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Martina Ayoub

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THÈSE

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Trois essais sur l'innovation verte et bioéconomie

Three essays on green innovation and bioeconomy

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Résumé en Français

L'urgence du changement climatique appelle à l'accélération des innovations environnementales. Le déploiement de ces innovations devrait être la priorité des économies et des nations du monde entier pour enrayer le changement climatique. Cependant, ce n'est pas une tâche facile. Golembiewski et al. (2015) a identifié quatre défis qui bloquent le développement de la bioéconomie en particulier et des innovations verte en général. Ces quatre défis sont particulièrement pertinents pour notre thèse :

1- L'innovation verte et la bioéconomie sont un domaine à forte intensité de connaissances. Dans le développement de l'innovation durable et verte (Lewandowski et al., 2019), les acteurs doivent acquérir des connaissances provenant de diverses disciplines scientifiques. Cette base de **connaissances complexes** peut provenir de **diverses sources** et de domaines scientifiques tels que les sciences du vivant, l'agronomie, l'écologie, les sciences de l'alimentation, les sciences sociales, l'écologie, la biotechnologie, la nanotechnologie, les technologies de l'information et de la communication (TIC) et l'ingénierie. Cette diversification des connaissances peut être une tâche fastidieuse et difficile. Il convient donc de relever ce défi en étudiant la manière dont les entreprises recueillent et intègrent les connaissances provenant de diverses disciplines et sources.

2- L'innovation verte et la bioéconomie nécessitent des **technologies complémentaires et convergentes**. L'exploitation des technologies développées dans divers domaines afin de développer des applications vertes peut favoriser l'innovation. Si nous acceptons que la connaissance est intrinsèquement composite et indivisible constituant un ensemble hétérogène (Antonelli et Colombelli, 2013), les entreprises devront décider dans quelles connaissances investir et comment ces connaissances peuvent se combiner avec d'autres connaissances et les capacités existantes. Par conséquent, la complémentarité des connaissances devient un défi qui mérite d'être étudié en explorant les décisions d'investissement des entreprises pour innover tout en exploitant la complémentarité les connaissances.

3- Les innovations peuvent être basées sur l'utilisation de la même biomasse pour différentes applications, ce qui soulève la question de la concurrence entre les secteurs. Elles peuvent également conduire à la **création de liens croisés entre différentes chaînes de valeur**, brouillant les frontières entre des industries auparavant distinctes. Les entreprises

devront relever le défi d'identifier les segments de marché à cibler et d'aligner leur production sur les attentes et les besoins des acteurs positionnés dans les différentes applications de la chaîne de valeur.

4- **Commercialisation et marché** : ce point est particulièrement lié à la manière de faire passer l'innovation de la phase d'exploration à l'exploitation réelle, autrement dit de la recherche aux produits commercialement viables. Il s'agit d'une tâche très difficile qui nécessite une collaboration entre les acteurs tout au long de la chaîne de valeur et, dans certains cas, entre différentes chaînes de valeur pour permettre la diffusion des technologies ou des innovations. En outre, les produits innovants sont confrontés à un problème de prix, car ils sont généralement plus chers que leurs équivalents pétrochimiques.

Notre objectif était d'étudier les stratégies développées par les acteurs pour répondre à ces défis. Dit autrement, nous explorons les stratégies développées par les acteurs pour obtenir le savoir-faire nécessaire pour innover dans la bioéconomie et l'innovation verte et pour s'intégrer dans les chaînes de valeur mondiales afin de diffuser et de commercialiser leur innovation. Dans cette optique, nous développons une analyse à trois niveaux. L'analyse s'appuie sur une optique de chaîne de valeur. La chaîne de valeur de la bioéconomie, ou de toute activité de production, comprend des activités en amont (production de matières premières) et des activités en aval (transformation et traitement). Dans cette thèse, nous mobilisons une réflexion similaire.

Le premier niveau commence par la production d'intrants (l'amont) qui provient de l'agriculture ou de la réutilisation des sous-produits des systèmes de production actuels (par exemple, les déchets, les résidus ou les effluents) ou de la culture de biomasse spécifique qui peut être mobilisée pour les produits biosourcés (par exemple, les microalgues ; les cultures spécifiques à des fins énergétiques) (Carraresi et al., 2018). Le deuxième niveau d'analyse est consacré à l'étude des entreprises situées en aval, impliquées dans des activités de transformation et engagées dans l'éco-innovation. Enfin, dans dernier niveau d'analyse, nous étudions une chaîne de valeur complète. Certaines innovations se caractérisent par une nature transsectorielle, comme la bioéconomie, ou les innovation vertes reliant simultanément plusieurs secteurs. Dans ce cas, une analyse centrée sur la chaîne de valeur complète est plus adéquate.

Le premier niveau d'analyse (premier chapitre) est centré sur l'agriculture qui joue un rôle prééminent dans la vision de la bioéconomie en tant que fournisseur de biomasse (par exemple, en amont). À ce niveau, nous souhaitons explorer les défis liés à la complexité des connaissances et à la variété des sources nécessaires pour acquérir ces connaissances. L'industrialisation de l'agriculture l'a rendue dépendante des pesticides et des connaissances provenant de sources extérieures. Cette uniformisation des connaissances a provoqué la rupture du lien auparavant intime et étroit entre les agriculteurs et leur terre (Pretty, 1995 ; Šūmane et al., 2018). Le passage à l'agriculture durable demande de renoncer aux connaissances standards pour des connaissances plurielles, diverses et hétérogènes qui proviennent d'une variété de sources. Nous explorons la diversité des stratégies d'approvisionnement en connaissances mises en œuvre par les agriculteurs pour cultiver différents types de cultures.

Nous exploitons une enquête sur les pratiques agricoles durables et les sources de connaissances. Nous utilisons un probit multivarié avec un calcul des effets marginaux. Les résultats nous permettent de classer les sources de connaissances en fonction de leur pertinence pour chaque culture et pratique. Ils mettent en évidence la nécessité de disposer de sources de connaissances internes et externes pour innover en matière d'agriculture durable. Ces résultats suggèrent que les connaissances peuvent être utilisées pour développer des produits multiples grâce à la capacité des agriculteurs à tirer des similitudes d'une base de connaissances diversifiée.

En résumé, il n'existe pas de stratégies uniques d'acquisition de connaissances car elles dépendent du contexte, des objectifs et des buts des agriculteurs. Cette analyse contribue à répondre au premier défi auquel est confrontée la bioéconomie et l'innovation verte, à savoir la complexité des connaissances et la variété des sources nécessaires. Nous rejoignons le point de vue de Levidow et al. (2013) et montrons l'importance pour les agriculteurs et les acteurs externes de se réunir et d'interagir afin de développer de nouvelles connaissances et de faire évoluer l'agriculture en s'appuyant sur les connaissances et les ressources biologiques locales.

Le deuxième niveau d'analyse se concentre sur les acteurs en aval qui sont engagés dans la transformation de la biomasse et le développement des processus de production et de produits écologiques. L'accent mis sur l'éco-innovation dans le deuxième chapitre est motivé par deux raisons. Premièrement, il est essentiel de comprendre le rôle de la biotechnologie

ainsi que d'autres domaines scientifiques (TIC, nanotechnologies..) dans la stimulation de l'éco-innovation. Cette analyse met en évidence les composantes importantes de l'éco-innovation. Deuxièmement, dans ce chapitre, nous relevons le défi lié à la complémentarité des connaissances. La littérature sur l'éco-innovation décrit celle-ci comme complexe et multidisciplinaire (OCDE, 2011). Nous examinons cette complexité en explorant la contribution de différents domaines de R&D à la génération de l'éco-innovation. Nous vérifions également l'existence d'une complémentarité entre ces différents domaines de connaissances en utilisant l'approche de Carree et al. (2011).

Nous utilisons l'enquête communautaire sur l'innovation de 2014 et les données sur les dépenses de R&D élaborées par le ministère de l'Enseignement supérieur et de la Recherche. Nous mobilisons un probit bivarié avec sélection de Heckman afin de tester nos hypothèses. Nous constatons que différents domaines de R&D contribuent à l'éco-innovation. De plus, il existe une complémentarité entre la R&D verte et la R&D en biotechnologie, qui est très probablement à l'origine de meilleures éco-innovations. Ces résultats mettent en évidence les principaux domaines de connaissance nécessaires au développement de l'éco-innovation. Ils montrent également l'importance des complémentarités et l'existence de synergies entre les domaines de connaissance utilisés pour développer l'éco-innovation. En outre, ils démontrent le rôle prépondérant de la biotechnologie dans le développement de l'éco-innovation.

La diffusion de l'éco-innovation, y compris la bioéconomie, nécessite des politiques de R&D ciblées pour soutenir les investissements des entreprises dans la R&D verte. Cependant, les politiques ne doivent pas seulement promouvoir l'innovation verte, mais aussi s'étendre au soutien des sciences fondamentales qui contribuent au développement de technologies à usage général (*general purpose technologies*) comme les biotechnologies et les TIC. Grâce à leur caractère omniprésent et aux synergies croissantes entre les différentes technologies, ces technologies peuvent permettre le développement d'applications environnementales et vertes dans de nombreux secteurs.

Le troisième niveau d'analyse se concentre sur la chaîne de valeur complète d'un secteur de la bioéconomie, celui des microalgues et des chaînes de valeurs connexes (multiples secteurs d'application). La perspective de la chaîne de valeur est utile dans le cas de la bioéconomie, car cette dernière a une nature intersectorielle reliant diverses industries utilisant les mêmes matières premières (Carraresi et al., 2018). Dans ce niveau (le troisième chapitre), nous abordons les défis liés à la sortie d'un espace protégé d'innovation et donc à

la commercialisation et aux répercussions de l'innovation sur la restructuration des chaînes de valeur impactées. L'objectif de ce chapitre est d'examiner les stratégies adoptées par les acteurs pour intégrer et transformer des chaînes de valeur afin de diffuser et commercialiser leur innovation.

Nous adoptons une approche d'étude de cas et nous recueillons des données provenant de sources hétérogènes. Les résultats de ce chapitre soulignent que les acteurs s'engagent dans des activités collectives d'exploration et d'exploitation. Ces activités requièrent différents types d'alliances entre les acteurs situés dans la chaîne de valeur principale des microalgues et les acteurs situés dans les chaînes de valeur adjacentes, à différents moments du processus d'innovation. Ces alliances conduisent à la restructuration des chaînes de valeur existantes et modifient les relations précédentes le long des chaînes de valeur.

Les défis auxquels est confrontée la bioéconomie en matière de diffusion et de commercialisation peuvent être résolus par l'établissement des alliances. Les acteurs s'engageant dans des alliances auront accès aux nouvelles connaissances et pratiques et amélioreront leur innovation. Ces alliances ouvriront la voie vers de nouvelles applications et faciliteront la commercialiseront. En d'autres termes, ces alliances aideront les acteurs de la bioéconomie à sortir l'innovation de leur niche afin de la diffuser et finalement contribuer à remplacer les régimes existants.

Les contributions de cette thèse à la littérature sont les suivantes. Premièrement, la complexité de la connaissance peut être surmontée par le développement de stratégies d'approvisionnement en connaissances stratégiques. Ces stratégies ne sont cependant pas uniformes. Elles dépendent fortement du contexte, des objectifs, des connaissances antérieures et des lacunes à combler dans les compétences des acteurs. Deuxièmement, il est nécessaire d'élaborer des politiques publiques qui tiennent compte de ces hétérogénéités dans les stratégies de recherche de connaissances et qui facilitent leur mise en œuvre. Dans le domaine de l'agriculture, les décideurs publics devraient travailler en étroite collaboration avec les agriculteurs afin de développer des outils adaptés à leurs besoins.

Troisièmement, nous contribuons aux débats en cours concernant l'allocation des ressources publiques. L'éco-innovation devrait figurer en tête de l'agenda politique. Nos résultats montrent que l'éco-innovation dépend d'autres domaines scientifiques pour progresser. Par conséquent, ces domaines requièrent une attention politique équivalente et

concertée si nous voulons réaliser et accélérer la transition vers la durabilité et la bioéconomie.

Quatrièmement, nous contribuons à la littérature sur les transitions en montrant le rôle des alliances comme outil d'intégration dans les chaînes de valeur. Cette intégration permet aux entreprises de commercialiser leurs produits innovants et d'atteindre le marché. Nous montrons également comment l'innovation développée dans des niches se diffuse et quelles sont les conséquences de cette diffusion sur la forme finale de la chaîne de valeur.

Notre travail n'est pas exempt de limites. Tout d'abord, l'utilisation de données transversales restreint notre compréhension des différentes stratégies développées par les acteurs afin d'acquérir les connaissances nécessaires pour innover. Ceci est particulièrement pertinent pour le premier et le deuxième chapitre. La deuxième limite est également liée aux enquêtes au niveau de l'entreprise où les données ne nous ont pas permis d'intégrer toutes les sources de connaissances (premier chapitre) ou d'étudier les comportements de collaboration (le deuxième chapitre).

La troisième limite concerne les outils méthodologiques et les données utilisées. Nous ne tenons pas compte de l'endogénéité émanant de l'échantillonnage de l'enquête dans le deuxième chapitre car l'ensemble de données était limité seulement aux entreprises innovantes.. La quatrième limite est l'utilisation d'une seule étude de cas (le troisième chapitre). L'application de notre cadre d'analyse à d'autres études de cas permettrait d'enrichir et d'améliorer notre approche conceptuelle.

Nous pouvons également déduire de multiples implications politiques pour la bioéconomie en particulier et l'éco-innovation en général. Premièrement, les politiques doivent faciliter la mise en réseau et la recherche de connaissances. Cela peut se faire par le développement de politiques qui répondent aux besoins des acteurs et prennent en compte le contexte dans lequel cet échange de connaissances a lieu. Ensuite, outre le soutien à la R&D ciblée, les politiques doivent également promouvoir les investissements dans les sciences fondamentales et encourager les synergies entre les domaines de connaissance, car la recombinaison des connaissances est également un moteur essentiel de l'innovation. Enfin, la nature intersectorielle de la bioéconomie exige des politiques intersectorielles qui favorisent des innovations polyvalentes et intersectorielles. Ces politiques, qui visent à gérer l'échange de connaissances et à assurer l'alignement des différentes chaînes de valeur, sont donc

cruciales pour soutenir et encourager les technologies intersectorielles afin de réussir la transition.

General Introduction

1 General Background

1.1 Context of the emergence of eco-innovation and the bioeconomy

The latest Intergovernmental Panel on Climate Change (IPCC) report stresses the need to speed up the transition to sustainability and decarbonisation to achieve the Paris agreement and keep the temperature below the critical levels (IPCC, 2022). This transition necessitates innovations with an environmental dimension to replace existing locked-in production systems entrenched in networks and broader socio-technical systems such as infrastructures, manufacturing systems, supply chains, and social practices (Geels et al., 2017). Studying these innovations and understanding the mechanisms through which they were/ and are still being developed, diffused and marketed is thus crucial to accelerating decarbonisation and reaching net-zero carbon targets.

In the academic sphere, Innovations with an environmental dimension have been at the centre of academic attention for the past decades. This type of innovation has many names: eco-innovation, sustainable innovation, environmental innovation, ecological innovation or green innovation (Carrillo-Hermosilla et al., 2009; Schiederig et al., 2012). Each concept involves a distinct definition of what the innovations with an environmental dimension entail leading to tensions and disagreement between scholars (Ghisetti et al., 2015) (see attempts of definition in (Kemp, 2010; Kemp and Pearson, 2007; Rennings, 2000). However, Kemp and Pearson, 2007 provide an extensively used definition:

“Eco-innovation is the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organisation and which results in a reduction of environmental risk, pollution and other negative impacts to relevant alternatives.”

In the political sphere, eco-innovations received unequivocal policy attention thanks to their promising feature in addressing climate change problems. Policies around the world aim at supporting the development of these hopeful monstrosities (Mokyr, 1990). The characterisation of Mokyr seems suitable for eco-innovations because they face competition from well-established and entrenched systems embedded with vast complementary

technologies and therefore needs support to develop and become viable. To this end, literature emerged on the micro and macro levels to study the factors driving eco-innovation, such as market pull, technology push, and regulation (see Popp, 2019) for an overview) and to provide theoretically and empirically grounded policy recommendations. Moreover, scholars were also interested in understanding the process of transition emanating from green innovations to achieve sustainability and decarbonization (see, for example (Geels, 2002; Geels and Schot, 2007)).

Under the umbrella of eco-innovation, the concept of the bioeconomy emerged as a solution to many environmental challenges. The bioeconomy proposes to use renewable biomass as the primary input in production activities to produce a wide range of high value-added products such as food and pharmaceutical products, bio-sourced materials and bio-energy (Staffas et al., 2013). This production is based on repurposing the by-products of current production systems (e.g., waste, residuals or effluents) or the development of specific biomass that can be mobilised for biobased products (e.g., microalgae; specific crops for energy purposes) (Carraresi et al., 2018; Falcone et al., 2019).

The expectations of the bioeconomy are not limited to its environmental benefits but also extend to include social and environmental repercussions. Consequently, the concept is becoming more attractive for policymakers, researchers and industries. The bioeconomy is supposed to provide services such as carbon sequestration, the conversion of waste and agricultural products to biofuel and other high value-added products limiting emissions of the transport sector and waste and potentially substituting fossil fuel and petrochemical products (European Commission, 2020). Besides the environmental benefits, the bioeconomy is expected to contribute to job creation, especially in vulnerable areas (rural and coastal). It will modernise primary sectors such as fisheries, agriculture and forestry to have an annual turnover of two trillion euros (Ronzon and M'Barek, 2018) by providing new applications and markets.

Thanks to the previously mentioned potentials, the bioeconomy received recognition and support from various institutions such as the Organisation for Economic Co-operation and Development (OECD) and the European Commission (McCormick and Kautto, 2013; Patermann and Aguilar, 2018). Many European countries also rushed to develop their national bioeconomy strategy. These countries include but are not limited to Germany, France, Italy, the United States, and the United Kingdom. Despite discrepancies among

national strategies, the core of these policies revolves around achieving a linkage between the use of biomass for the sustainable production of food, feed, energy and bio-based products with environmental protection, biodiversity and ecosystems restoration and conservation. This linkage will happen by enhancing circularity and sustainability in the bioeconomy. It will also transpire by developing policies oriented to the local needs, valorising local resources, and going beyond research to the actual implementation of the bioeconomy (Lutzeyer, 2019).

