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Gestion de la qualité de la ressource en eau potable dans un système socio-écologique : développement d'un modèle multi-agents à partir d'analyse institutionnelle

Amélie Bourceret

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CLERMONT-FERRAND

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Unité Mixte de Recherche Territoires

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Amélie Bourceret

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Gestion de la qualité de la ressource en eau potable
dans un système socio-écologique : développement
d'un modèle multi-agents à partir d'analyse
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Stefano Farolfi	Rapporteur
Claudia Palh-Wostl	Rapporteure
Geneviève N'Guyen	Examinatrice
Patrick Taillandier	Examineur
Laurence Amblard	Encadrante de thèse
Jean-Denis Mathias	Directeur de thèse

Avant-propos

Cette thèse a été réalisée à l'Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement (INRAE)¹, au centre des Cézéaux à Aubière au sein du Laboratoire d'Ingénierie pour les Systèmes Complexes (LISC) et de l'Unité Mixte de Recherche Territoires.

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Résumé

L'approvisionnement des citoyens en eau potable de qualité est un enjeu de santé publique, auquel s'ajoutent des enjeux environnementaux et économiques. L'agriculture est l'une des principales menaces pour la qualité de la ressource en eau potable, notamment à cause des pollutions diffuses dans les aires d'alimentation de captages. Les programmes de protection des captages vis-à-vis des pollutions diffuses d'origine agricole reposent principalement sur la participation volontaire des agriculteurs. L'objectif de cette thèse est d'étudier, à l'aide d'un modèle multi-agents, quels sont les impacts de la gouvernance sur l'évolution des pratiques agricoles, en prenant en compte les interactions entre les mesures de protection mises en œuvre, les dynamiques comportementales des agriculteurs et les facteurs liés au système écologique. Pour ce faire, nous avons dans un premier temps réalisé une revue de littérature des modèles multi-agents de systèmes socio-écologiques représentant la gouvernance. Nous nous sommes intéressés aux apports et perspectives de ce champ de recherche. Nous nous sommes appuyés sur cette revue afin de construire un modèle multi-agents pour analyser la gouvernance de la qualité de l'eau dans une aire l'alimentation de captage en décrivant les comportements des agriculteurs grâce à la théorie du comportement planifié. Un premier modèle nous a permis d'analyser l'efficacité et l'efficience de programmes de protection composés de deux mesures, une compensation financière et une mesure de formation. Nous avons ainsi pu tester l'impact des caractéristiques comportementales des agriculteurs et des interactions entre les agriculteurs sur les résultats des programmes en termes d'évolution des pratiques agricoles. Dans un second modèle, nous nous sommes intéressés plus particulièrement à l'effet de l'information sur le niveau de pollution de l'eau, en fonction des préférences environnementales des agriculteurs et de l'état initial du système écologique. Les simulations permettent de mettre

en évidence le rôle positif des instruments d'information dans la gestion de la qualité de l'eau. Cette thèse met en évidence, sur la base d'une approche pluridisciplinaire, le rôle des caractéristiques des mesures de protection, des agriculteurs et du système écologique dans l'impact de la gouvernance de la qualité de l'eau sur les évolutions des pratiques agricoles.

Mots-clefs Agriculture ; gouvernance ; modèle multi-agents ; qualité de l'eau ; théorie du comportement planifié

Abstract

Supplying citizens with quality drinking water is a public health issue, to which are added environmental and economic issues. Agriculture is one of the main threats to the quality of drinking water resources, particularly because of diffuse pollution in catchment areas. Programmes to protect water catchments from agricultural diffuse pollution rely mainly on the voluntary participation of farmers. The objective of this thesis is to study, with the help of an agent-based model, the impacts of governance on the evolution of agricultural practices, taking into account the interactions between the protection measures implemented, the behavioural dynamics of farmers and the characteristics of the ecological system. We first conducted a literature review of agent-based models of social-ecological systems representing governance to identify the contributions and perspectives of this field of research. We used this review to build an agent-based model to analyse the governance of water quality in a catchment area by describing farmers' behaviour using the theory of planned behaviour. A first model allowed us to analyse the effectiveness and efficiency of protection programmes composed of two measures, a financial compensation and a training measure. We tested the impact of behavioral characteristics of farmers and the interactions between farmers on the results of the programmes in terms of evolution of agricultural practices. In a second model, we focused on the effect of information on the water pollution level, in function of farmers' environmental preferences and the initial state of the ecological system. The simulations show the positive role of such information tools in water quality management. This thesis shows, on the basis of a multidisciplinary approach how the characteristics of protection measures, farmers and the ecological system interact in their effect on water quality governance.

Mots-clefs Agent-based model ; agriculture ; governance ; theory of planned behaviour ; water quality

Table des matières

1	Introduction	1
1.1	Contexte	2
1.1.1	Origines et conséquences de la pollution de l'eau	3
1.1.2	Politiques de gestion de la qualité de l'eau potable	5
1.2	Etat de l'art	7
1.2.1	La gouvernance dans les modèles multi-agents de système socio-écologique	8
1.2.2	Comportement des acteurs dans les modèles multi-agents	10
1.3	Questions de recherche	12
2	Governance in social-ecological agent-based models : a review	15
2.1	Introduction	19
2.2	Methods	23
2.2.1	Literature search : protocol and criteria	23
2.2.2	Data extraction and analysis	24
2.3	Results	25
2.3.1	Overview	25
2.3.2	Conceptualisation of governance	28
2.3.3	Implementation of governance : agent-based modelling versus variable-based modelling of governance	35
2.3.4	Governance and interactions in social-ecological agent-based models	40
2.4	Discussion	43
2.4.1	Highlights and limitations	43

2.4.2	Perspectives	46
2.5	Conclusion	49
2.6	Appendix	50
2.6.1	Appendix 1 : List of articles reviewed	50
2.6.2	Appendix 2 : Detailed questionnaire	56
3	Adapting the governance of social–ecological systems to behavioural dynamics : an agent-based model for water quality management using the theory of planned behaviour	65
3.1	Introduction	69
3.2	Conceptual framework	72
3.2.1	Agent-based models of social–ecological water systems	72
3.2.2	Theory of planned behaviour : background and application to farmers’ decision-making in a water system	74
3.3	Agent-based model	76
3.3.1	Resource system	77
3.3.2	Actors	77
3.3.3	Governance	83
3.3.4	Reference scenario	84
3.4	Results	86
3.4.1	Influence of the population characteristics on policy effectiveness	87
3.4.2	Influence of the characteristics of protection programmes on policy effectiveness	90
3.4.3	Mix of policy measures, not the most efficient policies but also not the least	96
3.5	Discussion and Conclusions	98
3.5.1	Contributions and policy implications	98
3.5.2	Limitations and perspectives	99
3.5.3	Concluding remarks	101
3.6	Appendix 1	102

3.7	Appendix 2 : Values of parameters	111
3.8	Appendix 3 : Ecological system sub-model	112
3.9	Appendix 4 : Construction of the social network	113
3.10	Appendix 5 : Calculation of training costs	114
3.11	Appendix 6 : Reference scenario	115
4	The potential of information-related instruments for water quality management in agriculture	117
4.1	Introduction	121
4.2	Conceptual framework	124
4.2.1	Influence of ecological system on the decision-making process in the adoption of farming practices promoted by environmental policies	124
4.2.2	Information instruments to enhance water quality . . .	125
4.3	Model	127
4.3.1	Previous model : TPB-based model of change in farming practices	127
4.3.2	Developments : the environmental component of the attitude and information measures	130
4.4	Results	135
4.4.1	Information-based measures enhance the perception of water quality and raise awareness to involve farmers in protection programmes	136
4.4.2	Impact of the variation in the initial state of the ecological system	141
4.4.3	Influence of heterogeneity in farmers' environmental preferences on the impact of information measures	144
4.5	Discussion and conclusions	152
4.5.1	Contributions and policy implications	152
4.5.2	Limitations and perspectives	153
4.5.3	Concluding remarks	155

5 Conclusion	157
5.1 Synthèse des travaux	157
5.1.1 Principaux résultats de la recherche	157
5.1.2 Apports transversaux	160
5.2 Discussion et perspectives	161
5.2.1 Inversion des comportements	162
5.2.2 L'apprentissage social	164
5.2.3 Mobilisation de données empiriques	165

Table des figures

1.1	Interactions entre la gouvernance, le système écologique et les agriculteurs	14
2.1	Origin of the decision-making process used for actors	31
2.2	Typology of governance and examples from the review of the literature	33
2.3	Types of links between sub-systems	41
3.1	Representation of a drinking water catchment area based on the SES framework and the theory of planned behaviour	75
3.2	Decision model schema based on the theory of planned behaviour	82
3.3	Share of low-input farmers for the reference scenario	85
3.4	Heat map of the final share of low-input farmers depending on the weights of TPB factors	87
3.5	Heat map of the final share of low-input farmers and of the difference between the initial and final share of low-input farmers	89
3.6	Heat map of the final share of low-input farmers	91
3.7	Heat maps of trade-offs between financial compensation and training measure for four populations	93
3.8	Iso-line participation at 90% on average based on training and financial compensation for four populations	95
3.9	Share of low-input farmers depending on financial compensation	97
4.1	Decision model schema based on the TPB	131
4.2	Environmental component of attitude depending on concentration.	133

4.3	Final share of low-input farmers depending on the share of farmers informed	137
4.4	Final share of low-input farmers depending on information providing.	138
4.5	Final share of low-input farmers depending on the awareness threshold.	140
4.6	Final share of low-input farmers and concentration according to the initial concentration.	142
4.7	Share of low-input farmers depending on the concentration of pollutants for three initial concentrations.	143
4.8	Final share of low-input farmers for all farmers depending on the environmental preferences of both groups.	147
4.9	Final share of low-input farmers for group 1 farmers depending on the environmental preferences of both groups.	149
4.10	Average share of low-input farmers and standard deviation depending on the differences between financial preferences of groups.	151

Liste des tableaux

2.1	Number of peer-reviewed publications according to Scopus search terms	26
2.2	Number of articles for each characteristic and in parentheses the percentage of the total per form of governance implemented. . .	37
2.3	A2 : Detailed questionnaire - Overview	56
2.4	A2 : Detailed questionnaire - Governance system variables . . .	56
2.8	A2 : Detailed questionnaire - Agent	60
2.11	A2 : Detailed questionnaire - Links between systems	63
3.1	Measures and their impact on an actor's decision-making . . .	84
3.2	Water parametrisation	111
3.3	Agent parametrisation	111
3.4	Farming practices	111
3.5	Agent variables	115
3.6	Governance system variables	115

Liste des abréviations

AAC	Aire d’Alimentation de Captage
ABM	Agent-Based Model
AES	Agro-Environmental Schemes
CAP	Common Agricultural Policy
CHAN	Coupled Human And Nature
CIEau	Centre d’Information sur l’Eau
DCE	Directive Cadre Eau
EEA	European Environment Agency
EP	environmental preference
EU	European Union
FAO	Food and Agriculture Organization
IAD	Institutional Analysis and Development
MAA	Ministère de l’Agriculture et de l’Alimentaion
MAE	Mesure Agro-Environnementale
MTES	Ministère de la Transition Ecologique et Solidaire
ODD	Overview, Design concepts and Details
OFB	Office Français de la Biodiversité
OIEau	Office International de l’Eau
PAC	Politique Agricole Commune
PCB	Perceived Behavioural Control
RICA	Réseau d’Information Comptable Agricole
SES	Social-Ecological System
SMEA	Syndicat Mixte des Eaux de l’Allier
SSE	Système Socio-Ecologique
TPB	Theory of Planned Behaviour
UE	Union Européenne
WFD	Water Framework Directive

Chapitre 1

Introduction

Préambule

Composante essentielle de tous les êtres vivants, l'eau est un élément indispensable à la vie. Elle permet le fonctionnement biologique des écosystèmes et de l'homme. Elle est également essentielle aux activités économiques, comme le refroidissement des centrales électriques, l'irrigation des cultures, l'alimentation des canaux ou l'industrie. En France, en 2017, la moitié de l'eau douce prélevée était destinée à la production d'énergie, 16% aux canaux de navigation, 8% étaient réservés aux activités industrielles et 9% aux activités agricoles. L'eau prélevée pour alimenter le réseau d'eau potable représente 17% du volume total (MTE, 2020). Les pouvoirs publics prêtent une attention particulière à la qualité de la ressource en eau potable en raison des risques sanitaires associés. L'approvisionnement des citoyens en eau potable de qualité est donc un enjeu de santé publique, auquel s'ajoutent des enjeux environnementaux et économiques (coût de production, traitement et protection).

L'agriculture est l'une des principales menaces pour la qualité de la ressource en eau potable, notamment à cause des pollutions diffuses dans les aires d'alimentation de captages. Des politiques publiques mises en place pour protéger la qualité de l'eau visent particulièrement les pratiques agricoles. Les pro-

grammes de protection des captages vis-à-vis des pollutions diffuses reposent principalement sur la participation volontaire des agriculteurs. Il est crucial de comprendre les déterminants de leur participation et d'analyser comment les programmes de protection peuvent favoriser les changements des pratiques agricoles à l'origine des pollutions.

L'objectif de cette thèse est d'étudier, à l'aide d'un modèle multi-agents, quels sont les impacts de la gouvernance sur l'évolution du système socio-écologique, en prenant en compte les interactions entre les dynamiques comportementales des agriculteurs et les caractéristiques du système écologique. Nous étudions plus particulièrement l'impact des mesures de protection des aires d'alimentation de captages en eau potable sur l'évolution des pratiques agricoles en mobilisant une approche pluridisciplinaire. Nous utilisons un outil de modélisation pour une analyse institutionnelle de la gouvernance dans un système socio-écologique où les comportements des agriculteurs sont opérationnalisés à partir d'une théorie issue de la psychologie sociale.

Dans ce chapitre introductif, nous présentons dans un premier temps le contexte de la protection de l'eau potable en France et dans un second temps comment la gouvernance est prise en compte dans les modèles multi-agents de systèmes socio-écologiques. Enfin, nous présentons les questions de recherche et l'organisation de la thèse.

1.1 Contexte

Dans cette section, nous nous intéressons aux origines et conséquences de la pollution de l'eau (Section 1.1.1) et présentons les principales politiques de gestion des pollutions diffuses d'origine agricole dans le contexte français (Section 1.1.2).

1.1.1 Origines et conséquences de la pollution de l'eau

Les différents types de pollution de l'eau et leurs conséquences

Les ressources mondiales en eau douce font face à différentes sources de pollution : les déchets organiques, les pathogènes, les fertilisants et les pesticides, les métaux lourds ou les polluants émergents (PROGRAMME MONDIAL POUR L'ÉVALUATION DES RESSOURCES EN EAU, 2020). La pollution industrielle correspond à des rejets de produits chimiques comme les hydrocarbures ou le polychlorobiphényle (PCB) qui polluent les cours d'eau et nappes phréatiques à cause notamment des eaux évacuées par les usines ou à des pollutions accidentelles de produits toxiques dans le milieu naturel (CIEAU, 2021). La pollution domestique contribue également à la dégradation de la qualité de l'eau. Elle est issue des eaux usées dans lesquelles se retrouvent des produits d'entretiens, des produits cosmétiques, des peintures, solvants, etc. Enfin, l'agriculture est l'une des causes majeures de la pollution au travers de l'épandage de déjections animales et l'utilisation de produits phytosanitaires et fertilisants.

Les conséquences de la pollution de l'eau sont multiples : sanitaires, économiques, sociales et environnementales. Tout d'abord, l'eau potable fait partie des besoins humains de base, une mauvaise qualité de celle-ci pouvant entraîner des infections microbiennes et des intoxications par des substances chimiques. Elle est responsable de la mort de 1 250 000 personnes dans le monde en 2016 (PROGRAMME MONDIAL POUR L'ÉVALUATION DES RESSOURCES EN EAU, 2020). La pollution de l'eau entraîne également la dégradation des écosystèmes qui a non seulement des conséquences environnementales avec la perte de biodiversité mais également des répercussions économiques et sociales. La pollution contribue à la diminution des services écosystémiques liés à l'eau, comme l'épuration des eaux, le captage et le stockage de carbone et la protection naturelle contre les inondations, rendant les sociétés plus vulnérables aux risques environnementaux. De plus, la mauvaise qualité de l'eau impacte le coût de traitement de l'eau potable. A titre d'exemple, en France, le respect des normes de qualité pour la production d'eau potable via la réalisation de traitements ou la

recherche de nouvelles ressources induit un surcoût estimé à entre 6,6 et 11,8% de la facture d'eau des ménages (BOMMELAER et al., 2011).

Pollutions diffuses d'origine agricole de la ressource en eau

Les captages sont des ouvrages de prélèvement exploitant une ressource en eau et alimentant le réseau d'eau potable. En France, 33500 captages sont en service où 66% du volume d'eau prélevée provient des eaux souterraines et 34% des eaux de surface. Parmi eux, 3000 sont jugés dégradés, principalement du fait de pollutions d'origine agricole. Les deux principaux polluants issus de l'activité agricole sont les nitrates et les pesticides. Ces pollutions représentent la principale cause de fermeture de captages en France avec 39% des fermetures entre 1994 et 2013 (OIEAU, 2020). En effet, les agriculteurs utilisent des fertilisants pour favoriser la croissance des végétaux et des pesticides pour lutter contre les organismes considérés comme nuisibles. Ces substances sont répandues sur les sols et sur les plantes mais ne sont pas complètement assimilées. Elles vont donc ensuite en partie s'infiltrer ou ruisseler et contaminer les cours d'eau et les eaux souterraines.

Les nitrates proviennent de la fertilisation azotée basée sur l'utilisation de produits de synthèse ou sur des apports d'engrais organiques (effluents d'élevage, boues de stations d'épuration, etc.). Une présence excessive de nitrates dans les cours d'eau favorise leur eutrophisation, c'est-à-dire un déséquilibre de l'écosystème aquatique. A partir d'un certain seuil, le nitrate rend l'eau impropre à la consommation. Ce seuil correspond à une norme de qualité environnementale qui ne doit pas être dépassée afin de protéger la santé humaine et l'environnement (LÉGI-FRANCE, 2009). Il correspond à une concentration inférieure à 50mg/l pour les nitrates. En 2018, 5% des eaux souterraines du réseau de suivi de la qualité de l'eau excédaient cette norme et 34% excédaient la valeur préconisée par l'Union Européenne (UE) (25mg/l) (SDES et al., 2020).

Les pesticides sont également présents dans les cours d'eau et dans les eaux souterraines. En 2018, dans près de 80% des 2340 points de mesures des réseaux

de surveillance de la qualité des eaux souterraines, au moins un pesticide était présent (sur 760 substances phytopharmaceutiques recherchées). Dans 35% des cas, les concentrations dépassaient la norme de qualité pour le total en pesticides et dans 47% des cas, la norme de qualité était dépassée pour au moins une substance (SDES et al., 2020).

Les pesticides et les nitrates sont les substances responsables du plus grand nombre de déclassements des masses d'eau dans le cadre de l'évaluation de leur état chimique prévue par la directive-cadre européenne sur l'eau (SDES et al., 2020).

1.1.2 Politiques de gestion de la qualité de l'eau potable

La protection de l'eau potable des pollutions diffuses d'origine agricole dans le contexte français est structurée depuis quelques années par les cadres réglementaires européen et national. Dans la première partie de cette section, nous présentons les politiques européennes qui encadrent la gestion de la qualité de l'eau. Dans la seconde partie, nous nous attardons sur la politique de protection des captages en France.

Cadre européen

Plusieurs politiques en Europe ont été mises en place ces dernières décennies pour protéger l'ensemble des masses d'eau. La directive Nitrates a été adoptée en 1991 par les pays européens dans le but de réduire la pollution des eaux par les nitrates issus des activités agricoles et de prévenir l'extension de ces pollutions (EUROPÉENNE, 2010). Sa mise en œuvre se traduit dans chaque pays par la délimitation de zones vulnérables aux nitrates où des programmes d'action spécifiques sont mis en place. Ces programmes d'action, renouvelés tous les 4 ans, incluent notamment une mesure qui impose un apport maximal en azote organique de 170 kg/ha.

En 2000, la directive-cadre sur l'eau (DCE) a été adoptée par l'UE (UE,

2000). Elle vise à prévenir et à réduire la pollution de l'eau, à promouvoir son utilisation durable, à protéger l'environnement, à améliorer l'état des écosystèmes aquatiques et à atténuer les effets des inondations et de la sécheresse (MTE, 2021). L'objectif d'atteindre un « bon état » (défini par la DCE comme un bon état écologique, chimique et quantitatif) des masses d'eau passe notamment par la mise en place de programmes de protection visant l'agriculture.

Les MAE à « enjeu eau » dont l'objectif est la préservation de la qualité de l'eau comptent également parmi les mesures visant spécifiquement les pratiques agricoles (VILLIEN et al., 2012). Ce sont des contrats de cinq ans prévoyant l'adoption, par les agriculteurs, de pratiques favorables à la qualité de l'eau, en échange de compensations financières. Les MAE sont apparues dans la politique agricole commune (PAC) depuis la première réforme en 1985 et ont beaucoup évolué par la suite avec la montée de l'intérêt pour l'environnement (GASSIAT et al., 2013). Les MAE peuvent être élaborées en soutien à d'autres politiques, comme appuyer la mise en œuvre de la Directive Cadre sur l'Eau (DCE). Elles font partie des outils de la politique de protection des captages en France.

La politique de protection des captages en France

En France, la protection de la qualité de l'eau se déroule notamment dans le cadre du Grenelle de l'environnement lancé en 2007 qui a réaffirmé l'objectif de la DCE (MTE, 2020). L'un des objectifs du Grenelle était de réduire la pollution d'origine agricole, en particulier les pollutions par les produits phytosanitaires et les nitrates. Une première étape a consisté à identifier un ensemble de captages prioritaires correspondant aux captages les plus menacés par les pollutions diffuses ou dont la ressource avait une importance stratégique (en termes de nombre d'habitants dépendant de la ressource ou d'absence de solutions palliatives). Plus de 500 captages prioritaires ont été identifiés dans un premier temps, auxquels 500 autres ont été ajoutés suite à la conférence environnementale de 2013 (OIEAU et OFB, 2017). Les démarches de protection de ces captages incluent une étape de caractérisation de l'état initial de

la ressource et de délimitation des aires d'alimentation de captages (AAC), c'est-à-dire une délimitation des zones sur lesquelles l'eau qui s'infiltré et qui ruisselle alimente le captage. Sur la base de la délimitation de ces AAC et de l'identification des types de transfert et des activités mises en jeu dans la contamination, des mesures de protection sont mises en œuvre avec pour objectif d'améliorer la qualité de la ressource en eau potable.

Les mesures de protection ciblant les agriculteurs visent à changer leurs pratiques de fertilisation et d'utilisation des intrants phytosanitaires pour des pratiques plus favorables à la qualité de l'eau. La mise en œuvre des actions repose sur la participation volontaire des agriculteurs. Or l'efficacité environnementale des mesures dépend du taux de participation des agriculteurs (DUPRAZ et al., 2007). La participation des agriculteurs est donc une dimension importante de la mise en œuvre de ces mesures. Plusieurs études ont montré que le taux de participation des agriculteurs constituait une contrainte à la mise en œuvre des programmes de protection des captages. Par exemple, dans une étude de l'Assemblée Permanente des Chambres d'Agriculture sur des actions territoriales pour la protection de la ressource en eau, la mobilisation des agriculteurs dans les démarches de protection des AAC est l'une des limites régulièrement décrites (CHAMBRES D'AGRICULTURE, 2018). Le taux de participation des agriculteurs est également faible dans le cas de MAE à « enjeu eau » utilisées dans certaines démarches de protection de captages, notamment pour les mesures impliquant un changement de pratique (CARVIN et al., 2020).

1.2 Modélisation multi-agents de la gouvernance et des processus de décision des acteurs dans les systèmes socio-écologiques

La compréhension des facteurs influençant la participation des agriculteurs aux démarches de protection est un enjeu essentiel de la définition des pro-

grammes de protection des captages en eau potable. Les aires d'alimentation de captages (AAC) peuvent être définies comme des systèmes socio-écologiques (SSE) où interagissent un système écologique (le bassin versant et la ressource en eau) et un système social (composé des acteurs présents dans l'AAC et d'un système de gouvernance). Les SSE sont invariablement dynamiques et complexes en raison des interdépendances non linéaires entre les systèmes écologiques et sociaux et de l'émergence d'effets à l'échelle macroscopique découlant du comportement individuel des acteurs (ANDERIES et al., 2019; MATHIAS, ANDERIES et al., 2020). Pour cette raison, les outils basés sur la simulation, comme la modélisation multi-agents, sont particulièrement pertinents pour améliorer la compréhension des processus conduisant à la durabilité des SSE en tant que systèmes adaptatifs complexes (MÜLLER-HANSEN et al., 2017; SCHULZE et al., 2017). Dans un premier temps, nous présentons comment la gouvernance est prise en compte dans la modélisation multi-agents de SSE. Dans un second temps, nous présentons les comportements des agriculteurs dans le cadre de mise en place de politiques agro-environnementales et leur prise en compte dans les modèles.

1.2.1 La gouvernance dans les modèles multi-agents de système socio-écologique

Un modèle multi-agents est un ensemble d'agents aux caractéristiques hétérogènes, situés dans un environnement, partageant des ressources communes et interagissant ensemble. Les agents sont des entités autonomes qui perçoivent partiellement leur environnement et peuvent agir dessus. Ils se coordonnent, prennent des décisions et communiquent (FERBER et al., 1995). Au départ, les modèles multi-agents ont été utilisés en intelligence artificielle, puis leur domaine d'application s'est étendu aux sciences sociales. Parmi les différentes approches de modélisation, les modèles multi-agents sont bien adaptés à l'étude des SSE et à l'exploration des interactions et du comportement collectif qui en résulte (GOTTS et al., 2018). Ce sont des outils dynamiques qui mettent en évi-

dence les rétroactions qui se produisent dans les SSE (HECKBERT et al., 2010 ; JANSSEN, ALESSA et al., 2008 ; SCHULZE et al., 2017). Ils offrent la possibilité de modéliser notamment des représentations, des modes de communication, des interactions, des processus de décision. Les résultats à l'échelle du système émergent de ces interactions individuelles.

En particulier, les modèles multi-agents sont utilisés pour simuler la gestion des ressources naturelles. Ils sont utiles non seulement pour analyser les SSE ou prédire les impacts de la gestion (ROUNSEVELL et al., 2012 ; SCHULZE et al., 2017), mais aussi pour mettre en évidence les comportements émergents résultant de la dynamique de la gouvernance. Ils ont un grand potentiel dans ce domaine, car ils permettent la compréhension des impacts de la gouvernance sur un système complexe qui met en jeu des dynamiques sociales et biophysiques. L'intérêt de l'utilisation des modèles multi-agents pour étudier la gouvernance est renforcé par l'intérêt croissant porté à l'analyse et la prise en compte de la gouvernance dans le domaine des SSE (HERRERO-JÁUREGUI et al., 2018). Elle est l'un des quatre sous-systèmes mis en exergue dans le cadre des Systèmes Socio-Ecologiques (Social-Ecological System Framework) d'Ostrom (2009). Aussi, le système de gouvernance fait partie de la définition du concept de SSE (GLASER et al., 2008 ; HERRERO-JÁUREGUI et al., 2018).

Les modèles multi-agents sont donc des outils pertinents pour l'étude de la gouvernance dans les SSE. Cependant, la plupart des revues sur les modèles de SSE traitant du système social se sont concentrés sur les acteurs et non sur la gouvernance (e.g. AN, 2012 ; GROENEVELD et al., 2017 ; MÜLLER-HANSEN et al., 2017 ; HUBER, BAKKER et al., 2018 ; SCHULZE et al., 2017 ; KREMMYDAS et al., 2018). La manière dont la gouvernance est conceptualisée et opérationnalisée dans les modèles agents de SSE est mal connue.

1.2.2 Comportement des acteurs dans les modèles multi-agents

Les systèmes de gouvernance influencent le comportement des individus d'où la nécessité de comprendre les processus de décision des acteurs. La représentation de la prise de décision dans les modèles multi-agents est basée sur des hypothèses concernant le comportement des humains, par exemple, leur rationalité ou leur capacité cognitive (SECCHI, 2017 ; DEANGELIS et al., 2019). Il s'agit d'un élément clef et une représentation de la prise de décision adaptée à l'objectif du modèle est un prérequis pour les modèles intégrant la gouvernance (SCHULZE et al., 2017).

Les modèles de processus de prise de décision peuvent s'appuyer sur des études empiriques ou sur des théories existantes. Plusieurs auteurs ont déjà examiné et analysé la diversité des représentations des processus de prise de décision. AN (2012) s'est intéressé aux modèles de décision utilisés dans les simulations de la dynamique des systèmes couplés homme-nature, et MÜLLER-HANSEN et al. (2017) au comportement humain et à la prise de décision dans les modèles du système terrestre. La prise de décision des agriculteurs a été étudiée dans des modèles-agents d'utilisation des terres (GROENEVELD et al., 2017), dans des modèles multi-agents agricoles européens (HUBER, BAKKER et al., 2018) et dans la modélisation pour l'évaluation des politiques agricoles (KREMMYDAS et al., 2018).

La littérature sur la gouvernance des SSE mobilise un grand nombre de théories comportementales (SCHLÜTER, BAEZA et al., 2017). Pourtant, les revues citées précédemment (AN, 2012 ; GROENEVELD et al., 2017 ; MÜLLER-HANSEN et al., 2017 ; KREMMYDAS et al., 2018) montrent que la diversité des processus de décision modélisés est relativement faible et utilise peu de théories comportementales différentes. Dans la plupart des modèles multi-agents, le modèle de prise de décision est fondé sur la théorie du choix rationnel (AN, 2012) et la prise de décision de l'agent est souvent basée sur des hypothèses simples (JAGER et al., 2000). SCHLÜTER, BAEZA et al. (2017) ont identifié les multiples

verrous de la mise en œuvre dans les modèles de théories alternatives du comportement humain et de la prise de décision : (1) dépasser les difficultés dues à la collaboration multidisciplinaire ; (2) améliorer les connaissances sur les théories utiles et utilisables dans les contextes de SSE ; et (3) opérationnaliser les théories.

L'une des approches en sciences sociales les plus couramment utilisées pour décrire les comportements des individus est la théorie du comportement planifié. Plus particulièrement, elle est l'une des plus utilisées pour comprendre la prise de décision des agriculteurs en ce qui concerne l'adoption de pratiques agricoles durables (TOMA et al., 2007). Cette théorie a déjà été utilisé dans le cadre de modèles multi-agents pour étudier la diffusion des technologies parmi les ménages (SCHWARZ et ERNST, 2009 ; GAMAL ABOELMAGED, 2010 ; ROBINSON et al., 2015 ; SCHWARZ, KUHN et al., 2016), la prise de décision des agriculteurs (KAUFMANN et al., 2009), les choix de mode de vie sain (RICHETIN et al., 2010), le recyclage des déchets (CESCHI et al., 2015), l'adoption de mesures de sécurité alimentaire (VERWAART et al., 2011) ou le comportement en matière de circulation (S. C. ROBERTS et al., 2012 ; YU et al., 2014). Cependant, l'utilisation de cette théorie reste limitée, notamment en ce qui concerne la représentation des comportements des agriculteurs dans ce type de modèles. SCALCO et al. (2018) et MUELDER et al. (2018) concluent que la théorie du comportement planifié utilisée dans les modèles multi-agents peut offrir un modèle utile de processus décisionnel délibératif pour les agents virtuels, tout en soulignant les défis de sa mise en œuvre dans le modèle, comme les choix d'architecture du modèle, des facteurs affectant la décision ou de la représentation de mécanismes de rétroactions.

1.3 Questions de recherche et organisation de la thèse

Dans cette thèse, nous proposons d'étudier l'impact de programmes de protection des AAC sur l'évolution des pratiques agricoles sur la base d'une approche pluridisciplinaire. Nous utilisons un modèle multi-agents pour analyser la gouvernance dans un système socio-écologique où les comportements des agriculteurs sont décrits grâce à la théorie du comportement planifié.

L'objectif de cette thèse est d'analyser quels sont les impacts de la gouvernance sur l'évolution des pratiques agricoles, en prenant en compte les interactions entre les dynamiques comportementales des agriculteurs et les facteurs du système écologique (voir Figure 1.1). Plus particulièrement, nous répondons aux questions de recherche suivantes :

- *Comment la gouvernance est-elle conceptualisée et mise en œuvre dans les modèles multi-agents de systèmes socio-écologiques ?* Nous réalisons un état de l'art sur la gouvernance dans les modèles multi-agents des SSE. Nous nous intéressons plus particulièrement aux apports et perspectives de ce champ de recherche.

- *Comment les interactions entre les facteurs comportementaux influencent-elles l'efficacité et l'efficience de programmes de protection de la ressource en eau potable ?* Nous nous intéressons plus particulièrement à l'effet des caractéristiques comportementales des agriculteurs, de leurs interactions et des caractéristiques des mesures mises en œuvre sur l'efficacité et l'efficience des programmes.

- *Comment une mesure d'information sur le système écologique agit-elle sur l'évolution des pratiques des agriculteurs ?* Nous nous intéressons particulièrement à l'effet de l'information sur le niveau de pollution de l'eau, ses causes et conséquences, en interaction avec les préférences environnementales des agriculteurs et l'état initial du système écologique.

