained in our empirical model can be explained by the difficulty of having a sufficient amount of data to consider the multiple aspects of soil quality and the variety of choices in farming practices actually used by the farmer. To take our

analysis a step further, it would be necessary to consider risk, uncertainty and technical changes in the optimization problem of the farmer. To be complete, one could consider the interactions among agents when changing farming practices choices.

However, our theoretical framework and our empirical model highlight the relevance of considering soil quality in the decision-making process of the farmer. Both theoretically and empirically, it appears that investing in soil quality is part of an optimal strategy to achieve a sustainable and profitable agriculture. The mitigated results of our empirical model in terms of SOM end values show the importance of considering a larger panel of farming practices and can serve as an interesting basis for discussion of the relevance of public policy instruments.

Actually, both the private and public interest are involved in preserving and maintaining soil quality at a sustainable level from an environmental and agricultural point of view. However, public policy and the instruments that are used must consider the complexity of the reactions in the dynamics of soil quality. One way to overcome this complexity is, for instance, to propose within the AEM the achievement of certain results as well as the means to achieve them. This would require an appropriate and individualized benchmark as captured by a given soil quality indicator, e.g., the ratio SOM/clay. Counseling entities, both private and public, have an important role to play in helping farmers to achieve a profitable and sustainable agriculture practice, which is desirable from both a private and public perspective.

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Annex 1: Computations of the soil investment models

Phase diagram and stability properties of our problem : ambiguity due to the prevalence of the cooperating benefits over the marginal damages on soil quality

The long-run or steady state equilibrium of the optimal control problem is determined by the intersection of the ($\dot{\mu} = 0$) and ($\dot{s} = 0$) demarcation curves which are such that:

$$\begin{aligned} A(s, \mu) &= \dot{\mu} \begin{matrix} \geq \\ \leq \end{matrix} 0 \\ \text{if } \mu(r + \delta(m(s, \mu))) - pf_s(m(s, \mu), s) &\begin{matrix} \geq \\ \leq \end{matrix} 0 \end{aligned} \quad (6.1)$$

$$\begin{aligned} B(s, \mu) &= \dot{s} \begin{matrix} \geq \\ \leq \end{matrix} 0 \\ \text{if } -\delta(m(s, \mu))s + g(u(s, \mu)) &\begin{matrix} \geq \\ \leq \end{matrix} 0 \end{aligned} \quad (6.2)$$

The slopes of the stationary loci are given by:

$$\begin{aligned} \left. \frac{d\mu}{ds} \right|_{B=\dot{s}=0} &= -\frac{\partial H_\mu / \partial s}{\partial H_\mu / \partial \mu} = -\frac{-\delta_m m_s s - \delta(m) + g_u u_s}{-\delta_m m_\mu s + g_u u_\mu} = -\frac{-\delta_m m_s s - \delta(m)}{-\delta_m m_\mu s + g_u u_\mu} \quad (6.3) \\ \left. \frac{d\mu}{ds} \right|_{A=\dot{\mu}=0} &= -\frac{\partial(\mu r - H_s) / \partial s}{\partial(\mu r - H_s) / \partial \mu} \\ &= -\frac{\partial(\mu(r + \delta(m(s, \mu))) - pf_s(s, m(s, \mu))) / \partial s}{\partial(\mu(r + \delta(m(s, \mu))) - pf_s(s, m(s, \mu))) / \partial \mu} = -\frac{\delta_m m_s \mu - pf_{ss} - pf_{sm} m_s}{r + \delta_m m_\mu \mu + \delta(m) - pf_{sm} m_\mu} \quad (6.4) \end{aligned}$$

To determine the stability properties of our problem, i.e., whether all solutions

converge toward the steady state, one can evaluate the Jacobian matrix

$$J = \begin{bmatrix} \partial\dot{s}/\partial s & \partial\dot{s}/\partial\mu \\ \partial\dot{\mu}/\partial s & \partial\dot{\mu}/\partial\mu \end{bmatrix} = \begin{bmatrix} H_{\mu s} & H_{\mu\mu} \\ -H_{ss} & r - H_{s\mu} \end{bmatrix} = \begin{bmatrix} -\delta_m m_s s - \delta & -\delta_m m_\mu s + g_u u_\mu \\ m_s(-H_{ms}) - pf_{ss} & r + m_\mu(-H_{ms}) + \delta \end{bmatrix} \quad (6.5)$$

at the steady state (s^*, μ^*) . Computing the trace of the Jacobian matrix, it appears that:

$$tr[J] = -\delta_m m_s s - \delta + r + m_\mu(-H_{ms}) + \delta = -m_s(\delta_m s - \delta_m s) + r = r > 0 \quad (6.6)$$

Since the eigenvalues of the Jacobian matrix equal its trace, at least one eigenvalue is positive, which implies that the fixed point (here, the intersection point of the $(\dot{\mu} = 0)$ and $(\dot{s} = 0)$ demarcation curves) is not locally asymptotically stable (Caputo, 2005). If the determinant of the Jacobian matrix is negative, the steady state is a local saddle point (Hediger, 2003; Narain and Fisher, 2006). Otherwise, if the determinant of the Jacobian matrix is positive, the steady state is an unstable node or at the center of an unstable spiral (Caputo, 2005), so that the system is not converging toward the steady state.

With a general form of the problem, that is, without specifying the functional forms of the different functions considered, the existence of an equilibrium can be found in the case where $H_{ms} > 0$. However, no conclusion can be made in the case where $H_{ms} < 0$.

When the marginal cooperating benefits are higher than the marginal damages on soil quality: Phase diagram and stability properties of our problem

In the case where $H_{ms} > 0$, which corresponds to the case where the marginal benefits of using productive inputs in terms of revenues are higher than the damages in terms of soil quality marginal value, there is a steady state equilibrium since the Jacobian

matrix is such that:

$$\begin{aligned}
\det J &= \begin{vmatrix} H_{\mu s} & H_{\mu\mu} \\ -H_{ss} & r - H_{s\mu} \end{vmatrix} = H_{\mu s}(r - H_{s\mu}) - H_{\mu\mu}(-H_{ss}) \\
&= (-\delta_m m_s s - \delta(m) + u_s)(r + \delta_m m_\mu \mu + \delta(m) - p f_{sm} m_\mu) \\
&\quad - (-\delta_m m_\mu s + u_\mu g_u)(\delta_m m_s \mu - p f_{ss} - p f_{sm} m_s) \\
&= (-\delta_m m_s s - \delta(m))(r + m_\mu(-H_{sm}) + \delta(m)) - (-\delta_m m_\mu s + u_\mu g_u)(m_s(-H_{ms}) - p f_{ss}) \\
&= (-\delta_m m_s s - \delta(m))(r + m_\mu(-H_{sm}) + \delta(m)) - (-\delta_m m_\mu s + u_\mu g_u) \left(\left(-\frac{H_{ms}}{H_{mm}} \right) (-H_{ms}) - p f_{ss} \right) \\
&= (-\delta_m m_s s - \delta(m))(r + m_\mu(-H_{sm}) + \delta(m)) - (-\delta_m m_\mu s + u_\mu g_u) \left(\frac{H_{ms}^2 - p f_{ss} H_{mm}}{H_{mm}} \right) \\
&= (-\delta_m m_s s - \delta(m))(r + m_\mu(-H_{sm}) + \delta(m)) \\
&\quad - (-\delta_m m_\mu s + u_\mu g_u) \left(\frac{p^2(f_{ms}^2 - f_{ss} f_{mm}) + \mu \delta_m (\mu \delta_m - 2p f_{sm}) + p f_{ss} \mu \delta_{mm} s}{H_{mm}} \right) \\
&< 0
\end{aligned} \tag{6.7}$$

From conditions (4.2), (4.3) and (4.7) and equations (4.31) to (4.34), given that r and p are positive and assuming that $H_{ms} > 0$, then $H_{\mu s} < 0$, $r - H_{s\mu} > 0$, $H_{\mu\mu} > 0$ and $H_{\mu\mu}(-H_{ss}) > 0$. From these results, the determinant of the Jacobian matrix is negative.