1.2 Towards a definition of the bioeconomy

Bioeconomy was not only a buzzword in policy and industry settings, but it also received substantial academic interest. The empirical research mobilising publications and citation datasets illustrate a drastic increase in bioeconomy research starting from 2005 (Birner, 2017; Bugge et al., 2016; Duquenne et al., 2020). Based on the literature, the concept's origin lies in Georgescu-Roegen's research in the 1970s and 1980s, where he developed the bioeconomy concept igniting some of the earliest discussions about economic degrowth (Martínez-Alier et al., 2010). However, this thesis focuses on the recent definition and reconceptualisation of the bioeconomy.

There is a lack of consensus about the definition of the bioeconomy. Three broad visions are introduced, gathering the different approaches researchers and institutions adopt to define the bioeconomy. This implies differential approaches to how bioeconomy is implemented, the type of innovation and knowledge mobilised; the main sector targeted, the economic model that drives it and policies to support it (for more details, see (Befort, 2020a)):

- The bioeconomy is considered a subsector of biotechnology (Befort, 2020). This vision is mainly shaped by the OECD. It fits the Schumpeterian theory of the Kondratiev cycle with an industrial revolution that will occur thanks to the industrialisation of biology (Vivien et al., 2019). In this view, the main actors are incumbents that develop biotech closely in collaboration with start-ups (Befort, 2020) to complement and create new knowledge (Bugge et al., 2016; Vivien et al., 2019). The knowledge-based on synthetic biology and fermentation is central to this view leading to value creation in a materialistic and nonmaterialistic sense (Birch, 2012).

- Biomass occupies a central role in the second vision of the bioeconomy. This vision is mission-driven, as the aim is to substitute oil with biomass (Befort, 2020). The European Commission advocates for this approach where raw materials should be transformed using biorefineries (European Commission, 2012). This vision highlights the importance of a broader knowledge scope drawing on multiple fields that are not only limited to biotechnology (Bugge et al., 2016). Accessing this knowledge would require collaboration between actors with different capabilities and know-how (Levidow et al., 2012) within and across sectors (McCormick and Kautto, 2013). In this conceptualisation, two types of innovation compete for biomass to substitute petrochemicals (Vivien et al., 2019). The first is the “drop-in”, which targets mature and well-established fossil fuel-based markets to provide an identical substitute to fossil-based products. Biorefineries carry on the same function as petroleum refining in this first type. The second is to develop new products that substitute existing products and deliver new functionalities.
- In the bio-ecology vision, sustainability is the primary concern. This approach highlights the importance of biodiversity conservation and ecosystem services. Economic growth and commercialisation are criticised in this view. Innovation has a different purpose focusing on sustainability issues (Bugge et al., 2016).

1.3 The main challenges faced by the green and bioeconomy

Based on these definitions, innovation and knowledge are the cornerstones of the bioeconomy regardless of the vision. This focus led the literature investigating bioeconomy from an innovation management standpoint. This literature aims to identify the challenges faced by the bioeconomy and provide guidance and recommendation on innovation management and implementation to favour the transition toward bioeconomy (Birte Golembiewski et al., 2015; Mertens et al., 2019; van Lancker et al., 2016). We adapt four challenges particularly relevant for this thesis from Golembiewski et al., (2015) that the bioeconomy in specific and green innovations generally needs to overcome to enable its development:

1. Green and bioeconomy innovation is a knowledge-intensive field as implied in the former conceptualisation of the bioeconomy as a “knowledge-based bioeconomy”. In

developing sustainable and green innovation(Lewandowski et al., 2019), actors must acquire knowledge from various scientific disciplines. This **complex knowledge base** can originate from **various sources** and scientific domains such as life sciences, agronomy, ecology, food science, social science, green, biotechnology, nanotechnology, information and communication technologies (ICT) and engineering. This diversification of knowledge can be a tedious and challenging task. This challenge, therefore, needs to be addressed by exploring how firms collect and integrate knowledge from various disciplines and sources.

2. Green and bioeconomy innovation requires **complementary and converging technologies**. Suppose we accept that knowledge is intrinsically composite and indivisible, constituting a heterogeneous bundle (Antonelli and Colombelli, 2013). In that case, it becomes a challenging task for actors to develop innovation and knowledge strategies. In other words, actors will need to decide on which knowledge to invest in and how this knowledge can work in combination with other knowledge stocks and existing capabilities of the firms. Therefore, knowledge complementarity becomes a challenge worth investigating by exploring firms' intentional investment decisions to achieve innovation and complementarity.
3. Innovations can be based on using the same biomass for different applications raising the question of competition between sectors. It can also lead to **cross-linkages** between different **value chains** blurring boundaries between previously distinct industries. Firms will face the challenge of identifying the market segments to target and aligning their production with the expectations and needs of actors positioned in different value chain applications.
4. **Commercialisation and market**: this point is particularly related to driving innovation from the exploration phase to actual exploitation, said differently from research to commercially viable products. This is a very challenging task that requires collaboration between actors along the value chain and across different value chains to enable the diffusion of the newly developed technologies or innovation. Moreover, the innovative products developed face a price challenge as they are usually more expensive than their petrochemical counterparts.

Despite the extensive research tackling the bioeconomy, the existing analysis is oriented to national, geographical and industrial/sectoral aspects of the bioeconomy (van Lancker et al., 2016). This level of analysis is somewhat ambiguous regarding the deliberate strategies developed by actors to innovate and participate in the bioeconomy (Birte Golembiewski et al., 2015). Moreover, the analysis is usually limited to one sector, ignoring the cross-industry nature of the bioeconomy (Tassinari et al., 2021). This renders the literature abstract and rarely deals with the bioeconomy at the firms' level (e.g., actor level) and the multisectoral nature of green and bio-based innovation. Actor-level analysis will be a suitable approach to studying the bioeconomy specifically and generally green innovation. First, an actor level analysis is particularly relevant thanks to the pivotal role of firms and farmers in achieving environmental goals and making the transition towards a greener economy. Second and more importantly, this level of analysis will enable us to map the strategies established by actors to develop the needed knowledge to innovate and commercialise their innovation through integrating/constructing value chains overcoming the previously mentioned challenges. Third, it will provide a concrete and accurate example that can be generalised and replicated, increasing our understanding of the construction and development of the green and bioeconomy. **Based on these arguments, the overarching research question of this thesis is:**

What strategies do actors develop to assemble the building blocks of internal and external knowledge needed for innovation and integrate value chains for diffusing and commercialising their innovations, enabling the transition to a sustainable green and bioeconomy?

2 Research Objectives

To answer the dissertation's central question, we develop a three-level analysis. This analysis is based on the value chain lens. The first level starts with biomass. Biomass or generally speaking production inputs comes from agriculture, from the repurposing of the by-products of current production systems (e.g., waste, residuals or effluents) or the cultivation of specific biomass that can be mobilised for the biobased products (e.g., microalgae; specific crops for energy purposes) (Carraresi et al., 2018). In this level, we take agriculture as a case study (Chapter 1). We explore the strategies designed by farmers to innovate and produce

more sustainable and greener agriculture. The second level of analysis is devoted to studying firms located downstream and involved in transformation and processing activities. We are interested in investigating the role of biotechnology as well as ICT, nanotech, advanced material, and social science in eco-innovation development. We do so by examining the strategies developed by actors to combine, match and draw synergies between knowledge fields to eco-innovate in production processes and products (Chapter 2). Finally, in a third level, we tackle issues related to the commercialisation and diffusion of bio-based and green products. We build a framework that studies the complete value chain. Some innovations are characterised by a cross-industry nature such as bioeconomy, or green innovation linking various sectors simultaneously. In this case, an analysis centred on the complete value chain is more adequate. Our aim is to provide a better understanding of the conditions and mechanisms that enable an emergent innovation (a niche) to expand, diffuse and reach the market. We are also interested in the repercussion of innovation on the final form of the value chain. We analyse the case study of microalgae (Chapter 3)

Our approach enables us to provide both a microlevel view of bio-based and green innovation and a meso level. In this way, the dynamics not discernible at one level can be observed at the other. We also decide to focus on actors' strategies to innovate and integrate value chains because green and bio-based innovations require new technological and innovative capabilities that rely on complex knowledge from diverse scientific fields beyond any narrow characterisation (OECD, 2011; van Lancker et al., 2016). A new kind of knowledge or new ways of knowledge generation and acquisition is needed to ensure the transition to and the development of the green and bioeconomy. Moreover, these economic activities require the reorganisation, the restructuring of production activities and their coordination. These changes can lead to new forms of emerging value chain or the modification of existing ones. Therefore, we assume that the development of a sustainable green and bioeconomy will have unevenly distributed implications for actors' activity and their position in various value chains, which further justify our three-level analysis. Below, we provide details for each level.

2.1 Upstream

We chose to focus in the first chapter on agriculture as it is the primary source of biomass. It is mainly dominated by small firms positioned upstream of the value chain, which

develop primarily incremental and organisational innovation. To contribute to the bioeconomy, become more sustainable/greener, and still meet food security targets, agriculture has to adopt the agro-ecological vision (third vision discussed above), where the main focus is on enhancing the ecological and natural processes in agriculture and reducing the dependence on external inputs and reviving farmers' intimate knowledge with nature (Levidow et al., 2013).

Shifting to sustainability calls upon the development of agricultural systems that rely on diversified species and farming techniques that promote ecosystem services (Jordan et al., 2007). These agricultural systems are more efficient and effective than the monoculture systems that mainly rely on the cultivation of corn or wheat. The latter perpetuates environmental issues and reliance on standardised external knowledge (Pretty, 1995).

The shift to sustainable agriculture requires innovation processes. These innovation processes rely on knowledge that is deemed complex, diverse and scattered between various actors (Levidow et al., 2013). This corresponds with the first challenge mentioned earlier about knowledge diversity and complexity and the need for collaborations to access and acquire this knowledge. Therefore, in the first chapter, we tackle this challenge of knowledge sourcing to overcome complexity and innovate in sustainable farming practices

Exploring the factors that affect sustainable farming innovation triggered a stream of work dedicated to identifying the sources of knowledge contributing to farmer innovation processes, their hierarchy and their overall importance (Barnes et al., 2019; McBride and Daberkow, 2003; Solano et al., 2003). Several studies focus on the difference in knowledge sourcing strategy based on the farmers' characteristics, the innovation objectives and the phase in the innovation process (Cofré-Bravo et al., 2019; Diederer et al., 2003; Gava et al., 2017). The literature consists mainly of case studies of specific contexts (e.g., dairy, livestock, cereal) in particular regions, investigating the knowledge sources contributing to on-farm innovation and providing a bird's eye view of farmers' knowledge sourcing strategies instead of a study of these strategies by crop type.

Farmers usually do not cultivate only one crop (de Roest et al., 2018; Morris et al., 2017). To grow multiple species, farmers must draw on different knowledge stocks that depend on the crop type and adapt farming practices accordingly (Galliano and Siqueira, 2021; Magrini et al., 2016; Meynard et al., 2018). Including a crop level analysis also reveal

that farmers do not hold the same amount of knowledge for all crops as they might have more knowledge about major crops such as cereals (Magrini et al., 2016). Besides internal knowledge, external sources of knowledge might be lacking for a specific type of crop (Meynard et al. 2018).

Based on these arguments, the shift in agricultural strategy necessitates the mobilisation of a new knowledge base relinquishing their old knowledge and innovation strategy and developing **crop-specific**, renewed **strategies** that will need to be investigated theoretically and empirically. Thus, knowledge sourcing strategies cannot be considered one-size-fits-all, with knowledge source importance ranked the same for different crops. Following this logic, in Chapter 1, we revisit the agricultural innovation literature to explore the importance of agronomic innovation and the diversity of knowledge acquisition strategies constructed by farmers to develop sustainable agriculture that departs from the standardised knowledge and the reliance on external inputs.

First research question: To what extent do farmers develop diverse knowledge acquisition strategies that differ based on crop type?

2.2 Downstream

At this level, we focus on actors situated downstream engaged in eco-innovation. Actors downstream develop innovative strategies to transform and process inputs acquired from upstream and produce environmental products and processes. Given the technological complexity of the knowledge needed for bio-based and green innovation, the second chapter focuses on large high-tech firms that are usually capable of investing in resources to develop technological innovation. Developing a sustainable green and bioeconomy necessitates first the mobilisation of a complex knowledge base from different scientific fields such as biotechnology, social science, green, biotechnology, nanotechnology, information and communication technologies (ICT) and engineering (van Lancker et al., 2016). Second, actors need to identify the potential synergies between the different scientific fields that can promote innovation (Birte Golembiewski et al., 2015).

We chose here to centre the analysis on eco-innovations for four reasons. First, bioeconomy is promoted as a solution to climate change where biotechnology is supposed to

drive transition through the development of greener products and processes. Therefore it falls within the sphere of eco-innovation. Second, eco-innovations are deemed complex (Barbieri et al., 2020a; de Marchi, 2012), combining knowledge spanning fields such as green technologies, biotech, nanotech, ICT, social sciences and others (OECD, 2011). Third, the case of eco-innovation provides the context to study the second challenge of knowledge complementarity and knowledge complexity. Fourth and most importantly, we are interested in understanding how biotechnology contributes to eco-innovation.

The multi-disciplinarity of knowledge is key to developing green and bio-based innovation and calls for investment in a diversified knowledge base. In the literature, the knowledge plurality of eco-innovation is investigated by using patents and their citation to trace the invention to the different sectoral and technological knowledge bases mobilised to develop it (Dechezleprêtre et al., 2017; OECD, 2011). This was mainly to study the hypotheses of knowledge spillovers between green and non-green technologies (Dechezleprêtre et al., 2017), to explore the knowledge recombination process leading to innovation and its influence on subsequent innovation (Barbieri et al., 2020; Nemet, 2012).

However, this type of analysis is oriented towards the output of the innovation process instead of the inputs (e.g., knowledge elements) used to generate eco-innovation internally. Using patent data and conducting a patent analysis does not clarify the firms' intentional knowledge diversification decision. This type of analysis disregards firms' choice to invest in producing distinct but complementary knowledge fields to eco-innovate, achieving synergies and economies of scope (à la Milgrom and Roberts, 1995, 1990). This implies that there is no clear understanding of the investment decisions that firms have to undertake to achieve multi-disciplinarity and, consequently, innovation.

The literature on internal inputs of eco-innovation rarely distinguishes between green R&D and other types of R&D, considering firms' investment as a homogenous bundle. Some scholars such as Lanoie et al., (2011) and Stucki et al., (2018) demonstrate that firms devote part of their R&D investment to green and environmental R&D. In the second chapter, we explore the role of green R&D, biotech R&D and other fields of R&D needed for eco-innovation. We aim to explore the strategies developed by actors intentionally to tackle complex innovation through internal investments and mix different domains of knowledge to create synergies. This mapping is core to allocating R&D budgets efficiently. It also raises the question of the complementarities between R&D fields to generate eco-innovation.

Second research question: Are investments in green R&D worthwhile and enough to successfully eco-innovate? What investments are needed to eco-innovate?

2.3 Value chain

Some innovations are characterised by a cross-industry nature such as bioeconomy, or green innovation linking various sectors simultaneously. Sectors (e.g. food, feed, chemistry, energy, fuel, and pharmaceutical sector), technologies and production systems seek to substitute scarce materials and resources by working in conjunction to derive products from renewable biological resources (Golembiewski et al., 2015; van Lancker et al., 2016). These resources can originate from biomass or the repurposing of by-products and waste.

This characterisation of the green and bioeconomy innovation renders the production, the transformation and the commercialisation process very complex (Carraresi et al., 2018). The complexity emanates from the integration of actors and activities in novel ways across previously separated industries. This complexity also raises the question of actors' capacities to develop linkages across the value chain(s) to drive their innovation from exploration to exploitation. These green and bio-based innovations necessitate the alignment of the whole value chain to develop successful innovation and push it to reach the market.

Therefore, the study of small firms upstream or large and high tech firms downstream provides only the picture of how innovation is created, but not how actors develop adequate strategies for its commercialisation and diffusion. The latter is a very complex process that requires specific strategies to be implemented. We explore the strategies established by actors to overcome the challenges of commercialisation and dealing with converging value chains in the third chapter on the case of microalgae. To understand this phenomenon in the bioeconomy, a value chain analysis is required.

However, it is worth noting that not all innovations developed reach commercialisation and market. The innovation trajectory from discovery to market is not straightforward. Established frameworks of strategic niche management (SNM) (Hoogma et al., 2002; Kemp et al., 1998) and the multi-level perspective (MLP) (Geels, 2019; Geels and Schot, 2007b) examine how innovation emerges (e.g., a bio-based innovation), gains momentum, and eventually challenges the dominant technology in a specific sector. The innovation process is

driven by incumbents and new entrants who influence the developmental trajectories of a niche innovation (Berggren et al., 2015; Geels et al., 2016). These frameworks say little about the mechanisms that drive the niche innovation's expansion, diffusion, and commercialisation. In other words, we know little about how innovation breaks out and leaves a protected space. Moreover, there is a lack of analysis of multi-purpose innovations spanning different sectors, as is the case of green and bio-based innovations.

To address these shortcomings, we argue in the third chapter that for innovation to succeed, it has to subscribe to the labour division studied through the global value chain lens. The literature on global value chains explains the coordination of the production process dispersed geographically across actors and the governance of economic activities, including innovation, by studying the role of core actors (e.g., lead firms) in driving global value chains (Gereffi et al., 2006; Gereffi and Korzeniewicz, 1994).

Third research question: How value chain links can be mobilised by niche innovation to confront it gradually with the selection environment enabling the niche innovation to phase out its protected space, expand, proliferate and gain momentum?

3 Theoretical background

To address the three questions developed in the previous section, we mobilise innovation studies literature. First, we draw on innovation management and economics literature. This first type of literature allows us to study the knowledge production function to explore the drivers of innovations. This literature will also enable us to tackle the first two challenges related to knowledge complexity and complementarity. Second, we mobilise transition studies literature, which adopts a meso-level perspective to study the emergence of innovation in a protected space up to progressing into a new regime. In the third chapter, we use this literature to address the challenges related to innovation commercialisation and value chain restructuration.