La première question de recherche a été traitée en réalisant une revue de la littérature des articles qui décrivent un modèle multi-agents d'un système socio-écologique représentant un système de gouvernance. Cette revue de littérature est présentée dans le **Chapitre 2**. Elle nous permet de mettre en exergue les apports et les manques de cette littérature. En particulier, notre revue montre que peu de théories de la gouvernance sont mobilisées et que les processus de prise de décision imbriqués dans la gouvernance sont souvent représentés de manière simplifiée, bien que ceux-ci soient cruciaux pour analyser les impacts de différents modes de gouvernance.

Cet état de l'art nous a permis de proposer un modèle qui a pour objectif de répondre en partie aux défis identifiés par la revue. Nous avons choisi d'utiliser un cadre conceptuel pour représenter le système socio-écologique et la gouvernance, et d'opérationnaliser la théorie du comportement planifié pour modéliser le processus de décision des agriculteurs. Dans le **Chapitre 3**, nous présentons un modèle multi-agents d'une AAC. Les résultats des simulations de ce modèle ont permis de traiter la seconde question de recherche. Dans ce modèle, des agriculteurs, appartenant à un réseau social, ont le choix entre deux pratiques, une pratique polluante et une pratique favorable à la qualité de l'eau. Un système de gouvernance est représenté dans le modèle comme mobilisant des incitations financières et de une mesure de formation afin d'inciter les agriculteurs à adopter une pratique agricole favorable à la qualité de l'eau. Les simulations réalisées mettent en exergue que l'impact du système de gouvernance sur la pollution de l'eau dépend des caractéristiques des agriculteurs et des interactions entre agriculteurs.

Le modèle présenté dans le **Chapitre 4**, basé sur le modèle précédent, nous a permis de répondre à la dernière question de recherche. Ce modèle intègre une interaction entre les agriculteurs, le système écologique et la gouvernance. Il a pour objectif de prendre en compte l'impact de l'état du système écologique sur les interactions au sein du SSE. L'état du système écologique entre ainsi dans

le processus de décision des agriculteurs. Le système de gouvernance inclut une mesure d'information des agriculteurs sur le niveau de pollution de l'eau ainsi que les causes et conséquences de cette pollution. L'information est considérée comme un instrument important dans les programmes environnementaux visant à modifier les pratiques des agriculteurs. Les simulations permettent de mettre en évidence le rôle positif de tels instruments d'information dans la gestion de la qualité de l'eau.

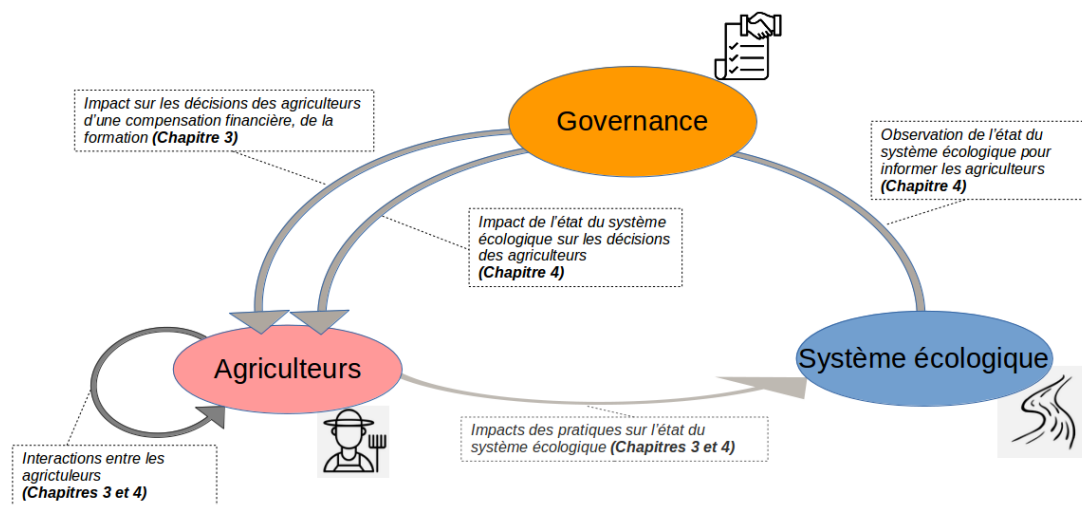


FIGURE 1.1 – Interactions entre la gouvernance, le système écologique et les agriculteurs représentées dans les différents chapitres

Chapitre 2

Governance in social-ecological agent-based models : a review

Article accepté : Cet article a été accepté pour être publié dans la revue
Ecology and Society (le 26/03/2021).

Objectif L'objectif de ce chapitre est de mieux comprendre comment la gouvernance est modélisée dans les modèles multi-agents de systèmes socio-écologiques. Pour cela, nous avons fait une revue de littérature. Les résultats de cette revue nous ont servi à faire nos choix pour construire les modèles présentés dans les Chapitres 3 et 4.

Contributions Cette revue fournit un aperçu détaillé de la conceptualisation et de la mise en œuvre de la gouvernance dans les modèles multi-agents de SES et met en évidence les apports et limites de la littérature existante ainsi que les perspectives de recherche. Nous nous sommes d'abord concentrés sur la conceptualisation de la gouvernance : (1) quelles sont les théories mobilisées pour la modélisation de la gouvernance et la prise de décision des acteurs et (2) quels liens existent entre la conceptualisation de la gouvernance et la formalisation des processus de prise de décision ? L'objectif était de caractériser la diversité des théories employées, de mettre en évidence les liens entre celles-ci et les théories du comportement des acteurs. De plus, il s'agit de décrire les types de gouvernance et de processus décisionnels utilisés. Dans un deuxième temps, nous nous sommes intéressés à la mise en œuvre de la gouvernance dans les modèles de SSE. Nous avons notamment cherché à identifier les différentes formes de mise en œuvre et leurs implications en termes de conceptualisation de la gouvernance, des liens entre la gouvernance et les autres systèmes et la diversité des agents. Enfin, la dernière partie vise à caractériser la représentation des liens - tant les types de lien que leur direction - entre le système de gouvernance, le système écologique et le système d'acteurs.

Résultats Les conclusions de ce chapitre sont les suivantes : (1) nous soulignons qu'une part importante de la littérature ne repose pas explicitement sur des théories permettant de justifier la modélisation des processus de gouvernance et de prise de décision des acteurs ; (2) nous soulignons que les institutions, bien qu'importantes dans le domaine des SSE, sont rarement représentées par rapport aux autres modes de gouvernance. Les modes de gouvernance qui sont le plus souvent modélisés sont les interventions de l'État, tandis que les

modes de gouvernance basés sur les collectifs d'usagers et le marché sont peu représentés; (3) nous donnons un aperçu de la manière dont les interactions entre la gouvernance et les autres systèmes au sein d'un SES sont opérationnalisées dans les modèles multi-agents; (4) nous distinguons deux types de mise en œuvre de la gouvernance : la mise en œuvre basée sur les agents et la mise en œuvre basée sur des variables. Les modèles correspondants diffèrent en termes de cadre théorique, de types de modes de gouvernance représentés ou de présence d'interactions.

Abstract Analysing governance is particularly important for understanding and managing social-ecological systems (SES). Governance systems influence interactions between actors and the ecological system and are in turn influenced by the changes that occur in the actors' and ecological systems. Agent-based models (ABM) are well adapted for studying SES, for exploring interactions and the resulting collective behaviour and for predicting the results of management processes. Considering the potential of ABM to analyse SES, we performed a literature review of the modelling of governance in ABM of SES and highlight the perspectives and challenges surrounding this issue. Our results show in particular that a significant share of the literature is not explicitly based on theories supporting the modelling of governance and actors' decision-making. Regarding the conceptualisation of governance, formal and informal institutions are rarely represented compared with diverse modes of governance. The governance modes that are mostly modelled are state interventions while the community-based and market-based modes of governance are scarcely represented. Finally, the overview of how interactions between governance and SES are operationalised in ABM highlights two main forms of implementation of governance : variable-based and agent-based implementations. The corresponding sets of models differ in terms of main theoretical background, types of governance modes represented or presence of interactions. Therefore, we recommend moving towards a greater diversity in the representation of governance and towards a better implementation of the dynamics of models, which can be facilitated by the explicit use of theories supporting the modelling of governance and the decision-making of actors and by the representation of governance as an agent.

2.1 Introduction

Social-ecological systems (SES) are tightly linked units of humans and nature in mutual interaction (BERKES, COLDING et al., 2003). Examples of SES include fisheries (SCHLÜTER, HINKEL et al., 2014), agricultural and food

systems (RIVERA-FERRE et al., 2013), forests (FISCHER, 2018) or landscapes (DUGUMA et al., 2015). Because they are essential for humanity, interest in these systems and in their governance has grown significantly. Indeed, the rise in tensions between the ecological and social worlds has become of increasing concern : water pollution, loss of biodiversity, sea level rise, increase in global epidemics, spread of pests, and deforestation (FAO, 2011).

Whereas social and ecological systems were usually studied separately, more and more studies are now focussing on both systems in an integrated way (e.g., POLLNAC et al., 2010 ; CINNER et al., 2012 ; ZHANG et al., 2013 ; MARTÍN-LÓPEZ et al., 2015 ; SCHOON et al., 2015). To understand and analyse these complex interacting systems, a study of governance is particularly important to help identify adequate management options (E. OSTROM, 2007). Governance "is [a] process by which the repertoire of rules, norms, and strategies that guide behaviour within a given realm of policy interactions are formed, applied, interpreted, and reformed" (MCGINNIS, 2011). Different types of governance are characterised in the diverse fields and approaches of social sciences, e.g., polycentric and monocentric governance, market-based governance, self-governance or democratic administration (E. OSTROM, 2010 ; MCGINNIS, 2011 ; CARLISLE et al., 2019). In this paper, we focus in particular on informal institutions, formal institutions and modes of governance, following WILLIAMSON (2000).

Governance forms part of the social system together with individual actors, groups of actors and organisations. The analysis of governance involves studying this social system and the feedback between the social system and the ecological system. Indeed, governance systems influence the behaviour of individuals or groups, and individuals or groups choose modes of governance, thus making it necessary to understand how these individuals or groups behave. Moreover, governance systems can have a direct impact on other systems as well as indirect impacts that require prior understanding of the links between systems in order to characterise the effects of governance. Therefore, to analyse governance in SES one has to consider its characteristics and to exa-

mine the actors and the links between the ecological system, the actors and the governance system.

Because SES are invariably dynamic and complex due to non-linear interdependencies between ecological and social systems and to the emergence of macro-scale effect arising from individual behaviour (ANDERIES et al., 2019; MATHIAS, ANDERIES et al., 2020), simulation-based tools are particularly relevant for improving our understanding of the factors and processes leading to the sustainability of SES as complex adaptive systems (MÜLLER-HANSEN et al., 2017; SCHULZE et al., 2017). These tools can also be used for management or decision support in an uncertain context, taking into account the evolutionary nature of SES and examining various possible strategies (ROUNSEVELL et al., 2012; FILATOVA et al., 2013; ANDERIES et al., 2019). In particular, studying governance in SES modelling is important. First, although many studies in the field of SES modelling have examined human–environment interactions, the focus has been on understanding the ecological rather than the social dynamics, and several authors now stress the importance of a better representation of the social system (GROENEVELD et al., 2017; SCHULZE et al., 2017). While governance is an important part of the social system, most reviews of SES models dealing with the social system focused on actors and not on governance. Second, governance is the subject of growing interest in the SES field (HERRERO-JÁUREGUI et al., 2018) : Research on SES increasingly focusses on governance and the definitions of SES take into account the role of institutions and governance (e.g., GLASER et al., 2008).

Among the different approaches in modelling, agent-based models (ABM) are well adapted for studying SES and for exploring interactions and the resulting collective behaviour (GOTTS et al., 2018). They are dynamic tools that highlight SES feedback (HECKBERT et al., 2010; JANSSEN, ALESSA et al., 2008; SCHULZE et al., 2017). ABM are computational systems with autonomous entities (agents) in an environment. Agents with heterogeneous characteristics have a dynamic behaviour and interact with each other and with the environ-

ment. Outcomes at the system scale emerge from these individual interactions. ABM are useful not only for analysing SES or predicting management results (ROUNSEVELL et al., 2012; SCHULZE et al., 2017), but also for highlighting emergent behaviour resulting from governance dynamics.

Several reviews have shown the relevance of ABM in studying SES, with a focus on the decision-making processes of the actors (AN, 2012; GROENEVELD et al., 2017; MÜLLER-HANSEN et al., 2017; HUBER, BAKKER et al., 2018), on the transparency and comprehensiveness of the models (SCHULZE et al., 2017) or on their initialisation (KREMMYDAS et al., 2018). JANSSEN et E. OSTROM (2006) have analysed the challenges related to ABM for the study of governance in SES, focussing on the conditions under which cooperative solutions are sustained. Nevertheless, their review is not focused on describing the modes of governance represented in ABM and their implementation. To the best of our knowledge, no review has concentrated specifically on the formalisation of the governance component, from conceptualisation to implementation, and the interactions between governance, actors and the ecological system. Thus, considering the potential of ABM to analyse SES, our paper aims at providing a review of the modelling of governance in social-ecological ABM and at highlighting the perspectives and challenges surrounding this issue. The review provides an initial entry point for agent-based modellers and the broader community of SES modellers with an overview of how the SES ABM integrate governance. Furthermore, the review is more generally of interest to researchers working on SES governance, as it discusses the potential of ABM in analysing governance of SES.

The objective of the paper is pursued by adopting a literature review approach. After describing the methodology used in this study, we present the results of the review, focusing on the conceptualisation of governance, on its implementation and on the links between governance and other systems within the SES. Finally, we discuss the findings and offer a conclusion : (1) We emphasise that a significant share of the literature is not explicitly based on

theories to support the modelling of governance processes and interactions or actor decision-making. (2) Moreover, we underline that institutions, although important in the field of SES, are scarcely modelled and that the governance modes that are mostly modelled are state interventions, while community-based and market-based modes of governance are rarely represented. Finally, we provide (3) an overview of how interactions between governance and other systems within an SES are operationalised in ABM and (4) highlight two types of implementation of governance : agent-based and variable-based implementation. The corresponding sets of models differ in terms of the main theoretical background, the types of governance modes represented or the presence of interactions.

2.2 Methods

2.2.1 Literature search : protocol and criteria

We conducted a review of the peer-reviewed literature identified in the database Scopus (<https://www.scopus.com>). We limited the literature reviewed to published articles and articles in press written in English. The articles selected include in their title, abstract or keywords one or more terms from each of the following groups : (1) “ABM” group : terms linked to agent-based modelling; (2) “SES” group : terms linked to social-ecological systems; and 3) “GOV” group : terms linked to governance. In the "ABM" group, terms were "agent-based", "multi-agent", "agent based", “multiagent” or “abm”. We focus only on models self-identified by authors as applying to an SES. We followed HERRERO-JÁUREGUI et al. (2018) describing the literature on SES and SCHULZE et al. (2017) reviewing ABM of SES to define our search command. Thus, the “SES” group includes the terms “socio-ecological”, “social-ecological” and “socio-ecosystem”. The set of terms for the “GOV” group was established in an iterative way. We first conducted a search with the “ABM” and “SES” groups and found 172 documents. We then established a list highlighting terms

related to governance with the highest occurrence. On this basis, the “GOV” group includes “govern”, “manag”, “rule”, “institution”, “polit” and “polic” in the final search command in Scopus :

```
TITLE-ABS-KEY ( ( ( "agent-based" ) OR ( "multi-agent" ) OR
abm OR ( "agent based" ) OR ( "multi agent" ) ) AND ( ( "social-
ecological" ) OR ( "socio-ecological" ) OR ( "socio-ecosystem" )
OR ( "human-environment" ) ) AND (govern* OR manag* OR
institution* OR polic* OR rule* OR polit* ) ) AND DOCTYPE
( ar ) AND ( LIMIT-TO ( LANGUAGE , "English" ) )
```

We compiled a list of 128 documents (on 19/10/2020), and refined the list based on the following criteria :

- *Criterion 1* : inclusion of an agent-based model. We selected only articles that describe an agent-based model and excluded reviews, frameworks, software or cyber-infrastructure descriptions. Thus, 35 articles were excluded.
- *Criterion 2* : inclusion of a governance component in the model. We excluded articles that do not have a governance component in their model. Thus, 47 articles were excluded.

At the end of the process, 45 articles were selected for the analysis (an article was removed because of too many difficulties to code it, see Appendix 2.1 for the list of selected articles).

2.2.2 Data extraction and analysis

As a guideline for the analysis, we focussed on how governance is conceptualised, formalised, implemented and linked to other systems in social–ecological ABM. We first concentrated on the conceptualisation of governance : (1) what are the theories underlying the modelling of governance and actors’ decision-making and (2) which links exist between the conceptualisation of governance, algorithms and the factors influencing the decision-making process? The aim

was to characterise the diversity of theories employed, to highlight the links between them and the theories of actors' decision-making processes and to describe the types of governance and decision-making processes used. Second, we focussed on the implementation of governance in SES models. We especially aimed to identify the different forms of implementation and to observe differences and similarities regarding the conceptualisation of governance, its links with other systems and the diversity of agents. Finally, the last part concerns the links – both the types and the direction – between systems. The objective was to describe and quantify these links.

To gather all the information needed to examine these issues, we created a transversal questionnaire following three axes : the representation of governance, the description of the diverse decision-making processes of actors, and the links between the ecological systems, the governance system and the actors (see Appendix for the detailed questionnaire).

We read the full texts of the selected articles and coded them. The first part of the coding frame is based on overview criteria such as source, year of publication, subject, type of research. The second part is developed on the basis of the aforementioned questions. All co-authors tested the questionnaire on eight articles to make the coding robust. Disagreement on certain responses allowed us to clarify the questions and response items and thus to improve the coding.

2.3 Results

2.3.1 Overview

Occurrence of governance in the selected literature

More than one quarter of the articles presenting an AMB for SES (“ABM” + “SES” command) do not provide any reference to governance, management or public policies (see Table 2.1). Moreover, one third of the articles in the

final search command (“SES” + “ABM” + “GOV” command) were excluded because they did not ultimately integrate governance (see previous section, “Literature search : protocol and criteria”). A close examination of these articles that were excluded reveals that the models are proposed to support governance, public policy decision-making or systems management but do not integrate governance in the model.

Search terms or commands	Publication counts
SES command	9503
social-ecological	5871
socio-ecological	3772
Socio-ecosystem	65
socioecosystem	12
GOV command	5201077
govern*	881440
manag*	2807633
institution*	667504
polic*	1000717
rule*	493502
polit*	510301
ABM command	39669
ABM and SES command	172
ABM and GOV command	11930
SES and GOV command	6542
SES and GOV and ABM command	128

TABLE 2.1 – Number of peer-reviewed publications according to Scopus search terms (on 19/10/2020). As per normal Boolean search rules, the specific phrase within quotation marks will be found and an asterisk will highlight any word that begins with the root/stem of the word truncated by the asterisk.

According to HERRERO-JÁUREGUI et al. (2018), "governance" is one of the ten most frequently used keywords in SES articles (articles found in Scopus with the terms "socio-ecosystem", "social-ecological system", "socio-ecological system"). However, the term is not one of the most frequently used keywords in the papers reviewed. Still, the inclusion of diverse terms used to describe governance in our search command (the "GOV" search command includes "govern", "manag", "rule", "institution", "polit" and "polic") allowed us to identify the papers that include a governance component but do not refer to the "governance" keyword.

Sources

The journals with the highest number of publications in our set of articles are 'Environmental Modelling and Software' and 'Ecology and Society'. These journals are interdisciplinary, which highlights the specificity of the subject studied (governance and modelling of SES). Almost 80% of the articles are published in interdisciplinary journals, related to environmental management, land use and agricultural policy. The most frequently cited sources are also Environmental Modelling and Software and Ecology and Society. Although these journals aim to be interdisciplinary, they are mainly anchored in the fields of ecology, ecological modelling and environmental engineering (source : SCImago Journal Rank). This is in line with the results of HERRERO-JÁUREGUI et al. (2018), according to whom 62% of SES studies are conducted by researchers whose primary field lies in the natural sciences, while 30% of studies are conducted by social scientists. Additionally, our research focusses on articles using formal models. It explains, for example, why the International Journal of the Commons, an interdisciplinary journal dedicated to furthering the understanding of institutions for the use and management of resources that are (or could be) used collectively, although well suited to our subject and embedded in the SES research community, is not present in the selected articles.

Software

Three quarters of the articles provide the reader with information on the platform or language used for the model. NetLogo is the most commonly used platform (50%), as compared with Repast (16%), Java or CORMAS (9% and 6%, respectively). One third of the authors justify their choice. NetLogo is often chosen because it is “particularly well suited for modelling complex systems developing over time” and “it provides the interface control tools [...] to set the parameters and scenarios of the model, and display simulation results” (H. HU et al., 2010). Its language is simple (VAN SCHMIDT et al., 2019) and the environment is user-friendly (MARTIN et al., 2015).

Types of SES and dynamics of ecological systems

In our research, agricultural systems dominate and are represented in a quarter of the models (e.g., BARNAUD et al., 2008; CAILLAULT et al., 2013). Then, other types of SES modelled are, by order of importance, pastoralism (e.g., GROSS et al., 2006), forestry (e.g., HUBER, REBECCA et al., 2017) and fisheries (e.g., KLEIN et al., 2017). As HERRERO-JÁUREGUI et al. (2018) found in empirical studies of SES, the most frequently analysed topics concern the exploitation of ecological systems. In the models reviewed, ecological systems are always implemented dynamically. Three types of models have been identified : transition rules, parametric equations and differential equations. The model most frequently used is that of differential equations.

2.3.2 Conceptualisation of governance

While half of the articles have a theoretical background, a quarter of the articles do not explicitly mention this. Most articles with a theoretical background refer to theories developed in the field of economics. These theories are generally grounded in neoclassical economics (60%), in which the environmental and natural resource management problems are approached from the

perspective of market dysfunction (e.g., environmental economics in HUBER, BRINER et al. (2013); game theory in SUGIARTO et al. (2017) or in TILMAN et al. (2018); evolutionary game theory in NHIM et al. (2019)). Other theories used belong to the field of institutional economics (e.g., J. WANG et al. (2013), HOLZHAUER et al. (2019) or RASCH et al. (2016) who used the theory of collective action (E. OSTROM, 2003)). First, the theories employed are based on decision-making theories of individuals or groups such as rational choice theory, bounded rationality or socio-psychological theories. Second, they can be applied to different types of governance. We make a distinction between informal institutions, formal institutions and modes of governance (WILLIAMSON, 2000)). The last type is divided into three main forms : community-based, market-based and state-based modes of governance (LEMOS et al., 2006). We analyse the conceptualisation of governance through these two dimensions : the decision-making theories used in models and the modes of governance represented.

Decision-making theories : from perfect rationality to social psychology theories

The actors' decision-making processes mainly concern the choice between different productive activities and the allocation of resources. The activities can be agricultural activities (choice of crops or farming practices), forestry activities or non-agricultural activities. The resources to be allocated are mainly land, labour and money. In a smaller proportion of articles, decisions are made about the extraction of resources (e.g., fish, timber, water). Other types of behaviours are more rarely analysed such as travel itineraries or locations of residence. In only one article do the decisions relate to a political process. In the work of GUZY et al. (2008), actors classify public policies according to ecological and economic criteria. Actors' behaviours are mainly individual : Aggregated actors are found in only four articles.

In the papers reviewed, the decision-making processes of the actors can

derive from theoretical frameworks (in the fields of economics, sociology and psychology) or from empirical input (e.g., data derived, participatory modelling) (see Figure 2.1). The formalisation of decision-making processes is empirical in a little less than half of the articles. In these articles, three types of data sources for the formalisation were found : primary data, secondary data and participatory modelling. The primary data represent the most important source of empirical formalisation (62% of empirical sources). The other half of the articles are based on theoretical frameworks.

The theories employed use assumptions concerning the behaviour of humans such as, for example, the rationality of humans or their cognitive capacity (VATN, 2005). The literature on SES management includes a large number of behavioural theories (SCHLÜTER, BAEZA et al., 2017). Because of the importance and diversity of decision-making processes and theories, several authors have already reviewed and analysed this topic from other angles than SES ABM including governance : decision models used in agent-based simulations of coupled human and natural system dynamics (AN, 2012)), decision-making in agent-based land use models (GROENEVELD et al., 2017), decision-making in European agricultural ABM (HUBER, BAKKER et al., 2018), human behaviour and decision-making in earth system models (MÜLLER-HANSEN et al., 2017), as well as agent-based modelling for agricultural policy evaluation (KREMMYDAS et al., 2018).

In ABM, the decision-making model is mainly grounded in rational choice theory (AN, 2012), and while a few decision-making theories have been formalised in SES modelling, agent decision-making has often been based on simple assumptions (JAGER et al., 2000). In 30% of the reviewed articles with theoretical decision-making, the agents' choices are based on rational choice theory. This theory assumes that agents make decisions according to their preferences and goals. Omniscient and perfectly rational agents maximise their expected outcomes, originally stated as their economic profit under resource constraint.

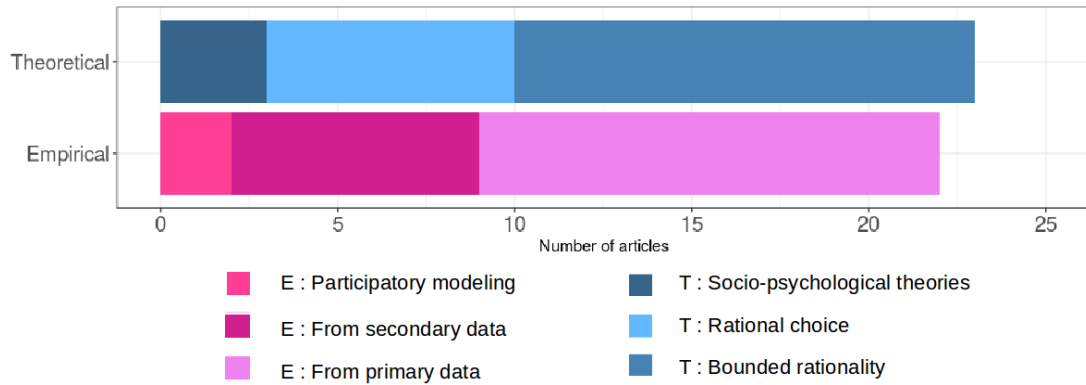


FIGURE 2.1 – Origin of the decision-making process used for actors. Numbers do not necessarily add up to 45, since one article may use several categories at the same time or because an assessment was not possible for some articles.

Rational choice theory uses the concept of utility. Introduced by Bernoulli, the concept of utility is used to model value, linking income and the concept of satisfaction. Well-being, consumption and the preservation of the environment can also be taken into account in the concept of utility. For example, in the work of AGRAWAL et al. (2013), the utility function of households involves different attributes : consumption of the extracted firewood, leisure and utility from adhering to institutional rules or community norms regarding firewood extraction. The theory of expected utility, developed by Von Neumann and Morgenstern, is a theory of decision-making in a risky environment which takes into account the incidence of cognitive biases in decision-making processes (e.g., TILMAN et al. (2018) that include risk aversion of fishers in their decision-making processes). The concept of utility is used in 16% of models and always includes other attributes in addition to money.

However, other theories introduce cognitive biases into rational decision-making processes. Simon’s research on bounded rationality highlights that rationality is limited in terms of an agent’s cognitive capacity and available information. Rational choice and bounded rationality theories are widely used in models of natural resource management (SCHLÜTER, BAEZA et al., 2017). In 57% of the articles where decision-making is based on theoretical assumptions, the decision-making processes refer to the bounded rationality concept.

Its applications can be broad, ranging from the simple addition of a constraint while remaining in a neoclassical paradigm (e.g., AGRAWAL et al., 2013), to a redefinition of the decision-making process (e.g., CAILLAULT et al., 2013).

The last set of articles using theories to model decision-making processes of actors refers to the literature on social psychology. Decision theories, such as the theory of planned behaviour (AJZEN, 1991), the theory of normative conduct (CIALDINI et al., 1991) or social learning theory (BANDURA, 1977), focus on specific aspects of decision-making processes such as the influence of norms, learning effects, judgement of consequences, repetition or conditioning effects on behaviour.

In the articles that mention theories relating to governance, i.e. half of the articles, actors' decision-making is more often based on theoretical than on empirical processes, whether for theories grounded in neoclassical economics or for theories grounded in institutional economics.

Modes of governance

To characterise the modes of governance represented in models, we use different typologies. WILLIAMSON (2000) distinguished four levels of social analysis. The top level is the level of informal institutions such as customs, taboos or norms. Rules are unwritten and unofficial. For instance, NHIM et al. (2019) analyse how the social norms of cooperation and punishment of non-cooperators evolve. The second level consists of formal institutions, e.g., legal frameworks, property rights, and other written and official rules. An example is represented by the work of KARIUKI et al. (2018), who analyse the impact of different land-tenure allocations (between communal, private and government) on the behaviour of the system. The third level refers to how actors formally interact with each other in a given formal and informal institutional environment. Different modes of governance frame these interactions. The last level deals with the allocation of resources. The first three levels relate to governance, and the social level more widely represented is the governance level, in almost all

articles. Nevertheless, a few articles integrate the formal and informal institutions in their models (see Figure 2.2).

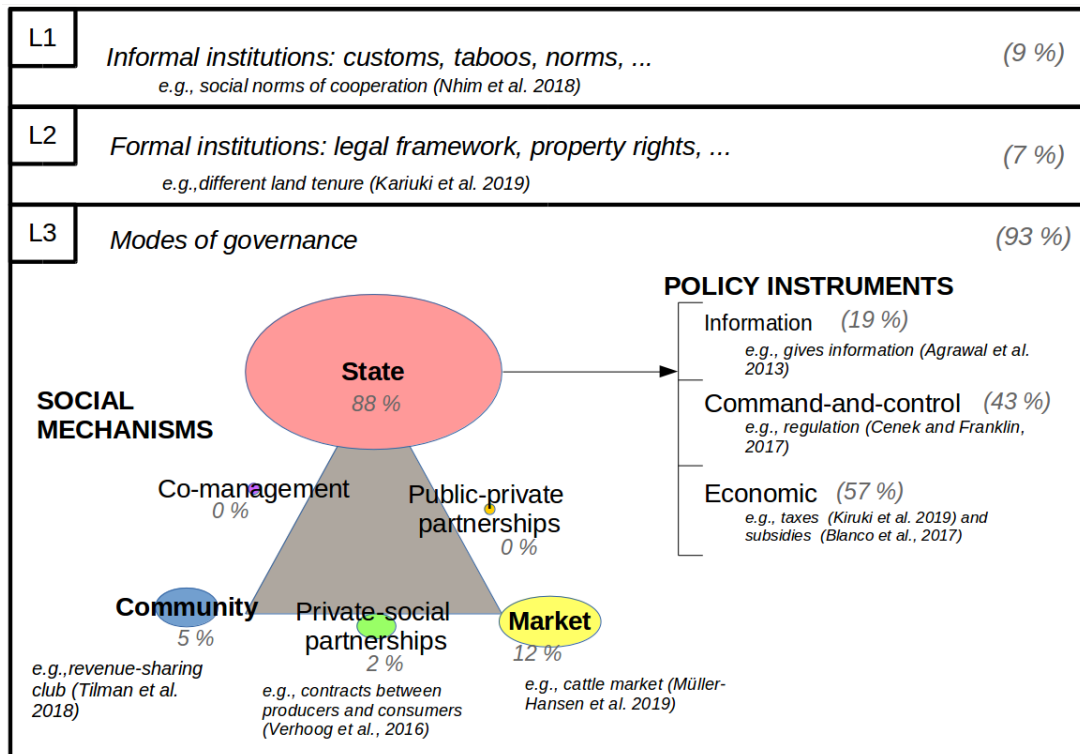


FIGURE 2.2 – Typology of governance and examples from the review of the literature : three levels of governance analysis. The size of the circles depends on the representation of the mode in the articles reviewed. Bold type indicates the main modes and normal type, the hybrid form. Percentages do not necessarily add up to 100%, since one paper may use several categories at the same time. (Adapted from WILLIAMSON, 2000, LEMOS et al., 2006, DRIESSEN et al., 2012, VILLAMAYOR-TOMAS et al., 2019)

Throughout the literature, there are different ways of classifying the modes of governance. LEMOS et al. (2006) identify three main types of governance mode : community-based, state-based and market-based modes of governance. Community-based modes of governance are represented in only two articles. The perceived strength of these modes is the deployment of solidarity relationships and time- and place-specific knowledge embodied in communities.

TILMAN et al. (2018) present an example of self-governance with a revenue-sharing club of fishers who are involved in reinsurance and management of the resources. The profit of the fishers depends, among other things, on their own fishing efforts and on the efforts of the other club members as well as on the split coefficient of the revenue-sharing. Market-based modes of governance are also rarely represented in models, in only 12% of articles that model modes of governance. They are systems of exchange between sellers and buyers where regulation is frequently based on prices (sometimes on quantities) (COMMAILLE et al., 2019). The state-based modes of governance are the more widely represented type, in 88% of articles that model modes of governance. State-based modes of governance can be further characterised by the corresponding type of policy instrument : command-and-control, economic instruments, information (VILLAMAYOR-TOMAS et al., 2019). Economic instruments are modelled in 57% of articles that model state-based modes of governance, mostly represented by taxes (e.g., GROSS et al., 2006) and subsidies (e.g., VAN SCHMIDT et al., 2019). Command-and-control instruments such as legislation, permits, quotas (e.g., KLEIN et al., 2017) are the second more commonly represented policy instruments, in 43% of articles that model state-based modes of governance. Command-and-control instruments and economic instruments were considered in neoclassical economics as the only options to correct market failures/externalities. In the traditional classification of policy instruments, information is also a state-based instrument. In the study by AGRAWAL et al. (2013), the organisation agent sends each household a signal indicating the sustainable level of resource extraction based on its assessment of the forest.