The slopes of the stationary loci are given by:

$$\begin{aligned}
\left. \frac{d\mu}{ds} \right|_{B=0} &= -\frac{\partial H_\mu / \partial s}{\partial H_\mu / \partial \mu} \\
&= -\frac{H_{\mu s}}{H_{\mu\mu}} > 0
\end{aligned} \tag{6.8}$$

$$\begin{aligned}
\left. \frac{d\mu}{ds} \right|_{A=0} &= -\frac{\partial(\mu r - H_s) / \partial s}{\partial(\mu r - H_s) / \partial \mu} \\
&= -\frac{-H_{ss}}{r - H_{s\mu}} < 0
\end{aligned} \tag{6.9}$$

From conditions (4.2), (4.3) and (4.7) and equations (4.31) to (4.34), given that r and p are positive and assuming that $H_{ms} > 0$, the gradient of the ($\dot{s} = 0$)-curve is positive. Given these conditions, the gradient of the ($\dot{\mu} = 0$)-curve is negative.

In addition, the slope of the trajectories in the (s, μ) space are such that:

$$\frac{d\mu}{ds} = \left(\frac{d\mu}{dt} \right) \cdot \left(\frac{dt}{ds} \right) = \frac{\dot{\mu}}{\dot{s}} \tag{6.10}$$

Hence, when a trajectory goes through a locus where $\dot{\mu} = 0$, it has a slope zero, and when it goes through a locus where $\dot{s} = 0$, it has an infinite slope.

Furthermore, when $\dot{s} = 0$ and $\dot{\mu} = 0$ and in the case where the steady state is a local saddle point (which is the case when $H_{ms} > 0$), we have:

$$\left[\underbrace{\frac{\partial \dot{s}}{\partial s}}_{-} \underbrace{\frac{\partial \dot{\mu}}{\partial \mu}}_{+} - \underbrace{\frac{\partial \dot{\mu}}{\partial s}}_{+} \underbrace{\frac{\partial \dot{s}}{\partial \mu}}_{+} \right] < 0 \Leftrightarrow \frac{-\partial \dot{s} / \partial s}{\partial \dot{s} / \partial \mu} > \frac{-\partial \dot{\mu} / \partial s}{\partial \dot{\mu} / \partial \mu} \quad (6.11)$$

from which one can conclude that the slope of the $\dot{s} = 0$ isocline is greater than the slope of the $\dot{\mu} = 0$ isocline in the neighborhood of the steady state. This is true if and only if the steady state is a local saddle point (Caputo, 2005).

Comparative statics of case 2, when $H_{ms} > 0$

Here, we aim at estimating the impact of a change in a given parameter c_1 , c_2 , p and r , i.e., the cost associated with soil degrading practices m , the costs associated with soil quality investment (or conservation practices), crop price and the discount rate, respectively. When one parameter changes, all variables change. However, the other parameters remain fixed and have a zero differential. To study this change, we evaluate the total differentials at the original equilibrium, that is, the total differentials of the first-order conditions (FOCs) when $\dot{\mu} = \dot{s} = 0$.

The FOCs at equilibrium are such that:

$$\tilde{H}_m = pf_m - c_1 - \mu\delta_m s = 0 \quad (6.12)$$

$$\tilde{H}_u = -c_2 + \mu g_u = 0 \quad (6.13)$$

$$\tilde{H}_\mu = -\delta(m)s + g(u) = 0 \quad (6.14)$$

$$\dot{\mu} - r\mu = -\tilde{H}_s \Leftrightarrow \dot{\mu} = r\mu - pf_s + \delta(m)\mu = \mu(r + \delta(m)) - pf_s = 0 \quad (6.15)$$

The total differentials of the system are such that:

$$(pf_{mm} - \mu\delta_{mm}s)dm + 0du - \delta_m s d\mu + (pf_{ms} - \mu\delta_m)ds + f_m dp - dc_1 + 0dc_2 + 0dr = 0 \quad (6.16)$$

$$0dm + \mu g_{uu} du + g_u d\mu + 0ds + 0dp + 0dc_1 - dc_2 + 0dr = 0 \quad (6.17)$$

$$-\delta_m s dm + g_u du + 0d\mu - \delta(m)ds + 0dp + 0dc_1 + 0dc_2 + 0dr = 0 \quad (6.18)$$

$$(\mu\delta_m - pf_{sm})dm + 0du + (r + \delta(m))d\mu - pf_{ss}ds - f_s dp + 0dc_1 + 0dc_2 + \mu dr = 0 \quad (6.19)$$

The determinant of the matrix of the system, denoted as B , is positive:

$$\begin{aligned} |B| &= \begin{vmatrix} pf_{mm} - \mu\delta_{mm}s & 0 & -\delta_m s & pf_{ms} - \mu\delta_m \\ 0 & \mu g_{uu} & g_u & 0 \\ -\delta_m s & g_u & 0 & -\delta \\ \mu\delta_m - pf_{sm} & 0 & r + \delta & -pf_{ss} \end{vmatrix} = \mu g_{uu} \begin{vmatrix} H_{mm} & -\delta_m s & H_{ms} \\ -\delta_m s & 0 & -\delta \\ -H_{ms} & r + \delta & -pf_{ss} \end{vmatrix} \\ &= \mu g_{uu} \begin{vmatrix} H_{mm} & -\delta_m s & H_{ms} \\ 0 & g_u & 0 \\ -H_{ms} & r + \delta & -pf_{ss} \end{vmatrix} \\ &= \mu g_{uu} \left(\delta_m s \begin{vmatrix} -\delta_m s & -\delta \\ -H_{ms} & -pf_{ss} \end{vmatrix} - (r + \delta) \begin{vmatrix} H_{mm} & H_{ms} \\ -\delta_m s & -\delta \end{vmatrix} \right) - g_u \left(g_u \begin{vmatrix} H_{mm} & H_{ms} \\ -H_{ms} & -pf_{ss} \end{vmatrix} \right) \\ &= \mu g_{uu} (\delta_m s (\delta_m s pf_{ss} - H_{ms} \delta) - (r + \delta) (-H_{mm} \delta + H_{ms} \delta_m s)) - g_u^2 (-H_{mm} H_{ss} + H_{ms}^2) \\ &= \mu g_{uu} ((\delta_m s)^2 H_{ss} - \delta_m s \delta H_{ms} + (r + \delta) H_{mm} \delta - (r + \delta) H_{ms} \delta_m s) - g_u^2 (-H_{mm} H_{ss} + H_{ms}^2) > 0 \end{aligned} \quad (6.20)$$

Applying Cramer's rule and using the same method as in case 1, we obtain the following comparative statics for the case where the damages caused by the use of productive inputs are overcompensated by its cooperating benefits with soil quality in terms of revenue ($H_{ms} > 0$):

$$m = m(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (6.21)$$

$$u = u(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (6.22)$$

$$\mu = \mu(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (6.23)$$

$$s = s(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (6.24)$$

Using this method, some impacts are ambiguously signed. Hence, an alternative methodology is used to determine the impact of a change in the discount rate and crop price on the steady state. Indeed, it is not the FOCs that are taken into account but only the ($\dot{s} = 0$) and ($\dot{\mu} = 0$) equations, using the expressions of m and u as implicit functions of soil quality s and marginal soil quality μ .