3.1 Micro-level

To answer the first two research questions, we mobilise innovation literature, especially the literature on firms' innovation process management and the central role of knowledge in this process.

3.1.1 Theoretical literature

The success of an organisation and its capacity to maintain its competitive advantage depends on the organisation's management of the innovation process (Adams et al., 2006). The main objective of this innovation management literature is to identify and measure the complex process of innovation. Many models and theories were conceived from a linear conceptualisation of innovation to a dynamic, recursive with feedback loops models (Buijs, 2003; Godin, 2016; Kline, 2016), where the technocentric view predominates.

In an attempt to derive the determinants of the innovation process, the input of innovation received substantial attention. These involve the resources mobilised by an organisation and include financial, physical, and human factors facilitating innovation generation (Adams et al., 2006), tangible but also intangible and implicit (Hall, 1993, 1992; Teece et al., 1997) physical, human and organisational assets (Barney, 1991). This focus on firms' specific endowments and core competencies explaining the success or failure in the marketplace started with Penrose, (1959), who emphasised the role of internal resources of the firm in enabling firms' growth. It led to the development of the resource-based view of competitive advantage (Barney, 1991). In the resource-based view setting, firms develop a competitive advantage through innovation and leveraging their internal inimitable, rare, valuable capabilities to capture economic rents emanating from firm-level efficiency (Conner, 2016).

In the same spirit, the knowledge-based view argues that firms' efficiency results from their knowledge. In other words, value creation relies more on intangible assets such as knowledge capabilities than tangible resources (Grant, 1996; Pemberton and Stonehouse, 2000). Therefore, the firm's resources include uncommon, idiosyncratic knowledge and economic and technical resources. In this line of thinking, collective knowledge, where knowledge is perceived as tacit and social (Spender, 1996), is distributed across actors of the same firm (Grant, 1996) and outside the firm.

Given that knowledge is not directly measurable or observable, it can only be approximated through concrete actions of the firm. The knowledge management literature mapped three functions to identify these actions: knowledge creation, accumulation, and sharing (Sher and Lee, 2004). According to these functions, firms create, gather, store, use and share knowledge.

3.1.2 Empirical literature

Empirical literature used firms' research and development (R&D) expenditure as the main driver of the innovation process. Many empirical studies tried to identify the intensity and the direction between R&D and innovation (Griliches and Mairesse, 1984; Pakes and Griliches, 1980). The relationship between innovation and R&D was found to be positive by Hall et al., (2010), while other scholars demonstrate a non-linear relationship between R&D and innovation (Artz et al., 2010). The empirical analysis was initially oriented toward internal R&D. However, with the rise of empirical and theoretical evidence about external knowledge's role in innovation development, the study of the different inputs included both internal and external factors (Acs and Audretsch, 1988; Peeters et al., 2006).

The empirical investigations of how firms acquire knowledge and transform it into innovation showed how firms mobilised their internal knowledge to internalise and acquire external knowledge from external sources through different organisation modes, i.e., cooperation (D'Aspremont & Jacquemin, 1988), social networks (Hargadon & Sutton, 1997; Powell, 1998), communities of practices, networks of practices and others (Wenger, 1998; Wenger & Snyder, 2000). Central to this idea of external knowledge and knowledge flow between and within firms is the notion of absorptive capacity (Cohen and Levinthal, 1989; Zahra and George, 2002). Thanks to firms' absorptive capacity, they can recognise, assimilate and apply external knowledge (Cohen and Levinthal, 1989).

The advent of innovation surveys enabled scholars to conduct extensive systematic econometric studies to pinpoint diverse external knowledge sources. They found that firms can access knowledge through the value chain links (suppliers, retailers, consumers and users), horizontally (competitors) and or laterally (universities, knowledge centres and institutes and others)(Becker & Dietz, 2004; Lokshin et al., 2008; Tether, 2002). This interest also led to the open innovation literature studying inbound and outbound innovation (Dahlander et al., 2021; Dahlander & Gann, 2010). However, this literature was mainly

oriented toward high tech firms and large companies and rarely discussed small firms and the low-tech sector. Further, it was centred around technological innovation and hardly studied agronomic, organisational, and managerial innovations (FAO, 2018; Sunding and Zilberman, 2001).

The previously mentioned literature also highlights that firms' resources can create additional value when shared across other activities within the firm (Markides and Williamson, 1994). Similarly, firms diversify their knowledge and know-how that can be shared among different R&D projects creating synergies, complementarities and reaching economies of scope in knowledge (Granstrand et al., 1997; Kim et al., 2016; Panwar et al., 1981; Teece, 1980). According to Antonelli (2003), the generation of technological knowledge is conditional on firms' competencies to draw together pieces of diverse knowledge, recombine them, hence complexity, and use these and knowledge together, hence complementarity.

Nevertheless, knowledge diversification has its limitation. Knowledge is an intrinsically indivisible commodity that cannot be used or purchased in parts, incurring a high cost of generation and acquisition (Warsh, 2006, p151). No firm can neither hold all knowledge (Antonelli and Colombelli, 2013) due to the wide range of costs of maintaining a highly diverse knowledge set nor invest partially in a few pieces of knowledge to innovate due to indivisibility (Antonelli, 2007).

3.2 Meso level

To answer the third question, we mobilise the literature about strategic niche management, the multi-level perspective and global value chain analysis. Innovation in evolutionary economics goes through origination, adoption and retention, where the entrepreneur develops “new combinations” that lead to new paths and trajectories (Schumpeter, 1934). These three phases depict how innovation emerges from ideation to an actualisation where it becomes the generic rule. This view of technological transition is further advanced by Geels, (2002)'s contribution by constructing a multi-level perspective (niche, socio-technical regime, socio-technical landscape). In this line of thinking, radical innovations emerge in the periphery by actors considered outsiders to the dominant regime.

The strategic niche management literature argues that a niche is developed for the purpose (Kemp et al., 1998) of providing a protected space for such radical, path-breaking innovations emerging in peripheral niches, developed by new entrants and more recently proved by also incumbents (Berggren et al., 2015; Geels and Raven, 2006a; Turnheim and Geels, 2019). To escape from the niche, a firm will link up to the process going on the regime and landscape level. The transition can take one of the multiple transition pathways conceptualised by (Geels and Schot, 2007) (substitution, reconfiguration, de-alignment/alignment, transformation).

However, the transition pathway is only observed after the transition has happened. The innovation journey from niche to the regime is not straightforward and obstacle-free. Few scholars map out the different barriers that innovation needs to overcome. For instance, Kemp et al., (1998) identify technological barriers, government policy and regulatory barriers, cultural and psychological barriers, demand and mass production barriers, and infrastructure and maintenance barriers. Similarly, (Geels, 2019) outlined technological, economic, social, cognitive and regulatory lock-in around the existing system that halts the progress of niches.

These obstacles can explain why some innovations successfully reach the market while others fail. The labour division literature also discusses the factors leading to the failure or success of innovation. Pavitt (1998) argues that successful innovation depends on matching firms' knowledge to the product innovated and the market. Arora et al., (1997) decompose technologies into modules where the production of the module is conducted by specialised firms situated upstream. In contrast, the combination of the different modules for various applications is developed by firms close to users or by users themselves. This division of labour enables each actor to devote their activities to their core competencies and enhance learning and knowledge transfer.

The concept of labour division is also present in innovation systems. In the conceptualisation of innovation systems by Andersen and Lundvall, (1997), the vertical relationships between firms are as crucial as horizontal ones. The focus on division of labour is within a given sector where production activities are divided between firms, and each firm is specialised in giving tasks. The introduction of innovation induces changes in labour division to better benefit from the technology through the development of new linkages between the innovative and other firms.

The recent progress in the innovation system literature extended the concept to include multi-sector instead of previously singled sector-focused analysis. Stephan et al., (2017) extended the technological innovation system framework to investigate multipurpose innovation with applications spanning various sectors using the concept of division of labour depicted in the value chain analysis. The global value chain analysis deals with the coordination of the production activities divided among geographically dispersed firms (Gereffi et al., 2005). The global value chain analysis explores how firms leverage innovation activities to upgrade their position in the value chain (Gereffi, 2019). The literature also investigates how different firms exploit their power to promote innovative activities along the supply chain and enable learning and knowledge exchange (de Marchi et al., 2013a).

4 Methodologies

This thesis mobilises a variety of data sets and methodological tools to answer the three research questions mentioned previously. The diverse data sets and tools allow us to explore the different actors involved in green innovation. It also enables us to explore the different angles and levels discussed previously. We rely on both quantitative and qualitative data, and we apply econometrics tools and a case study approach.

4.1 Knowledge production functions with probit regression

As a methodological tool, we use the knowledge production function (Chapters 1 and 2). The knowledge production function is the standard form representing the transformation of innovative inputs (R&D) into innovative outputs (patents). The work of Griliches explores the returns of R&D and its influence on firms' innovation performance laid the ground for the extensive use of the knowledge production function to identify relevant factors and measure their impact on innovation (Griliches, 1990, 1979; Griliches et al., 1984; Griliches and Pakes, 1984; Mansfield, 1980). Since then, a substantial body of research has emerged using the knowledge production function as a methodological tool (Bronwyn. Hall et al., 2010).

To estimate the knowledge production function, we use a probit regression analysis. The probit choice is because our main dependant variables (e.g., innovation) are dichotomous. Most innovation surveys collect qualitative information about firms' innovation behaviour. Probit regression aims to determine if an observation with specific characteristics falls in one of the categories. However, we cannot estimate the direct impact of a change in

the level of the explanatory variable on innovation probability; therefore, we accompany the probit regression with a marginal effect estimation.

In the first chapter, we mobilise the knowledge production function with a multivariate probit to study and compare the influence of different knowledge sourcing strategies on innovation in sustainable farming practices across various crop categories. The function enables us to rank and hierarchise sources based on their importance and gauges the most efficient sources for each crop and innovation category. This method highlights the complexity of knowledge and the variety of sources needed to switch to sustainable farming.

In the second chapter, the knowledge production function estimated using a bivariate probit and Heckman selection allows us to unravel the black box of eco-innovation by exploring the different technological fields that contribute to eco-innovation. It also facilitates the implementation of complementarity tests to scrutinise knowledge complementarity between different scientific domains. Therefore, it assists in providing evidence for the complexity of the knowledge base and the complementarity between the various fields of knowledge needed to eco-innovate. For complementarity, we use a test developed by Carree et al., (2011) as it is designed to derive complementarity from continuous variables and dichotomous.

4.2 Firm-level surveys

In the first chapter, we exploit a French data set, “Agricultural Practices Survey 2017”. The detailed information collected on farmers’ innovation behaviour in sustainable farming practices and other information related to farmer’s plots and farms, motivated the choice of dataset. This dataset provided the necessary details to answer the first research question. This survey is part of the Ecophyto plan to reduce chemical pesticide usage by shifting to more sustainable farming practices. The survey includes farmers with land in both metropolitan France and overseas regions; however, the latter, which include sugarcane cultivation, permanent grassland and meadows, are excluded due to their different policy requirements and general properties.

The farmers surveyed cultivate plots of between 0.1 hectares and 200 hectares. The sampling is done at the farm level, with data stratified according to the geographic location of the land, farming type (organic, non-organic) and farm size, and at the plot level, which

includes data on crops and soil types. The survey does not ask about farmers' characteristics. To complete the picture of farmers' characteristics, we match the dataset with the "General Agriculture Census 2010-2011". The survey targets all French farms with agriculture as the main activity, have a unique French business identification number, 0.2 hectares in size, or have a specific number of animal stock or a particular level of production.

In the second chapter, we use mainly two firms' surveys. The first is the community innovation survey (CIS). This survey is relevant because it provides information about firms' eco-innovation decisions in 2014. The definition of innovation in general in the CIS follows the definition of OECD. The survey limits the questions regarding eco-innovations to only innovating firms.

The second firms' level survey is a questionnaire developed by the French Ministry of Research and Higher education. It collects information about firms' research and development activities (R&D). The sampling starts with a repository of French firms that performed R&D historically. The repository is updated with information about firms' absorption by other entities or firms' cessation. The data is then completed with information from other surveys (research tax credit, innovative start-ups and others) and public tools that collect information about firms' research activities. The population is stratified into four groups based on R&D expenditures, and each is given a specific weight. A specific number of observations are sampled in each group to constitute the dataset we mobilise for the second chapter.

The definition of R&D activities in the survey follows the Frascati Manual of the OECD 2002. A given activity is considered part of R&D if it achieves technical improvements to products and processes. More specifically, R&D expenditures include activities related to :1) the study, construction and testing of prototypes, 2) the construction and exploitation of demonstration and pilots, 3) expenses related to special equipment and tools needed for the development of new processes or products, expenses incurred for plan preparations, reports, explanatory notes, formulas, usage instructions required for new process and products.

One particular variable of interest is firms' internal R&D expenditure, which encompasses firms' investments in six R&D domains. These include biotechnologies, nanotechnologies, green, information technology, advanced and new materials, and social

science and humanities. We use these different sub-categories to calculate firms' stock in each scientific domain and integrate them later on into the estimation equation.

We also match the data with two other surveys using firms' unique identification numbers. The first survey, developed by the national institute of statistics and economic studies (INSEE) and the Ministry of Finance, contains information about firms' tax reports to extract data about the firm's size. The second survey, developed by INSEE, outlines the industrial groups operating in France to cluster firms from the same industrial group together.

4.3 Case study

In the third chapter, we use a case study approach to explore the case of microalgae and study a complete value chain dedicated to the exploitation, production and commercialisation of green and bio-based products. We chose a case study approach as it enables us to conduct an in-depth analysis (Thomas, 2021; Yin, 2008) to define the narrative and follow the development trajectory of microalgae as a niche innovation. The case study approach allows confronting the proposed theoretical framework with empirical evidence to enrich and consolidate the former (Eisenhardt and Graebner, 2007).

To analyse the data collected, we mobilise a historical event analysis. This analysis aims first to characterise the microalgae promise cycle (e.g., niche emergence, growth and dynamics over time). Second, it allows the identification of political, economic and societal factors contributing to the emergence of the niche to investigate the enabling environment triggering innovations and lock-ins that might trap the innovation inside its protected space.

Finally, we complete the historical event analysis with a value chain lens. The guidance on conducting a value chain analysis can be found in Gereffi and Fernandez-Stark, (2011). The main idea is to match firms' supply with existing or future demand for their product. Afterwards, we explore how actors' position in the value chain changes and evolves over time. The value chain lens adds to the historical analysis by focusing on the linkages developed by actors to gradually leave the protected space and head towards production and commercialisation. With this multiple steps analysis, we can extract theoretical implications from observations (Langley, 1999).

4.4 Qualitative data

In the third chapter, we draw information from various data sources to understand the development trajectory of the microalgae. We first collected patent data. The patent data is collected from different sources 1) Patstat with IPC code “C12N 1/12” and keyword search in abstracts and titles for the period between 1995-2017, resulting in 8118 patents filled in this period, 2) An internet search, grey literature, reports, firms’ websites to identify patents filled between 1960-1995 and 2017-2021. The patent data aim to map the general trend in the patent filling to gauge the corresponding promise cycle. Moreover, we use this data to identify the most innovative firms in the sector of microalgae.

Along with the top 20 innovative firms, we build a firm dataset using market analysis information, literature, newsletters and reports. We ended up with 75 firms where we studied in-depth their business strategy, market segment, product development, and firms' evolution over time. The aim of this data set is twofold. First, we use it to study firms' behaviour along the promise cycle. Second, we identify the collaboration between the different firms and how actors constructed links along various value chains.

We completed the information collected with project datasets from CORDIS for the EU. We gathered reports from the Department of Energy and grey literature for the US. We use keywords search to identify 833 projects funded on CORDIS by the European Commission. The project database is essential to map the type of alliances built and their position in the value chain.

Finally, we also gather information about publications in the microalgae domain, conferences, NGOs, and associations. These data serve in mapping the promise cycle and identifying the most important publications and actors and their role in the microalgae development trajectory.

5 Thesis Outline

In this thesis, we identify four challenges facing the progress of the bioeconomy in specific and eco-innovation in general and ask an overarching question about the strategies developed by actors to overcome these challenges, as shown in Figure 0.1. Figure 0.1 provides a summary of the thesis outline. We tackle this question by focusing on the different

levels of the production activities using a value chain lens. In the first two-level (production of biomass and transformation activities), we explore the challenges related to knowledge complexity and knowledge complementarity. In Chapter 1, we focus on agriculture (source of biomass-upstream of the value chain) and study the role of different knowledge sources enabling farmers to achieve a transition to sustainable farming practice using farm-level survey and probit regression. This analysis highlights the multiplicity of knowledge sources and the complexity of knowledge needed by farmers to become sustainable. In Chapter 2, we study firms located downstream and explore the mix of knowledge fields used by them to eco-innovate. We further emphasise the role of the scientific disciplines (biotech, ICT, green and others) and scrutinise their complementarity. To study the third and fourth challenges related to the commercialisation of green and biobased innovation and the repercussion of the innovation of the value chain structure. We adopt a value chain analysis to account for all steps of production activities, including commercialisation. In this chapter, we investigate how bio-based innovation emerges, expands, reaches the market and diffuses.

5.1 First Chapter: One size does not fit all: The plurality of knowledge sources for transition to sustainable farming

Sustainable farming encompasses diverse practices that draw on various knowledge stocks. This knowledge must be adapted to suit the farmers' crops, the local environment and the farming system. To achieve this requires farmers to build on their knowledge and invest in acquiring knowledge from external sources. It should not be assumed that different farmers cultivating different crops adopt the same knowledge sourcing strategies. Therefore, the first chapter explores "to what extent do farmers develop diverse knowledge acquisition strategies that differ based on crop type?" To this end, we conduct a crop level analysis to study the relationship between knowledge sourcing and innovation in sustainable farming practices for different crop categories.

We exploit a French Ministry of Agriculture cross-sectional dataset on farming practices in 2017 and run a multivariate probit regression and equality of means test. The results reveal that farmers mobilise internal and external knowledge sources. The importance of different knowledge sources is ranked differently by different growers cultivating different crops and adopting different practices. Therefore, the knowledge needed by farmers and the strategies deployed for its acquisitions is heterogeneous based on the crop type and the

farming practice in question. This is derived from the assumption that farmers do not hold all knowledge and that the knowledge needed to innovate varies based on crop and practice type.