The three hybrid modes of governance are co-management (between State and Community), public-private partnerships (between State and Market), and private-social partnerships (between Market and Community) (LEMONS et al., 2006). Of the articles reviewed, only one presents a hybrid form, the private-social partnerships. In the article by VERHOOG et al. (2016), agricultural firms, waste water treatment facilities and consumers negotiate biogas contracts (quantity and price of the biogas), depending on the demand and supply of bio-

gas, and on the prices in markets external to the biogas system. Contracts are used as an input to arrive at capacities at which to construct new digesters, cleaners and biogas pipelines.

The crossover between the theories employed and the proposed typology shows that the articles that do not mention theories model state-based modes of governance, particularly command-and-control instruments, more than the other articles do. The modes of governance based on the market and private-social partnerships are mainly modelled in articles referring to institutional theories (e.g., in VERHOOG et al., 2016, biogas contracts between producers and consumers are analysed through the Institutional Analysis and Development (IAD) framework of E. OSTROM (2011)). Nevertheless, these articles referring to institutional theories also modelled command-and-control and economic instruments (e.g., GROSS et al. (2006) who address questions about institutions which provide subsidies and collect taxes). Finally, the articles mentioning the neoclassical trend are largely dominated by models representing economic policy instruments (e.g., KLEIN et al., 2017).

2.3.3 Implementation of governance : agent-based modelling versus variable-based modelling of governance

In the articles reviewed, governance is either modelled by an agent or a variable :

1. In the case of agent-based modelling of governance, agents are modelled with characteristics, objectives, decision-making processes, possibility of interactions, and sets of actions. Governance actors represented by an agent have the capacity to make decisions, to interact, and to adapt as an actor can. This type of implementation of governance was found in one third of the articles. A governance agent can represent a municipality (e.g., ACEVEDO et al., 2008, GAUBE et al., 2009), policy-makers (e.g., BITTERMAN et al., 2016), federal managers, the state (e.g., KLINE et al., 2017) or the government (e.g., LIU et al., 2013).

2. In the case of variable-based modelling of governance, governance is implemented as a set of variables (state variables or parameters), e.g., market support (e.g., ACOSTA-MICHLIK et al., 2008) or boat speed limits (e.g., CHION et al., 2013). This form is found in 80% of the reviewed articles. These different forms of implementing governance may reflect varying willingness in terms of the representation of governance. In fact, agents are able to perceive the environment, interact with it and communicate with each other (FERBER et al., 1995). They can assess situations and make decisions on the basis of a set of rules. They may execute various behaviours and have relationships with other agents (BONABEAU, 2002). Thus, the implementation of governance as an agent may be more adapted, even if this does not guarantee it, to represent an internal structure of governance more complex than a set of variables. The following paragraphs highlight similarities and differences between the articles according to the type of governance modelling (summarised in Table 2.2).

Similarities in number of actor types and in actors' decision-making process

The actors' decision-making process does not appear to be linked to the types of modelling of governance. Approximately 29% of the reviewed articles consider optimisation for representing rational behaviour (27% and 32% of articles using variable-based and agent-based governance, respectively). The remaining cases use some type of behavioural heuristics such as the probability of decisions based on criteria, choice of the best alternatives, and reaching a threshold, all used in the same proportion. These results, and all those that follow, concern articles whose authors self-identified the subject as relating to SES. We found that the use of optimisation is less important in the papers modelling the governance of SES than in articles focusing on a specific type of SES such as land use models, studied by GROENEVELD et al. (2017), or agricultural models, studied by KREMMYDAS et al. (2018). In fact, these authors found that 40% and 60%, respectively, of the articles they reviewed used optimisation in

decision-making.

Characteristics of articles	Variable-based governance	Agent-based governance	Comparison
Total number	35	12	
Different types of actors	7 (21%)	2 (18%)	S
Decision-making process : optimisation algorithm	11 (32%)	3 (27%)	S
Decision-making process : use of financial/ecologic/social factors	30/23/14 (88%/68%/41%)	8/6/5 (73%/55%/45%)	S
Theoretical background in neoclassical economics/institutional economics	12/5 (34%/14%)	2/3 (17%/25%)	D
Governance represented by State/others	26/8 (84%/25%)	11/0 (100%/0%)	D
Policy instruments : command-and-control/economic instruments /information	12/16/4 (44%/62%/15%)	4/5/3 (36%/45%/27%)	D
Bidirectionnal links with actors/the ecological system	5/0 (15%/0%)	4/2 (36%/18%)	D

TABLE 2.2 – Number of articles for each characteristic and in parentheses the percentage of the total per form of governance implemented. Comparison between forms of implementation : similarities (S) and differences (D). Numbers do not necessarily add up to 45 or 100%, since one article may use several categories at the same time or because an assessment was not possible for some articles.

Regardless of the specific evaluation procedure or the theory used to describe mechanisms, different factors can influence the decision-making processes. These factors are also not influenced by the types of governance modelling. The most important factor taken into account in decisions is the financial factor, seen in approximately 80% of the articles (88% for variable-based governance articles and 73% for agent-based governance articles). The second most important factor is the ecological factor, used in 62% of the articles (68% and 55%, respectively). Lastly, the social factor can represent the influence exerted by specific individuals or by a group of agents on the other actors. In 42% of the articles, social influence is reported, either by individual or collective actors (45% for variable-based governance articles and 41% for agent-based governance articles). In only one model is this influence both individual and collective. Social influence is principally collective; 18% of all articles mention individual influence and in 27%, collective influence. For instance, the governance agent may be influenced by the number of land managers that benefit from the subsidies (HOLZHAUER et al., 2019), or agents may be influenced by both collective and individual actors through the total harvest rate of all agents and by a random agent to whom they compare their income (TILMAN et al., 2018).

The types of governance modelling do not seem to be linked to the presence of different types of actors. We define a type of actor as a set of actors having the same possibility of actions. For example, DENG et al. (2018) describe two types of actors in their models, agricultural households (farming) and factories (producing) that influence the SES. Overall, 16% of the articles include different types of actors, ranging from two to six types. Within actor types, most of the individual actors are different to each other. The differences in actor characteristics mainly concern the initial allocation of production factors and the local environmental conditions, and a minor proportion of internal characteristics such as age or family name. Often, there are also differences in decision-making, mainly with different decision processes. In articles with several types of actors, there are always differences other than decision-making

processes. The potential differences between types are the same as those within a type : local environmental conditions, initial allocations of factors of production or internal factors (e.g., family name or age; see, for instance, GAUBE et al., 2009). The decision-making processes of governance agents are the same as those of other agents in two thirds of the models.

Differences in modes of governance and dynamics

The theoretical backgrounds of the conceptualisation of governance processes and interactions and of actors' decision processes are different between variable-based governance models and agent-based governance models. The share of articles that mention a theoretical background is the same for both types of implementation, but neoclassical economics are more widely represented in variable-based governance models whereas institutional economics are more widely represented in agent-based governance models. Likewise, the share of theoretical and empirical bases for decision-making processes is the same for both types of implementation, but the agent-based governance models are dominated by the use of the assumption of bounded rationality whereas actors' decision-making processes in variable-based governance models are based both on rational choice theories and on bounded rationality theory.

Informal and formal institutions are rarely represented in both types of implementation. However, differences are noted in terms of governance modes and policy instruments. In agent-based governance models, there are only state-based modes of governance : 36% of models implemented command-and-control instruments, 45% economic instruments and 27% information. In variable-based governance models, other modes of governance are represented : market-based or community and private-social partnerships. They account for 25% of the models. Economic instruments are the more widely represented form at 62%, followed by command-and-control instruments at 44%. Information is represented in only 15% of the articles. Thus, although a larger range of governance modes is represented in variable-based governance models, the focus is

more on economic instruments and less on information instruments compared with agent-based governance models.

The interactions between governance and other systems can provide a better understanding of the emerging dynamics of the model. When governance is represented as a variable, interactions are bidirectional with the actors in 15% of the models but there are never bidirectional with the ecological system. On the other hand, when governance is represented by an agent, interactions are bidirectional with the actors in 36% of the models and with the ecological system in 18% of the models. For instance, in the work of HOLZHAUER et al. (2019), the institutional agents' decision-making preferences are guided by public support from actors and actors receive subsidies from them.

The theories used for agent-based governance models are further away from neoclassical theories, for conceptualizing both governance and actors' decision-making. This may indicate a willingness on the part of the authors to get closer to reality. The three policy instruments are represented in a more homogeneous way. Moreover, the greater presence of bidirectional links may suggest a desire for more complexity. But these results are nuanced by the fact that the implementation of actors is similar between the two types of implementation. The presence of a typology of agents is the same in both implementations, the decision-making processes are the same as are the decision factors. Furthermore, formal and informal institutions are represented only in the variable-based governance models.

2.3.4 Governance and interactions in social–ecological agent-based models

Interactions in SES have several implications for the sustainability and management of these systems (FOLKE, CARPENTER et al., 2010). Governance influences interactions between actors and the ecological system and is in turn influenced by the changes occurring in the actors' and ecological systems. Links

can be unidirectional or bidirectional (see Figure 2.3).

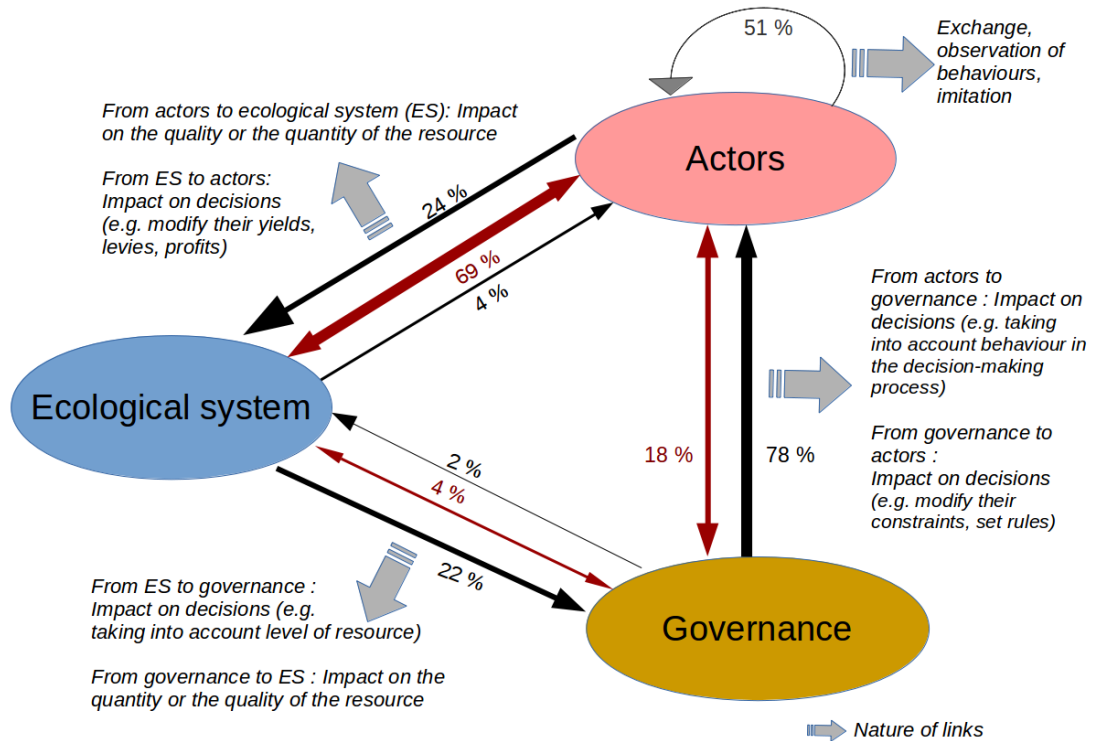


FIGURE 2.3 – Types of links between sub-systems (percentage of articles)

Governance systems affect the decisions of the actors in all but two articles, by incentivising or constraining actors in terms of possible actions. For example, in the work of CENEK et al. (2017), governance takes the form of a regulatory instrument which determines fishing dates that are taken into account by agents to decide on whether to fish or not. Governance can also take the form of an economic instrument and can modify the economic context by giving subsidies (e.g., VAN SCHMIDT et al., 2019) or by collecting taxes (e.g., GROSS et al., 2006). In three quarters of the models, the link between governance and actors is a unilateral one : from governance to actors. In other papers, the link is bilateral, i.e. actors also influence governance. For example, in the study by GUZY et al. (2008), actors rank the policies proposed by the agent of governance. Then, the agent of governance has to choose the policy to implement according to these ranks, among others. In two articles governance interacts only with the

ecological system (CHARNLEY et al., 2017; GONZALEZ-REDIN et al., 2019). In these articles, governance is represented by an agent that manages its own parcels of land.

Actors may also affect governance due to interactions between agents that may have unexpected effects on governance. In two thirds of the articles, agents have interactions with other actor agents. The interactions between agents can be direct or indirect. We define direct links as interactions occurring in the system of actors. Indirect links represent interactions through other systems. In 51% of the reviewed articles, interactions between actors are direct interactions such as the observation of behaviours, for example, the fishing effort of other fishers included in the calculation of profit (TILMAN et al., 2018) or the imitation of strategies between actors (MÜLLER-HANSEN et al., 2017). Indirect interactions, present in one third of the articles, occur through the ecosystem, for example, the use of a collective pasture leading to decreased availability of grass for others (MIYASAKA et al., 2017). In works with different types of agents, inter-type interactions are present in two thirds of the articles. For example, interactions could be the sharing of information on whale locations (PARROTT et al., 2011) or the exchange of biogas (VERHOOG et al., 2016).

In 70% of models, there is no link between the ecological system and the governance system. A quarter of the models have a link from the ecological system to governance. This is the case when ecological factors are taken into account in the calculation of variables for governance or in the decision-making process of a governance agent. For example, in the work of GROSS et al. (2006), subsidies depend on droughts. In two articles, the links are bidirectional (CHARNLEY et al., 2017; GONZALEZ-REDIN et al., 2019). In only one case, the link is from governance to the ecological system : a case where governance acts directly on the forest (cutting) (DUPONT et al., 2016). The lack of links between governance and the ecological system can be explained by the fact that the actions of governance on the ecological system are mainly through agents. In fact, if we consider the social system as a whole composed of governance and actors,

80% of interactions are bidirectional, 16% are from the social system to the ecological system and 4% are from the ecological system to the social system.

In all the articles reviewed except one, there is a link between the actors and the ecological system. The exception is the article by GONZALEZ-REDIN et al. (2019), where there are no actor agents but only governance agents. These agents represented governance forces driving the development of land for sugarcane production, the creation of new protected areas, and the restoration and maintenance of semi-natural areas, in which actors as farmers are implicitly included. In 69% of cases, it is a bidirectional link. It is often the case in articles modelling productive activities such as fisheries and agriculture (e.g., BITTERMAN et al., 2016; CENEK et al., 2017) that the actors are influenced by the level of resources or past yields and their actions affect the level of resources or future yields (e.g., CAILLAULT et al., 2013). Among the articles describing a unidirectional link, one quarter of the articles include links from the ecological system to actors. These links can take different forms : The ecological system directly influences the actors by modifying their outcomes (yields, profits) or decisions (e.g., CHION et al., 2013); the ecological system is taken into account in the decision-making process and thus influences behaviour. The second unidirectional link, from actors to the ecological system, is present in three quarters of the articles involving unidirectional links. The actors influence the quality or quantity of resources in the ecological system.

2.4 Discussion

2.4.1 Highlights and limitations

Our results show that half of the models have a theoretical background. A little less than two thirds of these models are grounded in neoclassical economics in which environmental and natural resource management problems are approached from the perspective of market dysfunction. State interven-

tion is the mode of governance mostly represented in the models (see Figure 2.2). Among the policy instruments, command-and-control and economic instruments are mostly represented. Informal and formal institutions, self-governance, or market-based modes of governance are also modelled but remain marginal. Market-based modes of governance are probably rarely represented because the challenges in SES are often issues that are not resolved by the market and therefore require public interventions.

In terms of implementation, governance as a variable is preferred to that as an agent. Governance is often represented as a test of the value of variables in different scenarios and therefore does not require representation with an agent. In variable-based governance models, there is a greater diversity of modes of governance represented even though command-and-control and economic instruments are the most widely represented. Agent-based governance models are more frequently based on institutional theories and represent instruments of information. These models present more interactions between governance and ecological systems or actors than variable-based governance models. Bidirectional links are found in approximately one fifth of all models. For the others, governance acts mainly on the ecological system through the actors by impacting their decisions. The links are between the agents that interact with each other and between the ecological system and the agents. Actors impact the ecological system (in terms of quantity or quality) and in turn are influenced by it in their decisions.

This review has shown the potential of ABM to analyse governance in SES. Until now, ABM have been mostly used to analyse or compare theories (JANSSEN et BAGGIO, 2017), to examine empirical case studies (MATTHEWS et al., 2007) and to predict the evolution of SES (GRIMM et RAILSBACK, 2005) but rarely to develop a new theory for analysing SES. Future research could consider the use of ABM to develop theories of SES, to improve our understanding and management of complex systems (LORSCHIED et al., 2019), to explore land use changes (O'SULLIVAN et al., 2016) or to analyse social-ecological

phenomena (SCHLÜTER, MÜLLER et al., 2019). However, the use of ABM also exhibits some drawbacks. Because ABM represent agents with their own individual properties, the number of parameters can be high and the model difficult to calculate (GOTTS et al., 2018). Moreover, models are often either highly conceptual or very case specific (SCHILL et al., 2019). Furthermore, ABM may lack transparency, which makes it difficult to determine the influence exerted on the system by a part of the system or by a specific parameter (GOTTS et al., 2018). Introducing governance underlines these issues. Indeed, adding dynamics and new processes with governance contributes toward complicating the model and increasing the number of parameters and the ensuing problems associated with this.

This review is limited to the set of articles that describe models self-identified by their authors as applied to a social–ecological system, socio-ecological system or socio-ecosystem in the title/abstract/keywords. While the concept of social–ecological systems lacks a common definition (COLDING et al., 2019; HERRERO-JÁUREGUI et al., 2018), other concepts describe systems including humans and nature as coupled human and natural systems (e.g., KLINE et al., 2017), earth systems (e.g., MÜLLER-HANSEN et al., 2017) or ecological–economic systems (e.g., GAO et al., 2018). Moreover, other fields of research focus on the same type of SES that we identified such as the energy–water–food nexus systems (NAMANY et al., 2019), land use and cover changes (PARKER et al., 2002), natural resource management (LOOMIS et al., 2008) or agricultural systems (KREMMYDAS et al., 2018). The choice of search commands may have implications in terms of the type of SES involved. For example, the inclusion of the term “coupled human and nature” (CHAN) would probably have led to the selection of more articles dealing with land use and land cover change, since these are areas that characterise research related to CHAN systems (AN, 2012). The tightening of our review based on these keywords allowed us to focus on the research conducted by the community of authors referring to the concept of SES.

Finally, our review of the literature was constrained by the heterogeneous descriptions of the models in the reviewed papers. In some cases, supplementary material is provided or the description of the model follows the ODD (Overview, Design concepts, and Details) (or ODD+Decision) protocol (GRIMM, BERGER et al., 2010; MÜLLER et al., 2013), while in other cases, models lack precision. The use of a common protocol for the description of models would certainly be very useful in limiting biases in the comparative analysis of models.

2.4.2 Perspectives

Although a diversity of theories that conceptualise governance processes and interactions exist, many articles do not explicitly refer to theories in model building. This diversity is, for instance, highlighted by COX et al. (2016), who identified, in a database of over 117 SES studies, more than 60 different theories across various fields such as geography, economics, ecology, biology and politics. Moreover, among the articles that refer to a theory, there is very little diversity in the theories implemented in SES ABM, which are mainly based on the neoclassical economics approach. Beyond the neoclassical economics field, theories are less modelled, even though they are recognised to be relevant for the analysis of SES. For example, the theory of collective action by E. OSTROM (2003) describing how structural variables affect the levels of cooperation is cited only once (J. WANG et al., 2013). Another part of the literature that is of relevance in this field is ecological economics. This trans-disciplinary field of research was promoted by Georgescu-Roegen (MISSEMER, 2013), who worked on the coevolution and interdependencies of human economics and natural ecosystems. He proposed new theories in the management of relationships between humans and the environment. Management theories in this field are mostly formalised. Thus, it could be very interesting to take them into consideration when modelling governance in SES ABM.

The lack of diversity applies not only to the theories but also to the modes of governance. Other dimensions of governance have not been modelled yet

in social–ecological ABM that include governance despite being identified as key for the sustainable management of SES, for instance, adaptive management and polycentric governance. The concept of adaptive management has emerged from the adaptive management framework that appeared in the 1970s (HOLLING, 1978; WALTERS et al., 1990) and then developed within the framework of SES (BERKES et FOLKE, 1998; FOLKE, HAHN et al., 2005). More recently, adaptive management has been defined as “a systematic process for improving management policies and practices by learning from the outcomes of management strategies that have already been implemented” (PAHL-WOSTL, SENDZIMIR et al., 2007). Although interest in this approach has been growing steadily since its inception, it is not implemented in any of the models reviewed here. Yet, ABM are well suited to the implementation of adaptive governance due to their ability to represent learning processes at different scales, notably at the level of governance agents (e.g., KLOS et al., 1997; SCHEFFRAN, 2016; MACQ et al., 2017). This is also the case for polycentric governance, a concept that was first introduced by V. OSTROM et al. (1961). Polycentricity characterises a governance system in which governing authorities at multiple scales interact to make and enforce rules (E. OSTROM, 2010; BIGGS et al., 2015; MATHIAS, LADE et al., 2017). According to CARLISLE et al. (2019), a growing interest in polycentricity on the part of commons scholars is evident in the number of articles and books that consider the advantages of polycentric governance for sustaining natural resources (e.g., BLOMQUIST et al., 2005; ANDERSSON et al., 2008; PAHL-WOSTL et KNIEPER, 2014). The advantage of ABM in describing polycentricity is that they can describe horizontal and vertical linkages in fine detail and highlight the potential emergence of sustainable system dynamics. Nevertheless, none of the models reviewed integrates this dimension of governance, probably because of the difficulties in translating these concepts into equations. In fact, it remains a challenge to implement this type of governance in ABM : These approaches are less formalised and can use large-scale variables (from more complex decision-making process due to the adaptation and learning process or from embedded levels of governance) that

compound difficulties in implementation. Nevertheless, some authors already modelled these dimensions of governance in other types of modelling (as ordinary differential equations) that can be inspiring for our topic (e.g., MATHIAS, LADE et al., 2017; AHLERING et al., 2020). The use of conceptual models and stylised models or the distinction between different cycles of adaptation could be approaches to follow in ABM. A better consideration of the various characteristics of governance would be advantageous in order to improve the relevance of ABM to the analysis of SES.

In the models reviewed, many authors propose ad hoc implementations of the governance or actors' decision-making processes without any reference to theories, based on the case study at stake or serving only the situation they seek to analyse. When processes are based on theories, they are mostly based on the assumptions of rational choice or bounded rationality. In some of these models, actors have no direct interactions with each other and their decision-making process is only influenced by financial factors. Thus, the system represented is closer to an economic system than a social system. This finding does not apply only to social–ecological ABM that integrate governance but to all social–ecological ABM (SCHULZE et al., 2017). There is a large difference between the diversity of decision theories developed in social sciences and the diversity of theories used in agent-based modelling of SES. However, the human decision-making sub-models are key elements, and therefore a representation of human decision-making suited to the purpose of the model is a prerequisite for models integrating governance (SCHULZE et al., 2017). SCHLÜTER, BAEZA et al. (2017) have identified the multiple challenges of the implementation of alternative theories of human behaviour and decision-making : (1) going beyond the difficulties due to multidisciplinary collaboration ; (2) improving knowledge about the theories that are useful and usable in SES contexts ; and (3) operationalising the theories. Decision-making models associated with theories that conceptualise governance processes and interactions should be improved and enriched by other decision theories so as to be closer to the real world. For example, one of the well-known theories in decision-making is used only once

in the models reviewed : the theory of planned behaviour. This theory, and the theory from which it originated, the theory of reasoned action, have proven their usefulness and capacity to reproduce behaviour, especially in the field of environmental governance and management. SCALCO et al. (2018) conclude that the theory of planned behaviour and its use in ABM can certainly offer a useful model of deliberative decision-making processes for virtual agents. This theory is particularly relevant in terms of natural resource management due to its ability to consider different factors (GRILLI et al., 2019 ; SI et al., 2019). Indeed, it could be a useful theory for analysing SES because of its capacity to include different elements from the ecological system (e.g., the role of the perception of the environment in actors' attitude), from the governance system (e.g., modifying the attitude or the perceived behavioural control) or from the others (e.g., included in the subjective norm). When addressing governance issues, other specific elements of decision-making are important such as the perception, the evaluation (SCHLÜTER, BAEZA et al., 2017) or the learning approach (shown, for instance, in triple-loop learning approaches (ARGYRIS et SCHÖN, 1978)). Indeed, integrating learning processes in governance in the context of increasing uncertainty due to climate change is important because they permit an adaptive response of the system (PAHL-WOSTL, 2009).

2.5 Conclusion

In this review, we examined the ABM literature on governance in SES in order to (1) provide a detailed overview of the conceptualisation and implementation of governance and (2) highlight the critical aspects and challenges for future research on governance in social–ecological ABM. First, a significant share of articles do not refer to theories of model governance. Few theories are implemented in the literature, especially in the field of collective action led by Ostrom, despite the fact that their relevance to SES analysis has been proved. Therefore, it may be important to also use these theories in social–ecological ABM. Furthermore, the decision-making processes intertwined with governance

are often described in a limited way and make little use of the diverse theories of decision-making, although these are crucial for the outcomes of governance. The effect of the choice of decision-making process on governance should therefore not be overlooked and care must be taken to ensure that these choices are well informed. Moreover, institutions (formal and informal), market-based and community-based modes of governance could be more widely represented in models, and, as a further research perspective, other dimensions of governance such as polycentric or adaptive governance. Finally, the representation of governance as an agent could help us move towards a greater diversity in the representation of governance and to a better implementation of the dynamics of the models linked to the governance of SES.

2.6 Appendix

2.6.1 Appendix 1 : List of articles reviewed

Agrawal, A., D. G. Brown, G. Rao, R. Riolo, D. T. Robinson, and M. Bommarito. 2013. Interactions between organizations and networks in common-pool resource governance. *Environmental Science & Policy* 25 :138–146.

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2.6.2 Appendix 2 : Detailed questionnaire

Overview	
Purpose	Phenomena addressed
Software	
Type of SES	
Type of dynamics of the ecological system	

TABLE 2.3 – A2 : Detailed questionnaire - Overview

I. Questions concerning Governance	
Questions	Responses
To which theoretical governance framework does the article refer ?	
How is governance represented in the model ?	Agent-based modelling Variable-based modelling

TABLE 2.4 – A2 : Detailed questionnaire - Governance system variables

Questions following if variable-based modelling	
How is governance implemented ?	Informal institutions Formal institutions Modes of governance → Market-based → Private-social partnerships → Community-based → Co-management → Public-private partnerships → State-based : Information/Command-and-control/Economic instruments
Does governance change over time ?	Yes → and it is exogenous → and it is endogenous No
The objectives of governance are to...	Agents Ecological system Both Other
To achieve its objectives, it takes into account factors....	Agents Ecological system Both Other
It acts on (process)....	Agents Ecological system Both Other

TABLE 2.5 – A2 : Detailed questionnaire - Governance system variables (continued)

Questions following if agent-based modelling	
How is governance implemented?	Informal institutions Formal institutions Modes of governance → Market-based → Private-social partnerships → Community-based → Co-management → Publi-private partnerships → State-based : Information/Command-and-control/Economic instruments
How is construct the decision-making process?	Rational choice Socio-psychological theories Bounded rationality Participatory modelling From primary data From secondary data
What are the objectives of agent?	Economic Ecological Social Risk management Preserve the spatial characteristics of the environment Other

TABLE 2.6 – A2 : Detailed questionnaire - Governance system variables (continued)

Questions following if agent-based modelling	
Which factors are involved in decision ?	Financial Human infrastructure Ecological system resource The others individually The others collectively Risk Other
Where do the data for decision making parameters come from ?	Literature Survey Assumed
Decision-making algorithm	Optimization Other (Threshold ; Heuristics ; Probabilistic after calculation ; Calculation and better choice) Utility function
Memory ?	Yes/No
Learning ?	Yes/No
Are there interactions between governance agent(s) and individual agents ?	Yes/No
What type(s) of interactions are there between the governance agent(s) and other agents ?	No Exchange Behavioural observations Environmental observations Observation of characteristics Through the ecosystem

TABLE 2.7 – A2 : Detailed questionnaire - Governance system variables (continued)

II. Questions concerning actors	
Questions	Responses
Are they different types of actors ?	Yes/No
Number of types of agents	
What are the difference between agents inter-types ?	No difference Local environmental conditions Allocation of factors of production Internal ("intangible factors" such as surname, knowledge) Same decision process but different decision parameters Different decision-making processes
Are there interactions between agents inter-types ?	Yes/No
What type(s) of interactions are they inter-types ?	No Exchange Behavioural observations Environmental observations Observation of characteristics Through the ecosystem
How are inter-types social interactions structured ?	No network Random → Uniform Based on characteristics ; → Geographical ; → Other ; Complete network
Is it possible to change of types ?	Yes/No

TABLE 2.8 – A2 : Detailed questionnaire - Agent diversity

General	
How is construct the decision-making process ?	Rational choice Socio-psychological theories Bounded rationality Participatory modelling From primary data From secondary data
What are the objectives of agent ?	Economic Ecological Social Risk management Preserve the spatial characteristics Other
Algorithm	
Which factors are involved in decision ?	Financial Human infrastructure Ecological system resource The others individually The others collectively Risk Other
Where do the data for decision making parameters come from ?	Literature Survey Assumed
Decision-making algorithm	Optimization Other (Threshold; Heuristics; Probabilistic after calculation; Calculation and better choice) Utility function
Memory ?	Yes/No
Learning ?	Yes/No

TABLE 2.9 – A2 : Detailed questionnaire - Agents variables, general and algorithm

Diversity intra-types	
What are the difference between agents intra-types ?	No difference Local environmental conditions Allocation of factors of production Internal ("intangible factors" such as surname, knowledge) Same decision process but different decision parameters Different decision-making processes
Interactions intra-types	
Type of interactions intra-types	No Exchange Behavioural observations Environmental observations Observation of characteristics Through the ecosystem
How are intra-types social interactions structured ?	No network Random → Uniform Based on characteristics ; → Geographical ; → Other ; Complete network

TABLE 2.10 – A2 : Detailed questionnaire - Agents variables, diversity and interactions

III. Questions concerning links between systems	
Questions	Responses
In wich direction are the links between the ecological system (ES) and the governance system (GS) ?	ES \rightarrow GS GS \rightarrow ES ES \leftrightarrow GS No link
What are the nature of these links ?	
In wich direction are the links between the ecological system (ES) and actors (A) ?	ES \rightarrow A A \rightarrow ES ES \leftrightarrow A No link
What are the nature of these links ?	
In wich direction are the links between actors (A) and the governance system (GS) ?	A \rightarrow GS GS \rightarrow A A \leftrightarrow GS No link
What are the nature of these links ?	

TABLE 2.11 – A2 : Detailed questionnaire - Links between systems

Chapitre 3

Adapting the governance of social–ecological systems to behavioural dynamics : an agent-based model for water quality management using the theory of planned behaviour

Article en cours de soumission L'article a été soumis à *Ecological economics* début mars et est en relecture par les rapporteurs (au 01/05/2021).

Objectifs Le chapitre précédent (Chapitre 2) propose un aperçu détaillé de la conceptualisation et de la mise en œuvre de la gouvernance dans les modèles multi-agents des systèmes socio-écologiques et met en exergue les défis pour la recherche future sur ce sujet. Parmi ceux-ci, deux ont retenus particulièrement notre attention : 1) les incitations économiques et réglementaires sont représentées de manière dominante ; 2) les processus de prise de décision imbriqués dans la gouvernance sont souvent représentés de manière simplifiée. Dans les aires d'alimentation de captages, les mesures politiques encourageant les pratiques agricoles en faveur de la qualité de l'eau font appel à de nombreux types d'instruments dont une partie est non réglementaire et non financière. Le changement de pratique des agriculteurs impulsé par ces instruments est important en terme de résultats pour la qualité de l'eau et il donc est nécessaire de comprendre l'effet de ces instruments sur la prise de décision des agriculteurs.

Contributions Le modèle multi-agents que nous proposons intègre une mesure économique (compensation financière) et une mesure non économique (formation). Le processus de prise de décision des agriculteurs est basé sur la théorie du comportement planifié. Le modèle représente une aire d'alimentation de captage d'eau potable dans laquelle les agriculteurs ont le choix entre deux pratiques, une pratique polluante et une pratique favorable à la qualité de l'eau. Le modèle vise à mieux comprendre l'impact des caractéristiques comportementales des agriculteurs sur l'efficacité et l'efficience des programmes de protection ciblant les pollutions diffuses. Nous explorons ainsi comment l'évolution des pratiques agricoles est influencée par, premièrement, les caractéristiques des agriculteurs et, deuxièmement, les caractéristiques des mesures politiques mises en œuvre.

Résultats Les apports de ce chapitre sont doubles : 1) les caractéristiques comportementales des agriculteurs et leurs pratiques initiales influencent l'efficacité et l'efficience des politiques. La prise en compte de ces caractéristiques dans la définition des politiques peut donc améliorer leur efficacité ; 2) dans les situations où les caractéristiques comportementales sont inconnues,

les politiques combinant à la fois des incitations financières et des mesures de formation sont plus coûteuses mais peuvent être une meilleure option que les politiques reposant sur une seule mesure.