Hence, we have the following set of equations:

$$\dot{s} = H_\mu = -\delta(m^*(s, \mu)) + g(u^*(s^*, \mu^*)) = 0 \quad (6.25)$$

$$\dot{\mu} = r\mu - H_s = \mu^*(r + \delta(m^*(s, \mu))) - pf_s(m^*(s, \mu), s) = 0 \quad (6.26)$$

Differentiating the system with respect to s , μ , p and r yields:

$$(-\delta_m m_s - \delta(m) + g_u u_s)ds + (g_u u_\mu - \delta_m m_\mu s)d\mu + 0dr + 0dp = 0 \quad (6.27)$$

$$(\mu\delta_m m_s - pf_{sm}m_s - pf_{ss})ds + (r + \delta(m) + \mu\delta_m m_\mu - pf_{sm}m_\mu)d\mu + \mu dr - f_s dp = 0 \quad (6.28)$$

Only considering changes in r gives the following system:

$$\begin{bmatrix} -\delta_m m_s - \delta(m) & g_u u_\mu - \delta_m m_\mu s \\ -H_{ms}m_s - pf_{ss} & r + \delta - m_\mu H_{ms} \end{bmatrix} \begin{bmatrix} ds/dr \\ d\mu/dr \end{bmatrix} = \begin{bmatrix} 0 \\ -\mu \end{bmatrix} \quad (6.29)$$

Applying Cramer's rule yields the following results:

$$\frac{ds}{dr} = \frac{\begin{vmatrix} 0 & g_u u_\mu - \delta_m m_\mu s \\ -\mu & r + \delta(m) - m_\mu H_{ms} \end{vmatrix}}{|J|} = \frac{\mu(g_u u_\mu - \delta_m m_\mu s)}{|J|} < 0 \quad (6.30)$$

$$\frac{d\mu}{dr} = \frac{\begin{vmatrix} -\delta_m m_s - \delta(m) & 0 \\ -H_{ms}m_s - pf_{ss} & -\mu \end{vmatrix}}{|J|} = \frac{\mu(\delta_m m_s s + \delta(m))}{|J|} < 0 \quad (6.31)$$

Similarly, only considering changes in p , the following system is obtained:

$$\begin{bmatrix} -\delta_m m_s - \delta(m) & g_u u_\mu - \delta_m m_\mu s \\ -H_{ms}m_s - pf_{ss} & r + \delta - m_\mu H_{ms} \end{bmatrix} \begin{bmatrix} ds/dr \\ d\mu/dr \end{bmatrix} = \begin{bmatrix} 0 \\ f_s \end{bmatrix} \quad (6.32)$$

Applying Cramer's rule yields the following results:

$$\frac{ds}{dp} = \frac{\begin{vmatrix} 0 & g_u u_\mu - \delta_m m_\mu s \\ f_s & r + \delta(m) - m_\mu H_{ms} \end{vmatrix}}{|J|} = \frac{-f_s(g_u u_\mu - \delta_m m_\mu s)}{|J|} > 0 \quad (6.33)$$

$$\frac{d\mu}{dp} = \frac{\begin{vmatrix} -\delta_m m_s - \delta(m) & 0 \\ -H_{ms} m_s - p f_{ss} & f_s \end{vmatrix}}{|J|} = \frac{f_s(\delta_m m_s s + \delta(m))}{|J|} > 0 \quad (6.34)$$

The comparative statics for the case where the damages caused by the use of productive inputs are overcompensated by its cooperating benefits with soil quality in terms of revenue ($H_{ms} > 0$) are the following:

$$m = m(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (6.35)$$

$$u = u(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (6.36)$$

$$\mu = \mu(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (6.37)$$

$$s = s(\bar{c}_1, \bar{c}_2, \bar{p}, \bar{r}) \quad (6.38)$$

When the marginal cooperating benefits are higher than the marginal damages on soil quality: Comparative dynamics

To conduct comparative dynamics, we used the same methodology as in case 1, that is, the methodology proposed by Caputo (2005) *via* envelope methods. It is a general method of comparative dynamics that can be applicable to any sufficiently smooth optimal control problem using a primal-dual approach (see Caputo, 2005 - chapter 11). The conditions necessary to use the theorems or corollary proposed by Caputo (2005) have to be verified for the specific set-up of our soil quality investment model when farming practices both positively and negatively impact soil quality. However, since the comparative dynamics conducted following Caputo (2005) do not directly consider

The primal form of our soil quality investment model is such that:

$$V(\alpha) \equiv \max_{m(\cdot), u(\cdot)} J[m(\cdot), u(\cdot), s(\cdot)] \equiv \max_{m(\cdot), u(\cdot)} \int_0^T e^{-rt} [pf(s(t), m(t)) - c_1 m(t) - c_2 u(t)] dt \quad (6.39)$$

$$\text{s.t. } \dot{s}(t) = k(m(t), s(t), u(t)) = -\delta(m(t))s(t) + g(u(t)), \quad (6.40)$$

$$s(0) = s_0, s(T) = s_T \quad (6.41)$$

where $\alpha \equiv (p, c_1, c_2, r)$ is the vector of time-independent parameters. We denote $z(t; \alpha)$, $v(t; \alpha)$ and $w(t; \alpha)$ the optimal paths of soil quality, soil degrading practices, and investment, respectively, in soil conservation practices. Comparative dynamics analysis is conducted on the vector $\alpha \equiv (p, c_1, c_2, r)$ of parameters.

We use the Dynamic Envelope Theorem proposed in Caputo (2005). According to the theorem, when assumptions (A.1) through (A.4) hold, the partial derivative of the optimal value function with respect to a parameter can be obtained by differentiating the Hamiltonian of the optimal control problem and then evaluating it along the optimal paths (that is, for $s(t) = z(t; \alpha)$, $m(t) = v(t; \alpha)$ and $u(t) = w(t; \alpha)$), and finally integrating the result over the planning horizon.

Before doing so, let us verify that assumptions (A.1) to (A.4) hold for our soil quality investment problem. The assumptions mentioned in Caputo (2005 - page 288) and applied to our case are as follows:

(A.1) $f(\cdot) \in C^{(2)}$ and $k(\cdot) \in C^{(2)}$ on their respective domains,

(A.2) There exists a unique optimal solution to problem (P) for each $\beta \in B(\beta^\circ; \delta)$, which we denote by the quadruplet $(z(t; \alpha), v(t; \alpha), w(t; \alpha), \lambda(t; \alpha))$, where $B(\beta^\circ; \delta)$ is an open $2 + 2N + A$ - ball centered at the given value of the parameter β° of radius $\delta > 0$.

(A.3) The vector-valued functions $z(\cdot), v(\cdot), w(\cdot), \lambda(\cdot)$ are $C^{(1)}$ in $(t; \beta)$ for all $(t; \beta) \in [t_0^\circ, t_1^\circ] \times B(\beta^\circ; \delta)$.