When we zoom in on the question of knowledge sourcing and explore farmers that grow multiple crops simultaneously, we find that farmers are capable of deriving commonalities (Breschi et al., 2003), interpreting and perceiving the various potential applications of pieces of knowledge to diversify in different crops.

These results have two implications. First, since knowledge is a primary driver of innovation, farmers must capitalise on their knowledge. Second, policies must be flexible and co-designed with farmers to support them and respond to their needs. In formulating policy, an account should be taken of differences in the knowledge sourcing strategies related to different crops to ensure a quick transition to sustainable farming.

5.2 Second Chapter: Mix and match: What is the best R&D recipe for eco-innovation?

Eco-innovation is allegedly complex and requires disparate knowledge from firms' know-how. The complexity of eco-innovation calls upon detaining an extensive portfolio of R&D and technologies. Thus, the second chapter is interested in identifying firms' R&D strategies and studying the extent to which green and non-green R&D can influence eco-innovation. To answer the main driving question of this chapter, “Are investments in green R&D worthwhile and enough to successfully eco-innovate? What investments are needed to eco-innovate?” This analysis is vital for understanding the mixture of knowledge and research that produces eco-innovation.

The second chapter uses unique data from the community innovation survey matched with the R&D means survey developed by the Ministry of higher education and research in France for 2014 and employs a bivariate probit model with Heckman selection. The aim is to investigate the influence of different R&D strategies developed internally by firms on eco-innovation.

The results, first, indicate the influence of green and non-green R&D stocks on eco-innovation. Second, the analysis highlights the importance of knowledge complementarity between specific R&D strategies for eco-innovation. The findings are relevant for

policymakers and firms to promote investment in R&D that enables eco-innovation development and ensures a quick green transition.

5.3 Third Chapter: Lost in transition: How to break out from the niche? The case of micro-algae

Multilevel perspective (MLP) and strategic niche management (SNM) have found favour for analysing innovation emergence, its interaction with socio-technical regimes, and the role of new entrants and incumbents in driving innovation. Parallel to these frameworks, the global value chain approach focuses on coordinating production activities and the governance of economic upgrading trajectories role of global actors (lead firms) resulting from innovation.

In the bioeconomy, the underlying dynamics of innovation involve transforming the existing petrochemicals value chains to develop sustainable bioproducts. Therefore, the context of the bioeconomy seems particularly relevant to applying our framework and taking a first step toward integrating the global value chain into niche studies. We are specifically interested in “How value chain links can be mobilised by niche innovation to confront it gradually with the selection environment enabling the niche innovation to phase out its protected space, expand, proliferate and gain momentum?” We introduce the concept of alliances, which relates to the types of interaction adopted by lead actors to drive the integration into global value chains.

We apply our proposed framework to the case of microalgae. Based on longitudinal and heterogeneous data about microalgae, we find that niche innovation links up to the value chain through participation in collective exploration and exploitation activities. Both exploration and exploitation activities leverage different forms of alliances between actors from the main and adjacent value chains at different points in the innovation trajectory. These activities also play a role in restructuration and modifying the existing structure of value chains.

Our findings suggest that the study of alliances as diffusion and commercial development tool for niches deserve further attention in transition studies. This would support a better understanding of niche innovation diffuse and eventually become the dominant

regime and therefore offer the potential to derive enhanced innovation policy recommendations beyond demand-pull, technology-push to intersectoral policies.

5.4 Contributions

The starting point of this thesis is the challenges identified by Golembiewski et al., (2015). These challenges represent the hills that the green and bioeconomy innovation has to climb. Identifying the strategies that actors put in place to manage these challenges calls for an analysis that accounts for actors' position in the value chain, the context in which innovation is developed, and the innovation process's objectives. Therefore, we answer the main question driving this thesis through three levels of focus discussed previously.

The first level of analysis focuses on the strategies crafted by different crop growers to acquire, collect and put into practice the knowledge needed to shift to sustainable farming practices. We contribute to the literature by showing that biomass producers overcome the challenge of knowledge complexity by developing networking strategies. These knowledge sourcing strategies are not a one-size-fits-all strategy as the relevance of the knowledge source depends on the type of practice and crop. The transition to sustainability requires the farmer to relinquish, adapt his old knowledge and relearn and complement this knowledge acquired internally with external knowledge. We also explored the relationship between knowledge and crop diversification for innovative farmers and shed light on how knowledge can be leveraged for innovations in sustainable farming practices and diversification of products.

The overall contribution of this chapter to the thesis can be summarised in three ways. The first is that we cannot assume that collaboration between actors (e.g. knowledge sourcing strategies) is uniform. Indeed, knowledge sourcing strategies are inconstant, different, changeable and variable as they rely on context, resources, objectives and goals. Second, standardisation of knowledge assumes that actors are supposed to be only recipients and do not engage in producing this knowledge. While the development of sustainable practices requires diverse knowledge, which is achieved by departing from standardised knowledge. Third, thanks to actors' proactivity in the innovation process, they build different knowledge sourcing strategies and actively derive commonalities between the knowledge stocks that enable them to diversify and achieve economies of scope.

In the second level of analysis, we focus on actors located downstream. We are interested in exploring the challenges related to knowledge complementarity and complexity. In the investigation of eco-innovation and the role of different technological fields contributing to its development, we find that eco-innovation is complex, mobilising stocks of knowledge from various scientific fields. Moreover, we find that actors can identify synergies between the different stock fields achieving complementarity between the different knowledge domains (biotechnology, green, ICT and others). Our contribution to the literature is, first, to highlight that firms combine knowledge production activities of different R&D fields to eco-innovate. Second, we contribute to the debate on R&D policy for the transition by expanding and pushing decision-makers to reassess priorities related to the search for solutions to environmental issues and regulations formulation.

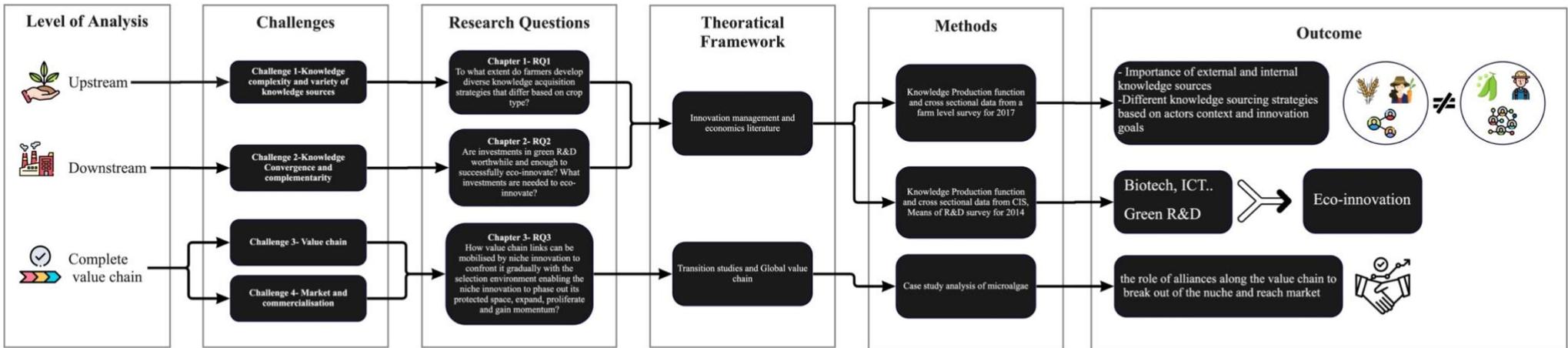
The overall contribution to the thesis is showing how actors overcome the challenge of knowledge complementarity by intentionally deciding on which knowledge to invest in and by mixing and matching the knowledge fields to achieve synergies and derive eco-innovation using knowledge from biotechnology, green, ICT, nanotechnology, advanced material, social science and humanities.

The third level of analysis studies the complete value chain. At this level, we focus on the challenge of commercialising bio-based products and value chain convergence. We contribute to the literature by illustrating that for biobased innovation to reach commercialisation and market, actors need to subscribe to labour division taking the form of the global value chain. This happens through collective exploration and exploitation activities. These exploration and exploitation activities entail different types of alliances between actors from the main and adjacent value chains at different points in the innovation trajectory. We also show that the alliances established along the various value chains have repercussions on existing value chains, leading to restructuring and modifying current value chains.

The overall contribution can be summarised as follows : the role of alliances along the value chains explains how actors can overcome the challenges related to commercialisation. These alliances constitute a tool to develop commercially and diffuse the bio-based innovation that might finally lead to a new sociotechnical regime. Our analysis contributes to the literature by crossing two frameworks: on one side, the global value chain and the second strategic niche management literature and multi-level perspective.

Figure 0.1: Dissertation structure and summary

What strategies do actors develop to assemble the building blocks of internal and external knowledge needed for innovation and to integrate value chains for diffusing and commercializing their innovations enabling the transition to a sustainable green and the bioeconomy



Chapter 1 One size does not fit all: The plurality of knowledge sources for transition to sustainable farming.

Foreword

This chapter is based on a paper with the same title. In March 2022, it was submitted to the Land-use policy journal.

A preliminary version of this paper was submitted and presented at the International Schumpeterian Society conference in July 2021, the Early Career Conference (ECC) – PhD Days in December 2020, SEEDS workshop in December 2020.

1 Introduction

‘During the past fifty years, agricultural policies emphasised external inputs as the means to increase food production. Pesticides replaced biological and mechanical methods for controlling pests, weeds, and diseases; information for management decisions comes from input suppliers, researchers, and extensionists rather than from local sources’(Pretty, 1995). Agricultural industrialisation has led to the standardisation of inputs, including knowledge, of the agricultural process, which has alienated farmers and made them reliant on a few sources of standardised knowledge (Morgan and Murdoch, 2000). This standardization led to the loss of local farming knowledge and the intimate connection with the local environment (Šūmane et al., 2018).

Currently, there is a need for resilient, sustainable agriculture to meet the demands of food security and the problems related to climate change and a growing population. Farmers need to invest in new knowledge and in innovative practices (Šūmane et al., 2018a) that exploit both technical and scientific knowledge and the individual farmer’s knowledge about local conditions (Ingram, 2008). These bits of knowledge are scattered across multiple actors, with the result that on-farm innovations depend not just on farmers’ competencies, but also on the broader networks of actors from which farmers seek knowledge (Cofré-Bravo et al., 2019) and with whom they interact in the agricultural knowledge and innovation system (Knierim et al., 2015).

Understanding the factors that affect innovation related to sustainable farming has triggered a stream of work that tries to identify the different sources of knowledge contributing to farmer innovation processes, their hierarchy and their overall importance (Barnes et al., 2019; McBride and Daberkow, 2003; Solano et al., 2003). Several studies focus, also, on how the knowledge sources exploited differs according to the farmers’ characteristics, the innovation objectives and the phase in the innovation process (Cofré-Bravo et al., 2019; Diederer et al., 2003; Gava et al., 2017). Most of this work is comprised of case studies of specific types of farming (e.g., dairy, livestock, cereal) in particular regions. They examine the knowledge sources contributing to on-farm innovation and provide a bird’s eye view of farmers’ knowledge sourcing strategies instead of an investigation of these strategies by crop type.

In the present paper, we build on this literature and conduct a crop-level analysis. This choice is based on the fact that farmers usually do not cultivate only one crop (de Roest et al., 2018; Morris et al., 2017). Corn and short rotations of corn and wheat account for respectively 6% and 5% of the cultivated land in France (Virgile Fuzeau et al., 2012), while 70% of US cultivated land is monoculture based on corn or a simple rotation (Roesch-McNally et al., 2018). In addition, sustainable farming practices draw on different knowledge stocks which depend on the crop type. Thus, a crop level analysis will show that knowledge sourcing strategies cannot be considered one-size-fits-all with knowledge source importance ranked the same for different crops.

We use a multivariate probit model with marginal effects, and employ data on France for 2017, to illustrate the heterogeneity of knowledge sourcing strategies related to different crops. We identify farmers who cultivate multiple crops on the same farm and test how their knowledge sourcing strategies change across different crop types. The results show, first, that sustainable farming practices rely on both internal and external knowledge and, second, that the importance of the knowledge sources varies based on the crop and type of farming practice. Third, we show that farmers growing multiple crops do not develop a different strategy for each crop type.

We contribute to the agricultural innovation literature by comparing innovation and knowledge sourcing strategies for traditional crops (e.g., cereals), new transition crops, crops used for industrial purposes and feed crops. We highlight that there is no one-size-fits-all knowledge sourcing strategy. Sustainable farming entails diverse practices, requiring farmers to learn and acquire new knowledge from a set of heterogeneous actors. This knowledge varies for different farming practices and crops. Finally, we explore the relationship between product (e.g., crop) diversification and knowledge sourcing at the farmer level to investigate whether farmers develop unique strategies for the different crops grown on their farms, and find potential evidence of economies of scope.

Section 2 provides a review of the literature and formulates the hypotheses. Section 3 describes the methodology, the data and the estimation procedure. Section 4 presents the results and some robustness checks and Section 5 provides a discussion, some conclusions and some limitations of the study and recommendations for future research.

2 Literature review

2.1 Innovation and knowledge sourcing in agriculture

Fuglie, (2016) 's study examines the concentration of R&D in developed countries and shows that it is conducted mostly by private multinational firms and focuses on specific crops such as corn. This concentration of R&D means that micro and small farmers, the majority in the agriculture sector (Pindado and Sánchez, 2017), are reliant on the inputs supplied by large corporations in the agricultural and other sectors (Fuglie, 2016; Robson et al., 1988)

However, farmers are not passive decision-makers and price takers; rather, they are active entrepreneurs who take risks and innovate to adapt to the changing conditions of their local context (Kangogo et al., 2021; Morris et al., 2017). Farmer innovativeness is based on knowledge generation and learning (Chantre and Cardona, 2014). To innovate in sustainable farming practices, farmers need new forms of knowledge and skills (Ingram, 2008) and need to relearn and seek distant knowledge (Šūmane et al., 2018) to engage in these diverse and knowledge-intensive practices that link the economic, environmental and social dimensions (Ikerd, 1993; Rose et al., 2019).

To build new knowledge, farmers must rely on their existing knowledge. The individual farmer's knowledge is a subset of the available local knowledge; it is a stock of complex know-how, practices and skills; it is highly adaptive and dynamic in nature; and it allows the farmer to innovate to adapt to the local environment (Šūmane et al., 2018). Experiential learning based on everyday practices constitutes the individual farmer's knowledge. Experimenting with new ideas and adapting existing ideas to the current farming context contributes to the accumulation of new knowledge (Lyon, 1996). The farmer's level of education and engagement in agricultural outreach provision provides knowledge on the latest developments in agricultural science (Parman, 2012).

Much farmer knowledge is tacit, sticky and difficult to exchange (Polanyi, 1966; von Hippel, 1994). It constitutes their absorptive capacity (Cohen and Levinthal, 1989; Galliano and Siqueira, 2021; Siqueira et al., 2021) and is mobilised to identify and acquire external knowledge from formal and informal sources (Parman, 2012). (Griliches, 1957)) hybrid corn study sparked research on the influence of external sources of knowledge for innovation. This

strand of work shows that multiple actors influence the advancement and spread of sustainable agriculture (Knickel et al., 2009; Wood et al., 2014).

Farmers' family members act as conduits for the transfer of tacit knowledge across generations (Ramirez, 2013). Friends, peers and neighbours have been identified, also, as critical informal sources of ideas and innovation (Cofré-Bravo et al., 2019; Rogers, 1995), enabling tacit and explicit knowledge¹ exchange within farmer networks of practices (Eastwood et al., 2012; Oreszczyn et al., 2010). These informal sources represent the farmer's social capital and are an asset which can be mobilised in times of need (Sutherland and Burton, 2011) to enable the sharing of costs and risks and the pooling of resources and knowledge (Carnahan et al., 2010).

Farmers seek knowledge from a range of formal actors (Giuliani and Bell, 2005). The agriculture sector is capital-intensive involving input suppliers transferring to farmers innovations conceived in other sectors such as machinery (Micheels and Nolan, 2016; Robson et al., 1988). Suppliers build trust by establishing individual relationships with farmers, which influence the latter's innovation decisions (Stuart et al., 2018). Farmers become user innovators by using the inputs supplied and adapting them to their context (Aubert et al., 2012). Within the agriculture supply chain, farmers are the providers of raw materials to downstream actors (retailers and consumers) (Yang et al., 2014), which, in turn, provide knowledge about product standards (Gaitán-Cremaschi et al., 2019). This knowledge is informative for farmers' technology, farming practice and marketing innovations (Kuokkanen et al., 2018).

The dismantling of extension services and their privatisation in many countries revealed several shortcomings, such as knowledge fragmentation and competition between advisors (Ingram and Morris, 2007; Klerkx and Proctor, 2013) and lack of interaction with small farmers which reduced their access to the knowledge related to their needs (Labarthe and Laurent, 2013). Some advisory systems are linked to universities (Lubell et al., 2014) which engage in formal innovation activities. However, universities focus mostly on

¹ Explicit knowledge differs from tacit knowledge in being leakier and easier to transfer at lower costs (Cowan et al., 2004). Tacit knowledge exchanges require intensive face-to-face interactions among the actors (Spencer, 2008).

fundamental, long-term research and are considered less critical than other sources of knowledge for farmer innovation (Lambrecht et al., 2015).

Farmers able to observe, discuss and conduct their practices in real conditions, with peers, on demonstration farms, promote social and interactive learning and help to diffuse tacit and codified knowledge (Ingram et al., 2018). Demonstration farms are effective if managed by credible farmers, who belong to large networks and are willing to adopt innovations (Brown et al., 2016). Knowledge can be accessed, also, through cooperatives, which act as knowledge hubs, gatekeepers and innovation intermediaries and facilitate the transfer of innovation to cooperative members (Kilelu et al., 2011). Cooperatives act to diffuse innovation and coordinate intra-group knowledge exchanges and interactions that provide the farmers with knowledge on different topics (Oreszczyn et al., 2010).