Abstract Nonpoint source pollution from agriculture is one of the main causes of water quality degradation. To cope with this issue, policy measures promoting farming practices in favour of water quality have been implemented in the European Union context. Many policy instruments are based on the voluntary commitment of farmers. Farmers' participation is therefore important in terms of water quality outcomes. We built an agent-based model of a drinking water catchment area, using the social–ecological systems framework and the theory of planned behaviour. The model aims at a better understanding of the impact of behavioural dynamics on the effectiveness and efficiency of policies targeting diffuse water pollution. Our model allows us to explore how the evolution of farming practices is influenced by, first, the behavioural characteristics of farmers and, second, the characteristics of the policy measures implemented. Our results are threefold : 1) the characteristics of farmers influence policy effectiveness and efficiency ; 2) taking into account farmers' behavioural characteristics in the definition of policies can improve the efficiency of policies ; 3) in situations where behavioural characteristics are unknown, policies combining both financial incentives and training measures are costlier but may be a better option than policies relying on a single measure.

3.1 Introduction

Water resources underlie the basic need of livelihoods, but are vulnerable due to demographic pressures, climate change or human activities. Accordingly, water security has become a prominent concern (FAO, 2011 ; DENG et al., 2018). Water pollution leads to the degradation of aquatic ecosystems, causes problems in drinking water supply and negatively affects economic activities such as fisheries and tourism. Sources of water pollution are diverse : industry effluents, discharge from urban wastewater treatment and losses from agriculture. Many European waterbodies are affected by pollutants and/or altered habitats and more than half of the river and lake water bodies in Europe are reported to have less than good ecological status (EEA, 2020).

In 2000, the European Union adopted the Water Framework Directive (WFD), with the multiple objectives of preventing and reducing water pollution, promoting the sustainable use of water, protecting the environment and improving the status of aquatic ecosystems. At the French level, the WFD has led, for example, to the identification of 1000 priority drinking water catchments as being particularly threatened by nonpoint source pollution where measures targeting farmers' practices have been implemented (MTE, 2020). The measures implemented include information and advisory instruments as well as economic instruments such as the agri-environmental schemes (AES) of the EU Common Agricultural Policy (CAP), which aim to encourage the adoption of environmentally friendly farming practices.

The implementation of the various protection measures is based on the voluntary commitment of farmers, which is influenced not only by economic factors but also by cognitive, social and institutional factors (LASTRA-BRAVO et al., 2015; METTEPENNINGEN et al., 2013; DESSART et al., 2019). These factors, influencing the choice of farming practice, the choice of input use or the choice to participate in AES, have been extensively studied (LASTRA-BRAVO et al., 2015; DESSART et al., 2019). One of the most frequently used approaches to understanding farmers' decision-making with regard to agri-environmental policies is Ajzen and Fishbein's theory of reasoned action (AJZEN et FISHBEIN, 1980), which was later extended to the theory of planned behaviour (TPB) (Ajzen 1991) (FALCONER, 2000; TOMA et al., 2007). In this frame, intention towards a behaviour is considered a trustworthy predictor as to whether or not the behaviour will be performed. Individual intention is influenced by three main factors : attitude, subjective norm and perceived behavioural control (PBC). This theory makes it possible to integrate social, economic and environmental issues that influence the intention towards a behaviour (AJZEN et FISHBEIN, 2005).

Each factor has a relative importance in the intention that is highly dependent on the investigated behaviour and population (AJZEN et FISHBEIN,

2005 ; FIFE-SCHAW et al., 2007 ; AJZEN, 2011). The relative effects of the TPB factors on the intention can vary among different populations, depending on the cultural and institutional contexts (e.g. AJZEN et KLOBAS, 2013). The impact of the relative importance of factors on behaviour has not been widely studied, especially in the case of farmers' behaviour. Previous studies have highlighted that these relative effects can differ between countries in the European context (KAUFMANN et al., 2009 ; METTEPENNINGEN et al., 2013).

We assume that behavioural dynamics and intention to change interact with policies and together influence farmers' choice of agricultural practice and their involvement in a programme to protect a water catchment area. The effectiveness and efficiency of the policies implemented are therefore dependent on behavioural characteristics and policy characteristics. In what follows, we define effectiveness as the difference between the outcomes achieved and the outcomes expected from a policy and efficiency as the relationship between the human and financial means used and the outcomes. Protection programmes in catchment areas include several measures, which can be combined, e.g. financial compensation and training, with different effects on their effectiveness and efficiency.

The objective of our study is to analyse how the characteristics of farmers and of the policies implemented jointly influence the evolution of agricultural practices and, therefore, the concentration of pollutants in drinking water catchment areas. For this purpose, we use a conceptual framework based on the social-ecological system (SES) framework developed by Ostrom (E. OSTROM, 2009 ; MCGINNIS et E. OSTROM, 2014) and the TPB (Section 3.2). We built an agent-based model of a water catchment area, described in the third section. This model allows us to analyse how water quality management is influenced by the governance system and the actor characteristics and dynamics (Section 3.4). More particularly : (1) We identify how the characteristics of farmers in a catchment area affect policy effectiveness. We focus on the relative importance of the factors and on the characteristics of the population in the catchment

area and the interactions between them (Section 3.4.1); (2) We characterise the effectiveness of different water quality protection programmes. We analyse the marginal effect of different measures of programmes targeting different farmer populations and show that their effectiveness is influenced by the interaction between the characteristics of the measures implemented and farmers' behavioural characteristics (Section 3.4.2); (3) We assess the efficiency of different water quality protection programmes. As effectiveness, the efficiency is influenced by both the characteristics of the policy measures implemented and farmers' behavioural characteristics (Section 3.4.3). Finally, Section 5 offers a discussion of findings and a conclusion.

3.2 Conceptual framework

3.2.1 Agent-based models of social–ecological water systems

Water catchments are areas where precipitated rainwater feeds the aquifer and thus contributes to the renewal of the resource. On these territories, different actors interact with each other and with the water system. To explore such interactions, we built a model based on the SES framework (E. OSTROM, 2009; MCGINNIS et E. OSTROM, 2014).

The SES framework developed from the Institutional Analysis and Development (IAD) approach (E. OSTROM, 2011) for analysing the governance of common-pool resources (E. OSTROM, 2007; E. OSTROM, 2009). It is now being used more widely, including the analysis of the various public goods and services generated by SESs (MCGINNIS et E. OSTROM, 2014; BAN et al., 2015; BENNETT et al., 2015). In the field of water quality, it has been used in several studies, e.g. to underline factors affecting the emergence and performance of collaborative water quality management (e.g. LUBELL et al., 2002; MADRIGAL et al., 2011; MONTENEGRO et al., 2020) or to examine the effect of multilevel

or polycentric governance on sustainable water use (NAGENDRA et al., 2014; NAIGA et al., 2015). However, to our knowledge, only one study has applied the SES framework to the protection of drinking water catchments (AMBLARD, 2019).

The IAD and subsequently the SES framework were constructed incrementally through the empirical analysis of a large number of case studies, leading to a multi-tier collection of concepts and variables (HINKEL et al., 2014). As first-tier variables, the framework conceptualises SESs into resource systems, resource units, governance systems, actors, interactions, and outcomes. In this paper, we use the framework to model the SES considered, a water catchment where a programme targets farming practices to control nonpoint source pollution (see Figure 3.1). The resource system considered is the catchment area, from which groundwater, as a resource unit, is abstracted for drinking water production. The social system involves actors – farmers – and a governance system – a protection programme which includes different types of measures such as financial incentives and training. The objective of the governance system is to reduce water pollution; thus, the outcome of interest in the study is the restoration of water quality.

Among the different approaches in modelling, agent-based modelling is a particularly relevant tool for understanding social–ecological phenomena because of its capacity to simulate the emergence of macroscopic patterns, the embeddedness of spatial and temporal scales, and the integration of agents in ecological and social environments (SCHLÜTER, ORACH et al., 2019). Indeed, in agent-based models (ABM), agents with heterogeneous characteristics are represented in a given environment. ABM have already been used for analysing SES or predicting management results (see reviews by ROUNSEVELL et al., 2012; SCHULZE et al., 2017). Regarding the governance of SES, they have been used to explore the impact of formal institutions, informal institutions or different modes of governance on resource management (Bourceret et al. unpublished manuscript).

3.2.2 Theory of planned behaviour : background and application to farmers' decision-making in a water system

In agent-based modelling of SES, representing the human decision-making is a key element (SCHULZE et al., 2017). Models of decision-making processes can be informed by empirical studies or by existing theories (e.g. rational choice theory, TPB (AJZEN, 1991), prosocial behaviour theory (BÉNABOU et al., 2006) or norm activation theory (SCHWARTZ, 1977)). In most ABM, the decision-making model is grounded in rational choice theory (AN, 2012) and agent decision-making has often been based on simple assumptions (JAGER et al., 2000).

The TPB is a social-psychological theory broadly used to describe behaviour. This theory is particularly relevant for representing decision-making processes in systems in the field of environmental and natural resource management (GRILLI et al., 2019; SI et al., 2019). For example, it has been used to describe recycling behaviour (e.g. AGUILAR-LUZÓN et al., 2012; CHAN et al., 2013; AHMAD et al., 2016), green purchase behaviour (e.g. ALBAYRAK et al., 2013) or transportation choices (e.g. BAMBERG et al., 2001; GROOT et al., 2007). More particularly, this theory is one of the most frequently used approaches for understanding farmers' decision-making with regard to agri-environmental policies and the adoption of sustainable farming practices. For instance, it has been used to study farmers' conservation behaviour (LYNNE et al., 1995; BEEDELL et al., 1999; BEEDELL et al., 2000; FIELDING, TERRY, MASSER, BORDIA et al., 2005) or to assess the influence of institutions on farmers' participation in conservation schemes (METTEPENNINGEN et al., 2013).

The TPB suggests that a given behaviour is influenced by the intention to perform this behaviour (AJZEN, 1991). The higher the intention to engage in a behaviour, the more likely its realisation. According to the theory, someone's intention towards a behaviour is a reliable predictor of whether or not he/she will perform the behaviour. In the case of farming practices in a water catchment area, a farmer's higher intention to adopt a low-input practice promoted

by a policy is assumed to lead to a higher chance of adopting this practice.

The concept of intention captures the motivations to perform the behaviour through three conceptually independent factors : attitude towards the behaviour, subjective norm and PBC (actors' decision-making box in Figure 3.1). Attitude is the judgement about the desirability of the behaviour and its consequences. The considerations about the influence and opinions of others on the behaviour of interest define the subjective norm. These others can be neighbours, friends, family or other important persons that may influence the farmer (link 2 in Figure 3.1). The PBC encompasses the beliefs about the individual's ability to succeed in the behaviour.

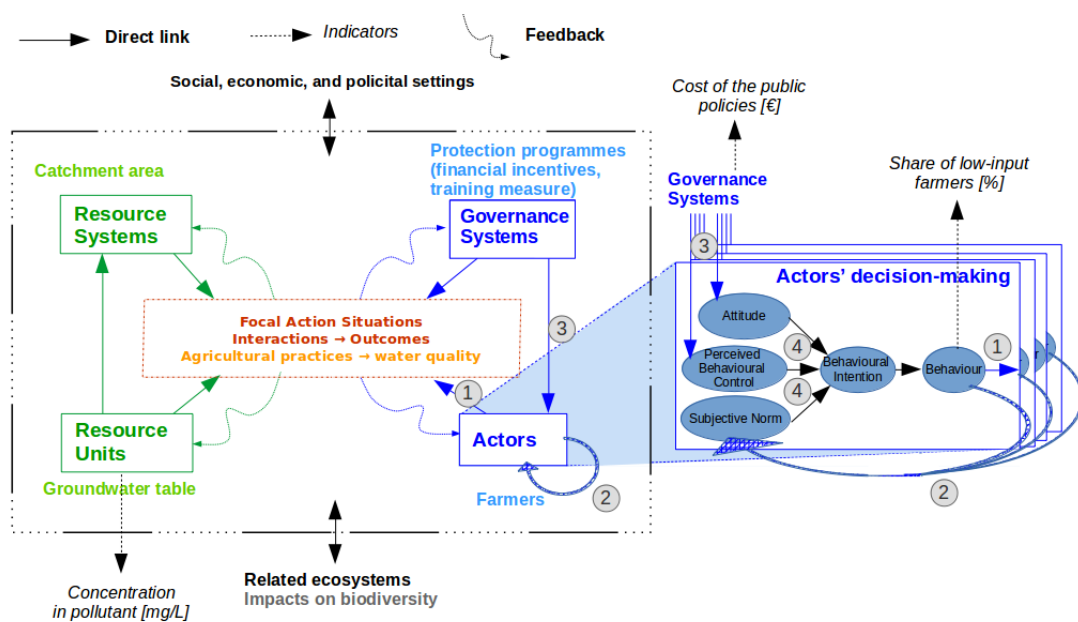


FIGURE 3.1 – Representation of a drinking water catchment area based on the SES framework and the theory of planned behaviour (source : AJZEN, 1991 ; MCGINNIS et E. OSTROM, 2014). Farmers' behaviours correspond to their agricultural practices (link 1). Link 2 represents the interactions between farmers affected by the subjective norm. The influences of the governance system on the factor attitude and perceived behavioural control are highlighted by the links 3. Links 4 represent the contribution of the three factors (attitude, perceived behavioural control and subjective norm) in intention.

The relative importance of factors in the intention is highly dependent on the behaviour and population being studied (AJZEN et FISHBEIN, 2005 ; FIFESCHAW et al., 2007 ; ACEVEDO et al., 2008 ; AJZEN, 2011) (link 4 in Figure 3.1). It can differ across cultural and institutional contexts (e.g. AJZEN et KLOBAS, 2013). Some authors used Hofstede's cultural dimension (2001) to test and explain differences in the relative importance of factors. For example, ENGLE et al. (2010), using a regional clustering of societal cultures (based on common language, geography, religion and history), highlighted that all three factors are important but not in every situation and every country and not to the same degree. KHALID (2018) compared cultural characteristics of Japan and Pakistan to provide insights into the association of culture and cognitions relevant to entrepreneurship.

The implementation of TPB within ABM has been used to study technology diffusion among households (SCHWARZ et ERNST, 2009 ; GAMAL ABOELMAGED, 2010 ; ROBINSON et al., 2015 ; SCHWARZ, KUHN et al., 2016), migration decisions (D. KNIVETON et al., 2011 ; D. R. KNIVETON et al., 2012 ; KLABUNDE et al., 2016), farmers' decision-making (KAUFMANN et al., 2009), healthy lifestyle choices (RICHETIN et al., 2010), waste recycling (CESCHI et al., 2015), adoption of food safety measures (VERWAART et al., 2011), segregation decisions (M. WANG et al., 2012), traffic behaviour (S. C. ROBERTS et al., 2012 ; YU et al., 2014) and ethical problem-solving (ROBBINS et al., 2007).

3.3 Agent-based model

The purpose of the proposed ABM is to explore how farmers, who are connected in a network, are influenced in their choice to join a protection programme by : (1) different behavioural characteristics of the farmer populations and (2) different characteristics of the protection programme (see Appendix 3.1 for Overview Design concepts and Details protocol description).

Three sub-systems are modelled :

- The resource system entity represents a catchment area with a groundwater that has a certain concentration of pollutant.

- An agent represents a farmer whose farming practice has the unintended consequence of releasing pollutants into groundwater. They decide whether to enter the protection programme or not, i.e. to adopt a low-input farming practice.

- The governance system represents the protection programme that aims to influence the adoption by farmers of the low-input practice (link 3 in Figure 3.1).

All parameters, value ranges, and sources of values can be found in Appendix 3.2.

3.3.1 Resource system

It is assumed that the water used for drinking water production is abstracted from a groundwater body. The resource system sub-model is a linear reservoir model. The linear reservoir model, in its simplest form, appears well adapted to quite diverse situations ranging from small, highly urbanised watersheds to watersheds of several hundred hectares (MTES, 2020). This model represents a single reservoir, whose storage and discharge laws vary linearly as a function of the water level. We assume that agricultural activities are the only source of groundwater pollution (link 1 Figure 3.1). See Appendix 3 for a description of the resource system model.

3.3.2 Actors

Actors, here farmers, are randomly spatially distributed in the environment. The environment is a discrete toric space of 10×10 patches. Each of the 80 farmers is located in a patch (x_i, y_i) . They all have the same farm area and the same type of production. At the beginning of the simulations, they all practice high-input farming. Each year (the time step of the model), they can

change their practice to low-input farming. Low-input farming practice (l) is more favourable to water quality than the high-input practice (h) but less economically profitable.

The intention of farmers to participate in the protection programme and therefore to change their farming practice is calculated. The intention is composed of the three factors of TPB : the attitude, subjective norm and PBC, weighted by their relative importance in the intention.

Calculation of behavioural intention $I_i(t)$

To calculate the coefficient of intention to change to low-input farming practice, $I_i(t)$, we use a linear function of the three basic factors weighted by their importance in intention, following BEEDELL et al. (2000).

$$I_i(t) = s_i(t) * \gamma_s + a_i * \gamma_a + p * \gamma_p \quad (3)$$

$$\gamma_a + \gamma_s + \gamma_p = 1 \quad (4)$$

where,

- $s_i(t)$ is the subjective norm, linked to the behaviour of others, - a_i is the attitude, i.e. the judgement of farmer i on the desirability of changing to low-input farming practice, and on the consequences of this change,

- p is the PBC, it is the beliefs of the farmer on his/her ability to adopt the low-input farming practice,

- γ_s , γ_a and γ_p are the weight of $s_i(t)$, a_i and p in intention.

We assume that the weight of factors affecting the intention is the same among the population of farmers in a given water catchment area. These weights (γ_s , γ_a , γ_p) characterise the population of farmers.

Calculation of the subjective norm $s_i(t)$

The subjective norm is the agent's perception of what the other important people for the agent (farmers in the network of the agent) think the agent should

or should not do. Farmers in a network can communicate about their farming practice (link 2 in Figure 3.1). Like most authors using TPB in ABM (SCHWARZ et ERNST, 2009; WARNKE et al., 2017; MUELDER et al., 2018; RAIHANIAN MASHHADI et al., 2018; TONG et al., 2018), we implement a descriptive norm in place of the subjective norm. We assume that what the farmer thinks the other important people think the agent should or should not do is equivalent to what the other important people do. Thus, the subjective norm is equal to the share of low-input farmers in his/her network. This factor is dynamic and evolves during the simulation :

$$s_i(t) = m_i(t)/n_i \quad (8)$$

where, $m_i(t)$ is the percentage of farmers in the set S_i doing the low-input farming practice, n_i the number of farmers in the set S_i , and S_i the set of farmers in the farmer's social network i (see Appendix 4 for the construction of the social network).

Calculation of the attitude a_i

METTEPENNINGEN et al. (2013) and FALCONER (2000) considered two different types of attitude : attitude towards the environment and environmental management on the farm and attitude towards the agro-environmental scheme (AES) and its implementation. We assume in the model that the attitude entails two aspects : a financial aspect and an environmental aspect (5). This factor is static and differs between the two types of farmers.

$$a_i = e * (1 - w_i) + f * w_i \quad (5)$$

$$f = (\pi_l - \pi_h + \phi)/(\pi_h - \pi_l) \quad (6)$$

$$e = 1 \quad (7)$$

We assume that the financial component of the attitude is the normalised difference between the low-input and high-input farming gross margins (6). Indeed, most farmers will not adopt an agro-environmental measure if the financial compensation is not in line with the cost of changing for a sustainable

farming practice (WILSON, 1992; DEFRANCESCO, GATTO, RUNGE et al., 2007; METTEPENNINGEN et al., 2013). Hence, the costs of change can be a barrier to the intention of changing farming practices. π_h and π_l are, respectively, the gross margins of the high-input and low-input farming practices. The assumed values of the gross margins of the high-input and low-input farming practices (π_h and π_l) are 900 and 600 €, respectively. A compensation (ϕ) can be provided to farmers depending on the protection programme. The financial component of the attitude can be negative or positive.

The environmental component of the attitude e is the judgement regarding the environmental desirability of the low-input farming practice, i.e. the environmental consequences of the low-input practice on the concentration of pollutant in the groundwater. We assume that the actors consider that the adoption of a low-input practice has a real impact on water quality and is completely desirable (7).

The financial preference (w_i) is the weight of the financial component of the attitude. We distinguish two types of farmers : "economicus" and "eco-friendly". The "economicus" type places more emphasis on the economic profit, hence the financial preference is higher than for the "eco-friendly" type, who attaches more weight to the environment. w_i equals 0.9 for economicus and 0.5 for eco-friendly.

Calculation of the perceived control p

The PBC (p) is the perception of the ease and the difficulty of performing the behaviour. This factor is static and the same for all farmers.

$$p = \theta + p_0 \quad (9)$$

METTEPENNINGEN et al. (2013) point out that several studies show that the adoption of an AES is influenced by the perception of ease of implementation and adequacy with farm characteristics. In the literature, the PBC of farmers is influenced by qualification (e.g. KAUFMANN et al., 2009), past experiences

(e.g. D. R. KNIVETON et al., 2012; DIEZ-ECHAVARRÍA et al., 2018), economic aspects (e.g. VERWAART et al., 2011; WARNKE et al., 2017) or available infrastructure or equipment (e.g. SCHWARZ et ERNST, 2009; LABELLE et al., 2018). In the model, we represent the PBC as the initial aggregation of past experiences, knowledge and qualification (p_0) and new knowledge acquired with the protection programme (θ). We assumed that the initial PBC (p_0) is zero and the same for all farmers.

Decision

The link between intention and behaviour raises two interlinked issues, regarding the strength of the link and its representation. Depending on the level of $I_i(t)$, the farmer will choose whether or not to change his/her farming practice ($B_i(t)$). Studies that implement the TPB in an ABM suggest that three different types of link between intention and behaviour can be implemented. First, when different behaviours occur, the intention for all of them is calculated and the maximum is chosen (e.g. KLABUNDE et al., 2016; RAIHANIAN MASHHADI et al., 2018). Second, intentions are compared with a behavioural threshold that determines whether the intended behaviour will be performed. If the behaviour is undertaken, the success of its realisation could take on different forms : systematic success (KAUFMANN et al., 2009; VERWAART et al., 2011); probability of a success (TONG et al., 2018); success function (WARNKE et al., 2017). Third, the intention is a probability of the behaviour (M. WANG et al., 2012).

Following KAUFMANN et al. (2009) and VERWAART et al. (2011), we have chosen to represent the transition from intention to behaviour by using a behavioural threshold :

$$\text{If } I_i(t) \geq \Omega_i \text{ then } B_i(t + 1) = 1 \quad (10)$$

Some studies comparing multiple analyses show that the gap between intention and behaviour can be more or less important depending on the behaviour studied (SHEERAN et al., 2016). The value of this behavioural threshold (Ω_i)

is distributed among the population according to a normal law. Thus, it is different for each simulation. This distribution is chosen to represent the diversity among individuals and the fact that the intention, although relatively good at predicting behaviour, is not a perfect predictor.

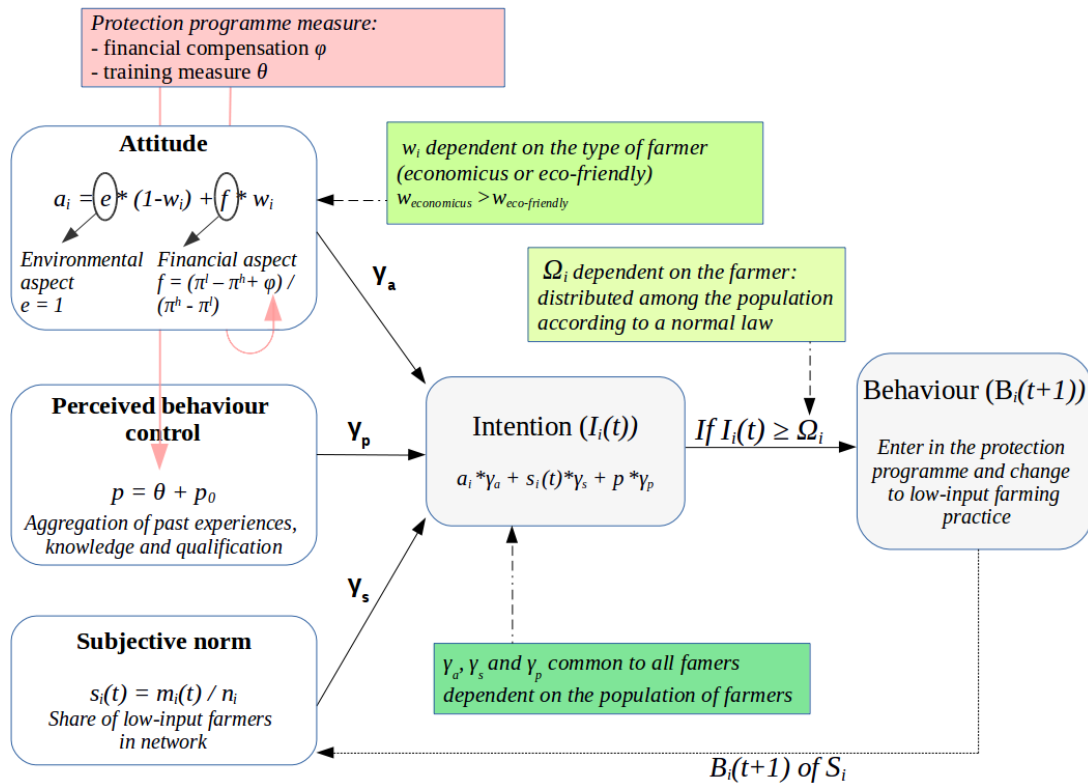


FIGURE 3.2 – Decision model schema based on the theory of planned behaviour (source : AJZEN, 1991). The pink box represents the protection programme measures. Squircles represent the process of the decision. Different levels of characteristics are in green : individual characteristics in light green (the threshold Ω), farmer-type characteristics in green (w), population-level characteristics in dark green. Dashed lines represent the feedback from the behaviours of the social network of the farmer i ($B_i(t + 1)$ of S_i) to the subjective norm of the farmer.

3.3.3 Governance

A programme aiming at protecting the drinking water catchment is implemented (link 3 in Figure 3.1). The farmer may or may not choose to participate in the programme. If farmers enter the process, they must change their farming practice to the low-input practice. The governance sub-model represents the choice of a protection programme based on the combination of the two following measures : financial compensation ; individual training and technical support (Table 3.1). The choice also includes the “level” of the measure (the amount of financial compensation, the intensity of training). The duration of the programme is 5 years.

Financial compensation. It is based on agri-environmental schemes of the EU CAP. Farmers voluntarily commit to adopting low-input farming practices in return for financial compensation. This compensation aims at covering the costs and income losses resulting from the change as well as the transaction costs. It influences the economic profits associated with a farming practice, hence the economic aspect of the attitude. The compensation is provided annually for 5 years. A compensation of 300€/year corresponds to the exact difference between the gross margins of low-input and high-input farming practice (π_h and π_l). We test a range of financial compensations from zero to twice this difference, i.e. 600€/year.

Training. Technical support and individual training are individual support measures offered to farmers in their change of practices (e.g. technical advice, meetings, technical tests, experiments). According to PAINÉAU et al. (1998) and LASTRA-BRAVO et al. (2015), training and information for farmers are key elements that promote a greater respect for the environment. In the model, this measure affects the perceived control by increasing the farmers’ knowledge about a farming practice. Knowledge persists in time. The training intensity is calibrated from 0 to 1. An intensity of 0.2 corresponds to a 1-year training course during a 5-year protection programme. We assumed that a 5-year training measure costs 2500€/programme. It was calculated from data on the costs

of training in a catchment protection programme implemented in France (see Appendix 5 for calculation).

Measure	Impact on	
	Attitude	Perceived behavioural control
Financial compensation (ϕ)	$f = (\pi_l - \pi_h + \phi) / (\pi_h - \pi_l)$	
Training (θ)		$p = \theta + p_0$

TABLE 3.1 – Measures and their impact on an actor’s decision-making

3.3.4 Reference scenario

In what follows, we present a reference scenario with which to analyse the processes involved in the system dynamics (see Appendix 3.2 and 3.6 for all detailed values). We run simulations for two time horizons : at 10 years, which corresponds to policy time scale, and at 500 years to evaluate ecological equilibrium. The results presented are representative on average. In the reference population, the three factors of intention used in the TPB have equal weights ($\gamma_a = \gamma_s = \gamma_p = 1/3$), there is no low-input farmer and half of the farmers are eco-friendly. The reference protection programme includes a financial compensation of 300€/year and a training measure with an intensity of 0.5.

As explained before, the intention to change depends on three factors :

- The PBC, which is the same whatever the type of farmer (economicus or eco-friendly). It means that training has the same effect on both types of farmers. This PBC is constant over time. Because we assumed that the initial PBC is zero, it is equal to 0.5 with the reference programme ;

- The attitude in which the weight of the financial component differs according to the type of farmer. Economicus farmers exhibit a higher weight of

the financial component (0.9) compared with eco-friendly farmers (0.5). This implies that economicus farmers are more sensitive to the financial compensation of a protection programme. The compensation (ϕ) is less than twice the difference between the gross margins of the high-input and low-input farming practices (π_h and π_l), so the ecological component is higher than the financial component. Consequently, economicus farmers have a lower attitude than eco-friendly farmers. With the reference programme, the attitude is equal to 0.5 for the eco-friendly farmers and to 0.1 for the economicus farmer. This attitude is constant over time ;

- The subjective norm depends on the social network of each farmer. Each farmer is influenced by the practice of farmers in his/her social network. The social network evolves over time ; it corresponds to the driver of the dynamics of the model.

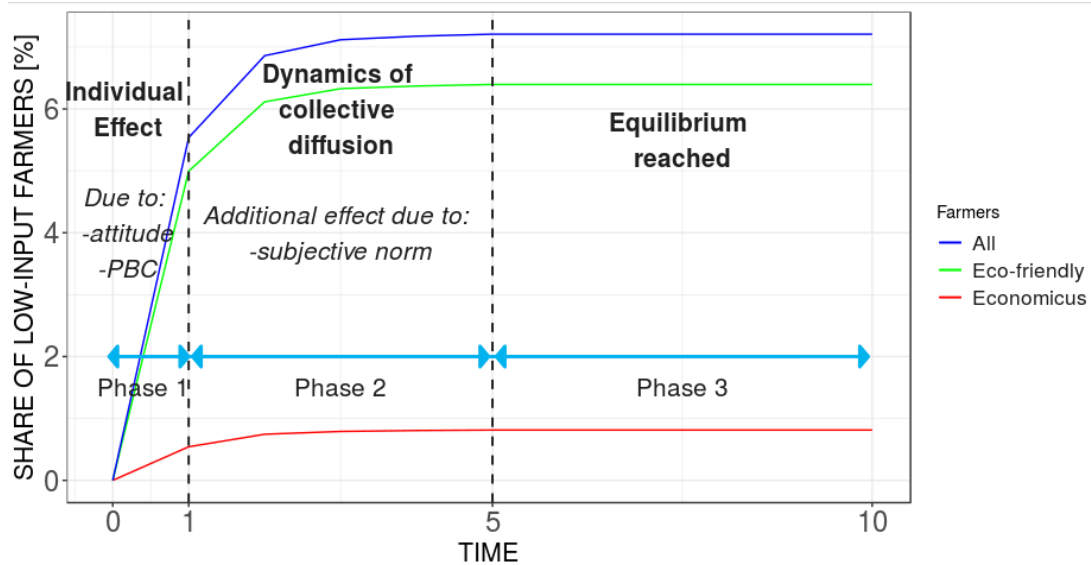


FIGURE 3.3 – Share of low-input farmers (%) (in blue all farmers, in green eco-friendly farmers and in red economicus farmers) for the reference scenario (the three factors of intention are equal : $\gamma_a = \gamma_s = \gamma_p = 1/3$, the financial compensation ϕ is equal to 300€ and the training intensity θ equals 0.5).

In Figure 3.3, the dynamics of low-input practice adoption by farmers are

represented for this reference scenario, divided into three phases. In the first phase, only the individual effects occur. Indeed, at $t = 0$, all farmers practice high-input farming, thus the subjective norm is null. More eco-friendly farmers than economicus farmers adopt low-input practices, because, as explained, the PBC is equal for types of farmers while attitude is higher for eco-friendly farmers than for economicus farmers. The second phase represents the effect of the collective diffusion of the low-input practice. Only the subjective norm evolves due to the evolution of the share of low-input farmers. After 5 years, 7.2% of farmers have adopted low-input practices (see blue line in Figure 3.3). Note that the dynamic of practice change is very fast because of the characteristics of the social network and of the low number of farmers and because the share remains stable after 5 years (phase 3 in Figure 3.3). The small percentage of low-input practice adoption has a marginal impact on the quality of water after 10 years (approx. 1.5% of pollutant decrease) as well as in the long term (approx. a decrease of 8% of pollutant in the water). The quality of water also depends of the characteristics of the water resource system, notably the water renewal rate.

3.4 Results

Based on the reference scenario, we explore how policy effectiveness, i.e. the evolution of farmers' practices and water pollution levels, depends on the characteristics of the farmer population (Section 4.1). Then, we examine how the characteristics of the protection programme, interacting with the behavioural characteristics of the farmer population, impact policy effectiveness (Section 4.2) and efficiency (Section 4.3).

3.4.1 Influence of the population characteristics on policy effectiveness

The influence of behavioural characteristics of the population

The behavioural characteristics of the populations have a strong influence on the final share of farmers adopting low-input farming practices (see Figure 3.4a) and on the concentration of pollutants. In the reference scenario in which there is no low-input farmer at the beginning, the higher the weight of the subjective norm for a population, the lower the diffusion of the low-input practice. Indeed, the subjective norm acts as a brake because of the assumption of no low-input farmer in the population before the implementation of the protection programme.