(A.4) $V(\cdot) \in C^{(2)}$ in β for all $\beta \in B(\beta^\circ; \delta)$.

Because of the assumptions made for the production function and the soil quality dynamics function, (A.1) holds. In addition, from the Mangasarian Sufficient Conditions theorem, since the Hamiltonian \tilde{H} of our problem is strictly concave in m , u , and s when μ is the costate variable, there is a unique global maximum of $J[\cdot]$ ¹. (A.3) and (A.4) are assumed to hold.

1. The Hessian matrix \mathcal{H} of the Hamiltonian \tilde{H} when examining the concavity of \tilde{H} is such that:

$$\mathcal{H}(m, u, s) = \begin{bmatrix} H_{mm} & H_{mu} & H_{ms} \\ H_{um} & H_{uu} & H_{us} \\ H_{sm} & H_{su} & H_{ss} \end{bmatrix} = \begin{bmatrix} H_{mm} & 0 & H_{ms} \\ 0 & H_{uu} & 0 \\ H_{sm} & & H_{ss} \end{bmatrix}$$

Let us observe that \mathcal{H} is a square symmetric matrix of order $n = 3$. If the $n = 3$ leading principal minors D_k (*i.e.* the determinants of the $(k \times k)$ matrix obtained by eliminating the $n - k$ last rows and $n - k$ last columns of the matrix) are alternatively < 0 (k odd) and > 0 (k even), then \mathcal{H} is negative-definite.

Hence, applying Theorem 11.1 yields:

$$V_p(\alpha) \equiv \int_0^T y(t; \alpha) e^{-rt} dt > 0 \quad (6.42)$$

$$V_{c_1}(\alpha) \equiv - \int_0^T v(t; \alpha) e^{-rt} dt < 0 \quad (6.43)$$

$$V_{c_2}(\alpha) \equiv - \int_0^T w(t; \alpha) e^{-rt} dt < 0 \quad (6.44)$$

$$V_r(\alpha) \equiv - \int_0^T t\pi(t; \alpha) e^{-rt} dt \leq 0 \quad (6.45)$$

where $y(t; \alpha) \equiv f(z(t; \alpha), v(t; \alpha))$ is the value of the production function of the farm, and $\pi(t; \alpha) \equiv pf(z(t; \alpha), v(t; \alpha)) - c_1v(t; \alpha) - c_2w(t; \alpha)$ is the instantaneous profits along the optimal path.

Information obtained from the dynamic envelope theorem is relative to the cumulative discounted profit and production functions. Equations (6.42), (6.43) and (6.44) are unambiguously signed: According to the assumptions of our model, the production function cannot be negative, nor can the productive inputs or the investment in soil quality conservation practices be negative. However, equation (6.45) is not ambiguously signed. Indeed, although $V(\alpha) > 0$ must hold for the farm to be able to thrive in the market, it may be possible that instantaneous profits along the optimal path may be positive or negative at any given point. This could be the case when significant investments in soil quality are made that do not yield productivity gains instantaneously. However, one could add a constraint whereby instantaneous profit has to be positive, in which case $V_r(\alpha) < 0$.

In our model, the integrand function of the soil quality investment model is linear in $\gamma \equiv (p, c_1, c_2)$. Thus, the model satisfies the conditions of Corollary 11.2 (Caputo, 2005). This implies that the optimal value function $V(\cdot)$ is locally convex in γ . Hence, when differentiating equations (6.42) to (6.44), one can use the convexity of $V(\cdot)$ to determine

Here, we have, in the case where $H_{ms} > 0$:

$$\begin{aligned} D_1 &= H_{mm} < 0 \\ D_2 &= H_{mm}H_{uu} - (H_{mu})^2 = H_{mm}H_{uu} > 0 \\ D_3 &= H_{uu}(H_{mm}H_{ss} - (H_{ms})^2) = H_{uu}(-\mu s \delta_{mm} s p f_{ss} + p^2(f_{mm}f_{ss} - (f_{sm})^2) \\ &\quad + \mu \delta_m(2p f_{sm} - \mu \delta_m)) < 0 \end{aligned}$$

Hence, \mathcal{H} is negative-definite. Since if the Hessian matrix of a function f is negative-definite $\forall x \in \mathbb{R}^n$ then f is strictly concave, we can conclude that \tilde{H} is indeed strictly concave in m, u and s when μ is the costate variable.

the signs of the second partial derivatives and infer from those signs the own-price effects:

$$V_{pp}(\alpha) \equiv \frac{\partial}{\partial p} \int_0^T y(t; \alpha) e^{-rt} dt = \int_0^T \frac{\partial y}{\partial p}(t; \alpha) e^{-rt} dt \geq 0 \quad (6.46)$$

$$V_{c_1 c_1}(\alpha) \equiv -\frac{\partial}{\partial c_1} \int_0^T v(t; \alpha) e^{-rt} dt = -\int_0^T \frac{\partial v}{\partial c_1}(t; \alpha) e^{-rt} dt \geq 0 \quad (6.47)$$

$$V_{c_2 c_2}(\alpha) \equiv -\frac{\partial}{\partial c_2} \int_0^T w(t; \alpha) e^{-rt} dt = -\int_0^T \frac{\partial w}{\partial c_2}(t; \alpha) e^{-rt} dt \geq 0 \quad (6.48)$$

Equation (4.91) shows that the cumulative discounted crop production is not decreasing in the crop price. One can observe that it is the discounted production function slope, integrated over the entire planning horizon, that is not decreasing. For a given and finite period of time, crop production could be decreasing while the crop price has increased. While in the short-term such behavior may appear irrational, as long as equation (6.46) is verified over the entire planning horizon, it is somehow rational. Similar reasoning can be applied with respect to the impact of an increase in the cost of soil degrading practices and the cost of conservation practices. Equations (6.47) and (6.48) demonstrate that the cumulative discounted use of soil degrading practices and the cumulative discounted investment in conservation practices are non-increasing in terms of their own prices.

The comparative dynamics of the discount rate r cannot be derived through the use of Corollary 11.2 since the integrand function $F(\cdot)$ of our soil quality investment model:

$$F(t, m, u, s; \alpha) \equiv [pf(s, m) - c_1 m - c_2 u] e^{-rt} \quad (6.49)$$

is not convex in the discount rate r . Hence, to conduct the comparative dynamics of the discount rate, we rely on Theorem 11.2 proposed in Caputo (2005).

From Theorem 11.2, with $\alpha \equiv (p, c_1, c_2, r)$, so that the discount rate r is the fourth element of the parameter vector α , and since $L_{\alpha\alpha}(\beta)$ is a negative semi-definite matrix, we have:

$$\begin{aligned} L_{rr}(\beta) &= -\int_0^T [F_{rs}(t, z(t; \alpha), v(t; \alpha); \alpha) \frac{\partial z}{\partial r}(t; \alpha) + F_{rm}(t, z(t; \alpha), v(t; \alpha); \alpha) \frac{\partial v}{\partial r}(t; \alpha) \\ &\quad + F_{ru}(t, z(t; \alpha), v(t; \alpha); \alpha) \frac{\partial w}{\partial r}(t; \alpha)] dt \end{aligned} \quad (6.50)$$

$$\begin{aligned} &= -\int_0^T [pf_s(t, z(t; \alpha), v(t; \alpha)) \frac{\partial z}{\partial r}(t; \alpha) + [pf_m(z(t; \alpha), v(t; \alpha)) \frac{\partial v}{\partial r}(t; \alpha) - c_1] \\ &\quad - c_2 \frac{\partial w}{\partial r}(t; \alpha)] t e^{-rt} dt \leq 0 \end{aligned} \quad (6.51)$$

As in the previous equations describing the comparative dynamics of our model, equation

(6.51) describes the impact of a change in the discount rate on the soil quality investment model over the entire planning horizon. However, the comparative dynamics of the discount rate are not easy to interpret, unlike the comparative dynamics of the crop price and the costs of soil degrading practices and soil conservation practices.