Links with associations and professional groups also foster learning and innovation (McBride and Daberkow, 2003). They may provide consultancy services and training (Lambrecht et al., 2015) and work to reinforce social bonds, peer interaction and trust (Aubert et al., 2012). Other innovation intermediaries include donor agencies (Klerkx and Leeuwis, 2009) and private consultancy firms which offer paid advice (Kilelu et al., 2011). Finally, farmers can access the latest innovations at agricultural exhibitions and fairs (Unay Gailhard et al., 2015), or via online platforms, journals and farming magazines, which provide information and codified knowledge and do not require interaction (Kilelu et al., 2011; Yiridoe et al., 2010).

Several studies that identify different sources of knowledge, rank their importance based on case studies. Solano et al. (2003) found that family and technical advisors were critical knowledge sources for dairy farmers' decision-making. Crop consultants and input suppliers had more influence than media and demonstration farms on precision agriculture innovation for corn and soybean farmers in the US (McBride and Daberkow, 2003). (Burton et al., 1999) show that other organic farmers are vital sources of information for organic farmers. Cofré-Bravo et al. (2019) highlight the dependence between the choice of knowledge source and the objectives of the farmer. For instance, farmers who prefer to use validated technologies rely more on family and friends. Based on the above, it can be seen

that there is no single best knowledge sourcing strategy; rather, it depends on the context and initial knowledge gap (Morone and Taylor, 2004).

2.2 Knowledge plurality and crop types

The shift from intensive agriculture to a more sustainable and resilient path relies on the farmer (Ikerd, 1993; Rose et al., 2021) searching for (Morgan and Murdoch, 2000) more complex knowledge (Ingram et al., 2018), engaging in relearning and side lining their intensive agriculture related knowledge (Šūmane et al., 2018). As these new practices involve different technologies and resources-saving techniques, and draw on unique knowledge and know-how (Pretty, 2008).

For example, bio-control practices involve biological and ecological knowledge related to the interaction between plants and the agro-ecosystem (Louah et al., 2017). This differs from the knowledge needed for mechanical control practices, involving knowledge about mechanical tools, their functions and how they should be used (Arino et al., 2012). Besides the inherent differences in knowledge, the application of a given practice is dissimilar between farms due to differences in local conditions and farmers' cognitive predispositions (Morgan and Murdoch, 2000; Šūmane et al., 2018).

Implementing sustainable farming practices requires these practices to be tailored to the type of crop being grown. Each crop requires unique knowledge about its cultivation, management and harvesting (Magrini et al., 2016; Meynard et al., 2018). Fernandez-Cornejo et al., (1994); Fernandez-Cornejo and Castaldo, (1998) point to the crop-specificity in relation to pests and the need to identify the appropriate technique to manage these pests and tailor farming practices. Meynard et al. (2018) discuss crop rotations and intercropping, which require an understanding of the crops involved, their interactions and their compatibility with the type of soil, farmers' equipment and climate conditions. Successful implementation of such practices requires adaptation of the knowledge to the crop type.

The cultivation of new crops can constitute an innovative transition strategy. Introducing a new crop could provide various benefits including enhanced sustainability and biodiversity, reduced yield gaps and reduced dependence on external inputs (water, fertilisers, etc.) (Kremen and Miles, 2012; Ponisio et al., 2015). New crops cultivated as part

of the transition to a sustainable farming system might require more complex knowledge and require the farmer to invest in learning, new equipment and new cultivation processes (Cholez et al., 2020; Meynard et al., 2018).

Farmers do not hold the same amount of knowledge for all crop types. They have great knowledge about major crops due to specialisation in cereals (Magrini et al., 2016). They can also seek knowledge from external sources such as advisors or actors along the supply chain as all research and supply chain actors efforts are oriented towards these high return crops (Mawois et al., 2019; Meynard et al., 2018). In the case of other crops, the external sources of knowledge and the amount of knowledge held by the farmer, might be more limited (Cholez et al., 2020; Magrini et al., 2016). Meynard et al. (2018) highlight a lack of knowledge among advisors on transition crops. They also demonstrate that downstream actors encourage innovation in linseed (i.e., rare crops in France) by providing multiannual contracts accompanied by training allowing farmers the time to learn and innovate. In the case of cultivation of peas and other legumes, whose supply chain is not well established, farmers tend to rely on experimental and demonstration farms.

The empirical literature on the influence of knowledge sources on farming practices focuses primarily on single crop cases (see (Prokopy et al., 2008)). Studying multiple crops requires large datasets (Fernandez-Cornejo and Castaldo, 1998) and only a few papers study two or three types of crops cultivated in developing countries (see (Matuschke and Qaim, 2009; Munshi, 2004)). Matuschke and Qaim (2009) study the case of India and find that traditional sources of knowledge (suppliers and extension services) are critical for hybrid wheat cultivation, but less critical in the case of cultivation of pearl millet. In other words, the importance of external knowledge sources for innovation varies among crop types.

H1: The importance of knowledge sources for the same farming practice varies among different crop categories

To ensure their survival, farmers adopt different business strategies in order to compete in the market (Mcelwee and Bosworth, 2010). One such strategy is diversification, which can include off and on-farm food and non-food activities, or any other activity which increases the income from the primary agriculture (Ilbery, 1991; McNally, 2001). In this study, the focus is on farm product diversification . Diversifying into on-farm activities and

technologies can increase income and production efficiency (Morris et al., 2017). It implies that the same inputs are used for several crops, which decreases the potential costs of separate production by inducing cost complementarity (de Roest et al., 2018), economies of scope (Panzar et al., 1981) and entry to new markets.

According to Mc Fadden and Gorman, (2016), the diversification activity might comprise innovation related to the production, management or marketing processes, or a reconfiguration of resources and introduction of new activities. They show that innovative farmers and diversifiers are engaged in multiple social networks related to their business objectives. The innovation literature also links product diversification and knowledge diversification (Sugheir et al., 2012). Knowledge diversity, by promoting ideas and innovative recombinations of knowledge, enables a diversified portfolio of products (Breschi et al., 2003; Sugheir et al., 2012). Knowledge also enables economies of scope by creating shared value across products (Breschi et al., 2003).

Successful knowledge and product diversification depend on the farmer's ability to access external knowledge (Cholez et al., 2020; de Roest et al., 2018). The influence of external knowledge sources on industrial firms' innovation and diversification is documented by (Rothaermel and Hill, 2005) and takes an inverted U shape. However, they do not examine whether firms adopt unique knowledge sourcing strategies for each product they diversify into. In the case of farmers, they need crop-based knowledge to cultivate multiple crops using sustainable farming practices. This knowledge is spread across multiple actors whose importance varies based on the crop and practice type. Therefore, crop diversification requires membership of and interaction in different crop-based networks.

H2: The influence of a given knowledge source will change with the different crops cultivated on the same farm.

3 Methodology

3.1 Data

The data come from the French Ministry of Agriculture 2017 "Agricultural Practices" survey. This survey is part of the Ecophyto plan to reduce chemical pesticide usage by

shifting to more sustainable farming practices. The survey asks about the farmer's cultivate practices. It includes farmers with land in both metropolitan France and overseas regions; however, the latter, which include sugarcane cultivation, permanent grassland and meadows are excluded due to their different policy requirements and general properties.

The farmers surveyed cultivate plots of between 0.1 hectares and 200 hectares. The sampling is done at the farm level, with data stratified according to geographic location of the land, farming type (organic, non-organic) and farm size, and at the plot level, which includes data on crops and soil types. The survey does not ask about farmers' characteristics. The survey data were matched to the most recent General Agriculture Census, conducted in 2010-2011, using farmer identification numbers. The different timings of the two data sets does not present a problem since the survey questions refer to the innovative farming practices implemented in the previous six years. The matching resulted in 18,458 observations of which 2,777 observations are farmers reporting two different crops grown on the same farm.

The crop types studied fall into five categories: cereals (durum and soft wheat, barley, triticale, cereal mix and maize), potatoes, crops for industrial purposes (rapeseed, sunflowers, soybeans, linen, oilseed flax), protein/transition crops (peas, fava beans), and feed crops (maize, a mix of feed crops). Protein and crops for industrial purposes are less prevalent in France and promoted as a potential diversification strategy for farmers to enable transition to a more sustainable farming system.

3.2 Variables description

3.2.1 Dependent variables

Despite productivity gains, agriculture industrialisation has detrimental effects on nature and human health. We need practices that minimise the effects of farming on nature and humans and allow sustainable production of food (Pretty, 2008).

We identify six sustainable farming practices. Crop rotation consists of alternating among various crops. Controlling their temporal sequence enables diversification, positive and indirect interactions among crops, reductions in pest infestations, diseases, weeds and soil erosion and enhanced the soil biological activity (Wezel et al., 2014). Intercropping refers to growing two or more crops on the same plot simultaneously. It controls the spatial

distribution of the crops and their interaction, benefitting productivity, resource efficiency and soil fertility (Arino et al., 2012; Meynard et al., 2018). Improved seed varieties refer to diseases and pest resistant seed which reduces use of pesticides and irrigation, and increases yields (Wezel et al., 2014). Mechanical control of sowing, ploughing, mechanical and manual weeding, and capture and trapping of plant predators (Arino et al., 2012). Biological control involves the introduction of predators, habitat management (hedges, grass strips), changing mating patterns, and agroforestry practices to reduce pesticide use, protect the land from wind and erosion and promote biodiversity (Wezel et al., 2014). Chemical control involves alternating chemical families to avoid chemical resistance, treating only infested crops and using (auto)-guidance systems to optimise dose applications. It is less green than the other five practices.

3.2.2 Explanatory variables

The explanatory variables are the knowledge sources. The first is the EcophytoPic portal, an online, interactive and open innovation tool that provides farmers with access to codified knowledge about alternative practices to chemical pesticides. It is described here as an online extension service. The second variable is a pest-monitoring tool that provides weekly updates on the predators and crops in each region to allow appropriately timed chemical treatments. The third variable is a unique form of demonstration farm, ‘DEPHY’. Extension advisors run demonstrations to disseminate knowledge about innovations, while scientist conduct demonstration farms for research purposes. Farmers can establish a DEPHY voluntarily to practice sustainable alternative agriculture systems, which, if successful, can be diffused more widely. The other explanatory variables describes the communities of practices and farmer networks (Dolinska and D’Aquino, 2016) and include technical advisors, suppliers, media and press, peers and other sources, included in the variable “other”.

3.2.3 Control variables

We control, first, for farmer characteristics (e.g., education, gender, age). Higher education is linked to greater absorptive capacity and innovation activity (Knowler and Bradshaw, 2007; Vecchio et al., 2020). Women are more environmentally aware and invest more in sustainable farming practices compared to men (Unay-Gailhard and Bojnec, 2021).

Younger farmers are more innovative and better able to transform knowledge into innovation (Brown et al., 2016; Vecchio et al., 2020).

Second, we control for farm characteristics. Organic farmers are more likely to innovate in sustainable farming practices (Weber and McCann, 2015); the sustainable farming practices studied here are oriented to crop management and cultivation. Hence intuitively, crop farms are more innovative in these practices than livestock farms. Farm and plot size have a positive influence on innovation (Brown et al., 2016; Yiridoe et al., 2010). Third, we control for geophysical characteristics (soil type, climate variability, prevalence of pests and diseases) that influence the type of crop and the farming practices employed (Kay et al., 2019; Teklewold et al., 2013). Fourth, we include crop type. Some crops require a specific practice (Fernandez-Cornejo et al., 1994). Fifth, we control for subsidies which reduce innovation risks (Weber and McCann, 2015).

3.3 Econometric Estimation

We build on the previous literature and estimate a knowledge production function linking innovation output to knowledge source (Griliches, 1979), using a Multivariate Probit (MVP) (Rodríguez-Entrena and Arriaza, 2013). The MVP assumes correlation of the error terms among the six equations. A likelihood test of the independence of the error terms tests this assumption (Cappellari and Jenkins, 2003). If accepted, the errors are correlated and the model specification is appropriate. A positive correlation coefficient implies complementarity and a negative coefficient implies substitutability of practices.

$$Y_{ifp}^* = X'_{ifp}\beta_i + \varepsilon_{ifp}, \quad i = 1, \dots, 6 \quad (1.1)$$

In equation (1.1), Y_{ifp}^* is the utility derived from innovation and unobserved preferences for the i^{th} practices of the f^{th} farmer and p^{th} plot with a linear combination of the observables X'_{ifp} . The error terms are clustered by farmer identification numbers (Chib and Greenberg, 1998). To estimate the model, I use six binary variables describing the level of adoption of sustainable farming practices where $Y_{ifp} = \{1 \text{ if } Y_{ifp}^* > 0; 0 \text{ otherwise}\}$ (1.2)

We calculate the average marginal effects of the unconditional expectations. These account for the direct and indirect effect of the explanatory variables on innovating in a given

practice while adopting other practices (for more details, see (Henningsen, 2015; Sodjinou and Henningsen, 2015)). We calculate the marginal effects because sustainable farming practices are adopted as a bundle and the adoption of one practice affects the other practices (Rodríguez-Entrena and Arriaza, 2013; Teklewold et al., 2013).

We investigate whether farmers cultivating multiple crops, develop a unique knowledge sourcing strategy for each crop, by testing the equality of the mean of each knowledge source variable across the various crops grown by the same farmer. We restrict this analysis to farmers growing more than one crop on their farm and innovating in at least one of the six sustainable farming practices.

4 Results

4.1 Descriptive statistics

The descriptive statistics are presented in Table 1.1. The data show that 90% of farmers are innovative. The most frequent innovative practice is crop rotation, 73.13%, followed by chemical control, 64.7%, mechanical control, 52.25% and intercropping, 46.83%. The least frequent practices are improved seed varieties, 43.15% and biocontrol, 8.55%. The percentage of farmers who consider their knowledge as a useful source for innovation is 68.27. The second-ranked source is suppliers (55.88%), followed by media and press (37.63%), technical advisors (34.74%), pest monitoring tool (26%), other (5.22%), online extension services (3.58%) and demonstration farms (2.177%). The ranking of knowledge sources is the same at crop level (data available upon request).

The average farmer surveyed is male, has primary level education and is 52.6 years old. The majority of farms are not organic; only 7.25% of farmers declared having organic farms. The average farm is 146.7 hectares and a typical plot is 6.7 hectares. Around 40.14% are crop farms, 22% are specialised livestock farms, 10.67% of plots benefit from environmental subsidies and 10.77% are on vulnerable land. Weather shocks affect 9.3% of plots and bird and pest attacks affect 1.3% of plots; both types of shocks occur on 0.8% of plots. The most frequent crop is triticale (9.8%), while the least frequent is fibre linen (1.2%). The largest crop group is cereals and the smallest is feed.

4.2 Results

We run a general MVP with the dependent variables sustainable farming practices and the main explanatory variables knowledge sources, and we control for farmer, farm, and plot characteristics. This analysis draws a general picture of knowledge sources hierarchy and importance. Rejection of the likelihood ratio test of independent errors, reported at the end of the general model, shows that an MVP specification is appropriate and the farming practices are not mutually independent. This model allows me to test the correlation among the six-innovation equation error terms. In Table 1.2, the positive coefficients indicate complementarity among the different sustainable practices.

The marginal effects of the knowledge sources, presented in Appendix Table 1.3 for the general model, are mostly positive and significant, with the exception of the coefficient of peers. This might be due to the farmer's inability to imitate the practices of their peers (Blesh and Wolf, 2014; Munshi, 2004; Solano et al., 2003). The results of this model can be interpreted in two ways. First, through a knowledge sources lens, which shows the difference in rankings across practices. Consistent with previous literature (Micheels and Nolan, 2016), we find that other farmers' knowledge is the most useful source for crop rotation (21%), intercropping (19%) and improved seed varieties (16%) (Myeni et al., 2019). Press and media have the largest effect on chemical control (15.5%), which requires codified knowledge discussed regularly in journals and magazines (Guichard et al., 2017). Suppliers have a similar influence on chemical control, demonstrating their critical role in input-intensive practices (Stuart et al., 2018; Weber and McCann, 2015).

Second, through a farming practice lens. To innovate in each practice, farmers combine knowledge from different sources with different intensities (Ingram, 2008; Stuart et al., 2018; Weber and McCann, 2015). Experience increases the innovation probability of crop rotation by 21%, press and media by 6.6%, suppliers by 13.8%, technical advisors by 11.6%, pest-monitoring tool by 6.1%, extension services by 3.7%, demonstration farms by 1.6%, other sources by 12.1% and peers by 0.7%.

The influence of education is mixed across the six practices which align with previous studies demonstrating different education impacts (Brown et al., 2016; Yiridoe et al., 2010).

Young farmers are more innovative than older ones. Men are more likely to innovate, which contradicts previous literature (Brown et al., 2016). Organic farmers innovate in all except chemical control. Subsidies encourage innovation (Weber and McCann, 2015). Farm size and plot size have a positive, limited influence on innovation (Yiridoe et al., 2010). Innovating in farming practices depends on the type of shock and the soil type. Each crop is linked to a specific combination of practices as in Fernandez-Cornejo and Castaldo (1998) (the results for the control variables are available upon request).

4.2.1 Analysis on the crop level

We examine five crop categories (cereals, proteins, feed, industrial crops and potatoes). We conducted separate MVPs for each crop category (see Tables 1.4-1.9). To identify knowledge sourcing strategies, we focus the interpretation of the result on essential sources such as farmers' knowledge, sources fostering collective learning and interactions (i.e., demonstration farms), traditional sources such as suppliers) and intermediaries (i.e., platforms).

Farmers' own experience is ranked highest for crop rotation and intercropping for all crops categories except potatoes. However, the intensity of the marginal effect of farmer's experience is not constant across crop types. It is highest for feed (32.1%) and cereals (24%) for farmers innovating in crop rotation, and for protein crops for growers innovating in intercropping (24.4%). These findings are consistent with work on the importance of farmers' experience of diversification practices, related to growing protein and industrial crops, and its usefulness for innovation sustainable practices among cereal growers (Chantre and Cardona, 2014; Meynard et al., 2018).

The intensity and the ranking of external knowledge sources vary among different crop growers and farming practices. Voluntarily demonstration farm has a positive and significant effect on all practices (Ingram et al., 2018) and, especially, for protein and industrial crops, with the highest marginal effects for improved seed varieties (15%) and biocontrol (11%). Input suppliers affect all practices, with the largest marginal effect (23%) recorded for feed growers who cultivate maize and other feed crops and chemical control, consistent with literature on the importance of fertilisers and pesticides suppliers on

innovation in practices related to their products (Stuart et al., 2018; Weber and McCann, 2015).