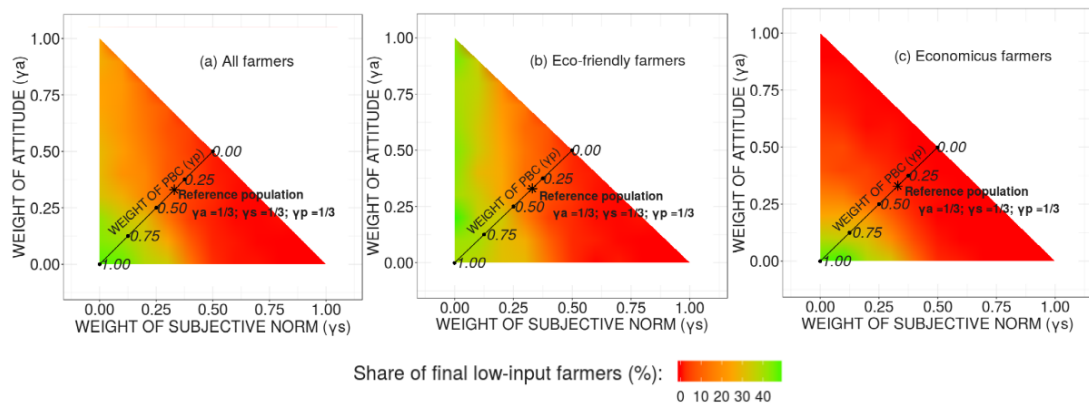


FIGURE 3.4 – Heat map of the final share of low-input farmers depending on the weights of TPB factors for (a) all farmers, (b) eco-friendly farmers and (c) economicus farmers, in the reference scenario. Whereas the share of eco-friendly low-input farmers is explained by the weight of subjective norm, the share of economicus low-input farmers is influenced by all factors and is higher with a higher PBC weight.

The difference in shares of low-input farmers between economicus and eco-friendly farmers increases with the weight of attitude. For eco-friendly farmers, the weights of attitude and PBC are equal in the reference protection

programme, thus only the weight of the subjective norm in the population influences the number of final low-input farmers (see Figure 3.4b). For economic farmers, the attitude is lower than the PBC, therefore a higher weight of PBC increases the final share of low-input farmers (see Figure 3.4c).

The influence of the initial share of low-input farmers

In the previous section, we investigated the case of no initial low-input farmers. However, we suppose that the presence of one or many initial low-input farmers may improve the effectiveness of the protection programme because of the subjective norm. In order to analyse the effect of initial low-input farmers on policy effectiveness, we tested different initial shares of low-input farmers according to different values of the importance of the subjective norm for the population (see Figure 3.5). Regardless of the weight of the subjective norm for a population (γ_s), the number of low-input farmers after the implementation of a protection programme increases with the initial share of low-input farmers (see Figure 3.5a). However, a higher-weight subjective norm does not necessarily lead to a higher final share of low-input farmers. In a context where there are initially few low-input farmers, the implementation of a protection programme will have a greater effects if the population gives less importance to the subjective norm. Below a threshold in terms of the initial number of low-input farmers, the subjective norm acts as a brake. Above this threshold, the final number of low-input farmers increases with the weight of the subjective norm. The subjective norm has a ripple effect on diffusion and accentuates the change in farming practices (see Figure 3.5a).

Nevertheless, the relative increase in the number of low-input farmers is not the highest in situations with a higher initial share of low-input farmers. Indeed, the highest increase is for populations including around one third of initial low-input farmers and having a high weight of the subjective norm (yellow area in Figure 3.5b). This corresponds to situations where there is both a greater possibility for a difference between the initial and final shares while at the

same time an initially sufficiently high share of low-input farmers to trigger the ripple effect of the subjective norm.

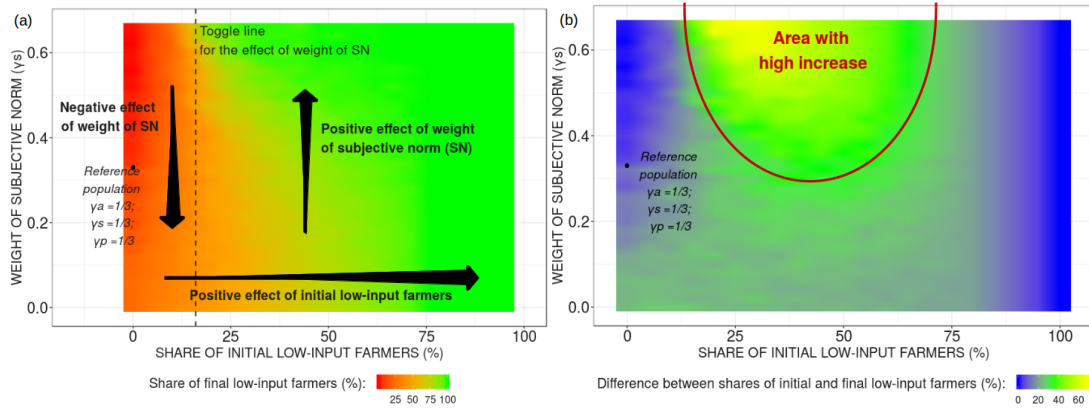


FIGURE 3.5 – Heat map of (a) the final share of low-input farmers and (b) the difference between the initial and final share of low-input farmers, depending on the weights of the subjective norm and on the initial share of low-input farmers in the reference scenario.

The influence of the share of eco-friendly farmers

We now suppose that the presence of more eco-friendly farmers may improve the effectiveness of the protection programme because of their favourable attitude towards the adoption of the low-input farming practice. In order to analyse the effect of the number of eco-friendly farmers on policy effectiveness, we tested different shares of eco-friendly farmers according to different values of the importance of the attitude for the population (see Figure 3.6).

Regardless of the weights of the factors in intention or the distribution between eco-friendly and economicus farmers, the share of low-input farmers after the implementation of the protection programme increases with the share of eco-friendly farmers in the population (Figure 3.6). The increase is higher for eco-friendly than for economicus farmers.

Eco-friendly and economicus farmers do not have the same sensitivity to

the increase in the weight of attitude. The impact of the weight of attitude depends on the weights of the subjective norm and PBC. As shown in section 4.1.1, for the reference scenario the subjective norm has a negative effect and PBC has the same effect as attitude for eco-friendly farmers. Thus, for eco-friendly farmers, the decrease in the weight of subjective norm increases the final share of low-input farmers (see Figures 3.6.2). Economicus farmers have a less favourable attitude towards the low-input practice than do eco-friendly farmers. The weight of PBC has a positive effect compared with the weight of attitude for economicus farmers. Thus, for economicus farmers, a lower weight of attitude increases the change to low-input practice (Figures 3.6.3). The share of low-input economicus farmers is the highest in Figure 3.6.b3, where the weight of subjective norm is fixed and the weight of PBC is the highest. It leads to an increase in the share of low-input eco-friendly farmers due to the influence of the subjective norm (see Figures 3.6.b2).

3.4.2 Influence of the characteristics of protection programmes on policy effectiveness

As explained earlier, a protection programme is composed of two policy measures (financial compensation and individual training) that may be combined in different ways. These different combinations in interaction with the behavioural characteristics of the population may affect the effectiveness of the protection programme. Therefore, in this section, we investigate this issue.

Adapting policy measures to population characteristics

Regardless of the relative importance of the factors in the intention, the level of financial compensation or the intensity of training proposed has a positive effect on the share of final low-input farmers. However, this positive effect differs in intensity according to the behavioural characteristics of the

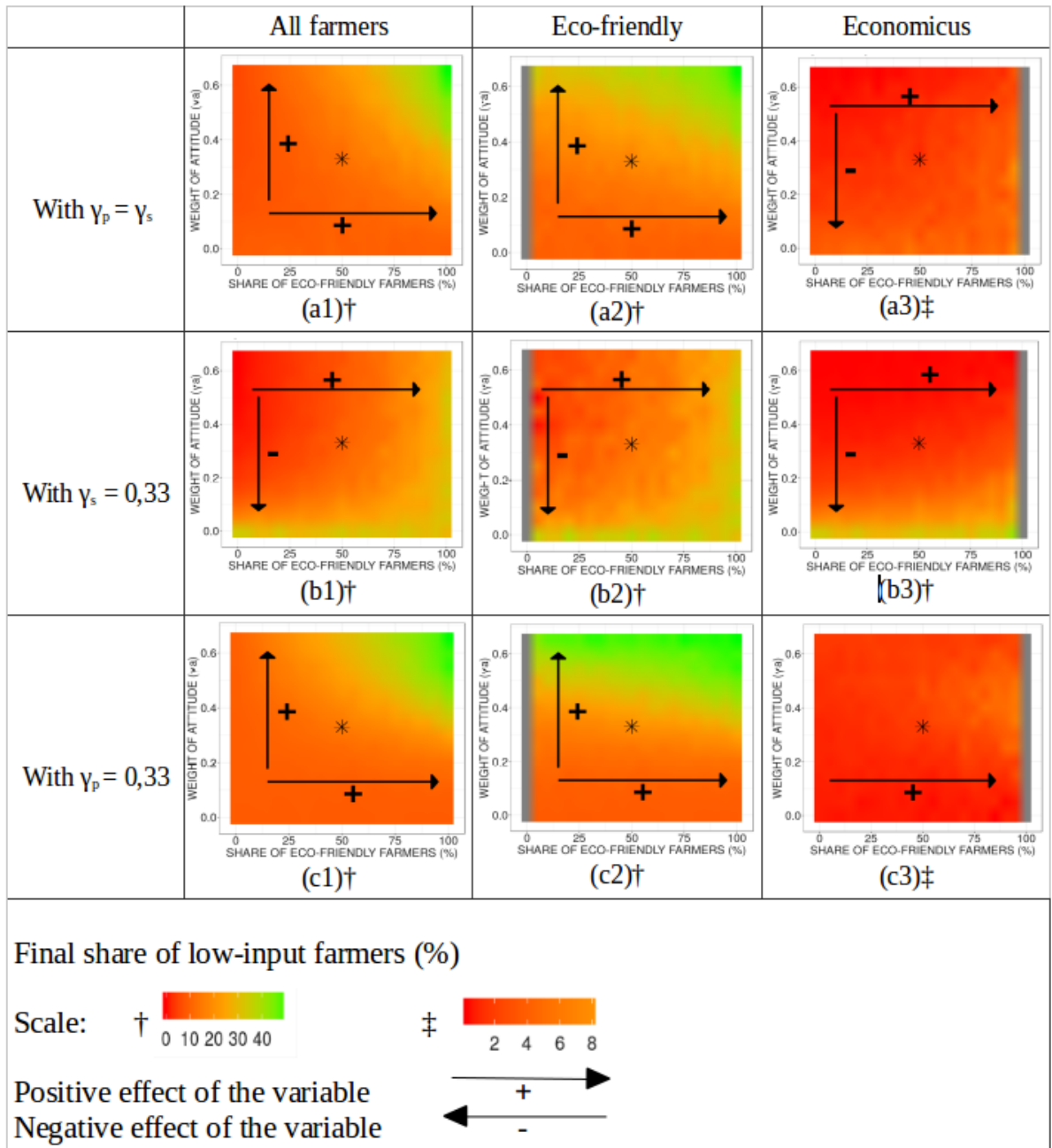


FIGURE 3.6 – Heat map of the final share of low-input farmers : (1) all farmers, (2) eco-friendly farmers and (3) economicus farmers depending on the weight of the attitude on the share of eco-friendly farmers, in the reference scenario, with (a) equal other weights ($\gamma_p = \gamma_s$) (b) a fixed weight of subjective norm ($\gamma_s = 0,33$) and (c) a fixed weight of PBC ($\gamma_p = 0,33$). * is the reference population ($\gamma_a = 1/3$ and 50% of eco-friendly farmers). The difference between the two types of farmers in the final share of low-input farmers is a function of the weight of attitude.

population. To analyse the coupled effects between the characteristics of the protection programme and the behavioural characteristics of the population, we compare the reference scenario population ($\gamma_a = \gamma_s = \gamma_p = 1/3$) with the three following populations :

- the attitude-influenced population which gives more importance to attitude ($\gamma_a = 0,5; \gamma_s = 0,25; \gamma_p = 0,25$) : therefore, the population is more sensitive to financial compensation, especially the economicus farmers ;
- the PBC-influenced population which values PBC more ($\gamma_a = 0,25; \gamma_s = 0,25; \gamma_p = 0,5$) : such a population is more sensitive to the intensity of training proposed by the protection programme ;
- the subjective norm-influenced population (which values subjective norms more, i.e. $\gamma_a = 0,25; \gamma_s = 0,5; \gamma_p = 0,25$) : this population is more sensitive to the dynamic effects caused by the social network.

For each population, many mixes of measure lead to the same share of low-input farmers. A mix of minimum levels of financial compensation and training intensity is needed to trigger a high level of adoption of low-input farming. We define a tipping area of the share of low-input farmers as an area where a small change in initial conditions (combinations of measures) leads to a large increase of low-input farmers' share. These areas differ from one population to another. They are linked to the social network and are less broad when the population is more sensitive to a subjective norm where the adoption of low-input agriculture is either nil or total (Figure 3.7d).

The intention of farmers in the attitude-influenced population is more sensitive to the financial compensation ; nevertheless, the minimal compensation of the tipping area is higher than for other populations. Likewise, while the intention of farmers in the PBC-influenced population is more sensitive to training intensity, the minimal intensity triggering the population shift to low-input practice is higher than for other populations.

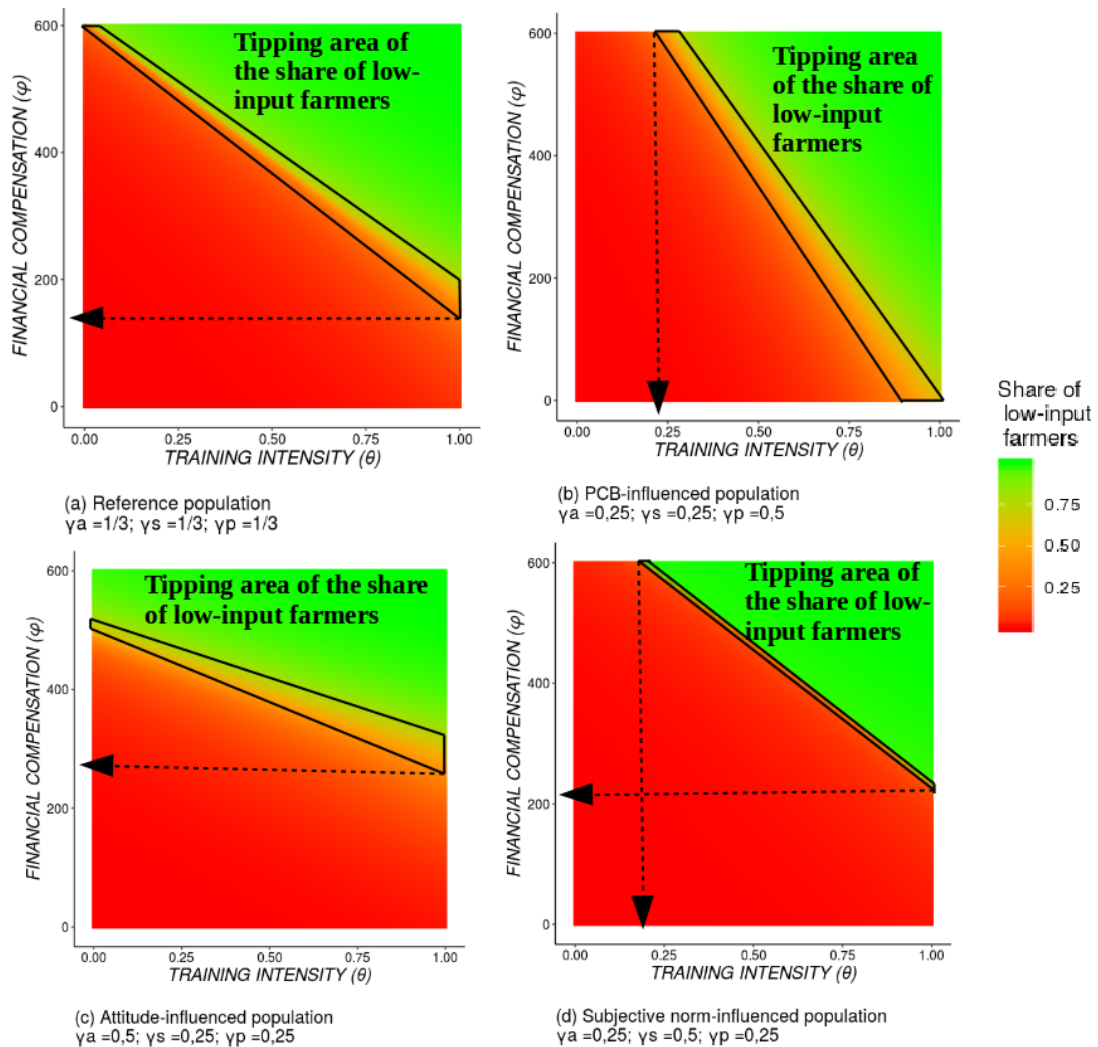


FIGURE 3.7 – Heat maps of trade-offs between financial compensation and training measure for four populations : (a) the reference population ($\gamma_a = 1/3; \gamma_s = 1/3; \gamma_p = 1/3$), (b) PBC-influenced ($\gamma_a = 0.25; \gamma_s = 0.25; \gamma_p = 0.5$), (c) attitude-influenced ($\gamma_a = 0.5; \gamma_s = 0.25; \gamma_p = 0.25$) and (d) subjective norm-influenced ($\gamma_a = 0.25; \gamma_s = 0.5; \gamma_p = 0.25$). Tipping areas and their orientation show the difference in sensitivity of populations to the measures.

By comparing the tipping areas, the attitude-influenced population (Figure 3.7c) shows a higher marginal effect of the financial compensation on the level of training intensity than other populations. That is to say, a small decrease in the amount of financial compensation must be compensated by a greater increase in training intensity than for other populations so as to lead to the same share of low-input farmers. On the other hand, a small decrease in the intensity of training must be compensated by a greater increase in the level of financial compensation for the PBC-influenced population than for the other populations so as to lead to the same proportion of low-input farmers.

Iso-lines of effectiveness of different policy measures according to populations

The iso-lines of involvement are curves where the mixes of policy measures engage the same share of low-input farming. An iso-line of involvement serves as a demarcation for two areas : one area representing the set of mixes of policy measures leading to a higher share of low-input farming and one area representing the set of mixes not leading to this share. The combination of iso-line zones for different populations makes it possible to define an area where a given level of effectiveness is achieved for all populations and an area where this given level of effectiveness is not achieved for any population.

The results show that in the case of some mixes of policy measures, regardless of which of the four populations described in Section 3.4.2.1 are concerned, the target of 90% of farmers adopting low-input farming is not reached (area B in Figure 3.8). On the contrary, some mixes of policy measures make it possible to reach the target for the four populations (area A in Figure 3.8). However, depending on the population actually concerned, the financial compensation and/or training intensity could have been less important and thus the total cost of the programme to reach the same result could have been lower (area C in Figure 3.8).

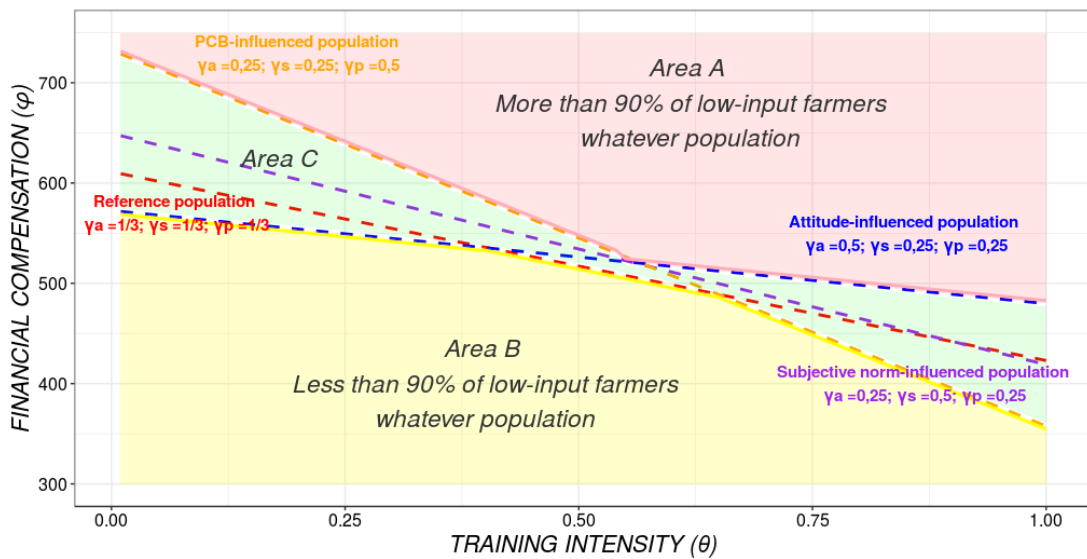


FIGURE 3.8 – Iso-line participation at 90% on average based on training and financial compensation for four populations : attitude-influence, reference (equal weight), subjective norm-influenced and PBC-influenced. Zone A in which, regardless of the behavioural characteristics of the population, 90% of the farmers will choose low-input farming. Zone B in which, regardless of the behavioural characteristics of the population, less than 90% of the farmers will choose low-input farming.

Thus, taking into account information about the farmer populations and their behavioural characteristics in the definition of policies can lead to measures with the minimal levels of financial compensation and/or training intensity needed to trigger farmers' adoption of the low-input practice. Without information on the behavioural characteristics of the population, policy makers may choose a mix of policy measures in a zone crossing all areas to reach at least a certain target of share of low-input farmers.

3.4.3 Mix of policy measures, not the most efficient policies but also not the least

As we have shown, different combinations of measures may lead to the same results. However, all combinations are not equivalent especially in terms of costs. In order to analyse the efficiency of policies, we analyse the combinations of measures with a fixed cost. We use the attitude-influenced and PBC-influenced population because they do not have the same sensitivity to the two measures.

Considering a fixed cost per farmer of 2500€, we tested the three following protection programmes : a whole-financial programme F, no training and a financial compensation of 500€/year ; an equilibrated training-financial programme E, two and half training sessions during the 5-year protection programme and a compensation of 250€/year ; and a whole-training programme T, one training session per year and no compensation. These different mixes of policy measures do not lead to the same final share of low-input farmers (Figure 3.9). The comparison of different mixes of policy measures for a given population allow us to find the most efficient mix. For the attitude-influenced population, the most efficient mix, with a fixed cost, corresponds to a whole-financial programme without training (point FA in Figure 3.9) while for the PBC-influenced population, it is a whole-training programme (point TPBC in Figure 3.9). These different policies are the most efficient for one type of population while they are the least efficient for the other.

Policies with average levels of each of the two measures lead to relatively similar shares of low-input farmers among different populations. Thus, without knowledge about a population, the choice of a mix of policy measures seems to reduce the variation in effectiveness of the protection programme for a fixed cost per farmer. A mix of policy measures, even if it is never the most efficient, guarantees to never be the least efficient policy.

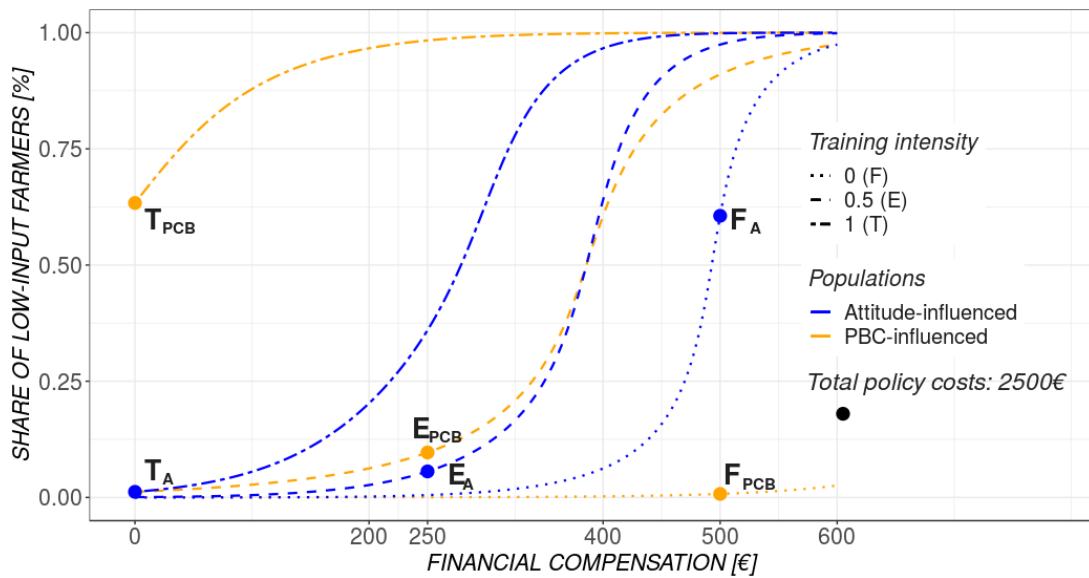


FIGURE 3.9 – Share of low-input farmers depending on financial compensation. Curves in orange and points X_{PBC} , Y_{PBC} and Z_{PBC} belong to PBC-influenced population ($\gamma_a = 0.25$; $\gamma_s = 0.25$; $\gamma_p = 0.5$). Curves in blue and points X_A , Y_A , and Z_A belong to attitude-influence population ($\gamma_a = 0.5$; $\gamma_s = 0.25$; $\gamma_p = 0.25$). Points are in the short dashed lines that represent the same total cost of a protection programme (2500€). Dashed lines, solid lines, dotted lines and two dashed lines are, respectively, from programmes with 1, 0.5 and 0 training intensity.

3.5 Discussion and Conclusions

The purpose of our study was to explore how the behavioural characteristics of farmer populations regarding drinking water catchments impact the efficiency and effectiveness of programmes designed to protect water quality. Our results showed that the involvement of farmers in protection programmes depends closely on the interactions between their behavioural characteristics and the governance system. The behavioural characteristics have to be taken into account in order to design efficient and effective policies. Mixes of policy measures with financial compensation and training are more expensive but may be a better option in cases where knowledge about behavioural characteristics is not available.

3.5.1 Contributions and policy implications

Despite the wealth of existing theories derived from experimental and empirical research in various fields (psychology, behavioural economics, sociology, etc.) and the recognised importance of human behaviour in SES models, many formal models are often still based on the over-simplifying assumptions of the rational actor (SCHLÜTER, BAEZA et al., 2017). However, farmers' decisions to adopt more sustainable practices can be affected by multiple behavioural factors (DESSART et al., 2019). Models used for real-world policy support should include agents who behave more closely to humans. A wrong representation of actors' decision-making processes can lead to the design of inadequate policies. Many examples can be cited where the agents' behaviour is not well understood and taken into account, leading to problems of policy effectiveness, or even unintended results, particularly in fields where social or environmental motivations matter in addition to economic motivations (BÉNABOU et al., 2006; BROWN et al., 2021). Our analysis therefore aimed at contributing to the operationalisation of a theory in social psychology, the theory of planned behaviour, in an SES model. The results highlight the links between the governance

system and the agents' decision-making processes and thus the importance of considering the behavioural processes of agents in the design of policies.

Previous studies focusing on the EU agri-environmental schemes (component of the EU Common Agricultural Policy (CAP)) have shown that a lower level of governance, at the local level rather than at the centralised EU level, helps to better adapt measures (e.g. the level of subsidies) to the characteristics of farmers (KUHFUSS, JACQUET et al., 2012; BAREILLE et al., 2020). In water catchment areas, AMBLARD (2019) concluded that strengthening the autonomy of local actors in adapting measures and compensations to the local context could improve the effectiveness of water quality management programmes. Our results highlight the importance of tailoring agri-environmental policies to the characteristics of farmers. Despite the decentralisation of the EU agri-environmental scheme, which leaves room for decisions at the Member State and local levels, the possibility to adapt the measures to the characteristics of farmers remains limited (KUHFUSS, JACQUET et al., 2012; SAÏD et al., 2017; AMBLARD, 2019). The decentralisation of agri-environmental schemes is still the subject of much debate in the post-2020 CAP negotiations (MAA, 2020), both in the EU context as well as in other settings (WRIGHT et al., 2016; VORLEY, 2002; BAREILLE et al., 2020).

3.5.2 Limitations and perspectives

Although TPB has already been implemented in different fields, the implementation of this theory in ABM still has limitations. In fact, TPB is based on conceptual psychological notions. The modeller has to decide how to implement these concepts and how to link them together (MUELDER et al., 2018). Our study constitutes a first step in the integration of TPB in an SES-ABM. Several perspectives and improvements are under consideration. First, we consider only the behaviour of change towards low-input farming, which implies little change in farm structure and organisation. This means that the model is less appropriate for representing the water catchment areas where

the evolutions considered involve substantial changes in farming systems, e.g. the conversion to organic farming. A perspective of the current work would be to modify the PBC – which in our model is a combination of knowledge, past experience and qualification – to include some of the barriers associated with such major changes. For example, a financial constraint due to the need for structural change in organic farming could be considered in the PBC (e.g. VERWAART et al., 2011). Second, we assumed that the learning process only includes a change in knowledge, but it can also change attitude beliefs, e.g. change the share of eco-friendly and economic farmers, or a change in networks, e.g. creation of new networks supported by training groups. Third, we have stylised the hydrological and bio-physical systems and neglected the possible feedbacks between the actors and the ecological system. A perspective would be to integrate a feedback between the ecological system and the actors through the influence of farmers' perception of the state of the ecological system. Finally, one remaining challenge would be to perform empirical studies to calibrate our model with real-world data on farmers' characteristics and decision-making processes. While we assumed that all farms are the same (in terms of size, gross margin, and environmental impacts) in the catchment area, this is a good approximation of reality in some areas but not in others. The characteristics of agriculture (e.g. size, location, type of farming systems) could be defined using data from the French agricultural census (e.g. XU et al., 2018). Further, the issue concerning the integration of real data in the decisional model, also described by SCALCO et al. (2018), is a recurring question, partly because the factors involved in intention are latent factors. Some statistical methods allow us to identify and estimate the behavioural characteristics of farmers through questionnaires, such as structural equation models (SEM) (e.g. KAUFMANN et al., 2009; SCHWARZ et ERNST, 2009) or by using fuzzy logic or regression coefficients (e.g. CASILLAS et al., 2004).

3.5.3 Concluding remarks

The ability of our model to capture the real-world patterns of the evolution of farming practices in a catchment area indicates that our findings may yield important insights for water governance. We highlighted that efficient water quality management requires adaptation to the local behavioural characteristics of targeted farmers to enhance their involvement. Moreover, improved knowledge about farmers' behavioural characteristics can reduce the costs of protection programmes. Nevertheless, this investment in knowledge also has a cost that should be taken into account in the global cost of the programme. There is therefore a trade-off between reducing the programme costs and investing in research on population characteristics. Finally, if knowledge on behavioural characteristics is not available, mixes of policy measures are more expensive but may be a better option. Understanding the impact of the characteristics of farmers on water policy outcomes is essential for designing public policies faced with increasing water security challenges. In view of the growing significance of pollution for the sustainability of water resources, we believe that our model and results may represent a valuable contribution to the growing literature on the interactions between resource management and society.

3.6 Appendix 1

After the ODD+D protocol for describing human decisions in agent-based models (MÜLLER et al., 2013).

Overview

I.i Purpose

I.i.a What is the purpose of the study? To explore how the choice by farmers, with either financial or environmental orientation, who are connected in a network, for whether or not to join a protection programme (and thus to practice low-input farming, the farming practice promoting by protection program) and the consequences in terms of drinking water quality are influenced, on the one hand, by different behavioural specifications and, on the other hand, by different characteristics of a protection programme.

I.i.b For whom is the model designed? For scientists of different disciplinary backgrounds, particularly those interested in natural resource governance.

I.ii Entities, state variables, and scales

I.ii.a What kinds of entities are in the model? One ecological entity : A groundwater with a certain concentration of nitrate. Two types of social entities : Farmers and governance. Dozens of agents represent farmers whose farming practices have the unintended consequence of releasing pollutants into groundwater. They decide to enter or not in the protection programme (which is whether or not to practice low-input farming promoting by the protection programme). Governance is represented by an agent and its function is to encourage farmers to become involved in the proposed protection programme, which aims to ensure that farmers practice low-input agriculture.

I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterized? Ecological entity : The groundwater has a certain quantity of water (Q). There is a natural flow that feeds (E) the groundwater and a quantity that exits (D) the groundwater. The concentration of pollutants in water ($C(t)$), in mg/l, is used as a proxy to measure water quality, i.e. the

quantity of pollutant ($N(t)$) relative to the quantity of water in the groundwater (Q). Farmers (one agent represent one farmer (i)) are characterized by : a location, a farming practice ($B_i(t)$), which can be low-input (l) or high-input (h), low-input farming practice is more favourable to water quality than the high-input practice but less economically profitable, a residual pollutant affecting the groundwater ($R_i(t)$) of the agent i depending on her practice, a social network (S_i), a behavioural type : economicus or eco-friendly, a decision model and a set of decision parameters, a behavioural threshold to change (Ω_i), a financial preference (w_i), an intention factors preferences ($\gamma_a \gamma_s \gamma_p$), a set of knowledge and past experiences about farming practices p . Governance is characterized by these variables : an amount of compensation (Φ), an intensity of training practice (θ).