Annex 2: Extracts of the bioeconomic model code on GAMS

BASELINE SCENARIO

OPTION NLP=MINOS;
Option Domlim= 75;

..... SET DECLARATION

SETS

C crops / SWHE, DWHE, SUNF, COLZ, BARL, MAIZE, ALFA /
CER(C) cereal crops / SWHE, DWHE, BARL/
NOSWHECOLZ(C) crops other than soft wheat and colza /DWHE, SUNF, BARL, MAIZE, ALFA /
S soils silt (S1) siltyclay (S2) clay-limestone (S3) / S1, S2, S3 /
MONTH month / JAN, FEB, MAR, APR, MAY, JUN, JUL, AUG, SEP, OCT, NOV, DEC /
OP operation of production / TILLAGE, SEMIS, FERTI_N, FERTI_P, FERTI_K, FERTI_MG, HERB, FONG, INSEC, HARVEST, PRESS, BROY, SEEDBED, CCROP1, CCROP2 /
FERTI(OP) fertilizers operation /FERTI_N, FERTI_P, FERTI_K, FERTI_MG /
NAT states of nature / N1*N100 /
T time period /1*51/
TFIRST(T) first period
TLAST(T) last period
*the set C (cultures) has a second name PC (preceding crop) :
ALIAS(C,PC)
ALIAS(C,PPC);

..... SCALARS DECLARATION

SCALARS

PHI risk aversion coefficient
 DRATE discount rate
 LANDAV land availability in 2016
 FUELP fuel price
 TOTAL_CAP Total decoupled CAP aids
 FERMAGE cost of land rent
 HRDAY number of working hours per day
 NWK number of week-end per month in days
 FIXEDCULTURESCOSTS for oats fall and meadows and no soil operation for fall and meadows and till=0 for oats

.....PARAMETERS DECLARATION
 TIME AVAILABILITY FOR WORK PER YEAR

PARAMETER

MWU(MONTH) number of man working unit per month
 NWD(MONTH) number of non-working day per month
 VAC(MONTH) number of vacancy day per month
 WD(MONTH) number of working day per month ;
 TIMEAVAIL(MONTH) time availability of work per month in hours;
 TTIMEAVAIL(T) total time availability of work per a year in hours ;
 SOIL(S) proportion of soil type

..... WORKING TIME PER CULTURAL PRACTICE, SOIL, AND CULTURE

TABLE OPERA_HNF(C,OP) number of passage for farming practices excepting N fertilization and tillage by crop
 TABLE OPERA_NFERTI(C,OP) number of passage for N fertilization practices by crop per N unit per hectare
 TABLE OPERA_TILL(C,OP) number of passage for tillage practice by crop and soil type
 PARAMETER
 TIME(OP) working time needed by operation in hours for one hectare for one passage
 WTIME_HNF(C,OP) total working time needed for each farming practices expect N fertilization for one hectare per culture ;
 WTIME_NFERTI(C,OP) total working time needed for N fertilization practices for one hectare per culture ;

..... OM MAX

OMMAX(S) maximal threshold of OM concentration per soil type (g per kg)

..... TIME DEFINITION

TFIRST(T) = YES\$(ORD(T) EQ 1);
TLAST(T) = YES\$(ORD(T) EQ CARD(T));
DISPLAY TFIRST, TLAST;

PARAMETER

PRCOUPL(C) coupled premium per culture and per hectare

..... CROP PRICES AND N FERTILIZER

PARAMETER

P(C) crop price in euros per hundred weight (7-years mean)
PFERTI(FERTI) fertilizers price in euro per kilo

..... PARAMETERS PRODUCTION FUNCTION

TABLE BETA0(C, S) Intercept of OM dynamics regression per culture and soil
TABLE BETA1(C, S) N Parameter of OM dynamics regression per culture and soil
TABLE BETA2(C, S) N² Parameter of OM dynamics regression per culture and soil
TABLE BETA3(C, S) OM Parameter of OM dynamics regression per culture and soil
TABLE BETA4(C, S) OM² Parameter of OM dynamics regression per culture and soil
TABLE BETA5(C, S) OM*N Parameter of OM dynamics regression per culture and soil
TABLE OMSTOCKFIX(C,S)

..... OM DYNAMICS

PARAMETERS

TABLE ALPHA0(C, S) Intercept of OM dynamics regression per culture and soil
TABLE ALPHA1(C, S) OM Parameter of OM dynamics regression per culture and soil
TABLE ALPHA2(C, S) OM² Parameter of OM dynamics regression per culture and soil

TABLE ALPHA3(C, S) N Parameter of OM dynamics regression per culture and soil
 TABLE ALPHA4(C, S) N² Parameter of OM dynamics regression per culture and soil
 TABLE ALPHA5(C, S) TILL Parameter of OM dynamics regression per culture and soil
 TABLE ALPHA6(C, S) RES Parameter of OM dynamics regression per culture and soil
 TABLE ALPHA7(C, S) TILL*N Parameter of OM dynamics regression per culture and soil
 TABLE ALPHA8(C, S) RES*N Parameter of OM dynamics regression per culture and soil
 TABLE ALPHA9(C, S) TILL*RES Parameter of OM dynamics regression per culture and soil
 TABLE ALPHA10(C, S) OM*N Parameter of OM dynamics regression per culture and soil
 TABLE ALPHA11(C, S) OM*RES Parameter of OM dynamics regression per culture and soil
 TABLE ALPHA12(C, S) OM*TILL Parameter of OM dynamics regression per culture and soil
 PARAMETER TOTALFUELCONS_WOTN(C) total fuel consumption (without tillage nor N fertilizers)
 PARAMETER TOTALFUELCONS_N(C) total fuel consumption per N unit per hectare
 PARAMETER MECCOSTC_WOTN(C) total mechanist costs (without tillage nor N fertilizers)
 PARAMETER MECCOSTC_N(C) total mechanist cost per N unit per hectare
 PARAMETER CTFERTI(C) costs of fertilizers per hectare of crop (other than N fertilizers)
 PARAMETER CTSPS(C) fixed costs of seeds and crop protection products, per hectare and per crop

..... CROP ROTATION

** INTENSIVE/SHORT CROP ROTATIONS

* PARAMETERS

*ROT(C,PC) crop rotations ;
 *ROT('COLZ', 'SWHE') = 1 ;
 *ROT('SWHE', 'COLZ') = 1 ;
 *LOOP((C), ROT('SWHE',NOSWHECOLZ)=1);
 *LOOP((C), ROT('COLZ',NOSWHECOLZ)=1);