Online extension service has the most negligible significant impact for all crops except potatoes, in line with Yiridoe et al., (2010) on the limited impact of online sources. Technical advisor influence is lower than other sources (e.g., suppliers) for almost all farming practices. Advisors provide paid advice that might not be affordable for small scale farmers. They also tend to recommend well-known practices and established innovations in order to avoid reputation damage. These findings highlight the differences in the importance and ranking of knowledge sources among different crop categories and support hypothesis 1.

4.2.2 Crop and knowledge diversification

The data include a sub-sample of farmers with two plots growing two different crop types. We exploit this feature and examine whether each farmer develops a different crop-based network to acquire the knowledge needed to innovate in sustainable farming practices for each crop grown on the farm. We calculate the mean of each source for the first and second crop to test hypothesis 2; the results are presented in Table 1.10.

The null hypothesis related to all knowledge sources is supported, implying no difference between knowledge sourcing strategies for the first and second crops. This suggests that farmers diversify their products, and experience economies of scope from their knowledge sourcing strategies. Farmers apply the same pieces of knowledge, acquired from a given knowledge source, to more than one crop type. The same source of knowledge is used with the same intensity to produce two different crops, which rejects hypothesis 2.

4.2.3 Robustness checks

We built an innovation index from zero to six and ran a negative binomial model with sample selection. The results are positive and significant for all sources except peers. Experience has the highest impact on innovation and online extension service has the lowest impact. The results are available upon request.

We reran the analysis for the 17 crops separately; the results were consistent with the results of the crop-based model. We also ran a simple probit regression with knowledge

sources as the dependent variable and added crop one and crop two as the main explanatory variables, to check whether the probability of using a knowledge source changes between the two crops. The results are consistent with our previous findings rejecting hypothesis 2.

5 Discussion

Farmers transitioning to a sustainable farming system must invest in new and diverse knowledge and innovative practices, which will vary depending on the farmer's context and crop choices. We explored these differences by studying the influence of knowledge sourcing strategies on innovation in sustainable farming practices for different crop categories.

The analysis provides two main findings. First, the central role of the farmer in the innovation process (Šūmane et al., 2018a). Second, the reliance of the move to sustainable farming on a multi-actor farmer network that starts with the farmer and extends to include supply chain actors, advisory systems, informal sources and online sources (Cofré-Bravo et al., 2019). Each of those actors holds a piece of the knowledge needed by the farmer to innovate; their importance in the agricultural innovation system varies.

The transition process is unique and does not follow specific guidelines; it is based on the farmer's context and goals. Comparing different crop growers, shows that transition journey differs for different crop settings. One reason for this heterogeneity is that farmers have different experience, which means they construct their knowledge and contribute to innovation differently. Specialisation and experience of cultivating cereals results in a different transition process from farmers who grow protein crops. Cereal farmers rely on adapting and updating experience in order to innovate in sustainable practices. In the case of protein crop growers, most of their knowledge is derived from experimentation and trial and error to innovate and redesign their farming systems.

This difference is crucial for understanding the different effects of a specific knowledge source on the transition to sustainable agriculture. The role of value chain actors is more pronounced for some practices and crop growers (see, e.g., Meynard et al., 2018). The study reveals, also, that the primary actors and primary sources of knowledge differ across crop growers and practice types, implying the existence of bundles of knowledge sources, which

can be mobilized to promote a specific practice among a type of crop growers. Targeting these bundles can be a more efficient way to diffuse knowledge and innovation and provide tailored advice for crop growers. The approach in this paper is more appropriate than a general analysis identifying a general ranking of the knowledge sources contributing to innovation.

The discussion in Knierim et al., (2015) of innovation systems in agriculture, hardly mentions crop types. The comparative dimension adopted in this paper shows that there are heterogeneous systems of innovation, based on crop types, in which the actors occupy different levels of importance. The main actors and types of knowledge exchanged are not homogenous across these systems. Some systems favour the exchange of tacit knowledge, in a collaborative learning approach (e.g., demonstration farms and protein growers), others are oriented to exchanges of standardised knowledge.

No single farmer possesses all the knowledge required to innovate to achieve a successful transition to sustainable farming (Knickel et al., 2009). Depending on their know-how, they seek related, but different knowledge from external sources, which results in knowledge complementarity and leads to innovation. The findings in this paper provide evidence of knowledge combination behaviour to enable innovation in sustainable farming practices and highlights the shift to a pluralistic mode of knowledge rather than standardised knowledge provided by specific actors.

Not all farms are based on monocultures; some have diversified into growing different crops. The analysis in this paper has shown that the use of knowledge sources does not change across crops grown on the same farm. The lack of sourcing diversification might stem from the high transaction cost of mobilising multiple sources (Sugheir et al., 2012) and avoidance of too much knowledge which complicates the decision-making process (Ovuakporie et al., 2021). Using the same sources with the same intensity for more than one crop implies that farmers exploit the same piece of knowledge to diversify in multi-product.

Diversification occurs thanks to knowledge commonalities (Breschi et al., 2003) and the capacity of farmers to interpret and perceive the various potential applications of pieces of knowledge. Economies of scope are derived from the reduced costs related to using the same inputs for different products (de Roest et al., 2018). This novel result has implications

for the transition to sustainable farming and suggests a double opportunity for farmers to innovate and diversify their products and their income and benefit from scope economies.

6 Conclusion

We employed a MVP and cross-sectional data for 2017 from the French Ministry of Agriculture, to study the relationship between knowledge sourcing and innovation in sustainable farming practices for multiple crop categories. The results show, first, the plurality of knowledge needed to innovate in sustainable farming practices; second, that the ranking of knowledge sources differs across crop categories and farming practices; and third, that innovative farmers do not develop a unique strategy for each crop grown on their farm. Rather, they use the same knowledge for multiple crops which provides economies of scope.

We contribute to the literature on agricultural innovation by highlighting the role of knowledge sourcing in the transition to sustainable agriculture. This transition requires the farmer to learn and develop new knowledge internally and complement it with external knowledge. We demonstrate that the relevance of the knowledge source depends on the type of practice and crop and that there is no one-size-fits-all sourcing strategy. We also explored the relationship between knowledge and crop diversification for innovative farmers and shed light on how knowledge can be leveraged for innovations in sustainable farming practices and diversification of products

The limitation of this study are related to the inability to observe all the knowledge sources surveyed in the literature. The data do not include sources such as users, cooperatives, retailers, families and universities, which limits our understanding of their role and impact on the transition to a sustainable farming system. Another limitation is that the data are cross-sectional. They do not include the temporal dimension of innovation and did not allow the study of the importance of knowledge sources based on the farmer's position in the innovation process.

However, this paper provides relevant insights for farmers by showing the need to invest in knowledge and combine it with external knowledge acquired from various actors to innovate successfully in sustainable farming. Also, the co-design of flexible policies that take account of farmers' needs is crucial to accelerate the transition. Contracting between value

chain actors and farmers would allow the sharing of risk and encourage innovation in sustainable farming and investment in transition crops. Finally, the development of policy measures to facilitate farmers' access to multiple knowledge sources (Autant-Bernard et al., 2013) and provide tailored advice would promote innovation and speed transition.

This article highlights the need for more research on the link between knowledge sources, chemical pesticide levels and crop yields. Future research could investigate the relationship between knowledge sources and the choice of a given combination of practices. Also, future papers can compare knowledge sourcing before and after innovation, to examine whether farmers adopting sustainable practices use different networks to explain. This type of analysis can contribute to understanding how innovation can transform farmers' knowledge sourcing strategies after going green.

7 Tables

Table 1.1: Variable definition and descriptive statistics.

Variables	Description	Mean	St.dev
Dependent variables			
Crop rotation	Using crop rotation practices (yes=1, no=0)	0.731	0.443
Inter-cropping	Using inter-cropping practice (yes=1, no=0)	0.468	0.499
Improved seed varieties	Using improved seed varieties (yes=1, no=0)	0.431	0.495
Mechanical control	Using mechanical control (yes=1, no=0)	0.522	0.499
Biological control	Using biological control (yes=1, no=0)	0.0855	0.279
Chemical control	Using chemical control (yes=1, no=0)	0.647	0.477
Explanatory variables			
Experience	Experience as knowledge source (yes=1, no=0)	0.682	0.465
Press and media	Press and media as knowledge source (yes=1, no=0)	0.376	0.484
Suppliers	Suppliers as knowledge source (yes=1, no=0)	0.558	0.496
Technical advisors	Technical advisors as knowledge source (yes=1, no=0)	0.347	0.476
Pest monitoring tool	Pest monitoring tool as knowledge source (yes=1, no=0)	0.261	0.439
Online extension	EcophytoPic Portal as knowledge source (yes=1, no=0)	0.035	0.185
Demonstration farm	Dephy as knowledge source (yes=1, no=0)	0.021	0.145
Other sources	Other sources as knowledge source (yes=1, no=0)	0.052	0.222
Peers	Peers as knowledge source (yes=1, no=0)	0.014	0.120
Control variables			
Elemeduc	Elementary school education (yes=1, no=0)	0.824	0.380
Highedu	High school education (yes=1, no=0)	0.370	0.483
Shorteduc	One year university degree (yes=1, no=0)	0.039	0.194
Longeduc	More than one year university degree (yes=1, no=0)	0.031	0.175
Sex	The farm manager is a female=1, male =0	0.116	0.320
Age	The age of the farm manager	52.65	9.610
Bio	Organic farm system (yes=1, no=0)	0.072	0.259
Sau	Farm' size in hectares	146.7	98.46

Supp	Plot' size in hectares	6.760	7.003
Crop farm	Farm is specialised in arable crops (yes=1, no=0)	0.401	0.490
Livestock farm	Livestock husbandry farm (yes=1, no=0)	0.220	0.415
Zone1	The soil is in a vulnerable area (yes=1, no=0)	0.107	0.310
Zone2	A part of the farm's soil is in a vulnerable area (yes=1, no=0)	0.741	0.437
Hshoc	Bird attack leading to > 30% loss of yield (yes=1, no=0)	0.013	0.115
Wshoc	Climate shock leading to > 30% loss of yield (yes=1, no=0)	0.093	0.291
Both	The farm experienced bird attack and a climate shock (yes=1, no=0)	0.008	0.092
Maec	Received a subsidy for adopting green practices (yes=1, no=0)	0.106	0.308
Barely	Cultivating barely (yes=1, no=0)	0.085	0.279
Triticale	Cultivating triticale (yes=1, no=0)	0.098	0.298
Rapeseed	Cultivating rapeseed (yes=1, no=0)	0.066	0.249
Sunflower	Cultivating sunflower (yes=1, no=0)	0.046	0.209
Pea	Cultivating pea (yes=1, no=0)	0.054	0.226
Sugarbeet	Cultivating sugarbeet (yes=1, no=0)	0.033	0.179
Potatoes	Cultivating potatoes (yes=1, no=0)	0.0453	0.208
Fava beans	Cultivating fava beans (yes=1, no=0)	0.054	0.227
Cereal mix	Cultivating cereal mix (yes=1, no=0)	0.026	0.161
Soyabean	Cultivating soyabean (yes=1, no=0)	0.030	0.198
Feed mix	Cultivating feed mix (yes=1, no=0)	0.051	0.220
Durum wheat	Cultivating durum wheat (yes=1, no=0)	0.042	0.201
Soft wheat	Cultivating soft wheat (yes=1, no=0)	0.087	0.282
Maize	Cultivating maize seed (yes=1, no=0)	0.114	0.318
Maize feed	Cultivating maize feed (yes=1, no=0)	0.087	0.281
Linen	Cultivating fibre linen (yes=1, no=0)	0.012	0.110
Oil flaxseed	Cultivating oil seed flax (yes=1, no=0)	0.026	0.159

Table 1.2: Errors correlation matrix for the general-based model.

	$\rho_{crop\ rotation}$	$\rho_{intercroppin}$	$\rho_{improved\ seed}$	$\rho_{mechanical\ contr}$	$\rho_{bio-control}$
$\rho_{intercropping}$	0.332***				
$\rho_{improved\ seeds}$	0.207***	0.453***			
$\rho_{mechanical\ contr}$	0.199***	0.245***	0.262***		
$\rho_{bio-control}$	0.151***	0.244***	0.257***	0.213***	
$\rho_{chemical\ control}$	0.087***	0.136***	0.205***	0.184***	0.067***

Likelihood ratio test of equality of the standard errors, $X^2(15) = 3750.79$, $Prob > X^2 = 0.0000$

Standard errors in parentheses

Significant at ***1%, ** 5%, * 10%

Table 1.3: Average marginal effects for the general model.

Variables	Crop rotation	Intercropping	Improved seed varieties	Mechanical control	Biocontrol	Chemical control	Equality test
Experience	0.210*** (0.080)	0.194*** (0.042)	0.160*** (0.031)	0.170*** (0.029)	0.021*** (0.011)	0.122*** (0.055)	99507.89***
Press and media	0.066*** (0.025)	0.104*** (0.021)	0.136*** (0.027)	0.144*** (0.025)	0.045*** (0.024)	0.155*** (0.070)	62053.91***
Suppliers	0.138*** (0.047)	0.126*** (0.023)	0.114*** (0.020)	0.133*** (0.019)	0.004 (0.002)	0.155*** (0.061)	185797.57***
Technical advisor	0.116*** (0.044)	0.148*** (0.024)	0.129*** (0.020)	0.104*** (0.015)	0.031*** (0.015)	0.113*** (0.049)	92771.39***
Pest monitoring tool	0.061*** (0.023)	0.099*** (0.020)	0.092*** (0.018)	0.076*** (0.013)	0.023*** (0.012)	0.082*** (0.037)	49155.05***
Online extension	0.031 (0.011)	0.097*** (0.020)	0.055** (0.011)	0.029 (0.005)	0.025*** (0.013)	0.011 (0.005)	104666.18***
Demonstration farms	0.016 (0.006)	0.093*** (0.019)	0.084*** (0.016)	0.075*** (0.013)	0.045*** (0.024)	0.152*** (0.069)	106964.27***
Other sources	0.121*** (0.046)	0.128*** (0.026)	0.149*** (0.029)	0.192*** (0.033)	0.054*** (0.029)	0.152*** (0.069)	62150.43***
Peers	0.007	0.012	-0.066	-0.056	0.002	-0.031	187930.03***

	(0.003)	(0.002)	(0.014)	(0.009)	(0.001)	(0.014)
Equality test	94843.43***	261576.17***	312061.63***	334536.93***	52938.60**	46025.35***

The marginal effects are based on multivariate probit regression with the control variables in Table 1.1

Row test: The impact of each source is not constant across the six farming practices.

Column test: Each source has a distinct impact on each innovation type.

Standard errors in parentheses.

Significant at*** 1%, ** 5%, * 10%

Table 1.4: Average marginal effects for crop rotation.

Variables	Cereal	Protein	Feed	Industrial	Potatoes	Equality test
Experience	0.239 *** (0.04)	0.115*** (0.061)	0.312*** (0.051)	0.172*** (0.059)	0.12*** (0.08)	4881.31***
Press and media	0.0814*** (0.021)	0.066*** (0.04)	0.121*** (0.032)	0.065*** (0.029)	0.07** (0.06)	5688.52***
Suppliers	0.15*** (0.034)	0.095*** (0.058)	0.148*** (0.036)	0.11*** (0.047)	0.07** (0.06)	2365.76***
Technical advisor	0.105*** (0.029)	0.106*** (0.064)	0.121*** (0.035)	0.008** (0.041)	0.10** (0.08)	4274.56***
Pest monitoring tool	0.044* (0.012)	0.077*** (0.049)	0.054* (0.015)	0.055* (0.026)	0.09** (0.07)	3345.88***
Online extension	0.054 (0.0163)	0.018 (0.012)	-0.082 (0.020)	0.0515 (0.026)	0.14** (0.18)	18437.04***
Demonstration farms	-0.05 (0.012)	-0.007 (0.004)	-0.056 (0.014)	0.132 (0.082)	0.13 (0.18)	19383.12***
Other sources	0.133*** (0.47)	0.036 (0.025)	0.192*** (0.075)	0.085*** (0.048)	0.03 (0.03)	15390.91***
Peers	-0.020 (0.005)	0.097* (0.078)	-0.143 (0.032)	-0.073 (0.030)	-0.20 (0.12)	27815.33***

The marginal effects are based on multivariate probit regressions for five crop categories with control in Table 1.1

The test investigates the equality between knowledge sources' coefficients across crop categories. Equality is rejected at a p-value of 0.000, thus, the difference is not equal to zero.

We present the critical value in the last column.

Standard errors in parentheses

***Significant at 1%, **Significant at 5%, *Significant at 10%

Table 1.5: Average marginal effects for intercropping

Variables	Cereal	Protein	Feed	Industrial	Potatoes	Equality test
Experience	0.194*** (0.037)	0.244*** (0.032)	0.224*** (0.048)	0.205*** (0.026)	0.14*** (0.02)	8034.13***
Press and media	0.144*** (0.027)	0.123*** (0.021)	0.147*** (0.034)	0.097*** (0.016)	0.10*** (0.02)	66348.49***
Suppliers	0.126*** (0.028)	0.061** (0.012)	0.127*** (0.034)	0.166*** (0.026)	0.13*** (0.02)	91360.83***
Technical advisor	0.154*** (0.030)	0.108*** (0.019)	0.132*** (0.032)	0.172*** (0.026)	0.10*** (0.02)	4797.52***
Pest monitoring tool	0.123*** (0.024)	0.119*** (0.020)	0.112*** (0.027)	0.088*** (0.015)	0.10*** (0.02)	75015.21***
Online extension	0.165*** (0.033)	0.12* (0.026)	0.13 (0.031)	0.022 (0.004)	0.19** (0.05)	64845.57***
Demonstration farms	0.007 (0.001)	0.23*** (0.061)	-0.070 (0.023)	0.146** (0.031)	-0.05 (0.01)	58727.18***
Other sources	0.145*** (0.031)	0.13** (0.030)	0.159*** (0.037)	0.099 (0.020)	-0.08 (0.02)	72050.65***
Peers	0.102 (0.022)	0.004 (0.0008)	0.078 (0.020)	0.034*** (0.006)	0.09 (0.02)	57565.07***

The marginal effects are based on multivariate probit regressions for five crop categories with control in Table 1.1

The test investigates the equality between knowledge sources' coefficients across crop categories. Equality is rejected at a p-value of 0.000, thus, the difference is not equal to zero.