NB : The letters and symbols in brackets refer to the equations from Supplementary Materials

I.ii.c What are the exogenous factors / drivers of the model ? Nothing

I.ii.d If applicable, how is space included in the model ? N/A

I.ii.e What are the temporal and spatial resolutions and extents of the model ? One time step equals to one year and the simulations were run at two time horizons : at 10 years that corresponds to policy time scale and at 500 years to evaluate ecological equilibrium. Rectangular grid 10*10 represented a water catchment area.

I.iii Process overview and scheduling

I.iii.a What entity does what, and in what order ? Step 1 : Governance - Update of the protection program. Step 2 : Farmers - Choice to enter or not in the protection programme and therefore switch or not their farming practice → Submodels Calculation of intention and Decision. Step 3 : Ecological system - Update of watershed (concentration of pollutants) → Submodel Update concentration

Design Concepts

II.i Theoretical and Empirical Background

II.i.a Which general concepts, theories or hypotheses are underlying the model's design at the system level or at the level(s) of the submodel(s) (apart from the decision model)? What is the link to complexity and the purpose of the model?

The ecological submodel is a linear reservoir model whose storage law and discharge law vary linearly as a function of the water level. "The linear reservoir model, in its simplest form, appears well adapted to quite variable situations ranging from small, highly urbanized watersheds to watersheds of several hundred hectares." (MTES, 2020).

The governance submodel is a choice of a protection programme that can include the following measures : financial compensation, individual training and technical support. The choice is about the level of the measure (amount of the compensation and intensity of the training). Financial compensation : They are based on agri-environmental scheme that are EU Common Agricultural Policy's instruments. Farmers voluntary commit to adopt low-input farming practices in return for a financial compensation. This compensation aims at covering the costs and income losses resulting from the change as well as transaction costs. It influences the economic profits associated with a farming practice, hence the economic component of the attitude. The compensation is provided annually for five years. Training : Technical support and awareness raising are individual support measures to farmers in their changes of practices (e.g., technical advice, meetings, technical tests, experiments). According to PAINÉAU et al. (1998) and LASTRA-BRAVO et al. (2015), training and information for farmers are key elements that promote a greater respect for the environment. In the model, this measure affects the perceived control by increasing farmers' knowledge about a farming practice. Knowledge persists in time.

II.i.b On what assumptions is/are the agents' decision model(s) based? We adapt the theory of planned behaviour (TPB) ((AJZEN, 1991)). In this frame, the intention towards a behaviour, considered as a trustworthy

predictor as whether or not the behaviour will be performed, is influenced by three global variables : judgment about the desirability of the behaviour and its consequences (attitude towards behaviour); considerations about the influence and opinions of others on that behaviour (subjective norm); and beliefs about the individual's ability to succeed in the behaviour (perceived behavioural control).

II.i.c Why is a/are certain decision model(s) chosen ? One of the most frequently used approach to understand farmers' decision-making with regard to agri-environmental policies is the theory of reasoned action developed by AJZEN et FISHBEIN (1980) (TOMA et al., 2007; FALCONER, 2000) who was later extended to the TPB (AJZEN, 1991).

II.i.d If the model / a submodel (e.g. the decision model) is based on empirical data, where does the data come from ?

II.i.e At which level of aggregation were the data available ?

II.ii Individual Decision Making

II.ii.a What are the subjects and objects of decision-making ? On which level of aggregation is decision-making modeled ? Are multiple levels of decision making included ?

Farmers decide if there are involved in the protection programme and accordingly apply low-input farming practice. Governance chooses the characteristics of the protection program : minimum duration, amount of compensation, training intensity.

II.ii.b What is the basic rationality behind agents' decision-making in the model ? Do agents pursue an explicit objective or have other success criteria ? Farmers act if their intention exceeds a threshold. This intention is a function of their beliefs about the behaviour in term of attitude, subjective norm and perceived behavioural control.

II.ii.c How do agents make their decisions ? If the farmer is not in the protection programme (and thus do not practice low-input farming), she com-

compares her intention to be involved in the programme ($I_i(t)$) and her behavioural threshold (Ω_i). If the behavioural threshold is exceeded, she enters in the programme and change to low-input farming.

1. Calculation of intentions ($I_i(t)$), which is a linear function of the following factors weighted ($\gamma_a \gamma_s \gamma_p$) by their contribution in the intention : - attitude (a_i) : weighted sum of a comparison between profit and environmental component - subjective norm ($s_i(t)$) : percentage of low-input farmers in networks - perceived behavioural control (p) : knowledge and past experiences 2. Compare intentions with behavioural threshold (Ω_i)

Attributes of farmers concerning the decision-making process are : a weight of the importance of attitude in intention, a weight of the importance of perceived behavioural control in intention and a weight of the importance of subjective norm in intention, a weight of the importance of the financial component of the attitude, a weight of the importance of the environmental component of the attitude, behavioural threshold (indicate when the intention become a behaviour).

II.ii.d Do the agents adapt their behavior to changing endogenous and exogenous state variables? And if yes, how? Yes, attitude is modifying by compensation from the protection programme and perceived behavioural control is modifying by the training intensity of the protection programme.

II.ii.e Do social norms or cultural values play a role in the decision-making process? Yes, a social norm represented by the percentage of low-input farmers in an agent's network constitutes the subjective norm.

II.ii.f Do spatial aspects play a role in the decision process? No

II.ii.g Do temporal aspects play a role in the decision process? Yes, - the farmers communicate to others their farming practice from the last year

II.ii.h To which extent and how is uncertainty included in the agents' decision rules?

II.iii Learning

II.iii.a Is individual learning included in the decision process? How do individuals change their decision rules over time as consequence of their experience? No

II.iii.b Is collective learning implemented in the model?

II.iv Individual Sensing

II.iv.a What endogenous and exogenous state variables are individuals assumed to sense and consider in their decisions? Is the sensing process erroneous? Individuals sense characteristics of protection programme, profit of different farming practices. No process erroneous.

II.iv.b What state variables of which other individuals can an individual perceive? Is the sensing process erroneous? Farmers know the farming practice of others. No process erroneous.

II.iv.c What is the spatial scale of sensing? Networks

II.iv.d Are the mechanisms by which agents obtain information modeled explicitly, or are individuals simply assumed to know these variables? Farmers are assumed to know these variables.

II.iv.e Are costs for cognition and costs for gathering information included in the model? No

II.v Individual Prediction

II.v.a Which data uses the agent to predict future conditions? Data from the protection program (change the expected profit of farming practices and expected control).

II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions? Farmers' attitude is the judgement about the desirability of their behaviour and consequences. This attitude is divided in a financial and an environmental component. The financial component of the attitude use the expected income from the farming practice and the environmental component use the output effect of farming practice on watershed.

II.v.c Might agents be erroneous in the prediction process, and how is it implemented? No, they are not erroneous. For the financial component, they calculate the difference normalized between the expected income of actual farming practice and the other farming practice. For the environmental component, it's equal to 1 as we assume that the actors consider that the adoption of low-input practice has a real impact on water quality and is completely desirable.

II.vi Interaction *II.vi.a Are interactions among agents and entities assumed as direct or indirect?* Direct interactions through communication about farming practices

II.vi.b On what do the interactions depend? Social network (based on links with farmers which are in one of the 8 patches around the farmer that are randomly renewed with other farmers - based on the Small World model of WILENSKY (2015) which is an adaptation of a model proposed by WATTS et al. (1998)

II.vi.c If the interactions involve communication, how are such communications represented? Communication about farming practices

II.vi.d If a coordination network exists, how does it affect the agent behaviour? Is the structure of the network imposed or emergent? N/A

II.vii Collectives *II.vii.a Do the individuals form or belong to aggregations that affect, and are affected by, the individuals? Are these aggregations imposed by the modeller or do they emerge during the simulation?* Individuals are affected by the practice of farmers in their network.

II.vii.b How are collectives represented? N/A

II.viii Heterogeneity *II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?* There are two types of farmers, eco-friendly and economicus. Differences are in the decision-making process, in the weight of finance component in calculation of attitude (a_i).

II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents? They are heterogeneous in their decision-making. They don't have the same weight of the importance of the financial component of the attitude. Eco-friendly farmers place more emphasis in environment than in profit in the calculation of attitude. Economicus on the contrary place more emphasis in profit.

II.ix Stochasticity

II.ix.a What processes (including initialization) are modeled by assuming they are random or partly random? Stochasticity is in part in initialisation only. Location, type, social network and the behavioural threshold are assigned randomly to farmers. The random distribution of the behavioural threshold follows the normal law. The social network is random.

II.x Observation *II.x.a What data are collected from the ABM for testing, understanding, and analyzing it, and how and when are they collected?* Number of farmers entering in protection programme. Evolution of factors attitude, subjective norm and perceived behavioural control in function of farmers' types and farming practices. Evolution of intention in function of farmers' types and farming practices. Costs of protection programme. Concentration in nitrates.

II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence) Number of farmers involved in the protection programme and concentration in nitrates depend on behavioural characteristics and measures of the protection programme.

Details

II.i Implementation Details *III.i.a How has the model been implemented?* Netlogo version 6.0.3. The code is available here : <https://github.com/ABourceret/behaviouralDynamicsInSES.git>

III.i.b Is the model accessible and if so where?

III.ii Initialization

III.ii.a What is the initial state of the model world, i.e. at time $t=0$ of a simulation run ? 80 farmers, 50% type economicus / 50% type eco-friendly, all in high-input farming

III.ii.b Is initialization always the same, or is it allowed to vary among simulations ?

III.ii.c Are the initial values chosen arbitrarily or based on data ? The initial values for the watershed have been estimate based on data (groundwater body, withdrawn) from the catchment area of the Allier (AMBLARD et REYNAL, 2015 ; L'ALLIER, 2015) Data for farmers are assumed.

III.iii Input Data

III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time ? No

III.iv Submodels

III.iv.a What, in detail, are the submodels that represent the processes listed in 'Process overview and scheduling' ?

III.iv.b What are the model parameters, their dimensions and reference values ? See below

III.iv.c How were submodels designed or chosen, and how were they parameterized and then tested ?

3.7 Appendix 2 : Values of parameters

Name	Water parametrisation	Value
Q	Groundwater body	200[millionm ³]
E	Withdrawn	4[millionm ³]
C(0)	Initial water pollution	60[mg/L]

TABLE 3.2 – Water parametrisation

Name	Agent parametrisation	Value
	Grid size	10*10
n	Number of farmers	80
$B_i(0)$	Farming practice of farmer i at t=0	high
w_i	Weight of the financial aspect in attitude for economicus farmers	0.9[w.u.]
	Weight of the financial aspect in attitude for eco-friendly farmers	0.5[w.u.]
Ω_i	Behavioural threshold of farmer i	N(0.5 ;0.125)
S_i	Social network	
p_0	Initial aggregation of past experiences, knowledge and qualification	0

TABLE 3.3 – Agent parametrisation

Name	Farming practices	Value
π_l π_h	Gross margin [€/ha/an]	low : 600 high : 900
$R(B_i^t)$	Residual pollutant affecting the groundwater	low : 0 high : 3

TABLE 3.4 – Farming practices

3.8 Appendix 3 : Ecological system sub-model

The water resource system is represented as a groundwater with a certain quantity of water (Q). There is a natural flow that feeds the groundwater and a quantity that exits the groundwater, consisting of a natural flow and a quantity of water abstracted. We consider that the quantities of water feeding and leaving (natural flow and abstracted water) the groundwater system are equal and constant over time (E). The concentration of pollutants in water ($C(t)$), in mg/L, is used as a proxy to measure water quality. It is the ratio between the quantity of pollutant ($N(t)$) and the quantity of water in the ground water :

$$C(t) = N(t)/Q$$

Depending on the soil and climate conditions, the characteristics and use of inputs, farming practices can contribute to water pollution (link 1 in Figure 3.1), measured by the residual pollutant affecting the groundwater ($R_i(t)$ of the farmer i). We assume that agricultural activities are the only source of groundwater pollution and that only the high-input farming practice leads to a residual pollution of groundwater. Thus, the pollutant quantity ($N(t)$) is :

$$N(t + 1) = N(t) * (1 - E/Q) + \sum_i R_i(t)$$

At $t = 0$, all farmers practice high-input farming. We assume that the high-input farming practice of the whole population has led to an initial pollutant concentration of 60 mg/L in the reservoir.

3.9 Appendix 4 : Construction of the social network

The construction of the social network is based on the Small World model of WILENSKY (2015), which is an adaptation of a model proposed by WATTS et al. (1998). The network develops based on a neighbouring network and on a probability to rewire a link with another random farmer. It begins with a network where each farmer is connected to his/her neighbours located on nearby patches ($x_i \pm 1; y_i \pm 1$). Half of the connections are rewired, i.e. half of the connections are deleted and replaced by new connections with random farmers. Two coefficients characterising the network are calculated : the clustering coefficient and the average path length. The clustering coefficient of the network is the average of clustering coefficients of all farmers. The clustering coefficient of a farmer is the ratio of existing links connecting a farmer's neighbours to each other to the maximum possible number of such links. The average path length is the average shortest path between all pairs of farmers. Networks with short average path lengths and high clustering coefficients are considered as small world networks. In our model, the clustering coefficient is approximately equal to 0,111 and the average path length is 2,571. For each simulation, the network is different because it depends on the random placement of farmers in the grid and on the random rewired links.

3.10 Appendix 5 : Calculation of training costs

We calculated the training costs used in the model based on data from a planning document concerning a water quality protection programme implemented in drinking water catchments in the Allier department in France and the website of the firm in charge of the farmers' training.

The document indicates that the planned training sessions, carried out by the VIVEA organisation, are 15 days per farmer for the 5-year programme (EAUX DE L'ALLIER SMEA, 2013). The aim of this training is to improve the agronomic knowledge of individual farmers and encourage them toward the overall direction of more water-quality-friendly practices.

In 2019, VIVEA carried out 1,920,000 hours of training for 94,000 beneficiaries (VIVEA, 2019). The recorded cost of these training sessions was €47.14 million, i.e. an hourly rate of €24.6/h and an average rate per beneficiary of €501.5. If we consider that a training day is 7 h, the training would cost 2583€ per farmer.

According to these calculations, we assumed in our model that a 5-year training costs 2500€/farmer.

3.11 Appendix 6 : Reference scenario

Name	Farmer population variables	Reference scenario	Scale
γ_a	Weight of attitude in intention [w.u.]	1/3	[0.1]
γ_s	Weight of subjective norm in intention [w.u.]	1/3	[0.1]
γ_p	Weight of perceived behavioural control in intention [w.u.]	1/3	[0.1]
	Initial share of low-input farmers [%]	0	[0.100]
	Share of eco-friendly farmers [%]	50	[0.100]

TABLE 3.5 – Agent variables

Name	Governance system variables	Reference scenario	Scale
ϕ	Financial compensation of the AES [€/year]	300	[0.600]
θ	Training intensity	0.5	[0.1]

TABLE 3.6 – Governance system variables

Chapitre 4

The potential of information-related instruments for water quality management in agriculture

Article en préparation

Objectif Le chapitre précédent (Chapitre 3) décrit un modèle d'une aire d'alimentation de captage en eau potable dans lequel des agriculteurs choisissent leur pratique agricole. Ce chapitre a permis de mettre en avant que les caractéristiques des agriculteurs influencent l'efficacité et l'efficience des politiques publiques. Dans le premier modèle, seuls les liens unidirectionnels de la gouvernance aux agriculteurs et des acteurs au système écologique sont modélisés. Pourtant, la littérature montre que l'état du système écologique a un impact sur la prise de décision des agriculteurs quant à l'adoption de mesures pro-environnementales. De plus, la gouvernance peut avoir un effet rétroactif sur ces liens, avec par exemple la fourniture d'information concernant le système écologique. Ce sont ces interactions que nous nous proposons de modéliser dans ce chapitre.

Contributions Nous avons donc développé un modèle, basé sur celui du chapitre précédent. Nous utilisons la même théorie pour décrire le processus de décision, c'est à dire la théorie du comportement planifié, dont nous développons l'opérationnalisation en ce qui concerne de l'attitude par rapport à l'environnement. Nous ajoutons la prise en compte du système écologique dans le processus de décision des agriculteurs. Le programme de protection modélisé inclut un instrument d'information. Deux types d'information sont donnés aux agriculteurs par le système de gouvernance, la première est une information sur l'état du système écologique, i.e. la concentration de polluant dans l'eau, et la seconde concerne les causes et conséquences de la pollution de l'eau. Le modèle a permis l'exploration de l'impact des mesures d'information, l'effet de l'hétérogénéité des préférences environnementales des agriculteurs (l'importance accordée à l'environnement par rapport au financier dans l'attitude) et l'influence de l'état initial du système écologique (niveau initial de pollution de l'eau) sur l'évolution des pratiques agricoles.

Résultats Les conclusions du chapitre sont les suivantes : 1) le ciblage des agriculteurs ayant des préférences environnementales plus élevées est plus efficace que l'absence de ciblage lorsque seulement la moitié de la population

peut être ciblée par la campagne d'information ; 2) l'hétérogénéité des agriculteurs en termes de préférences environnementales a une influence sur leur implication dans le programme de protection qui dépend des préférences environnementales moyennes du collectif d'agriculteurs ; 3) à partir d'un certain niveau de pollution initial, plus le niveau de pollution initial est élevé, plus l'implication des agriculteurs dans le programme de protection est importante.

Abstract In drinking water catchment areas, poor water quality, due in part to agricultural practices, is addressed by public policies that encourage farmers to change their practices. Among the instruments available to influence the behaviour of farmers, public policies can include information measures. These information measures are important considering that farmers' decision-making is influenced by a set of constraints such as imperfect or incomplete information, cognitive biases or lack of time. In particular, farmers' perception of the state of the ecological system (such as water quality in water catchment areas) and their awareness of the causes and consequences of water pollution influence their willingness to adopt farming practices in favour of the environment. Public policies therefore have a role to play in disseminating information about the state of the ecological system and the causes and consequences of water pollution. In this article we investigate how information measures may influence changes in farming practices and thereby the pollution in the water system. We built an agent-based model of a drinking catchment area to explore the impact of the information measures, the effect of the heterogeneity in farmers' environmental preferences and the influence of variations in the initial state of the ecological system (level of water pollution). Our results show that : (1) targeting farmers who have higher environmental preferences is more effective than no targeting when less than the whole population can be subject to the information campaign ; (2) the heterogeneity in farmers' environmental preferences has an influence on their involvement in the protection programme depending on the average environmental preferences ; (3) the higher the initial pollution level, the higher the involvement of farmers in the protection programme.

4.1 Introduction

In drinking water catchments, protection of water quality is important due to the various consequences of pollution on the environment, on general health and on the economy. Water quality refers to the condition of the water, including the chemical, physical and biological characteristics, based on the stan-

dards of its usage. In France, for instance, the normative definition of drinking water quality is assessed in relation to limits and references for approximately 60 parameters (bacteriological, physico-chemical and radiological) set by regulations (SOLIDARITÉS ET DE LA SANTÉ, 2021). Poor water quality is the main reason for the closure of drinking water catchments (OIEAU, 2020).

Farming practices are one of the major sources of diffuse pollution in catchment areas. Thus, in these areas, it is important to understand the reasons why farmers choose to adopt environmentally friendly practices. Among the various factors that influence farmers' choices regarding agricultural practices promoted by environmental policies (see for instance DESSART et al., 2019), their perception of water quality (GACHANGO et al., 2015), i.e. the subjective evaluation of water quality, can be relatively close to the reality (MOSER, 1984; MICHEL-GUILLOU, 2009; GACHANGO et al., 2015). For example, GACHANGO et al. (2015) found in specific areas in Denmark that farmers perceive water quality to be above average. This perception influences farmers in their choice to be involved in environmental policies through different processes (LUBELL et al., 2002; BOSCH et al., 2009; AMBLARD, 2019). The perception of water quality and the behavioural process in which it is implicated differ amongst farmers. Other factors are important in the decision-making process of farmers : their awareness of the consequences of this pollution (MICHEL-GUILLOU et MOSER, 2006), their awareness of the consequence of their practices (Z. HU et al., 2011) or their environmental concerns (TOMA et al., 2007).

Sometimes resource users do not behave favourably for the water quality due to a lack of information, perspective and understanding of the benefits of eco-friendly behaviours. Thus, public policies have a role to play in disseminating information on the state of the ecological system and on the consequences of a deterioration in the system. Some studies showed that information measures improved the effect of financial or regulatory instruments (e.g. SHEEDER et al., 2011; BARNES, TOMA et al., 2013; KUHFUSS, PRÉGET et al., 2016). The variety of land managers – encompassing the differences in their constraints to

change, in the factors that motivate their decisions, or in how they balance off business, social and personal factors – involves different types of information at different times, with differing degrees of advice and prescription (GARFORTH et al., 2003). For BLACKSTOCK et al. (2010), recognising the diversity of farming styles related to management decisions is essential in supporting the integrated management of diffuse agricultural pollution.

We developed an agent-based model with decision-making by agents that accounts for social influences, the heterogeneity of farmers and the ecological perception in the individual's motivations. The model represents a social-ecological system of a water catchment area in which farmers decide on their farming practices that impact water quality. The main purpose of the model is to perform a dynamic analysis of the diffusion of low-input farming practices where farmers are sensitive to the quality of the water. We use the model to simulate behavioural reactions of farmers to policy interventions.

In Section 4.2, we present the conceptual framework of our study. Then, we describe the agent-based model of a water catchment area in Section 4.3. This model allows us to analyse the impact of information-related instruments on water quality. More specifically : (1) We characterise the effectiveness of different water quality protection programmes. We focus on two information measures, one measure based on the provision of information about the concentration of pollutants in water and a second measure based additionally on the provision of information about the consequences of this concentration (Section 4.4.1); (2) We assess the impact of the state of the ecological system on farmers. We focus on the impact of the initial concentration of pollutants in water on farmers' behaviour (Section 4.4.2); (3) We identify how the diversity amongst farmers affects policy effectiveness, and focus on the heterogeneity in environmental preferences (Section 4.4.3). Finally, Section 5 presents a discussion of the findings and a conclusion.

4.2 Conceptual framework

Firstly, we discuss how the ecological system influences the decision-making process of farmers with regard to the choice of environmentally friendly practices. Secondly, we present how information on the ecological system could be complementary to regulatory and financial instruments in the context of water quality management.

4.2.1 Influence of ecological system on the decision-making process in the adoption of farming practices promoted by environmental policies

The ecological system can influence the behaviour of actors by modifying their outcomes (inputs, outputs or profits) or their decisions (e.g. MICHEL-GUILLOU, 2009; DESSART et al., 2019). In the field of drinking water management, the level of water contamination by nitrates and/or pesticides plays an important role in stakeholders' incentives to cooperate in the protection of drinking water catchments (LUBELL et al., 2002; BOSCH et al., 2009). Two mechanisms have been highlighted on this context : fear of regulation and questioning the importance of changing practices. Several studies have shown how the threat of applying regulatory measures when the level of pollution is high may stimulate the involvement of agricultural stakeholders in collective action to protect water catchments/watersheds (HARDY et al., 2010; GROLLEAU et al., 2012; AMBLARD, 2019). By contrast, some studies have noted that the good quality of the water resource, i.e. the absence of water pollution, can constitute an impediment to the agricultural stakeholders' involvement (GARIN et al., 2012; AMBLARD, 2019). The good quality of the water resource appears to be an obstacle to the participation of farmers who question the legitimacy of undertaking costly changes in their farming practices in the absence of any observed pollution (AMBLARD, 2019).

Moreover, the environmental concerns of farmers have an influence on their

adoption of sustainable practices (TOMA et al., 2007; BEST, 2010). D'SOUZA et al. (1993) found that farmers who are aware of on-farm environmental issues are more likely to implement sustainable practices. OKUMAH, MARTIN-ORTEGA et al. (2018) report that awareness of diffuse pollution mitigation measures affects compliance through the mediating effects of participation in agri-environmental schemes. A study found that positive environmental stewardship attitudes mediate the relationship between awareness of water quality problems and farmers' willingness to improve actions to improve water quality in Indiana (FLORESS et al., 2017).

Nevertheless, although the environmental consequences of agricultural practices may influence farmers, they first have to be aware of them, which is not always the case. While several studies have found that farmers do recognise the consequences of water quality related to agricultural practices (e.g., WARD et al., 1995; Z. HU et al., 2011), other studies showed that farmers are not necessarily conscious of these consequences (e.g. POPP et al., 2007). Moreover, some studies report that farmers have a mostly negative opinion of the perceived environmental benefits of water management (e.g. BARNES, WILLOCK et al., 2009; MORTON et al., 2017; INMAN et al., 2018). MICHEL-GUILLOU et MOSER (2006) found that there are differences between groups of farmers in the recognition of the existence of a water pollution problem : Farmers who have adopted pro-environmental practices feel more involved in this problem than farmers who have maintained traditional practices.

4.2.2 Information instruments to enhance water quality

Information instruments are state-based instruments similar to economic and command-and-control instruments (VILLAMAYOR-TOMAS et al., 2019). Economic instruments rely on market forces and changes in relative prices to modify the behaviour of actors in a way that supports environmental protection or improvement. Command-and-control tools influence environmental outcomes by regulating processes or products, limiting the discharge of speci-

fied pollutants, and by restricting certain polluting activities to specific times or areas. SHORTLE et al. (2012) note that economic incentives in the U.S. context have largely failed to improve water quality, and others have found that financial incentives alone do not account for changes in behaviour (e.g., CZAP et al., 2012; SHEEDER et al., 2011).

Like the economic instruments, information instruments involve a voluntary commitment of farmers to adopt practices in favour of water quality. They include public education and information campaigns. VILLAMAYOR-TOMAS et al. (2019) highlighted that such policies can be based on : (1) providing information in a relatively neutral way or (2) providing an appropriate interpretation of the information to guide behaviour in a particular direction. For example, the authority in charge of water management can monitor the concentration of pollutants in water and inform farmers about it. An alternative/complementary action is to provide information about the consequences of this pollution with the objective of raising awareness. According to LASTRA-BRAVO et al. (2015) and OKUMAH, CHAPMAN et al. (2021), training, awareness-raising and information for farmers are key elements that promote environmentally friendly practices. Awareness-raising of the environmental consequences of farming are generally considered a necessary step towards adopting practices that improve water quality (ERVIN et al., 1982; PROKOPY et al., 2008; BLACKSTOCK et al., 2010). BLACKSTOCK et al. (2010), based on a literature review, highlighted that raising awareness amongst farmers can alone be effective in persuading farmers to adopt favourable water practices.

The concept of nudge, developed in behavioural economics, defines information that influences the decision-making of individuals without changing the structure of economic incentives or restricting their available options. For example, KUHFUSS, PRÉGET et al. (2016) investigated the effect of information on a social norm as a behavioural nudge on the maintenance of practices promoted by agri-environmental schemes (AESs) and found a positive effect. The information is used in a complementary way to enhance the effect of an

economic instrument. BARNES, TOMA et al. (2013) also found that nudges play a positive role in the implementation of regulatory policies. An optimal mix of policies can lead to positive effects for improving water quality.

This brief review highlights the importance of information-based instruments in the management of environmental systems, which constitutes the main incentive of our modelling approach. We therefore developed a model involving actors whose decision-making process partially depends on the state of the ecological system, in a context where a mix of policies includes information instruments.

4.3 Model

We adapt a model from a previous study (Bourceret et al., unpublished) of an agent-based model for water quality preservation using the Theory of Planned Behaviour (TPB). First, we present the elements of the previous model that we used in our current model (Section 4.3.1). Second, we present the adaptations made to the model : the development of a specific part (of the environmental component of the attitude) to analyse the effect of an information policy on the change in farming practices (Section 4.3.2).

4.3.1 Previous model : TPB-based model of change in farming practices

In the model, individual farmers are connected in a social network, and their decision of whether or not to join a protection programme (and thus to practice low-input farming promoted by the protection programme) is based on the TPB (AJZEN, 1991). Each farmer calculates an intention to change to low-input practices, i.e. the level of motivations to adopt low-input practices, based on three independent factors : attitude, subjective norm and perceived behavioural control. Attitude is described as the financial and environmental

judgment about the desirability of adopting the low-input farming practices. The considerations about the influence and opinions of others on the behaviour of interest define the subjective norm. Farmers' decisions are influenced by other farmers' practices in the social network. The perceived behavioural control is the aggregation of past experiences, knowledge and qualification. Farmers with an intention higher than a personal threshold, will change to low-input farming.

Resource system

It is assumed that the water used for drinking water production is abstracted from a groundwater body. The resource system sub-model is a linear reservoir model whose storage law and discharge law vary linearly as a function of the water level. We consider that the quantities of water feeding and leaving (natural flow and abstracted water) the groundwater system are equal and constant over time. The concentration of pollutants in water ($C(t)$), in mg/L, is used as a proxy to measure water quality. We assume that diffuse pollution from agricultural activities is the only source of groundwater pollution and only high-input farming practices have residual pollutants in groundwater.

Actors

Decision process

The coefficient of intention to change to low-input farming practices, $I_i(t)$ is calculated. $I_i(t)$ is a linear function of the three basic factors.

$$I_i(t) = s_i(t) + a_i(t) + p \quad (1) \text{ where,}$$

- $s_i(t)$ is the subjective norm, linked to the behaviour of others,
- $a_i(t)$ is the attitude, i.e. the judgement of farmer i on the desirability of changing to low-input farming practices, and on the consequences of this change,
- p is the perceived control of behaviour, it is the beliefs of the farmer on

his or her ability to adopt the low-input farming practices,

Depending on the level of $I_i(t)$, and on a behavioural threshold, the farmer will choose whether or not to change their farming practices :

$$\text{If } I_i(t) \geq \Omega_i \text{ then } B_i(t+1) = l \quad (2)$$

The value of this behavioural threshold is distributed among the population according to a normal law. Thus, it is different for each simulation. This distribution is chosen to represent the diversity among individuals and the fact that the intention, although relatively good at predicting behaviour, is not a perfect predictor.

Factors

The subjective norm is the agent's perception of what the other people who are important to the agent (farmers in the network of the agent) think the agent should or should not do. Farmers in a network can communicate about their farming practices. We assume that what the farmer believes that the other important people think the agent should or should not do is equivalent to what the other important people do. Thus, the subjective norm is equal to the share of low-input farmers in the network. This factor is dynamic and evolve during the simulation (dotted line in Figure 4.1.). The construction of the social network is based on the Small World model of WILENSKY, 2015 (2015), which is an adaptation of a model proposed by WATTS et al. (1998).

The perceived behavioural control is the perception of the ease and difficulty of performing the behaviour. This factor is static and the same for all farmers. In the model, we represent the perceived behavioural control as the initial aggregation of past experiences, knowledge and qualification and new knowledge acquired with the protection programme. We assumed that the initial perceived behavioural control is zero and the same for all farmers.

We assume in the model that the attitude comprises two components : a financial component and an environmental component (3).

$$a_i(t) = e_i(t) * w_i + f * (1 - w_i) \quad (3)$$

The financial attitude towards the protection programme and its implementation is the difference between low-input farming and high-input farming gross margins, normalized. The costs of change can be a barrier to the intention of changing farming practices. π_h and π_l are, respectively, the gross margin of the high-input farming practices and of the low-input farming practices. Compensation can be provided to farmers depending on the protection programme ($\phi(t)$). $e_i(t)$ is the environmental component of the attitude (see 3.2. for details).

Like many authors, we used the term "preference" to describe the relative weight of the components of the attitude, and more specifically "environmental preference" to describe the relative weight of the environmental component of the attitude (w_i) (e.g. VERWAART et al., 2011 ; ROBINSON et al., 2015 ; MUELDER et al., 2018). We define two groups of farmers in the model. Each group is composed of 50% of farmers. All farmers in a group have the same environmental preference (w_i).

4.3.2 Developments : the environmental component of the attitude and information measures

We used new conceptual foundations explaining the attitude of agents towards the environment ($e_i(t)$). The purpose of the proposed agent-based model is to explore how the choice by farmers, who are connected in a network, to join a protection programme (and thus to practice low-input farming promoted by the protection programme) is influenced by the environmental component of the attitude, i.e. by the perception of the concentration of pollutant and by the awareness of the consequences of the farming practices and of pollution. The agent-based model is implemented in NetLogo (version 6.0.3) (WILENSKY, 1999).

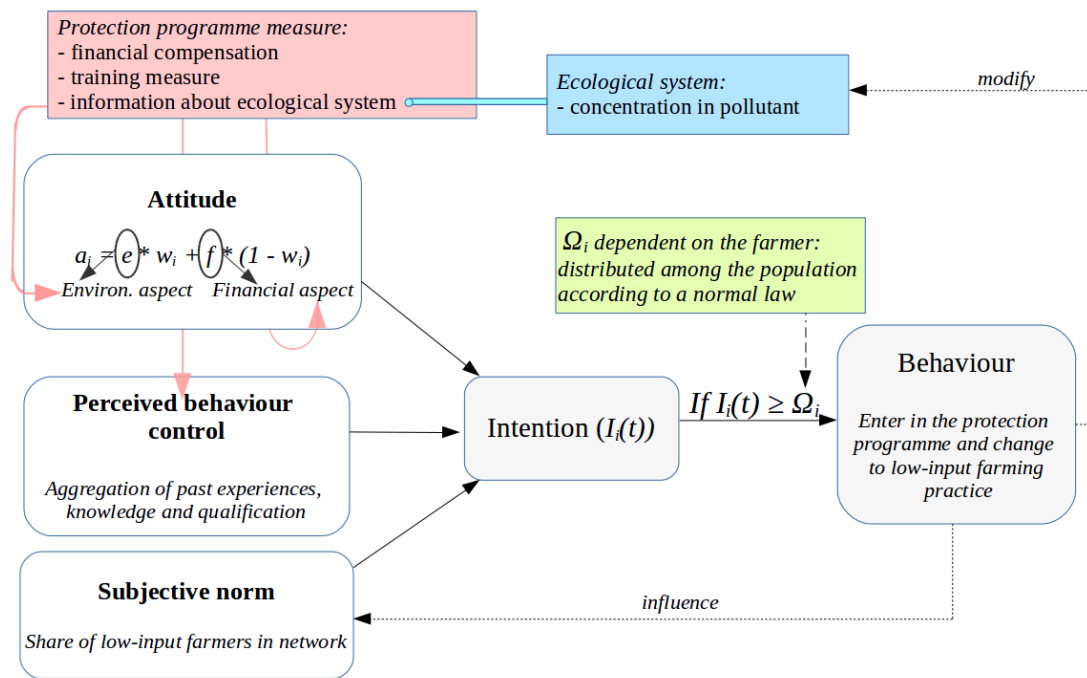


FIGURE 4.1 – Decision model schema based on the TPB (source : AJZEN, 1991, adapted from Bourceret et al., unpublished). The pink box represents the protection programme measures. Squircles represent the process of the decision. The individual characteristic (the threshold Ω) is shown in green. Dashed lines represent the feedback from the behaviours of the social network of the farmer i to the subjective norm of the farmer and to the ecological system. The blue box represents the influence of the ecological system on the attitude.