** NON-INTENSIVE/LONG CROP ROTATIONS

PARAMETER

ROT(C,PC) crop rotations ;
 ROT('SWHE', 'SUNF') = 1 ;
 ROT('SWHE', 'MAIZE') = 1 ;
 ROT('ALFA', 'SUNF') = 1 ;
 ROT('ALFA', 'ALFA') = 0.7 ;
 ROT('SWHE', 'ALFA') = 0.3 ;

LOOP((CER), ROT('COLZ',CER)=1);
 LOOP((CER), ROT(CER, 'COLZ')=1);
 LOOP((CER), ROT('SUNF',CER)=1);
 LOOP((CER), ROT('MAIZE',CER)=1);

..... VARIABLES DECLARATION

VARIABLE

DISCU Discounted utility
 EXPECTPROFIT(T) Expected profit
 F(C,PC,S,T) Yield per culture and soil type

POSITIVE VARIABLE

CROPAREASCT(C) Total crop area
 CROPAREAWOPC(C,S,T) Total crop area
 TILLMEANS(S,T) Average tillage intensity
 RESMEANS(S,T) Average residue use
 CROPAREASC(C,T) Crop area
 CROPAREAS(S,T) Cultivated area for each soil type
 CROPAREATOT(T) Total cultivated area
 LABOR(T)
 WTIME_TILL(C,S,T)
 WTIME(C,S,T)
 FUELTILLCONS(C,S,T)
 MECCOSTSC_TILL(C,S,T)
 RES(C,S,T) Residue use
 TILL(C,S,T) Tillage intensity
 OMSTOCK(C,PC,S,T) OM stock per culture and soil type
 OMSTOCKTOT(S,T) OM stock mean per soil type
 CROPAREA(C,PC,S,T)
 CFERTI_NS(C,S,T) cost of N inputs per culture and soil type
 CTFERTI_NS(T) total cost of N inputs per time period
 FERTI_N(C,S,T)
 OMSTOCKTOTS(S,T)
 TOTALFERTI_N(C,S,T) Total N fertilizers used per soil type and crop
 TOTALCFERTI_N(C,S,T) Total N fertilizer cost per soil type and crop
 TOTFERTI_N(S,T) Total N fertilizer cost per soil type
 TOTCFERTI_N(S,T)
 TOUTFERTI_N(T) Total N fertilizer units used
 TOUTCFERTI_N(T) Total N fertilizer cost ;

.....INITIALIZATION

..... EQUATIONS DECLARATION

EQUATIONS

FERTINBORNEINFEQ(C,S,T)
FERTINBORNESUPEQ(C,S,T)
OMBORNEINFEQ(C,PC,S,T)
OMBORNESUPEQ(C,PC,S,T)
TILLBORNEINFEQ(C,S,T)
TILLBORNESUPEQ(C,S,T)
RESBORNEINFEQ(C,S,T)
RESBORNESUPEQ(C,S,T) ;

..... CONSTRAINTS ON CROP ROTATION

EQUATIONS

CROPAREASCTEQ(C)
CROPAREASEQ
CROPAREASCEQ(C,T)
CROPAREATOTEQ(T)
CROPLANDT1EQ(T)
CROPLANDT2EQ(T)
CROPLANDEQ(T)
CROPLANDS1EQ(T)
CROPLANDS2EQ(T)
CROPLANDS3EQ(T)
ROTATIONEQ(C,PC,S,T) ;
CROP PRODUCTION FUNCTION

EQUATION

FEQ(C,PC,S,T);

..... SOM DYNAMICS FUCTION

EQUATION

OMSTOCKS1T1EQ(C,PC,S,T)

OMSTOCKS2T1EQ(C,PC,S,T)
 OMSTOCKS3T1EQ(C,PC,S,T)
 OMSTOCKEQ(C,PC,S,T)
 OMSTOCKTOTSEQ(S,T)
 TILLMEANSEQ(S,T)
 RESMEANSEQ(S,T)

;

..... PRODUCTION COSTS

EQUATION

TOTALFERTI_NEQ(C,S,T)
 TOTALCFERTI_NEQ(C,S,T)
 TOTFERTI_NEQ(S,T)
 TOTCFERTI_NEQ(S,T)
 TOUTFERTI_NEQ(T)
 TOUTCFERTI_NEQ(T)
 CFERTI_NSEQ(C,S,T) cost of N inputs per culture and soil type FUELTILLCONSEQ (C,S,T)
 MECCOSTSC_TILLEQ (C,S,T);

..... WORKING TIME PER CULTURAL PRACTICE, SOIL, AND CULTURE

EQUATIONS

LABORCONSTRAINTEQ(T)
 LABOREQ(T)
 WTIME_TILLEQ(C,S,T) total working time needed for tillage practices for one hectare per culture and per soil type
 WTIMEEQ (C,S,T) total working time needed for the entire set of operation for one hectare ;

..... LIQUIDITY CONSTRAINT

EQUATION

LIQCONSTRAINTEQ(T) ;
 LIQCONSTRAINTEQ(T).. EXPECTPROFIT(T)=G=0 ;

..... EXPECTED PROFIT

EQUATION

EXPECTPROFITEQ(T);

..... DISCOUNTED UTILITY

EQUATION

OBJEQ ;

OBJEQ.. DISCU =E= (SUM (T, (1/(1+DRATE))**(ORD(T))* (EXPECTPROFIT(T)))) ;

..... MODEL RESOLUTION

MODEL base_scenario_certain /ALL/

OPTION NLP=MINOS;

SOLVE base_scenario_certain USING nlp MAXIMIZING DISCU ;

DISPLAY

EXPECTPROFIT.L, DISCU.L, CROPAREA.L, F.L,FERTI_N.L, TILL.L, RES.L, CROPAREAS.L,
CROPAREATOT.L, CROPAREASCT.L, CROPAREASC.L, OMSTOCK.L, OMSTOCKTOTS.L,
OMSTOCKTOTS.M, TOTALFERTI_N.L, TOTALCFERTI_N.L, TOTFERTI_N.L, TOTCFERTI_N.L,
TOUTFERTI_N.L, TOUTCFERTI_N.L, TILLMEANS.L, RESMEANS.L ;

Annexe 3 : Analyses statistiques et modèle bioéconomique - Données à utiliser

Type de l'échantillon

— Échantillon avec une hétérogénéité de productions et de pratiques

L'idéal serait d'avoir un échantillon représentatif des agriculteurs adhérent à une coopérative du Grand Ouest. A défaut, une typologie intéressante peut être obtenue avec un échantillon présentant une hétérogénéité de productions et de pratiques (grandes cultures, élevage, polyculture élevage, agriculture conventionnelle, intégrée, biologique, AEI, nouvelle agriculture...).

Données sur plusieurs années

- Au minimum, données sur 3-4 ans : prendre en compte les rotations
- Données sur 10-20 ans : prendre en compte la variation de la qualité du sol

L'objectif de la typologie est de construire des groupes d'individus, basés sur leurs ressemblances. Ces ressemblances, pour le sujet qui nous intéresse, sont liées à leurs pratiques, et en particulier leurs pratiques culturales. Or ces pratiques sont étroitement liées aux rotations de cultures : le précédent cultural, la culture intermédiaire, les apports d'engrais ou de produits de protection des plantes... Mais également les rendements et les revenus en découlant, qui vont dépendre de l'assolement de l'année considérée et de la position qu'il occupe dans la rotation. Ainsi, si l'on observe qu'une seule année, il est difficile d'avoir une idée correcte des performances d'une exploitation. Par conséquent, la typologie obtenue sera biaisée. Avoir des données sur 3-4 ans permet de prendre en compte les rotations. Des données sur une dizaine d'années permettent de prendre en compte l'évolution des exploitations et de mieux prendre en compte l'évolution de la qualité du sol.