We present the critical value in the last column.

Standard errors in parentheses

***Significant at 1%, **Significant at 5%, *Significant at 10%

Table 1.6: Average marginal effects for improved seed varieties.

Variables	Cereal	Protein	Feed	Industrial	Potatoes	Equality test
Experience	0.149*** (0.026)	0.142*** (0.021)	0.196*** (0.052)	0.166*** (0.025)	0.12*** (0.02)	13397.88***
Press and media	0.164*** (0.024)	0.135*** (0.018)	0.152*** (0.039)	0.144*** (0.021)	0.17*** (0.03)	8260.71***
Suppliers	0.111*** (0.021)	0.144*** (0.021)	0.117*** (0.035)	0.127*** (0.021)	0.04 (0.01)	32607.82***
Technical advisor	0.151*** (0.023)	0.104*** (0.015)	0.129*** (0.035)	0.143*** (0.021)	0.12*** (0.02)	12147.15***
Pest monitoring tool	0.082*** (0.014)	0.126*** (0.017)	0.09*** (0.025)	0.090* (0.014)	0.08** (0.02)	65642.54***
Online extension	0.10** (0.017)	-0.066 (0.012)	0.151** (0.039)	0.080* (0.014)	0.02 (0.00)	85698.73***
Demonstration farms	0.125* (0.022)	0.15* (0.025)	0.067 (0.020)	0.064*** (0.012)	-0.23 (0.05)	51672.10***
Other sources	0.161*** (0.028)	0.067 (0.011)	0.163*** (0.042)	0.080 (0.015)	0.11 (0.02)	72126.38***
Peers	-0.079 (0.019)	-0.095 (0.017)	-0.005 (0.001)	0.135*** (0.026)	-0.07 (0.01)	67447.27***

The marginal effects are based on multivariate probit regressions for five crop categories with control in Table 1.1

The test investigates the equality between knowledge sources' coefficients across crop categories. Equality is rejected at a p-value of 0.000, thus, the difference is not equal to zero.

We present the critical value in the last column.

Standard errors in parentheses

***Significant at 1%, **Significant at 5%, *Significant at 10%

Table 1.7: Average marginal effects for mechanical control.

Variables	Cereal	Protein	Feed	Industrial	Potatoes	Equality test
Experience	0.159*** (0.021)	0.152*** (0.022)	0.210 *** (0.040)	0.178 (0.025)	0.14*** (0.03)	15995.07***
Press and media	0.15*** (0.018)	0.163*** (0.024)	0.139*** (0.028)	0.144*** (0.023)	0.20*** (0.04)	4283.05***
Suppliers	0.153*** (0.020)	0.201*** (0.030)	0.175*** (0.036)	0.129** (0.022)	0.03 (0.01)	38147.67***
Technical advisor	0.085*** (0.127)	0.135*** (0.023)	0.125*** (0.027)	0.116** (0.021)	0.13*** (0.03)	86929.48***
Pest monitoring tool	0.067*** (0.010)	0.039 (0.007)	0.095 (0.021)	0.088*** (0.016)	0.07** (0.02)	50292.54***
Online extension	0.017 (0.002)	0.09 (0.018)	0.005 (0.001)	-0.007 (0.001)	0.11 (0.03)	56065.93***
Demonstration farms	0.037 (0.006)	0.149* (0.034)	0.162 (0.036)	0.072 (0.016)	-0.03 (0.01)	69103.71***
Other sources	0.207*** (0.037)	0.119* (0.026)	0.285*** (0.061)	0.181*** (0.049)	0.22*** (0.07)	29962.03***
Peers	0.059	-0.064	0.126	-0.228	-0.34**	72190.60***

(0.009) (0.011) (0.028) (0.040) (0.07)

The marginal effects are based on multivariate probit regressions for five crop categories with control in Table 1.1

The test investigates the equality between knowledge sources' coefficients across crop categories. Equality is rejected at a p-value of 0.000, thus, the difference is not equal to zero.

We present the critical value in the last column.

Standard errors in parentheses

***Significant at 1%, **Significant at 5%, *Significant at 10%

Table 1.8: Average marginal effects for biocontrol.

Variables	Cereal	Protein	Feed	Industrial	Potatoes	Equality test
Experience	0.023** (0.013)	0.022 (0.014)	0.040*** (0.032)	0.021*** (0.010)	-0.04* (0.03)	9923.04***
Press and media	0.035*** (0.018)	0.034** (0.020)	0.061*** (0.041)	0.059*** (0.024)	0.03* (0.03)	6962.76***
Suppliers	0.009* (0.005)	0.018 (0.011)	-0.025* (0.020)	0.006*** (0.003)	0.04** (0.03)	9529.17***
Technical advisor	0.040*** (0.020)	0.028* (0.017)	0.020 (0.015)	0.013 (0.006)	0.03* (0.03)	9111.24***
Pest monitoring tool	0.014*** (0.008)	0.046*** (0.026)	0.046** (0.032)	0.015 (0.007)	0.03* (0.03)	8049.77***
Online extension	0.046* (0.024)	0.007 (0.004)	0.039 (0.027)	0.017 (0.008)	0.06 (0.04)	9118.94***
Demonstration farms	0.007 (0.004)	0.11*** (0.052)	0.053 (0.036)	0.042 (0.018)	0.02 (0.01)	7851.74***
Other sources	0.044 (0.023)	0.10*** (0.049)	0.042 (0.029)	0.090* (0.036)	-0.02 (0.02)	12992.77***
Peers	-0.001 (0.001)	-0.026 (0.018)	0.057 (0.038)	-0.048 (0.028)	0.24** (0.13)	13230.24***

The marginal effects are based on multivariate probit regressions for five crop categories with control in Table 1.1

The test investigates the equality between knowledge sources' coefficients across crop categories. Equality is rejected at a p-value of 0.000, thus, the difference is not equal to zero.

We present the critical value in the last column.

Standard errors in parentheses

***Significant at 1%, **Significant at 5%, *Significant at 10%

Table 1.9: Average marginal effects for chemical control.

Variables	Cereal	Protein	Feed	Industrial	Potatoes	Equality test
Experience	0.135*** (0.05)	0.112*** (0.056)	0.148*** (0.052)	0.127*** (0.053)	0.11*** (0.07)	875.18***
Press and media	0.176*** (0.062)	0.141*** (0.067)	0.141*** (0.047)	0.164*** (0.065)	0.17*** (0.10)	1217.30***
Suppliers	0.143*** (0.053)	0.105*** (0.055)	0.232*** (0.068)	0.113*** (0.050)	0.09*** (0.06)	3545.10***
Technical advisor	0.115*** (0.047)	0.114*** (0.06)	0.12*** (0.042)	0.09*** (0.047)	0.09*** (0.06)	3044.45***
Pest monitoring tool	0.087*** (0.036)	0.0815*** (0.044)	0.135*** (0.046)	0.069 (0.033)	0.05* (0.04)	14798.37***
Online extension	-0.013 (0.005)	0.051 (0.030)	0.053 (0.020)	0.043 (0.022)	0.10 (0.08)	12921.15***
Demonstration farms	0.15* (0.075)	0.173*** (0.122)	0.198* (0.075)	0.055 (0.029)	0.21 (0.24)	14143.61***
Other sources	0.12** (0.058)	0.07 (0.042)	0.202*** (0.078)	0.115** (0.066)	0.16*** (0.15)	9140.34***
Peers	-0.040 (0.016)	0.133 (0.089)	-0.124 (0.051)	0.067 (0.036)	-0.11 (0.07)	15169.01***

The marginal effects are based on multivariate probit regressions for five crop categories including the controls in Table 1.1

The test investigates the equality between the knowledge source coefficients across crop categories. Equality is rejected at a p-value of 0.000, thus, the difference is not equal to zero.

We present the critical value in the last column.

Standard errors in parentheses

Significant at *** 1%, ** 5%, * 10%

Table 1.10: T-Test of mean equality of knowledge sources for crop one and two.

Sources	Sources average for the first crop	Sources average for the second crop	Difference	St. Err.	t-value	The alternative hypothesis (the mean is different from zero)
Press and media	0.400	0.400	0.001	0.019	0.027	0.978
Suppliers	0.598	0.593	0.005	0.019	0.254	0.798
Technical advisors	0.405	0.413	-0.007	0.019	-0.400	0.689
Pest monitoring tool	0.307	0.322	-0.014	0.018	-0.770	0.438
Online extension	0.034	0.039	-0.005	0.007	-0.677	0.497
Demonstration farm	0.029	0.025	0.004	0.006	0.064	0.519
Peers	0.019	0.017	0.001	0.005	0.254	0.799
Other sources	0.061	0.057	0.004	0.009	0.434	0.663

Chapter 2 Mix and match: What is the best R&D recipe for eco-innovation?

Foreword

This chapter is based on a paper with the same title co-authored with Stephane Lhuillery (NEOMA BS).

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1 Introduction

Eco-innovation² is introduced as the lifebuoy that will enable us to achieve sustainability transition (Fagerberg et al., 2016) thanks to its positive influence on pollution reduction and efficient use of resources. Thanks to these arguments, societal pressure urges governments worldwide to provide effective and stringent policy measures to incentivise firms' investments to eco-innovate (Garcia-Quevedo et al., 2022; Hinkel et al., 2020). However, to successfully tailor regulatory measures, two questions arise that need to be addressed empirically. Firstly, Are investments in green R&D worthwhile and is it enough to successfully eco-innovate? Despite the importance of the first question, empirical evidence investigating the returns of green R&D on eco-innovation are scarce (see, however (Lanoie et al., 2011; van Leeuwen and Mohnen, 2017)

Secondly and most importantly, what investments are needed to eco-innovate? Scholars described eco-innovation as complex and multi-disciplinary (de Marchi, 2012; Igami and Saka, 2007), based on combinatory knowledge from diverse fields (Barbieri et al., 2020b). The described multi-disciplinarity of eco-innovation implies that green technological progress depends on research efforts in a wide range of fields, the crossing between them is beyond the narrow categorization of green knowledge (OECD, 2011). This feature of eco-innovation entails that its technological knowledge is composite and is not a homogenous bundle (Antonelli and Colombelli, 2013). This view of eco-innovation substantially influences firms and government spending decisions and policy formulation on whether to invest and support targeted research and innovation or encourage knowledge multidisciplinary and complementarity by supporting generic technologies and knowledge.

Knowledge plurality of eco-innovation was investigated in the literature by tracing back patents and their citation to different sectors and technological fields to study the hypotheses of knowledge spillovers between green and non-green technologies, to explore the knowledge recombination process leading to innovation generation and its influence on subsequent innovation (Barbieri et al., 2020a; Nemet, 2012). However, this type of analysis is based on the output of the innovation process instead of the knowledge elements used to generate eco-innovation internally. A patent analysis does not explain the firms' intentional knowledge

² In this paper, we use indifferently eco innovation, sustainable innovation, environmental innovation or green innovation as synonymous (Schiederig et al., 2012). The same rule applies for R&D.

diversification strategy and their decision to invest in producing distinct but complementary knowledge fields to eco-innovate, achieving economies of scope (à la Milgrom and Roberts, 1995, 1990).

In this paper, we are interested in the role of knowledge multidisciplinary in eco-innovation but on the micro-level. We examine firms' resources allocated to knowledge creation through internal investments in different fields of R&D and compare if the probability of eco-innovation is better when firms invest in green and non-green R&D capabilities. We focus on three types of R&D fields (green, ICT and biotech) as the individual advances in these fields have already provided excellent solutions to climate change and environmental challenges. However, the real potential may arise from using these fields together to achieve broader applications and solve complex issues related to climate change and other global challenges. Combining a French innovation and an annual R&D survey for 2014, we use an econometric model first to investigate the positive influence on eco-innovation of the environmental R&D and also of ICT and biotech R&D investments. Second, we scrutinise the complementarity between green R&D and other R&D fields for eco-innovation, probably leading to superior eco-innovation. This article confirms that eco-innovations rely on green R&D but also on biotech R&D and ICT R&D. It further shows that eco-innovation is even more likely to emerge when firms combine green R&D and biotech R&D activities.

This paper extends eco-innovation literature on the micro-level by highlighting the sources of eco-innovation. Eco-innovation depends on non-environmental R&D investments and the mix done between environmental R&D and other R&D fields. These insights emphasise that firms combine knowledge production activities of different R&D fields to eco-innovate. In doing so, our article contributes to the debate on R&D policy for the transition by expanding and pushing decision-makers to reassess priorities related to the search for solutions to environmental issues and regulations formulation.

The paper is organised as follows. In the next section, we provide a literature review and the hypotheses. The third section describes the methodology, the data and the estimation procedure, while the fourth section presents the results and conducts a sensitivity analysis. The fifth and final section discusses the results and implications for managers and policymakers.

2 Literature Review and hypotheses

2.1 R&D and the eco-innovation literature

Climate change urgency triggered extensive research to study the factors affecting eco-innovations (Demirel and Kesidou, 2011). These factors include market pull factor (Horbach et al., 2012; Triguero et al., 2013), policy factors (Ghisetti and Pontoni, 2015; Horbach et al., 2012), firms specific factors such as size, location (Wagner, 2008), technology push factors such as internal R&D, acquisition of external knowledge (Ghisetti et al., 2015; Marzucchi and Montresor, 2017), organisational capabilities, and environmental management schemes (Wagner, 2008).

Following previous results (OECD, 2011), the literature focused on R&D and environmental R&D as the central determinant of environmental innovation. Green R&D has multiple benefits for companies: it increases firms' knowledge stock to eco-innovate and develops new processes and products (Demirel and Kesidou, 2011). It enhances absorptive capacities and enables firms to transform acquired external knowledge into an eco-innovation (Ghisetti et al., 2015). It also allows firms to use their cumulative local knowledge to solve issues and continue innovating in the same field (Battke et al., 2016), possibly reinforcing path dependency (Popp, 2019). Empirical papers confirm that past eco-innovation and patents indeed affect future innovation (Barbieri et al., 2020a; Braun et al., 2012), suggesting a first-mover advantage and barriers to market entry for the markets of sustainable products.

However, green R&D is rarely distinguished from other R&D activities. Environmental R&D is approximated by the general R&D budget, mixing “dirty” and green knowledge production activities (e.g.,(Horbach et al., 2012)). Despite empirical discrepancies (Cainelli et al., 2011), the literature implicitly assumes that dirty R&D is the main determinant of eco-innovation. Several arguments support this endeavour: 1) serendipity in R&D can lead directly to eco-innovations, 2) eco-innovations are ultimately the windfalls of dirty R&D activities. 3) Knowledge for environmental innovation can spill out from dirty R&D projects. 4) Environmental progress can unpredictably emerge as a latent property from existing dirty innovations (see Andriani et al., 2017). These views align with the evidence suggesting that eco-innovations are not explicit targets for R&D units (see Steger, 1993)

However, recent contributions contest these arguments. Lanoie et al. (2011) show that 9.3% of firms in their sample from different countries declare a “budget for research and development specifically related to environmental matters” (page 823). The result is in line with Stucki and Woerter (2019) who found that 10% of firms in their sample are involved in green energy R&D. Recognizing and disentangling green R&D from other R&D types is essential for two reasons. First, firms might invest in various R&D fields, and the identification of eco-R&D returns on investments is core to allocating R&D budgets and subsidies efficiently to green R&D activities (Montmartin and Massard, 2015). Second, the separation between eco-R&D and non-eco-R&D raises the question of non-green R&D components and the issues of the complementarities between R&D fields that firms strategically fashion to generate eco-innovation.

To the best of our knowledge, only one paper by van Leeuwen and Mohnen, (2017) identifies the contribution of green R&D investments to eco-innovations by confirming the positive influence of green R&D on eco-innovation. They find that an increase of 1% in eco-R&D intensity increases significantly the likelihood of innovating on pollution-reducing and resource-saving by 0.36% and 0.24% respectively. However, the article neither confronts the contributions of multiple R&D fields producing eco-innovations nor investigates potential complementarities between them. The present paper aims to fill these gaps.

2.2 The complexity of eco-innovations

We start with the premise that eco-innovative firms conduct R&D activities in various fields (OECD, 2011). The surveyed literature confirms that eco-innovation is highly novel and relies more than other fields on a diverse knowledge base (de Marchi, 2012) from various domains (green and non-green) (Corrocher and Ozman, 2019; Popp, 2019). Such multidisciplinary in eco-innovation does not imply a global pool of knowledge shared between all fields but rather implies the existence of key fields important for eco-innovations (Acemoglu et al., 2016; Barbieri et al., 2021). The challenge is then to select and identify the role of potential knowledge fields contributing to eco-innovations.

The literature focused primarily on the role of green ICT (Faucheux and Nicolaï, 2011). They are enabling greener products and services. Examples include ICT systems in cars for fuel-efficient driving, smart grids and smart meters that replace conventional grids to allow consumers to adapt their consumption and suppliers to stabilise demand by limiting

greenhouse gas emissions (OECD, 2011). Patent data in large companies even allows the identification of green ICT clusters likely to lead to eco-innovations (see Cecere et al., 2014). Other general-purpose technologies (GPTs) such as advanced materials, biotechnology and nanotechnologies were identified early on as essential drivers of eco-innovations by policymakers (OECD, 2012, 2011). However, they received less attention in eco-innovation literature.

The previously surveyed literature provides evidence of the strategic diversification of knowledge involved in eco-innovation activities. A first caveat in the literature using patent data is that the multidisciplinary knowledge used for eco-innovation can be overestimated by examiners in patent offices, biased algorithms assigning IPC codes or by the classifications of green technologies proposed by scholars and institutions (Angelucci et al., 2018; Haščič and Johnstone, 2011). The second problem is that existing studies provide only indirect insights about the multiplicity of R&D activities driving eco-innovations. The combination behaviour of different R&D activities is only analysed by studying firms' collaboration with external entities (Cainelli et al., 2011; Tumelero et al., 2019). The existing research does not study the internal coordinated knowledge production activities, combining ICT R&D, biotech R&D or nanotech R&D activities with green R&D to achieve eco-innovation.