Environmental component of the attitude

$e_i(t)$ is the environmental component of the attitude, a_i , which is the judgement of farmer i on the desirability of changing to low-input farming practices, and on the consequences of this change. Thus, $e_i(t)$ is the judgement of farmer i on the environmental desirability of changing to low-input farming practices and on the consequences of this change, i.e. the environmental consequences of changing to low-input practices. We assumed that $e_i(t)$ is a function of the perception of the water quality, which is represented by the proxy of the concentration of pollutants in the groundwater.

We assumed that the environmental component of the attitude depends on three parameters : (1) the perception of the concentration of pollutants ($C_i(t)$); (2) an individual awareness threshold (α); (3) a sensitivity to this awareness threshold (q). Following MATHIAS, ANDERIES et al. (2020), we chose a function based on a sigmoid shape (s-shaped). If farmers perceive a good water quality, they judge that there is no environmental desirability for their change to low-input farming practice. The perception of a high concentration of pollutants implies a belief in the importance of changing practices that contribute to increasing the environmental component of the attitude.

$$e_i(t) = C_i(t)^q / (C_i(t)^q + \alpha^q) \quad (4)$$

α is the awareness threshold for a favourable attitude, and it corresponds to the environmental attitude inflection point (see Figure 4.2). Around this awareness threshold, the environmental attitude increases quickly. If $C_i(t) = \alpha$, $e_i(t) = 0.5$. q is the degree of sensitivity to change in the environmental attitude. If q is high, then the farmer will have a rapid change in environmental attitude and if q is low then the change in environmental attitude will be more gradual. We set $q = 5$, which implies a relatively high rate of environmental attitude change. Note that other high values of q – yielding sudden perception change – will not change the results qualitatively.

$C_i(t)$ can be informed by the authority in charge of water quality manage-

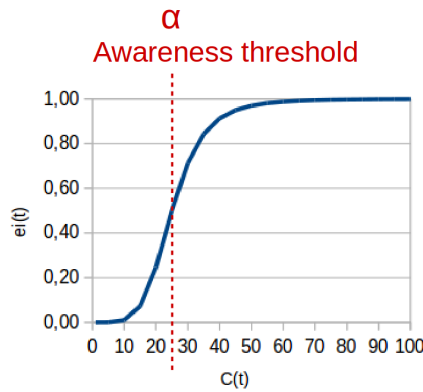


FIGURE 4.2 – Environmental component of attitude depending on concentration.

ment or can be the belief of the farmers if they do not have any information about this. (a) If the farmer receives the information about the concentration of pollutants in the water, then $C_i(t) = C(t)$. This information is given by an agent of governance (see below). (b) Following GACHANGO et al. (2015), who found in their study that farmers perceive the water quality to be above average, we assumed that on average, farmers in our model, if they do not have information about the concentration of the water, perceive the concentration of pollutants in the water to be lower than in reality. The belief regarding the concentration is distributed among the population according to a normal law and is stable during the simulation. The belief is distributed at the initialisation of the model and is different for each simulation. This distribution is chosen to represent the diversity among individuals.

If the farmer is informed about the concentration, $C_i(t) = C(t)$ (a)

If the farmer is not informed about the concentration, $C_i(t) = C_i$ (b)

Information measures

A programme aiming at protecting the drinking water catchment is implemented. The farmer may or may not choose to participate in the programme. If the farmer enters the process, he or she must change their farming practices to low-input farming. The protection programme is based on a combination

of the following measures : financial compensation, training and information. The duration of the programme is 5 years. The financial compensation and training measures are fixed for all simulations : They are considered as fixed parameters in the programme in order to study the influence of information-based measures. The financial compensation and the training are involved in the calculation of the financial component of attitude and in the perceived behavioural control¹.

Financial compensation (fixed measure in what follows). This measure is based on agri-environmental schemes of the EU CAP. Farmers voluntarily commit to adopting eco-friendly farming practices in return for financial compensation. This compensation aims at covering the costs and income losses resulting from the change as well as covering transaction costs. It influences the economic profits associated with a farming practice, hence the financial aspect of the attitude. The compensation is provided annually for 5 years. In the following analysis, we fixed the amount of compensation at 300€/year, which covers exactly the difference between the gross margins of low-input and high-input farming practices (π_h and π_l). This implies that the financial component of the attitude is equal to zero.

Training (fixed measure in what follows). Technical support and individual training are individual support measures to farmers when they change their practices (e.g. technical advice, meetings, technical tests, experiments). In the model, this measure affects the perceived control by increasing farmers' knowledge about a farming practice. Knowledge persists in time. In the following analysis, the training intensity is fixed at 0.75.

1. The following results can be found in Bourceret et al. (unpublished) : 1) the higher the financial compensation and the training intensity, the higher the final share of low-input farmers ; 2) the characteristics of the population of farmers (including the relative importance of attitude, subjective norm, and perceived behavioural control, the repartition of the environmental preferences and farmers' initial practices) influence the effectiveness and efficiency of the programme combining the financial compensation and training.

We focus on two information measures that influence the environmental component of attitude : information about the concentration of pollutants in water and information about the consequences of this pollution.

- *Information measure about pollution level.* The information given to the farmers is the exact concentration of pollutants in groundwater. This information measure can target all farmers or a certain share of farmers depending on the intensity of the diffusion. When a farmer is concerned by the information measure, he or she receives information about the pollutant concentration at each step. The information modifies $C_i(t)$ in the calculation of the environmental component of attitude (equation 4).
- *Information measure about the negative consequences of water pollution on health, economy and biodiversity (termed “awareness-raising measure” in what follows).* The objective is to lower the awareness threshold of farmers. Therefore, the information will modify α in the calculation of the environmental component of attitude (equation 4). The modification of the awareness threshold for a farmer is permanent.

4.4 Results

In the first and the second section, we explore the effect of this measure in the context of two specific groups of farmers, eco-friendly and economicus, with different fixed environmental preferences (EPs). First, we explore how the information-based measures impact the evolution of farmers’ practices and water pollution levels. We analyse more specifically the impact of the measure when it targets one group of farmers. Then, in the second section, we analyse the influence of the initial state of the ecological system on the policy effectiveness (Section 4.4.2). Finally, we return to the general case with two groups whose EPs may vary. We examine the impact that the heterogeneity in the EPs of farmers has on the effectiveness of the information measure (Section 4.4.3).

4.4.1 Information-based measures enhance the perception of water quality and raise awareness to involve farmers in protection programmes

In this section, we test the impact of the two information-based measures on the evolution of farmers' practices considering two groups of farmers, eco-friendly and economicus, with specific EPs. The eco-friendly farmers place more emphasis on the environment than do the economicus farmers, who attach more importance to economic profit. Hence, the EPs for the eco-friendly farmers are higher than for the economicus farmers. w_i is equal to 0.5 for eco-friendly farmers and to 0.1 for economicus farmers. First, we test the impact of the information measure on the evolution of low-input practices and on the concentration of pollutants in water. Then, we analyse the effect of targeting farmers according to their EPs. Finally, we test the effect with additional information about the consequences of pollution (awareness-raising measure).

Policy effectiveness depends on the share of farmers concerned by the information measure

The final share of low-input farmers increases with the share of farmers affected by the information measure. The final share of low-input farmers increases linearly approximately from 29% to 40% (see Figure 4.3). The concentration of pollutants also follows a linear decrease.

In both groups, the involvement of farmers increases with the share of farmers affected by the information measure. Nevertheless, whatever the informed farmers' share, eco-friendly farmers are more involved than economicus farmers. That is because the subjective norm and the perceived behavioural control are the same for both groups and only the attitude, which is different between groups, is higher for eco-friendly farmers. Indeed, due to compensation that is equivalent to the difference in profit between the two farming practices (see Section 4.3.2), the financial component is equal to zero. Consequently, only

the environmental component of attitude plays a role in the attitude. This is higher for eco-friendly farmers, who place more emphasis on the environmental component of attitude.

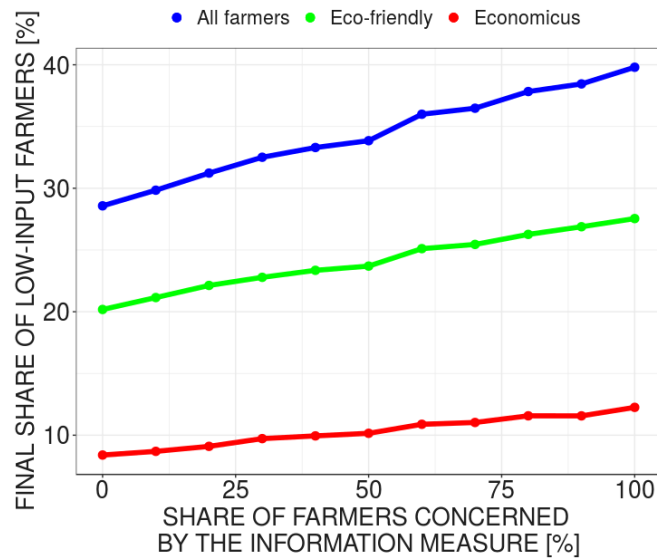


FIGURE 4.3 – Final share of low-input farmers depending on the share of farmers informed

Targeting farmers according to their environmental preference

In addition to choosing how many farmers are affected by the information measure on the concentration of pollutants, policy makers can target which groups of farmers (according to their EP) will be affected by the information measure. Indeed, depending on how the information is disseminated, it could affect different groups of farmers. For example, information can be disseminated through a cooperative that groups together the same type of farmer, through an agricultural magazine read by a certain type of farmer, or through a network to which only one type of farmer belongs (e.g. the DEPHY network in France that brings together farmers with higher EPs, committed to a voluntary approach for reducing the use of pesticides (LAPIERRE, 2018)).

We compared four policies in relation to information measures : (1) only eco-friendly farmers are informed (i.e. 50% of total number of farmers); (2)

only economicus farmers are informed (i.e. 50% of total number of farmers); (3) all farmers are informed; (4) 50% of random farmers are informed; (5) no information (see Figure 4.4).

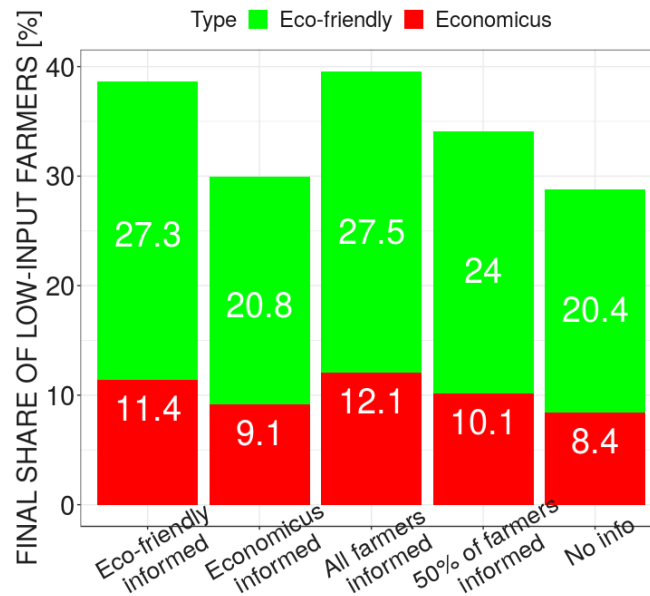


FIGURE 4.4 – Final share of low-input farmers depending on information providing. Information is provided to : (1) all eco-friendly farmers (i.e. 50% of total number of farmers); (2) all economicus farmers (i.e. 50% of total number of farmers); (3) all farmers; (4) 50% of random farmers; (5) no information.

When eco-friendly farmers are targeted for information dissemination, more farmers change their farming practice than when economicus farmers are targeted and when half of the farmers are randomly targeted. Even if they do not receive information, there are more eco-friendly farmers adopting low-input practices when economicus farmers are informed than when no farmers are informed due to the diffusion of behaviour through the subjective norm. This illustrates the two drivers of the model : an individual driver through the attitude $a_i(t)$ and a social driver through the subjective norm $s_i(t)$. For the economicus farmers, the diffusion through the subjective norm (social driver) has a higher impact than the information (individual driver), as seen when comparing the cases where economicus farmers are informed and where half of the farmers are informed. The eco-friendly farmers are more receptive to the

information (individual driver) than to the subjective norm (social driver).

Thus, for the same share of 50% of farmers informed, an information policy targeting the group of farmers with higher EPs is more effective than no targeting. For a constant cost of information dissemination, targeting farmers according to their EP is more efficient. However, if the objective is to involve as many farmers as possible in the programme, the more effective programme is the one where all farmers are affected by the information measure.

Policy effectiveness depends on awareness threshold

As we have shown, the environmental component of attitude depends on the information about the pollutant concentration in water. We now consider the provision of information about the consequences of the pollution (awareness-raising measure) that lowers the awareness threshold. We suppose that an awareness-raising measure may improve the effectiveness of the protection programme because it increases the environmental component of attitude, and its effect is higher when combined with the provision of information about the pollutant concentration (see Figure 4.5).

The concentration of pollutants can vary from 0 to 50 mg/L. A concentration of 50 mg/L corresponds to the concentration where all farmers have high-input practices, and is the initial situation. Nevertheless, without information, the farmers perceive on average a concentration equal to 35 mg/L. The lower the awareness threshold, the lower the final concentration of pollutants and the higher the final share of low-input farmers. Three sets of awareness thresholds emerge. Considering only the awareness-raising measure (Figure 4.5-a), in the first set, from 0 to 20 mg/L, whatever the thresholds, the final share of low-input farmers is high. In this situation, at $t = 0$, the environmental component of attitude is equal to 1. Then, from an awareness threshold of 20–50 mg/L, the environmental component of attitude decreases from 1 to 0 and consequently the final share of low-input farmers decreases. Finally, when the awareness threshold is higher than 50, the environmental component for a

perceived concentration of 35 is approximately equal to 0. Thus, there is no difference between awareness thresholds higher than 50. They correspond to a significantly light involvement of farmers.

With the two information measures combined (about concentration and awareness-raising) (Figure 4.5-b), there are still three sets of awareness thresholds, nevertheless they are shifted. Information about pollution concentrations increases the final share of low-input farmers with a low awareness threshold. The set of awareness threshold with a high impact of the awareness-raising measure is extended to 65 mg/L.

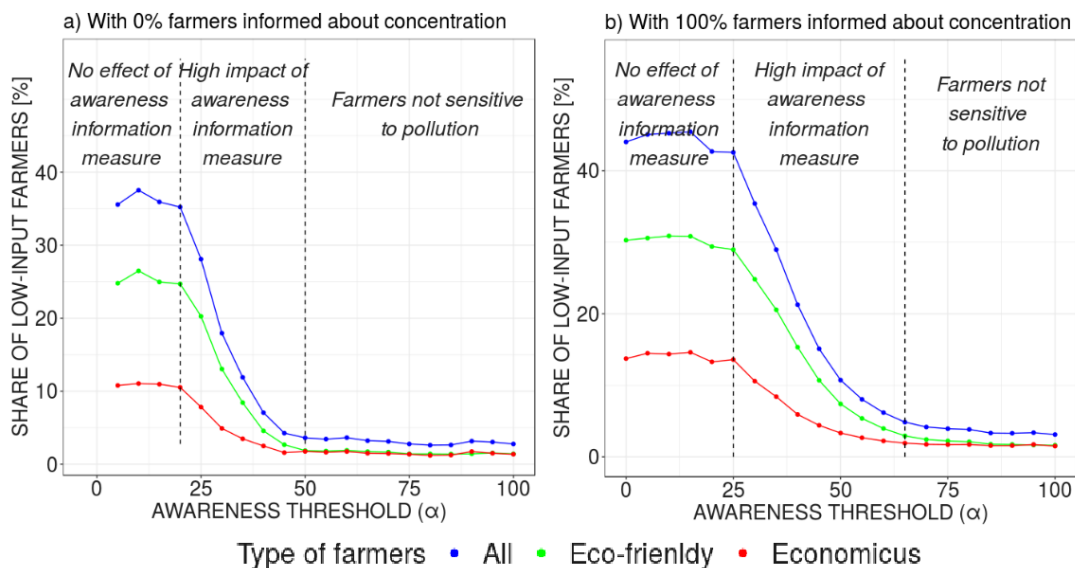


FIGURE 4.5 – Final share of low-input farmers depending on the awareness threshold with : a) no information about the concentration and b) all farmers informed about the concentration of pollutants in water.

Consequently, a policy measure to lower the awareness threshold does not have an impact on the share of low-input farmers and on the final concentration in all situations. Indeed, if the initial awareness threshold is low, it is not necessary to invest in a policy measure targeting the awareness threshold. Also, if the awareness threshold is very high and the policy measure is not able to lower

it below a certain threshold, the measure does not have an effect. Finally, an awareness-raising measure has a greater impact when the awareness threshold is medium, whether with or without information on pollutant concentrations. Nevertheless, information about these concentrations allows the awareness-raising to have an impact on farmers with higher awareness thresholds.

4.4.2 Impact of the variation in the initial state of the ecological system

In the previous section, we analysed the model assuming that the initial concentration of pollutants corresponds to a static situation before the implementation of the protection programme. In this static situation, all farmers practice high-input agriculture and, consequently, the concentration of pollutants in water is equal to 50 mg/L. However, we suppose that the initial concentration changes the intention of farmers to practice low-input farming. In order to analyse how this influences policy effectiveness, we tested the effect of different initial concentrations of pollutants in the water. To simplify our analysis, we still assume that half of the farmers are eco-friendly and half are economicus.

Policy effectiveness depends on the initial concentration of pollutants in water

The final share of low-input farmers increases with the initial concentration (see Figure 4.6). Below a certain level of initial concentration, the final share of low-input farmers and the final concentration are the same. Then, farmers' involvement increases steadily with the initial concentration. Finally, above a certain initial concentration, the share of low-input farmers is quite stable.

A high initial concentration leads to a higher involvement of farmers in the protection programme from the beginning of the programme. Then, other farmers are involved due to the subjective norm, and even if the concentration

decreases (final concentration lower than initial concentration), the subjective norm maintains the level of farmers' involvement. When there is less concentration, the farmers are involved later, when the concentration increases.

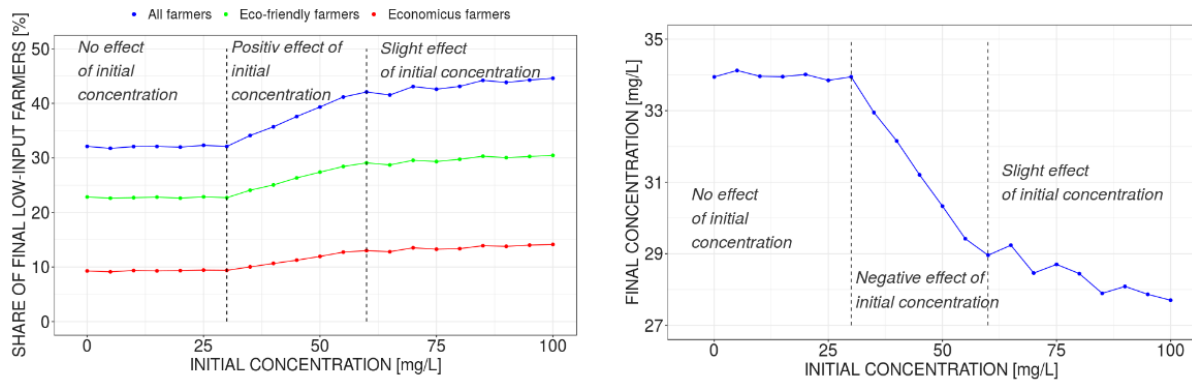


FIGURE 4.6 – Final share of low-input farmers and concentration according to the initial concentration.

Pathway of low-input farmers depending on concentration of pollutant

In the previous section, we presented the effect of initial concentrations on the final share of low-input farmers. To go further, we analysed the pathway of the share of low-input farmers depending on the concentration for different initial concentrations. We chose three initial concentrations with different effects to illustrate our analysis (see Figure 4.7) : (1) low initial concentration (0 mg/L); (2) medium initial concentration (34 mg/L); (3) high initial concentration (50 mg/L). We compare the pathway with the equilibrium states depending on fixed shares of low-input farmers. These equilibrium states correspond to the balance between the quantity of pollutant exiting the groundwater and the quantity of pollutant entering through the high-input practices of farmers (dashed lines in Figure 4.7).

1) In the first case, there is a low initial pollution. Since at the beginning of the simulation, all farmers practice high-input agriculture, the concentration will naturally increase. And, even if there are some low-input farmers thanks to the protection programme, as long as the share of low-input farmers remains

low, i.e. below the equilibrium states (dashed line in Figure 4.7), the concentration of pollutants increases with the share of low-input farmers. Close to the equilibrium states there is a slight decrease in the concentration.

2) When the initial concentration is medium, the concentration first increases with the final share of low-input farmers, and then it decreases. Indeed, while the quantity of pollutants entering the system is higher than the quantity exiting, the concentration increases. It corresponds to a concentration lower than the concentration at the equilibrium state for the same share of low-input farmers. After a few steps, when the concentration is higher than the equilibrium, the concentration of pollutants decreases until reaching equilibrium. This is due to the time it takes for the ecological system to react.

3) The last case represents the cases where the concentration decreases during the entire simulation. In this simulation, the initial concentration is higher than the concentration of pollutants entering the system ; at each further step, the concentration in water is still higher than the concentration entering, until the equilibrium. Thus, the concentration decreases with the share of low-input farming.

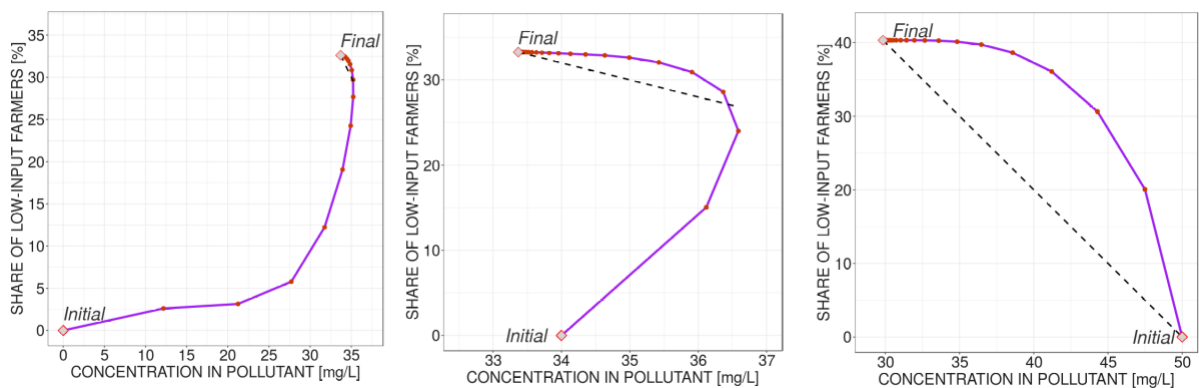


FIGURE 4.7 – Share of low-input farmers depending on the concentration of pollutants for three initial concentrations : (1) low initial concentration (0 mg/L) ; (2) medium initial concentration (34 mg/L) ; (3) high initial concentration (50 mg/L). Dashed lines are equilibrium states.

4.4.3 Influence of heterogeneity in farmers' environmental preferences on the impact of information measures

In the previous sections, we investigated the case of a moderate EP for the eco-friendly farmers and a low EP for the economicus farmers. We now return to the general case where the population is split into two equal-size groups, and within each group, all individuals exhibit the same EP, denoted w_1 for individuals of group 1 and w_2 for individuals of group 2. We suppose that different EP combinations between groups lead to modifications in the effectiveness of the policy.

Influence of different combinations of EPs

We recall that EPs can vary from 0 to 1. We test different combinations of values of EPs for both groups of the population (w_1, w_2) . We represent in Figure 4.8-a the final share of low-input farmers depending on w_1 and w_2 , and in the figure 4.7b different cuts from 4.8-a. For both groups, the environmental component is higher than the financial component (see Section 4.4.1). This means that the EP plays an important role and therefore the higher the EPs, the higher the final share of low-input farmers.

First, let us analyse the results in the case of a uniform population where the EPs of the groups are equal, i.e. all farmers have the same EP ($w_1 = w_2$). This corresponds to the dashed lines (b-cut) in Figure 4.8-a and 4.7-b. For a uniform population, the higher the EPs, the higher the final share of low-input farmers.

Second, let us analyse the results in the case of a fixed average population where the average EPs (a) of groups is fixed, i.e. $a = (w_1 + w_2)/2$. The average of EPs can vary from 0 to 1. For example, a population with a fixed average of 0.5 (thus $w_1 = 1 - w_2$) and a population with a fixed average of 0.25 (thus $w_1 = 0.5 - w_2$) correspond to the dotted lines in Figure 4.8-a and 4.8-b (c-cut and d-cut), respectively. For these two cases, the final share of low-input

farmers for a population with a fixed average of EPs depends on the difference between the EPs of the groups. We called the difference in EPs between the groups "the heterogeneity of the population", i.e. the higher the difference, the more heterogeneous the population. For the population with a fixed average of 0.5 (c-cut in Figure 4.8), the closer the EPs, i.e. centre of the figure, the higher the final share of low-input farmers. By contrast, the further the EPs, i.e. the more heterogeneous is the population, the lower is the final share of low-input farmers. The opposite holds true for the population with a fixed average of 0.25 (d-cut in Figure 4.8).

The c-cut and d-cut highlight that the effect of the heterogeneity of the groups depends on the average of EPs and highlight the two drivers of the model. First, the individual driver through the environmental component of attitude has a different weight depending on the farmers' groups (EPs). Second, the social driver through the subjective norm has the same weight for all farmers. When the fixed EP average is equal to 0.5, the driver leading to more changes in low-input farming is the individual driver. When the fixed EP average is equal to 0.25, the driver leading to more changes in low-input farming is the social driver.

Third, in order to find the threshold above which the individual driver becomes more important than the social driver, we plotted the evolution of two types of populations in Figure 8b in purple : a dashed line for the uniform population ($w_1 = w_2$) and a solid line for a heterogeneous population. This latter corresponds to the two cuts of a1 and a2 from Figure 8a., i.e. the first part of the curve is if $a \in [0; 0.5]$, $w_1 = 2 * a$ and $w_2 = 0$ and the second part is if $a \in [0.5; 1]$, $w_1 = 1$ and $w_2 = 2 * a - 1$. As expected, the final share of low-input farmers increases with the average of EPs. The final share of low-input farmers is higher with a heterogeneous population when the average of EPs is low and is higher with a uniform population when the average of EPs is high. The average threshold where the final share of low-input farmers from the uniform population becomes higher than the final share of low-input farmers

from the heterogeneous population for the same average corresponds to an average intention of farmers from the uniform population above the average behavioural threshold. Above this point, it means that the individual driver is sufficient on average to encourage farmers to change their practices. Below this point, the individual driver is not sufficient and in this case the social driver becomes more important.

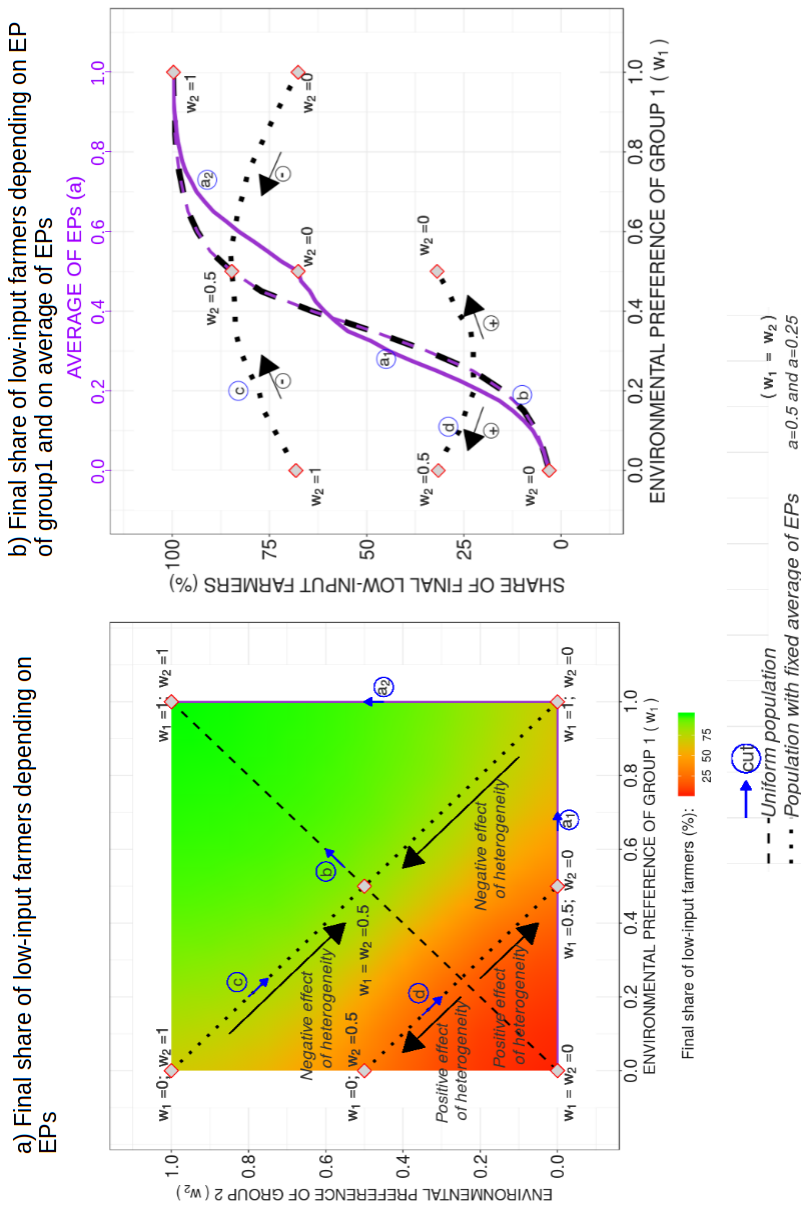


FIGURE 4.8 – 4.8-a) Final share of low-input farmers for all farmers depending on the environmental preferences (EPs) of both groups. 4.8-b) Cuts from Figure 4.8-a : cut a_1 and a_2 (solid lines) correspond respectively to $w_2 = 0$ and $w_1 = 1$; cut b (dashed line) corresponds to the evolution of the uniform population ; cut c and d (dotted lines) correspond to the population with a fixed average of EPs for respectively, an average of 0.5 and 0.25.

These results show the behaviour of the whole population, especially in terms of the final low-input farmers. However, in the case where the population is not uniform, the two groups behave differently according to their EP ($w_1 = 1 - w_2$). For the sake of clarity, we only represent the final share of low-input farmers of group 1. Indeed, in the case of a uniform population, group 2 behaves in the same way as group 1 (because $w_1 = w_2$) and for the fixed average populations, group 2 behaves like group 1 with $w_1 = a/2 - w_2$.

As can be seen in Figure 4.9-a, the final share of low-input farmers for group 1 increases with the EP of group 1 and of group 2. Nevertheless, the increase is higher with the EP of group 1 than with the EP of group 2. Indeed, the behaviour of group 1 is naturally more influenced by its own characteristics than the social influence of group 2. We can see this difference with the two cuts b and c. They correspond to the evolution of w_1 with w_2 fixed at 0.5 for b-cut and to the evolution of w_2 with w_1 fixed for c-cut. The b-cut illustrates the social influence of the EP of group 2 on the final share of low-input farmers in group 1. And the c-cut illustrates the influence of the EP of group 1 on the final share of low-input farmers in group 1.

For a fixed average of EPs equal to 0.5, the effect of the EP of group 1 on the final share of low-input farmers of group 1 differs from the effect of the EP of group 2. The final share of low-input farmers of group 1 increases when its own EP increases (a1-cut : dark yellow dotted line in Figure 4.9-b) but decreases when the EP of group 2 increases (a_2 -cut : blue dotted line in Figure 4.9-b). Since the average is fixed, if the EP of group 2 increases then the EP of group 1 decreases. The two drivers of this effect on the final share of low-input farmers in group 1 are : (1) the EP of group 1 decreases and thus the strength of the individual driver of group 1 decreases ; (2) the social influence from group 2 increases. The individual driver of a group is stronger than the social driver.