Taille de l'échantillon

- Données sur 3-4 ans : env. 100 exploitations
- Données sur 10 ans ou plus : autant d'exploitations que possible, un échantillon de 20-50 exploitations serait intéressant

Il s'agit d'un compromis entre le nombre d'exploitations et la période pour laquelle on dispose des mêmes données pour les mêmes exploitations. Comme nous étudions la qualité du sol, et que la dynamique de formation et de dégradation du sol est lente, plus longue est la période considérée, plus grandes sont les probabilités de dégager une tendance, voire même une causalité entre pratiques et variation de la qualité du sol. Ainsi il est plus intéressant d'avoir des données sur 20 exploitations sur 20 ou 30 ans, que d'avoir des données pour 3000 exploitations sur un an (inexploitable).

Typologie : données pour chaque année

Pratiques agricoles

Données à l'exploitation

- Cultures sur l'exploitation (y compris les prairies temporaires ou permanentes, et le type de prairies (graminées, légumineuses, mélange graminées légumineuses))

Il s'agit d'avoir la meilleure idée possible de l'utilisation agronomique des sols.

- SAU (ha)
- Surface des différentes cultures (ha)

Données à la parcelle

- Surface (ha)
- Culture
- Irrigation (mm/mois)
- Précédent cultural
- Amendements (CaO, MgO, So₃, Cu, Zn, Bore, Sodium) (kg/ha)
- Culture intermédiaire (engrais vert, piège à nitrates), si oui, quand et en lien avec quelles cultures ?
- Pratiques de travail du sol (labour, travail profond avec retournement, sans retournement, travail superficiel), et à quelle fréquence
- Apports d'azote organique : compost (T/ha), fumier (T/ha) , lisier (m³/ha) et purin (m³/ha), au pâturage (kg/ha ?)
- Dose totale d'azote minéral (unités/ha)
- Nombre total d'apports d'azote minéral
- Dose totale de phosphore (unités de P₂O₅/ha)
- Nombre total d'apports de phosphore
- Dose totale de potasse (unités de K₂O/ha)
- Nombre total d'apports de potasse
- Nombre de produits phytosanitaires et de passages
- Dose (kg/ha), nombre de produits herbicides et de passages

- Dose (kg/ha), nombre de produits fongicides et de passages
- Dose (kg/ha), nombre de produits insecticides et de passages
- Dose (kg/ha), nombre de produits régulateurs de croissance et de passages
- Rendement (quintal/ha)
- MAE (euros/ha)
- Primes couplées (euros/ha)

Structure des exploitations et caractéristiques économiques

Données à l'exploitation

- Surface agricole utile (SAU) totale (ha)
- Effectif moyen des troupeaux (bovins, ovins, caprins, porcs en UGB, volailles (m^2 de bâtiment ou nombre de têtes))

Cette donnée, couplée notamment au type d'engrais organique utilisé, apporte des informations sur le profil des agriculteurs : uniquement cultivateur mais utilisateur d'engrais organique, éleveur-cultivateur utilisant les sources d'engrais organiques disponibles sur son exploitation, etc.

- Orientation
- Statut juridique
- Unité de travail annuel (UTA), familiale ou autre
- Âge du premier exploitant (ans)
- Formation générale et agricole les plus élevées
- Formation continue (via coopératives) ou groupes animés par les coopératives

Les données relatives à l'âge et à la formation sont intéressantes à mettre en perspective avec les pratiques de conservation du sol (et par extension les pratiques AEI). En effet, ces pratiques nécessitent une démarche d'innovation pouvant être capturée par ces indicateurs.

- Valeur ajoutée brute (différence produits et charges variables) avant de retirer le fermage (euros)

Même si dans la phase de typologie les coûts ne sont pas pris en compte, il est néanmoins intéressant de confronter pratiques agricoles, qualité du sol, et rentabilité de l'exploitation. En effet, l'AEI se propose de répondre non seulement aux enjeux de productivité et de durabilité, mais également de rentabilité.

Par ailleurs, il est intéressant de considérer cette valeur sans tenir compte du fermage afin de ne pas différencier les agriculteurs locataires des agriculteurs propriétaires. En effet dans cette typologie, nous ne nous intéressons pas à l'impact du statut de propriétaire.

Données à la parcelle ou à l'exploitation

- MAE (euros, euros/ha ou euros/m, selon le type de MAE)

Généralement, les MAE génèrent des impacts positifs pour le sol, et en tant que telles sont intéressantes à considérer dans notre typologie.

Indicateurs de la qualité des sols

Données à la parcelle

- Azote total (g/kg)
- Phosphore assimilable (mg/kg)
- Carbone organique du sol (g/kg)
- pH
- Texture
- Profondeur du sol (mètre)
- Réserve utile en eau (millimètre d'eau)
- Zone humide (oui ou non)
- Présence importante de cailloux (oui ou non)

Ces deux dernières données mettent en évidence des contraintes pour l'agriculteur, pouvant expliquer ou conditionner certains de ses choix.

Modèle bioéconomique

Données pour la simulation...

Une fois la typologie faite, un modèle bioéconomique empirique sera construit. L'objectif de ce modèle empirique est de déterminer quelles sont les pratiques agricoles optimales (en matière d'intensité du travail du sol, d'apports en engrais et de rotations de cultures) à mettre en œuvre pour maximiser le revenu de l'agriculteur sur le long terme, tout en prenant en compte le facteur de production qu'est le sol. A terme, le modèle sera utilisé comme un outil de conseil.

... et la calibration

Avant de faire des simulations avec le modèle, il faut s'assurer qu'il fonctionne bien, c'est-à-dire qu'il propose des résultats cohérents avec la réalité. C'est l'étape de calibration. Sur la base de données historiques, nous allons faire des simulations avec le modèle, et comparer les résultats obtenus en matière de qualité du sol, rendement et de revenus avec les résultats observés. Cela nous permettra d'ajuster au mieux les fonctions de production et de dynamique de la qualité du sol, et de vérifier que le modèle est opérationnel.

Données à la coopérative ou à l'exploitation (selon disponibilités)

- Consommations intermédiaires (prix moyen par campagne ?)
 - Coûts des semences (euros/kg)
 - Coûts des engrais (N, NP, PK, NPK) (euros/kg)
 - Coûts des produits de conditionnement du sol (euros/kg)
 - Coûts des produits de protection des cultures (herbicides, fongicides, insecticides) (euros/kg)
 - Coûts des produits pétroliers (chauffage et fuel) (euros/litre)

Données à l'exploitation

- Surface totale des terres cultivées (ha)
- Cultures (nombre, nom et surface totale associée par culture (ha))
- Besoin en travail par culture et par mois (heures/ha)

Pour les opérations de labour, de décompactage, d'ameublement, de déchaumage, d'émiettage, de semis, de fertilisation (N, NP, PK, NPK et autres amendements), d'herbicides, de fongicides, d'insecticides, de binage, de récolte)

- Consommations intermédiaires
 - Dépenses liées à l'électricité (euros/kWh), à l'eau (euros/m³)
- Facteurs de production pérennes
 - Prix de location de la terre (et intérêts des prêts en cours) (euros)
 - Équipement et machines (coûts annuels): valeur de l'équipement possédé, cotisation annuelle dans les cuma, coûts annuels prestations des entreprises agricoles, et dépenses de location (euros)
 - Coûts d'assurance (euros)
 - Travail contractuel (salaire + taxe patronale) (euros), dépenses liées à la voiture (euros)
- Paiement de base (PDB) (euros)
- Valeur ajoutée brute (différence produits et charges variables) avant de retirer le fermage (euros)

Données à la parcelle

- Surface (ha)
- Culture
- Précédent cultural
- Profondeur du sol (mètre)
- Intensité du travail du sol (labour, travail profond avec retournement, sans retournement, travail superficiel)
- Culture intermédiaire (couverture du sol) (oui ou non, si oui, laquelle)
- Apports en engrais azotés (quantité (unité/ha) et nombre de passages)
- Apports en engrais phosphatés (quantité (unités/ha) et nombre de passages)
- Rendement (quintal/ha)
- Aides couplées (euros/ha)
- MAE (type), (euros ou euros/ha ou euros/m selon le type de MAE)

Annexe 4 : Compte-Rendu

Acquisition de données

Dans le cadre de cette thèse, nous avons sollicité différents partenaires afin d'avoir les données les plus complètes et détaillées possible pour la conduite de notre étude statistique et le calibrage de notre modèle empirique (voir Annexe 3). Cette thèse a été financée pour partie par la Chaire AEI dont trois coopératives du Grand Ouest sont membres. Cela représentait une opportunité d'avoir accès à des données de qualité.

Nous avons été en contact avec différents partenaires et interlocuteurs au sujet de l'accès aux données pendant une majeure partie de la seconde année de thèse (de février à décembre 2016).

Nous avons tout d'abord contacté l'animatrice de la Chaire AEI, en lui présentant les données dont nous avons besoin. Elle nous a ensuite dirigés vers les personnes ressources de chacune des trois coopératives. L'une des coopératives avait fait un travail d'enquête de 4 ans portant sur les mêmes variables d'intérêt que les nôtres. Toutefois, cette coopérative a décidé de valoriser ces données et leurs résultats d'abord en interne avant de les communiquer en externe. Une autre coopérative n'avait pas les données demandées. La dernière les avait, mais disséminées dans différentes bases de données. Le coût d'extraction de ces données a été jugé trop important pour accéder à notre demande.

Nous avons également eu des échanges avec des collègues agronomes et écologues qui travaillent sur la qualité du sol et l'influence des pratiques agricoles sur celui-ci, notamment en menant des enquêtes. Toutefois, les données collectées correspondaient à une seule année culturale et n'étaient pas utilisables en l'état en ce qui nous concernait.

Nous avons eu des discussions très intéressantes avec des collègues utilisant les bases de données publiques sur les sols, qui ont pu nous orienter sur l'usage des données issues de la BDAT. Un autre collègue nous a facilité l'accès aux données issues d'Agreste, notamment en ce qui concernait les recensements agricoles et les enquêtes pratiques culturales.

Finalement, devant l'impossibilité d'avoir accès aux données des coopératives, nous avons utilisé les données qui étaient disponibles, à savoir les données publiques issues du Ministère de l'Agriculture et de la BDAT. Ces données, pour les plus précises, sont au niveau cantonal, quand certaines ne sont disponibles qu'au niveau régional. D'autre part, leur date de collecte diffère d'une source de données à l'autre. Pour le calibrage de notre modèle empirique, nous avons eu accès aux données d'une exploitation Terrena. L'agriculteur présent sur cette exploitation avait déjà travaillé avec le LARESS.

L'ensemble détaillé des démarches entreprises pour l'acquisition de données est disponible pour un usage interne au niveau de la Chaire AEI.

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RÉSUMÉ

ABSTRACT

Gestion de la variation de la qualité des sols par les agriculteurs : enjeux pour la rentabilité et la durabilité des exploitations agricoles françaises

La qualité des sols constitue un enjeu majeur en termes d'environnement et de préservation du potentiel agronomique et économique des exploitations agricoles. Les pratiques agricoles ont des impacts sur la qualité des sols, dont certains entraînent une dégradation des sols et mènent à une réduction de leur productivité. La thèse a pour objectif de caractériser et d'éclairer les enjeux économiques de moyen et long terme de la variation de la qualité des sols en mobilisant des outils théoriques, statistiques et empiriques. Nous tentons, en simulant différents scénarios économiques, d'identifier les leviers permettant de préserver le potentiel des sols. Nous utilisons un modèle dynamique de contrôle optimal où l'agent-agriculteur rationnel maximise son profit dans le temps sous contrainte de la dynamique de la qualité des sols. Il y a deux facteurs de production : les intrants productifs (tels les engrais minéraux azotés) et la qualité du sol, capturée par sa matière organique (MO). La qualité du sol est impactée par les intrants productifs utilisés par l'agriculteur, qui peut investir dans la qualité de ses sols via l'utilisation des résidus de culture, l'intensité de labour et les choix des rotations. Nos résultats montrent que l'investissement dans la qualité des sols fait partie d'une stratégie optimale de l'agriculteur qui, face à l'augmentation des prix des engrais et de l'énergie, substitue ainsi les fonctionnalités écosystémiques de son sol aux intrants chimiques. Les résultats mitigés de nos simulations en termes de MO montrent l'importance de considérer un large panel de pratiques mais permettent de discuter l'usage des instruments de politique publique et le rôle du conseil privé et public dans l'adoption des pratiques agroécologiques.

Mots-clés : qualité du sol, facteurs de production coopérants, pratiques de conservation, contrôle optimal, agroécologie

Soil quality management by farmers: profitability and sustainability issues for agricultural farms

Soil quality is a major issue for the environment and the preservation of the agronomic and economic potential of farms. Farming practices have substantial impacts on soil quality; some are detrimental and lead to a long-term decrease in productivity. The objective of this thesis is to characterize the mid-term and long-term economic issues related to soil quality changes using theoretical, statistical and empirical tools and to propose a dynamic bioeconomic model that highlights these issues. Using the simulations of different economic scenarios, we seek to identify the levers that make it possible to preserve the agronomic and economic potential of soil. The model used is a dynamic optimal control model where the rational agent-farmer with perfect information maximizes his profits over time under a soil quality dynamics constraint. We consider two production factors: productive inputs (such as mineral nitrogen fertilizers) and soil quality, captured by the quantity of soil organic matter (SOM). Soil quality is negatively impacted by the productive inputs used by the farmer, who can invest in his soil quality (crop residue use, tillage intensity, crop rotation choice). Our results show that soil quality investment is a component of the farmer's optimal strategy. The farmer substitutes the ecosystemic functionalities of his soil for chemical inputs in response to the increase in fertilizers and energy prices. However, the mitigated results of our empirical model in terms of SOM final values show the importance of considering a large range of farming practices. Our results offer a basis for interesting discussion regarding the relevance of public policy instruments and the role of public and private counseling in the adoption of agroecology practices.

Keywords: soil quality, cooperating production factors, conservation practices, optimal control, agroecology



AGROCAMPUS OUEST • Institut supérieur des sciences agronomiques, agroalimentaires, horticoles et du paysage
65 rue de Saint-Brieuc – CS84215 – F-35042 Rennes Cedex
Tél. : 02 23 48 50 00
www.agrocampus-ouest.fr