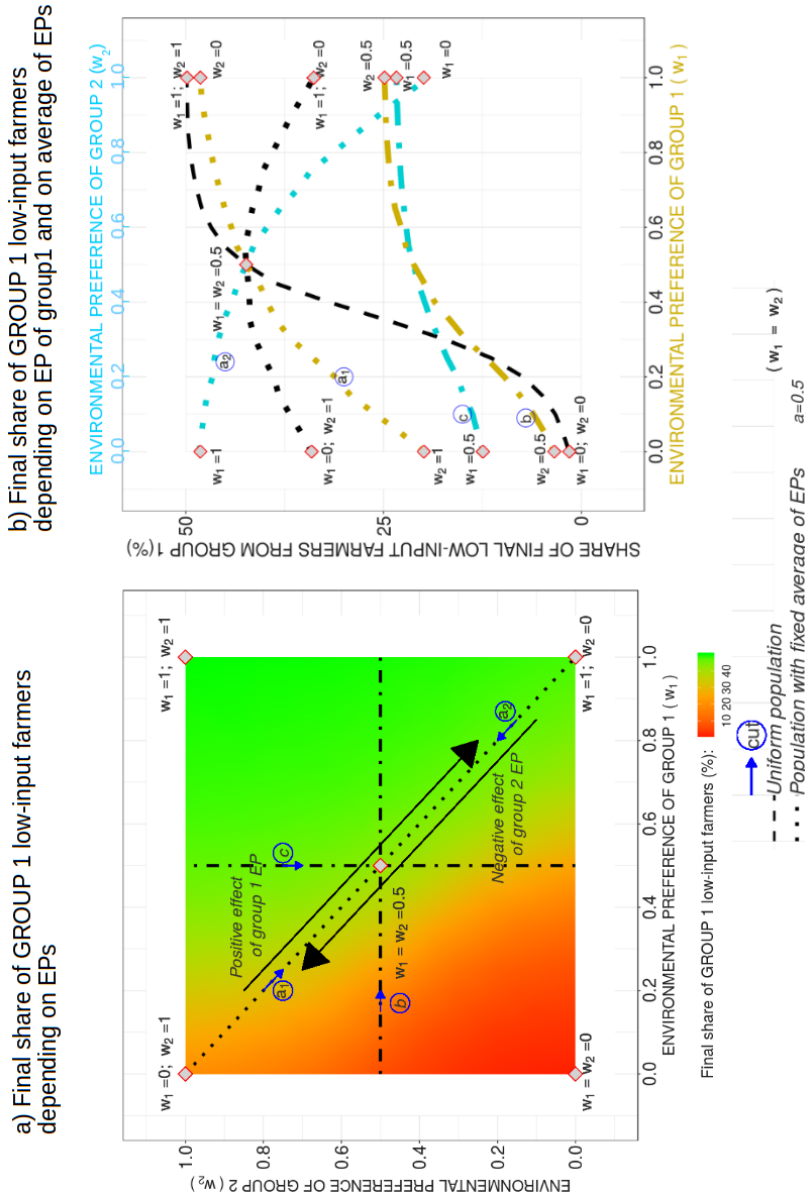


FIGURE 4.9 – 4.9-a) Final share of low-input farmers for group 1 farmers depending on the environmental preferences of both groups. 4.9-b) Cuts from Figure 4.9-a : cut a_1 and a_2 (dotted lines) correspond respectively to the evolution of w_1 and to the evolution of w_2 with a fixed average of EPs of 0.5 ; cut b (vertical dotted and dashed line) corresponds to the evolution of w_1 with $w_2 = 0.5$; cut c (horizontal dotted and dashed line) corresponds to the evolution of w_2 with $w_1 = 0.5$.

How does the difference in EP between the two groups impacts the change in farming practice ?

In this section, we analyse the effect of the difference between the EPs of the two groups ($d = w_1 - w_2$). The objective is to see whether within a population of two groups of farmers with distinct EPs, having more or less the same EPs (variation of d) has an influence on the final share of low-input farmers, apart from the positive effect of EPs (see 4.3.1). In what follows we assume that group 1 has a higher EP than group 2 ($w_1 > w_2$). Instead of presenting results according to w_1 and w_2 , we present results according to d in order to underline the role of the difference in EPs between groups.

In Figure 4.10, we represent the average final share of low-input farmers according to the difference d between EPs. For a given value of difference d , we may have several combinations of EPs w_1 and w_2 . For instance, when there is no difference between EPs ($d = 0$), the preferences can range from a full attraction for the environmental component ($w_1 = w_2 = 1$) to an attraction only for the financial component ($w_1 = w_2 = 0$). The lower the difference between the EPs of the groups, the higher the standard deviation of the final share of low-input farmers because of the highly diverse situation involved by the different combinations of EPs.

We also represent the final share of low-input farming for the difference with maximum EPs and with minimum EPs. For instance, if we consider the highest combination when $d = 0$ it corresponds to $w_1 = w_2 = 1$ and when $d = 1$ it corresponds to $w_1 = 1$ and $w_2 = 0$. For instance, if we consider the lowest combination when $d = 0$ it corresponds to $w_1 = w_2 = 0$ and when $d = 1$ it corresponds to $w_1 = 1$ and $w_2 = 0$. For the highest combinations, the final share of low-input farmers decreases with the difference in EP (dashed dotted line in Figure 4.10). For the lowest combinations, the final share of low-input farmers increases with the difference in EP (dashed line in Figure 4.10).

Below a certain threshold, the final share of low-input farmers increases with the difference in EP between the groups. An increase in the difference

implies that the EP of group 1 increases and/or the EP of group 2 decreases (because we assume that group 1 has a higher EP than group 2 ($w_1 > w_2$)). When the average of EPs varies (see Section 4.3.1), the drivers vary in the same direction and what is observed is that, depending on the average, one or the other driver induces a greater effect on the farmers' change in practices. The drivers have a different effect on the difference in EP. Indeed, when the difference increases, the effect of the individual driver of group 1 is positive and acts in the opposite direction of the individual driver of group 2. Up to a certain threshold, the social driver greatly compensates the negative effect of the individual driver of group 2. Nevertheless, above a threshold, the final share of low-input farmers decreases with the difference between w_1 and w_2 . Indeed, a great difference has a negative impact because it means that half of the farmers have a very low EP that is a constraint to changes in low-input farming and the social influence is lower.

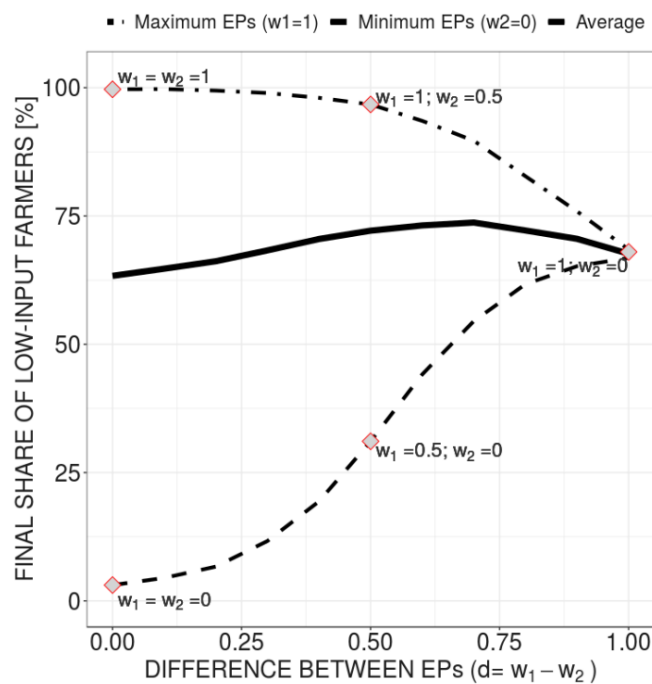


FIGURE 4.10 – Average share of low-input farmers and standard deviation depending on the differences between financial preferences of groups. From 0 to 1 for each financial preference (w_i) with a step of 0.1 and 1000 runs.

4.5 Discussion and conclusions

4.5.1 Contributions and policy implications

Water pollution has become a major environmental concern, and improving water quality is one of the main management goals at both national and supra-national scales. The purpose of our study was to explore the role of information measures in programmes designed to protect water quality. Although the literature recognises that information-based policies are favourable in the context of environmental policies, the decision-making mechanisms involved are poorly described.

The first contribution of this paper is therefore to formalise the role of information in farmers' decision-making processes. Our results showed that the involvement of farmers in protection programmes depends on the information they are given about water pollution and about the consequences of this pollution. Also, the difference between environmental preferences impacts the diffusion of low-input farming practices. The higher the average of farmers' environmental preferences, the more farmers will change their practices to ones more favourable to water quality. If these preferences are not the same between farmers, when the average preference is sufficiently low then this heterogeneity between farmers is a favourable factor for the adoption of the practices, whereas with a high average preference it is unfavourable. Thus, the difference in environmental preferences between farmers has to be taken into account in the choice of public policies. This is in line with the study by GARFORTH et al. (2003), who found that an important point in the provision of information and advice is to recognise the diversity between land managers having different factors that motivate their decisions. It is important to recognise the heterogeneity of those managing land–water relationships and to tailor advice to these different farming contexts and cultures. Finally, different initial concentrations are also a determinant of the involvement of farmers. It increases with the initial pollution level. Nevertheless, these conclusions are to be interpreted in

light of two caveats. First, we suppose that there is no irreversibility in the ecological system. Second, the time during which the policy is not implemented and during which the concentration of pollutants increases could have negative consequences such as an increase in the cost of depolluting to produce drinking water or an increase in health costs.

The second contribution of this article is methodological. The operationalisation and implementation in a mathematical model of the concept of an information instrument and its impact on the decision-making process contribute to the debates on the definition of the concept and its use. The role of information has already been studied in a model using the TPB but only with regard to the financial aspect of the behaviour (VERWAART et al., 2011 ; MUELDER et al., 2018) and, to the best of our knowledge, it has not been implemented in the context of an environmental factor.

More specifically, in terms of implementation, the article contributes toward extending the use of environmental concepts in the attitude domain of the TPB coupled with the use of information. We propose a formalisation of the environmental component of attitude using an awareness threshold and the state of the ecological system. This differs from the environmental attitudes that have already been modelled in different ways, representing the CO₂ emission-saving of solar panels (MUELDER et al., 2018), environmental friendliness of energy conservation behaviours (RAIHANIAN MASHHADI et al., 2018) or the environmental productivity of a farming practice (XU et al., 2018).

4.5.2 Limitations and perspectives

We proposed to formalise the role of information in farmers' decision-making processes through a dynamic model. We analyse four avenues for future work : the heterogeneity of farmers, the environmental attitude process, the change in environmental preferences, and the possibility to return to high-input farming practices.

First, concerning the heterogeneity of farmers, we consider only two homogeneous groups of farmers with different environmental preferences. Nevertheless, we may explore the influence of having more groups or including variations in the groups. For example, BROCH et al. (2012), using a survey, analysed the heterogeneity in farmers' AES preferences and found four groups with divergent preferences regarding their willingness to accept compensation and to engage in groundwater and biodiversity protection.

Second, the description of the processes of the environmental component of attitude could be enriched. The influence of the concentration of pollutants is the same during the simulation; nevertheless, it could be correlated with the variation in concentration and with the behaviour of the farmer or of the farmer's network. For example, if the farmer sees that the concentration decreases and all of the network has changed practice, he or she is more likely to change their behaviour than if they see no change. Indeed, slower changes in water quality may result in farmers being less motivated to change to low-input practices (OKUMAH, CHAPMAN et al., 2021). Additionally, the process could be modulated as a function of the trust in public authorities. The trust in public authorities has a positive effect on the participation in AESs (ARNAUD et al., 2007).

Third, a process of change in the environmental preferences could be considered. The information about the consequences in addition to changes in the awareness threshold could also change the environmental preference. In this case, the information will have consequences not only on the behaviour of the farmers but also on their decision-making process, with longer-term change.

Finally, we did not include in our model the possibility to revert to the original farming practices after a few years of entering the protection programme. However, in Europe the AES contracts end after 5 years and the farmers are free of any contractual commitment concerning their land management choice and therefore can revert to their last practices. The introduction of a reversion process could be interesting in order to highlight the difference in the mid-term

influence of economic instruments and information instruments. For example, KUHFUSS, PRÉGET et al. (2016) show that information about what other farmers intend to do can greatly influence a farmer's decision in maintaining the practices of the protection programme after it ends.

4.5.3 Concluding remarks

In this paper, we investigated the role of information measures in the change in farming practices and thus their impact on water pollution. The agent-based model of a drinking catchment area allowed us to explore the impact of the information about pollution and the consequences of pollution, the effect of the diversity of environmental preferences among farmers and the influence of the initial state of the ecological system. Our contributions are methodological and theoretical. Firstly, the implementation of information in such a model and the description of the environmental attitude contribute to debates on the use of these concepts in computer models. Secondly, we highlighted that targeting farmers who have higher environmental preferences is more effective than no targeting when half of the population can be subject to the information campaign. Moreover, the heterogeneity between farmers in terms of environmental preferences has an influence on the involvement of farmers in the programme depending on the average environmental concern. Finally, under certain conditions, the higher the initial pollution, the higher the involvement of farmers in the protection programme.

Chapitre 5

Conclusion

5.1 Synthèse des travaux

5.1.1 Principaux résultats de la recherche

Les trois chapitres de cette thèse apportent des éléments de réponse aux questions de recherche posées dans l'introduction :

- *Comment la gouvernance est-elle conceptualisée et mise en œuvre dans les modèles multi-agents de systèmes socio-écologiques ?* La revue de littérature des modèles multi-agents de gestion des systèmes socio-écologiques montre qu'une part importante de la littérature n'est pas explicitement basée sur des théories appuyant la modélisation de la gouvernance et la prise de décision des acteurs. De plus, en ce qui concerne la conceptualisation de la gouvernance, les institutions formelles et informelles sont rarement représentées par rapport aux divers modes de gouvernance. Les modes de gouvernance qui sont le plus souvent modélisés sont les interventions de l'État, tandis que les modes de gouvernance basés sur la communauté et le marché sont peu représentés. Par conséquent, un défi actuel réside dans l'utilisation d'une plus grande diversité de théories et la représentation de modes de gouvernance plus diversifiés. En outre, les processus décisionnels influencés par la gouvernance

sont souvent représentés de manière simplifiée et font peu appel aux diverses théories de la prise de décision. L'effet du choix de la représentation du processus décisionnel sur l'analyse des impacts de la gouvernance ne doit pas être négligé. Enfin, l'analyse de l'opérationnalisation des interactions entre la gouvernance et le SSE met en évidence deux formes principales d'opérationnalisation : une forme basée sur des variables et une forme basée sur des agents. Les modèles correspondants diffèrent en termes de cadre théorique, de types de modes de gouvernance représentés ou de présence d'interactions. Il ressort de la revue de littérature que l'utilisation d'un cadre conceptuel incluant la gouvernance comme sous-système pourrait améliorer sa représentation dans les modèles multi-agents socio-écologiques. L'utilisation de tels cadres permettrait de s'assurer que l'importance de la gouvernance et des interactions avec les autres systèmes, dont le système écologique, soient bien pris en compte.

- *Comment les interactions entre les facteurs comportementaux influencent-elles l'efficacité et l'efficacité de programmes de protection de la ressource en eau potable ?* L'efficacité et l'efficacité des politiques sont influencées par différentes caractéristiques comportementales des agriculteurs, comme les préférences des agriculteurs entre les différentes composantes de l'intention de changer de pratique et les préférences environnementales, et des facteurs liés à leurs pratiques (tels que la répartition entre les pratiques agricoles avant l'implémentation d'un programme de protection). Dans les situations où les caractéristiques comportementales sont inconnues, les politiques combinant à la fois des incitations financières et des mesures de formation permettent potentiellement d'atteindre un niveau de participation des agriculteurs plus élevé que les politiques reposant sur une seule mesure. Par contre, si les caractéristiques comportementales sont connues, leur prise en compte dans la définition des politiques peut améliorer leur efficacité. En effet, les résultats de différentes mesures de protection dépendent des caractéristiques comportementales des agriculteurs et donc la connaissance de celles-ci permet de définir des politiques ciblées. Ces résultats soulignent l'im-

portance d'adapter les politiques agro-environnementales aux caractéristiques des agriculteurs lorsque ces dernières sont connues. Des études antérieures centrées sur les programmes agroenvironnementaux de l'UE ont montré que la définition des mesures à une échelle locale plutôt qu'à l'échelle de l'UE, permet de mieux adapter les mesures (par exemple, le niveau des subventions) aux caractéristiques des agriculteurs (KUHFUSS, JACQUET et al., 2012; BAREILLE et al., 2020). Cependant, malgré la décentralisation croissante de la mise en œuvre de la politique agro-environnementale de l'UE, la possibilité d'adapter les mesures aux caractéristiques des agriculteurs reste limitée (KUHFUSS, JACQUET et al., 2012; SAÏD et al., 2017; AMBLARD, 2019).

- *Comment une mesure d'information sur le système écologique agit-elle sur l'évolution des pratiques des agriculteurs ?* Premièrement, le ciblage des agriculteurs ayant des préférences environnementales plus importantes est plus efficace que l'absence de ciblage lorsque seule la moitié de la population peut faire l'objet de la campagne d'information. Deuxièmement, en fonction de la préférence environnementale moyenne de la population d'agriculteurs, l'hétérogénéité des agriculteurs en termes de préférences environnementales a une influence plus ou moins importante sur leur implication dans le programme de protection. Lorsque les préférences environnementales des agriculteurs sont faibles en moyenne, une plus grande hétérogénéité favorise la participation des agriculteurs au programme de protection. Lorsque les préférences environnementales des agriculteurs sont fortes en moyenne, c'est une plus grande uniformité des préférences environnementales des agriculteurs qui favorisera la participation. Enfin, les agriculteurs étant influencés par leur perception de l'état du système écologique, plus le niveau de pollution initial est élevé avant la mise en œuvre du programme de protection, plus l'implication des agriculteurs est importante. Dans ce cas, toutes choses égales par ailleurs, un plus haut niveau de pollution initial avant la mise en œuvre du programme conduit à un plus faible niveau de pollution après la mise en œuvre du programme. Ce résultat est dépendant des hypothèses faites

sur le système écologique et les processus de décision des agriculteurs. Les résultats impliquent qu'il est important dans le cadre des politiques publiques utilisant la fourniture d'information et de conseils, de reconnaître la diversité des agriculteurs en termes de facteurs influençant leur décision et d'adapter les informations à ceux-ci et aux différents contextes.

5.1.2 Apports transversaux

Cette thèse est le résultat d'un travail pluridisciplinaire où différents champs ont été combinés : l'informatique avec la modélisation multi-agents, la psychologie sociale avec l'utilisation de la théorie du comportement planifié et l'économie institutionnelle avec l'analyse de la gouvernance. Rarement des travaux se sont positionnés à l'intersection de ces trois champs. Un apport transversal de cette thèse est l'apport méthodologique que constitue le croisement de ces champs disciplinaires.

Même si la modélisation multi-agents est de plus en plus mobilisée pour étudier les phénomènes sociaux, elle reste néanmoins peu utilisée dans les sciences sociales (MANZO, 2014). De nombreuses théories du comportement existent, issues de la recherche expérimentale et empirique, mais, malgré cette richesse, de nombreux modèles multi-agents de SSE sont souvent basés sur les hypothèses simplificatrices de l'acteur rationnel (SCHLÜTER, BAEZA et al., 2017). L'une des raisons de cette faible utilisation des théories comportementales en sciences sociales réside dans le décalage entre les concepts subjectifs abstraits (comme les attitudes, les perceptions, les normes ou les intentions) et les besoins d'opérationnalisation dans un code informatique de modèle formel (MUELDER et al., 2018). L'ouverture des concepts laisse place à différentes formalisations possibles qui ne jouent pas en la faveur de l'utilisation de ces théories dans les modèles formels. Pourtant, les modèles utilisés pour appuyer les politiques publiques devraient inclure des agents dont le comportement est plus proche de celui des acteurs réels. La théorie du comportement planifié est une théorie en psychologie sociale déjà utilisée dans la modélisation multi-agents. Cependant,

elle reste peu utilisée dans les modèles multi-agents décrivant les comportements des agriculteurs (on peut néanmoins citer KAUFMANN et al., 2009 et XU et al., 2018). Des défis subsistent quant à son opérationnalisation comme le passage d'une théorie statique à un modèle dynamique, la modélisation des rétroactions, le choix dans les facteurs jouant sur la prise de décision et leur représentation (SCALCO et al., 2018 ; MUELDER et al., 2018). Cette thèse concourt donc à enrichir la littérature sur l'opérationnalisation de la théorie du comportement planifié dans un modèle multi-agents de SSE.

Enfin, nous avons associé analyse institutionnelle et modélisation pour l'étude de la gouvernance. La prise de distance de l'économie institutionnelle vis-à-vis de la pensée néoclassique se situe au niveau des fondements scientifiques comme la description du comportement humain – notamment la rationalité limitée des individus et le concept d'esprit institutionnalisé (suivant des normes sociales par exemple) – mais également par rapport aux outils méthodologiques (CHAVANCE, 2012). Dans le domaine de l'économie institutionnelle, la modélisation mathématique, encore peu utilisée, est un champ en émergence (voir par exemple POTEETE et al., 2010). Nous avons formalisé mathématiquement une théorie de la décision prenant en compte des éléments tels que l'influence d'une norme sociale, l'information incomplète (dans la formation de l'attitude par rapport à l'environnement) ou les connaissances. La gouvernance dans le modèle agit sur ces facteurs avec la fourniture d'information ou de formation. Cette thèse contribue donc aux travaux reposant sur l'utilisation d'outil de simulation pour l'analyse institutionnelle de la gouvernance.

5.2 Discussion et perspectives

Dans chaque chapitre de cette thèse, nous avons présenté les apports de notre travail mais aussi les limites associées. Deux limites importantes concernent la revue de littérature (Chapitre 2). La première résulte du choix que nous avons fait à propos des mots-clefs dans la commande de recherche,

qui nous permet de sélectionner les articles d'une communauté utilisant un vocable proche de « social-ecological system » mais qui exclut d'autres travaux. La deuxième est liée au contenu des articles, avec une hétérogénéité des descriptions des modèles dans les articles, qui a comme conséquence l'absence de données permettant d'analyser certains articles. Dans les chapitres présentant le modèle et les résultats des simulations réalisées (Chapitres 3 et 4), nous pouvons souligner plusieurs limites. Les dynamiques concernent le changement de pratique, l'évolution de l'intention via l'attitude et la norme sociale. Cependant, les agriculteurs n'ont pas la possibilité de retourner vers la pratique antérieure, et les préférences et le contrôle perçu du comportement sont statiques. Le processus d'apprentissage et l'hétérogénéité des agriculteurs ont été simplifiés. Le système hydrologique a été peu développé. Enfin, nous n'avons pas utilisé de données empiriques. Nous développons ici trois limites de cette thèse qui sont pour nous des opportunités en terme de perspectives de recherche pour le futur.

5.2.1 Inversion des comportements

Dans le modèle présenté, les agriculteurs ont uniquement la possibilité de passer d'une pratique à hauts intrants à une pratique à faibles intrants. Pourtant, dans la réalité, les programmes de protection ont une durée limitée et les agriculteurs ont la possibilité de choisir de revenir à une pratique antérieure. Par exemple, dans le cadre de la politique agricole commune de l'UE, les MAE, qui sont des contrats signés avec l'agriculteur, ont en France une durée de cinq ans. A la fin du contrat, l'agriculteur est libre de choisir ou non de revenir à des pratiques antérieures. Lorsque les agriculteurs ne perçoivent plus les compensations financières associées aux mesures agro-environnementales, la pérennisation des changements de pratique est en jeu.

Il pourrait donc être intéressant d'intégrer dans le modèle la possibilité de retour à une pratique agricole antérieure. Cette possibilité soulève de nombreuses questions sur les mécanismes qui font que les agriculteurs reviennent

ou non à leur ancienne pratique. Plusieurs études ont étudié les réactions des agriculteurs à la fin des contrats agro-environnementaux et les résultats sont divers. Par exemple, l'analyse coût-bénéfice d'un programme de conservation des sols faite par LUTZ et al. (1994) a montré que les compensations financières ne persuadent les agriculteurs de modifier leur comportement que tant qu'elles continuent à être versées. D'autres auteurs comme M. J. ROBERTS et al. (2007) soulignent que bien que plus de la moitié des agriculteurs sont revenus à des choix de cultures antérieurs après la fin d'un programme environnemental aux USA, 40% déclarent garder la couverture végétale promue dans le programme. C'est la même proportion identifiée par KUHFUSS, PRÉGET et al. (2016) dans une enquête montrant que plus de 40% des agriculteurs enquêtés ont l'intention de garder les pratiques adaptées dans le cadre d'une MAE même si la mesure s'arrête.

Les raisons qui poussent les agriculteurs à retourner ou non vers leurs pratiques antérieures sont diverses. La première, en lien avec la fin des compensations financières, est une contrainte et motivation d'ordre économique (e.g. LUTZ et al., 1994). D'autres motivations peuvent rentrer en jeu, comme la modification des croyances sur la pratique nouvelle promue dans le programme de protection, le processus d'apprentissage par accumulation d'expérience (DEFRANCESCO, GATTO et MOZZATO, 2018), le changement d'habitude et la création de nouvelles habitudes (HIEDANPÄÄ et al., 2014) ou la volonté de correspondre à la nouvelle norme sociale induite par le programme (KUHFUSS, PRÉGET et al., 2016)).

L'ajout d'un mécanisme décisionnel portant sur la continuation ou sur l'arrêt de la participation au programme et le retour à la pratique antérieure peut apporter au modèle des possibilités d'analyses complémentaires. Par exemple, la durabilité des programmes pourrait être analysée en comparant la capacité des mesures à engendrer des comportements durables dans le temps. Ce modèle pourrait par exemple contribuer aux débats sur l'intérêt des paiements directs pour protéger la nature (voir par exemple SWART, 2003). De plus, il pour-

rait contribuer à l'analyse de l'impact de l'accumulation d'expérience ou de la perte de connaissance d'une pratique, ou encore de l'effet d'une modification du réseau et de la norme sociale des agriculteurs.

5.2.2 L'apprentissage social

Bien que les revues et les méta-analyses sur la théorie du comportement planifié ont montré que cette théorie est un relativement bon prédicteur du comportement (par exemple, ARMITAGE et al., 2001), la parcimonie de cette théorie offre une marge de manœuvre pour l'intégration d'autres théories afin d'augmenter sa capacité prédictive (FIELDING, TERRY, MASSER et HOGG, 2008). Par exemple, l'apprentissage social est un concept important contribuant à expliquer le comportement des agriculteurs, comme l'adoption d'une nouvelle pratique agricole (REBAUDO et al., 2013 ; SHAIJUMON, 2018). Le couplage entre la théorie du comportement planifié et l'apprentissage social a déjà été proposé par NOGUERA-MÉNDEZ et al. (2016) dans le cadre d'une étude sur le comportement pro-environnemental des agriculteurs. Ils ont proposé un cadre conceptuel utilisant la théorie du comportement planifié et le concept d'apprentissage social à plusieurs niveaux (ARGYRIS, 1999). L'apprentissage social est un concept d'apprentissage collaboratif qui prend en compte l'environnement d'apprentissage et les interactions sociales. D'après REED et al. (2010) : "[P]our être considéré comme un "apprentissage social", un processus doit : (1) démontrer qu'un changement de compréhension a eu lieu chez les individus impliqués ; (2) démontrer que ce changement va au-delà de l'individu et se situe dans des unités sociales plus larges ou des communautés de pratique ; et (3) se produire à travers des interactions et des processus sociaux entre les acteurs au sein d'un réseau social ". L'apprentissage social est une perspective de plus en plus reconnue sur le rôle des agriculteurs dans la production et la diffusion des connaissances agricoles (KROMA, 2006). Bien qu'il en soit encore à ses balbutiements conceptuels, l'apprentissage social fait l'objet d'une attention croissante en tant que processus efficace de gestion du changement dans la

gestion des ressources agricoles et naturelles (par exemple, KING et al., 2002). Selon NOGUERA-MÉNDEZ et al. (2016) et PRICE et al. (2014), la prise en compte de l'apprentissage social dans les programmes pro-environnementaux peut être bénéfique pour les impacts environnementaux. Des recherches ont montré que certains agriculteurs sont plus susceptibles de tester et d'adopter de nouvelles idées, expériences et connaissances, telles que des pratiques agricoles à faible niveau d'intrants, lorsque les innovations émergent d'un groupe ou d'un réseau (KROMA, 2006). La gestion des systèmes agro-écologiques nécessite donc des arrangements sociaux tels que des réseaux d'agriculteurs (KROMA, 2006). Le capital social et les réseaux sont identifiés comme des outils cruciaux pour les processus d'apprentissage et d'adaptation, en facilitant l'action collective entre les acteurs (PARASKEVOPOULOS, 2001).

La prise en compte de l'apprentissage social des agriculteurs par les programmes de protection pourrait contribuer à améliorer leur efficacité. Par exemple, une communauté de pratique associant les agriculteurs exploitant des parcelles dans une aire d'alimentation de captage pourrait être créée par un programme de protection. Dans cette communauté de pratique, l'agriculteur améliorerait ses connaissances et son expérience, et construirait un réseau au travers duquel le processus d'apprentissage se produira.

5.2.3 Mobilisation de données empiriques

Une des limites du modèle est l'absence de données empiriques. Le défi à relever serait de calibrer le modèle avec des données réelles sur les caractéristiques et les préférences des agriculteurs. Cela permettrait entre autres de valider les hypothèses qui ont été faites, de limiter l'exploration de l'espace des paramètres pour obtenir des résultats de simulations basées sur des hypothèses plus proches de la réalité ou d'étudier de nouvelles questions de recherche. Dans cette perspective de mobilisation des données empiriques, deux voies pourraient être explorées. L'utilisation de données issues des statistiques agricoles, par exemple, les données du RICA en France, pourrait alimenter le

modèle avec des données sur le nombre d'agriculteur ayant déjà une pratique à bas intrants, les profits des agriculteurs, le nombre d'agriculteurs dans l'AAC ou encore la taille des exploitations. En effet, nous avons supposé que toutes les exploitations sont identiques (en termes de taille, de marge brute et d'impacts environnementaux) dans les AAC, mais bien qu'il s'agit d'une bonne approximation de la réalité dans certaines AAC, ce n'est pas le cas dans toutes. Néanmoins, ces données ne concerneraient pas les caractéristiques comportementales des agriculteurs pour lesquelles des enquêtes seraient nécessaires. Des questionnaires déjà développés dans le cadre de la théorie du comportement planifié (AJZEN, 2019) et des techniques statistiques utilisées permettent d'obtenir les poids des préférences des agriculteurs (SOK et al., 2020). En effet, bien que ces variables soient des variables latentes, il existe des possibilités pour les représenter comme des modèles d'équations structurelles (par exemple, KAUFMANN et al., 2009; SCHWARZ et ERNST, 2009) ou en utilisant la logique floue ou les coefficients de régression (par exemple, CASTELLA et al., 2005).

Pour conclure...

Cette thèse est un travail pluridisciplinaire d'utilisation d'un outil de modélisation, un modèle multi-agents, pour l'étude de la gouvernance dans un système socio-écologique où les comportements des agriculteurs sont opérationnalisés à partir d'une théorie issue de la psychologie sociale, la théorie du comportement planifié. Les résultats, permettent néanmoins de caractériser les effets des facteurs (individuels et sociaux) sur les impacts des différentes mesures de la gouvernance (instruments financiers, de formation et d'information). Les diverses perspectives de modélisation offertes par ce travail ouvrent des pistes prometteuses pour les recherches futures sur la gouvernance dans les systèmes socio-écologiques.

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Gestion de la qualité de la ressource en eau potable dans un système socio-écologique : développement d'un modèle multi-agents à partir d'analyse institutionnelle

L'approvisionnement des citoyens en eau potable de qualité est un enjeu de santé publique, auquel s'ajoutent des enjeux environnementaux et économiques. L'agriculture est l'une des principales menaces pour la qualité de la ressource en eau potable, notamment à cause des pollutions diffuses dans les aires d'alimentation de captages. Les programmes de protection des captages vis-à-vis des pollutions diffuses d'origine agricole reposent principalement sur la participation volontaire des agriculteurs. L'objectif de cette thèse est d'étudier, à l'aide d'un modèle multi-agents, quels sont les impacts de la gouvernance sur l'évolution des pratiques agricoles, en prenant en compte les interactions entre les mesures de protection mises en œuvre, les dynamiques comportementales des agriculteurs et les facteurs liés au système écologique. Pour ce faire, nous avons dans un premier temps réalisé une revue de littérature des modèles multi-agents de systèmes socio-écologiques représentant la gouvernance. Nous nous sommes appuyés sur cette revue afin de construire un modèle multi-agents pour analyser la gouvernance de la qualité de l'eau dans une aire d'alimentation de captage en décrivant les comportements des agriculteurs grâce à la théorie du comportement planifié. Un premier modèle nous a permis d'analyser l'efficacité et l'efficacité de programmes de protection composés de deux mesures, une compensation financière et une mesure de formation. Dans un second modèle, nous nous sommes intéressés plus particulièrement à l'effet de l'information sur le niveau de pollution de l'eau, en fonction des préférences environnementales des agriculteurs et de l'état initial du système écologique. Cette thèse met en évidence, sur la base d'une approche pluridisciplinaire, le rôle des caractéristiques des mesures de protection, des agriculteurs et du système écologique dans l'impact de la gouvernance de la qualité de l'eau sur les évolutions des pratiques agricoles.

Mots-clefs

Agriculture ; gouvernance ; modèle multi-agents ; qualité de l'eau ; théorie du comportement planifié