Based on the literature underlining the strategic and managerial integration of eco-innovations in organisations (e.g., Abbas and Sağsan, 2019; Huang and Li, 2017; Wagner, 2008), the complexity of the eco-innovations (De Marchi, 2012) and the share of firms declaring formal R&D activities for environmental purposes (Lanoie et al., 2011; Stucki and Woerter, 2018), we think that firms intentionally allocate and organise systematically their internal knowledge production to eco-innovate. They eco-innovate by strategically investing in different intended internal search activities that are done in multiple fields. Consequently, we expect that eco-R&D is intuitively the primary driver of eco-innovations. We also hypothesise that internal R&D done in ICT and biotech contributes to eco-innovations. A first hypothesis is, therefore:

H1a: Eco R&D positively influences eco-innovation

H1b: ICT and Biotech R&D positively influence eco-innovation

R&D decision has to fit with other structural choices of the firm for better performance and complement other production process inputs (Milgrom and Roberts, 1995, 1990). To innovate, firms might have to master more than one knowledge field and employ them in the complementarity. In this case, the complementarity is driven by the differences between knowledge fields generated at the same time by different agents in different areas and the need to use them together to enable innovation (Breschi et al., 2003). This complementarity highlights that knowledge is the input for generating new goods and services and new knowledge. Taking on diversified knowledge stocks enables firms to reap the benefit of multiple knowledge fields such as cross-utilisation, exploitation of resources, avoidance of familiarity trap (Kim et al., 2021), and radical innovation development (Fleming, 2001; Schumpeter and Backhaus, 2006).

The development of eco-innovation requires a diverse and broad knowledge portfolio and not only in green R&D (OECD, 2011). Signs of synergies between knowledge fields are visible all around us. Take, for instance, biotech and green R&D; firms can mix both fields to reduce their environmental impacts. One famous example of this mix is the bioeconomy biotech (Arundel and Sawaya, 2009), which spawned subfields such as white biotech that uses biomass as feedstocks and develops greener industrial processes to reduce emissions (Lokko et al., 2017; Tylecote, 2019). The union between these fields can alter the production process, leading to incremental (e.g. less enzymes) or radical (e.g. using novel protein as replacement for meat) eco-innovation (Triguero et al., 2018).

ICTs also synergise with green R&D. The literature described two types of ICTs (Cecere et al., 2014). Green ICTs reduce their carbon footprint, while IT for green attenuates the environmental impacts of other sectors (Faucheux and Nicolai, 2011). According to (Tylecote, 2019), scientists also managed to weld ICT and biotech. ICT is used to conduct data analysis and to achieve advances in biotech. This link spawned bioinformatics (Lewis et al., 2016) employed to solve climate change problems (Appio et al., 2017).

These linkages imply potential complementarity between the R&D fields. However, empirical analysis rarely focused on the complementarity between internal R&D fields for eco-innovation. Instead, the focus was on the complementarity between different innovations (Galliano and Nadel, 2018) organisational and environmental management systems and the ICT adoption (Antonioli et al., 2018). Some tested for complementarities using a correlation

test between ICT adoption and eco-innovation (Cainelli et al., 2012). However, this test did not use R&D variables. Only Garcés-Ayerbe and Cañón-de-Francia, (2017) find evidence of complementarity between general R&D stock and green investment. A second hypothesis is :

H2: Complementarities exist between the R&D investments done by firms, namely between green R&D & biotech R&D, green R&D & ICT R&D, and ICT R&D & biotech R&D.

Knowledge is an intrinsically indivisible commodity that cannot be used or purchased in parts, incurring a high cost of generation and acquisition (Warsh, 2006). The concept of indivisibility is related to both complementarity and complexity. According to (Antonelli, 2003), the generation of technological knowledge (eco-innovation) is conditional on firms' competencies to draw together pieces of diverse knowledge, hence complexity, and use these and knowledge together, hence complementarity. However, no firm can hold all knowledge (Antonelli and Colombelli, 2013) due to the wide range of costs of maintaining a highly diverse knowledge (see below) nor invest partially in a few pieces of knowledge to innovate due to indivisibility (Antonelli, 2007). Firms strategically and intentionally choose which knowledge is developed internally and which pieces of knowledge are better acquired externally to build up the necessary pool of knowledge to innovate (Antonelli and Colombelli, 2013; Hagedoorn and Wang, 2012). This argument implies that the internal investment decisions consider the different bundles of knowledge fields developed internally as substitutes. Investing in a specific bundle means letting go of other pieces of knowledge that cannot be produced internally only partially because of indivisibility.

Considering diversified bundles of knowledge as a substitute can also stem from the cost of knowledge diversification (Corrocher and Ozman, 2019). Firms need to allocate time and resources to integrate diverse knowledge fields while maintaining effective communication, and information processing (Hashai, 2015). The benefits of knowledge diversification access can be restrained by firms' need to acquire standard inputs (Teece, 1980b) and the cost of maintaining products unrelated to the firms' core activity (Corrocher and Ozamn, 2019). It becomes challenging for firms to gauge practical innovation because of the above-mentioned cost and the cognitive barriers created with excessive diversification (Fleming, 2001), blocking firms from achieving economies of scope (Kim et al., 2021). In

this case, benefits from diversification are low, while the cost of creating and maintaining this disparate knowledge base is high. In this spirit, we hypothesise that:

H3: Green, biotechnology and ICT R&D are substitute inputs in eco-innovation production

3 Methodology

3.1 Data Description

The data is from the French annual national firm-level survey about the R&D means from 2008 to 2014 developed by the Ministry of higher education and research. The survey has information about the different forms of R&D (green, biotech, nanotech, ICT, advanced materials, and social and human sciences R&D). The sampling method relies on a repertoire of French firms that executed R&D historically, and it is constantly updated with information related to cessation or absorptions. External resources are used to complete the dataset, including other surveys (research tax credit, innovative start-ups and others) and public tools that collect information about firms' research activities.

The population is stratified into four groups based on R&D expenditures. A specific number of observations are sampled in each group and given a particular weight based on their group type. This data is used to calculate R&D stock for the various forms of R&D. We are interested in studying the complementary relationship between the different R&D fields and their impact on environmental innovation. Thus, we match the R&D survey dataset with the community innovation survey (CIS) for 2014 to extract information about environmental innovation behaviour, and we merge the dataset using the firms' ID.

We also match the data with two other surveys. Therefore, we match with a first survey, developed by the national institute of statistics and economic studies (INSEE) and the Ministry of Finance, containing information about firms' tax reports to extract data about the firm's size. The second survey, developed by INSEE, outlines the industrial groups operating in France to cluster firms from the same industrial group together.

3.2 Variables description

3.2.1 Dependent variable

Researchers struggle to define eco-innovation (Befort, 2021a; Ghisetti et al., 2015). Kemp and Pearson., (2007)' s definition is the most commonly used for eco-innovation. It entails "the production, assimilation or exploitation of a product, production process, service or management or business methods that are novel to the firm and which result, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives". This definition includes innovations that are not necessarily new to the world but new to the firm adopting them, as mentioned in the Oslo Manual.

The community innovation survey (CIS, 2014) similarly defines eco-innovation with two questions. The first question aims to gauge if firms develop innovative production processes that generate environmental benefits. These benefits can be reducing material, energy use, air pollution, water, soil and noise pollution, replacing materials with less polluting types, substituting fossil fuels with renewable energy, and waste recycling. The second question investigates if the firms innovate in products and services that, once used, their consumption leads to environmental benefits. These benefits can be reducing CO2 footprint, air, water, noise and soil pollution, and if the products are easily recycled or more durable. These two questions represent our two dependent variables.

3.2.2 Explanatory variables

The explanatory variables include the different stock of R&D. Green R&D entails R&D activities aiming to reduce air, soil, noise, water pollution, waste management, and protection of biodiversity and their different habitats. Biotech R&D depends on OECD definition. This definition is " the application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services" (Beuzekom and Arundel, 2009).

Nanotech R&D is about manipulating, studying, and exploiting very small-sized structures and systems (less than 100 nanometers). ICT R&D groups activities about the software and simulations development for research purposes. Advanced materials R&D

accounts for new materials unique to the firm or new to the market. Finally, social and human sciences R&D involves economics, management, marketing and others.

We calculate R&D stocks using the perpetual inventory method as knowledge takes time to generate innovation or patents. Thus, both present and past R&D are essential for innovation and not just the annual flow of knowledge. We use R&D survey data from 2008 up to 2014 to estimate R&D stocks for a given firm i at time t following equation (2.1):

$$R\&Dstock_{it} = (1 - \delta)R\&Dstock_{it-1} + R\&Dstock_{it} \quad (2.1)$$

Where δ is the depreciation rate of R&D equal to 0.15; nevertheless, the amortisation rate is not constant across technological fields. Indeed, previous papers demonstrated that the depreciation rate varies among technological areas. The rate was usually higher than 15% (Li and Hall, 2020). We add green, biotech and ICT R&D as separate inputs in the equation. We then add a variable to reflect the intensity of investments in R&D by deducting the sum of green, biotech and ICT R&D from the total R&D expenditures. The resulting variable describes investments in other fields such as nanotech, advanced materials, social science and humanities R&D.

3.2.3 Control variables

The first set of control variables is firms' specific factors, including size and sectors. The size describes the number of employees of the firm in 2014. Size has a positive and significant impact on eco-innovations (Cainelli et al., 2015). The binary variables describing industrial sectors take one when a firm is in a specific industry and zero otherwise. Previous literature indicated that sectoral differences significantly influence innovation development (Gilli et al., 2014; Rammer and Rexhauser, 2012). We add variables describing firms' affiliation to industrial groups, whether they belong to a foreign, French group (reference group) or independent (Chassagnon and Haned, 2015; Mairesse and Mohnen, 2004). We control for the type of market targeted by the firm, whether local, national, European or international (reference group) (Frenz and Ietto-Gillies, 2009; Hashi and Stojcic, 2010).

The second set of variables includes policy and market pull factors. Following the literature on the factors affecting eco-innovation, we add a variable equal to one for firms introducing eco-innovation because of regulations. The second equals one when firms

innovate because of market demand, and the third for green subsidies (Chassagnon and Haned, 2015). Finally, we also control for firms' cooperation with external knowledge sources as empirical evidence demonstrates their positive impact on eco-innovation.

3.2 Econometric Estimation

Following the literature, we use Griliches's KFP to estimate the impact of the R&D fields on eco-innovation (Griliches, 1979; Hall et al., 2010). The analysis exploits the uniqueness of the French survey on R&D expenditures for 3 types (Biotech, green, ICT) to compare their effects on eco-innovation. We also investigate the complementary between the R&D types to provide evidence for knowledge complementarity.

Only innovative firms fill the eco-innovation part in the CIS survey, implying a sample selection bias. To account for it, we use a two steps selection model that estimates regression models when the data suffers from selection bias. In this case, eco-innovation is only observable for a part of the data. The first step is an equation that estimates a probit model using all observations. At this step, firms decide to carry on general innovation activities.

If they choose to innovate, they can develop green or non-green innovations as a second step. We regress a binary variable equal to one for the first equation when the innovation is a product, process, marketing or organisational over in-house R&D and other control variables. We restrict the R&D variable to the first equation as all firms are asked to fill their R&D expenditure regardless of their innovative activities.

For the second step, we use two simultaneous equations; the dependent variables, Y_i^* are latent variables. They describe the utility derived from eco-innovation (e.g., product or process) and unobserved preference for eco-innovation with a linear combination of observables, including X_i (the R&D fields) and $Controls_i$ and the error term ε_i :

$$Y_i^* = \alpha_i + \beta X_i + \gamma Controls_i + \varepsilon_i \quad i = 1, \dots, N \quad (2.2)$$

We estimate equation (2.2) using a bivariate probit. We assume there will be a correlation between the error terms implying complementarity between the two types of eco-innovation. Previous research indicated that product innovation often requires process

innovation (Bönte and Dienes, 2013). We add a variable describing firms' cooperation attitude with external actors to account for spillovers.

We use the Carree et al., 2011 approach for continuous variables to test complementarity. We are interested in how R&D stocks are mobilised to eco-innovate. We restrict the complementarity test to three variables: green, biotech, and ICT R&D, as these fields are pervasive and have wide economic applications triggering innovation in other fields. The test is in equations (2.3) and (2.4):

$$Y_i = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_{12} x_1 x_2 + \alpha_{13} x_1 x_3 + \alpha_{23} x_2 x_3 + \alpha_{123} x_1 x_2 x_3 + \varepsilon_i \quad (2.3)$$

$$Y_i = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_{12}(x_1 x_2 - x_1 x_2 x_3) + \alpha_{13} x_1 x_3 + \alpha_{23} x_2 x_3 + (\alpha_{12} + \alpha_{123}) x_1 x_2 x_3 + \varepsilon_i \quad (2.4)$$

We are interested in the significance of the coefficients of the variables $x_1 x_2 - x_1 x_2 x_3$ and $x_1 x_2 x_3$. The t-value of the former t_1 and of the latter is t_2 . The test for complementarity implies that the coefficients $\alpha_{12} \geq 0$ and $\alpha_{12} + \alpha_{123} \geq 0$ with at least one of the two inequalities holding strictly and $t_1 > t_c$ and $t_2 > -t_d$ or $t_1 > -t_d$ and $t_2 > t_c$. t_c and t_d are critical t-values. The critical t-values are based on the Bonferroni method to reduce type I error in which $t_c = 1.96$ and $t_d = 1.65$ are the distribution of the critical value at 10% for significant two-sided level, ($A/2^{n-2}A=10\%$, $n=3$ is the number of R&D strategies).

4 Results

4.1 Descriptive statistics

This section provides preliminary descriptive statistics on the variables included in this study. Table 2.1 describes and define the data mobilised for the econometric estimation. Firms innovating in marketing, organisational, product, process, or conducting any innovative activities represent more than half of the dataset (61%). More than half of innovating firms (68%) also develop eco-innovation where the environmental benefits are felt on the firm level in the processes adopted internally, while around half of innovating firms (57%) invested in

eco-innovation with the environmental gains emitted from the consumption and the after usage of goods and services.

The R&D stock variables are divided by the firms' number of employees (size) and then transformed using logarithmic transformation. In this format, the highest R&D is ICT, followed by biotech and finally green R&D. Among innovative firms, around 34% claim that regulations played a role in incentivising them to introduce environmental measures and eco-innovate. A lesser number (18%) of firms decided to eco-innovate to respond to market demand for greener products and processes. Only 7% of firms developed green innovation thanks to subsidies, potentially implying that taxation is more efficient than subsidies.

Around 50% of innovative firms established cooperation with external actors. Firms that established these alliances did so to access the competencies needed for their innovation process. Most firms target and sell their products on both local and national markets (around 85%) against 66% that target the European market. We have almost the same percentage of independent firms and firms affiliated with foreign industrial groups (around 24%). We also conduct a correlation between the different variables of the model and report the results in Tables 2.2 and 2.3.

4.2 Main results

4.2.1 Selection model

We report the result of the bivariate probit with Heckman selection in Table 2.4. The likelihood-ratio test of equation independence is rejected at a 1% p-value, indicating the existence of sample selection, justifying the use of the Heckman model to correct it. The total internal R&D expenditure stock is positive and strongly significant in the selection equation. These results align with the previous literature (Chassagnon and Haned, 2015; Ghisetti et al., 2015; Popp, 2019), indicating that R&D is essential for innovation.

Firms' size is positive and significant at a 1% p-value confirming previous findings of the importance of size in influencing innovation probability, meaning that larger firms are more likely to innovate (Cainelli et al., 2012; Chassagnon and Haned, 2015). Firms affiliated with a foreign group are more likely to innovate than French groups, whereas firms that do not belong to an industrial group are less likely to innovate. This evidence comes in harmony with literature that finds a positive and significant relationship between being affiliated with

an industrial group and innovation. A potential explanation is that larger firms have more resources and are more capable of risk-taking (Chassagnon and Haned, 2015; Mairesse and Mohnen, 2004). Firms targeting local, national and European markets are more likely to innovate than firms targeting international markets, similar to the findings of Frenz and Ietto-Gillies, (2009); Hashi and Stojcic (2010).

4.2.2 Eco-innovation model

We can deduce that the eco-process and product innovation are complements. The likelihood-ratio test of independence is rejected, implying that the error terms of the two probit equations are correlated at a p-value of 1%. We also compute the average marginal effects to explore how an explanatory variable affects a firm's decision to eco-innovate. The findings show that green R&D positively influences the probability of eco-innovations; it is significant for eco-product and process innovation at a 5% p-value. A 1 percent increase in green R&D increases the likelihood of eco-product innovation by 0.046 percentage points and the eco process by 0.025 percentage points.

The results confirm the *H1.a* about the role of green R&D in eco-innovation. Apart from the positive influence, the findings suggest that green R&D is more relevant for eco-product. The literature is mixed due to differences in the measurement of eco-innovation and green R&D. Frondel et al., (1979) show that green R&D is more relevant for cleaner production innovation than the end of pipe. While Lanoie et al., (2011) do not find a significant influence of R&D on firms' environmental performance, which is explained by firms devoting their green R&D for product innovation and less for process innovation. In contrast, van Leeuwen and Mohnen, 2017 report a positive and significant impact of green R&D on pollution-reducing innovation and resource-saving innovation.

Biotech R&D has a positive and significant effect on eco-process innovation at a p-value of 5%, and it increases its probability by 0.031 percentage points. However, this impact is negative and insignificant for eco-product innovation. This result might be because of the use of biotech to develop greener technologies and incorporate them into the production process, as is the case for white biotech (see examples in (Triguero et al., 2018; Tylecote, 2019).

ICT R&D contributes to eco-product innovation by increasing its probability by 0.0101 percentage points at 1%. However, the impact of ICT R&D is not significant on eco-process innovation. The findings align with the literature about ICT firms diversifying into eco-innovation (Corrocher and Ozman, 2019) and the importance of ICT adoption in driving eco-innovation (Antonioli et al., 2018). The residual R&D positively and significantly impacts the two eco-innovations, incurring a 0.040 percentage point rise in their probability. This finding highlights the importance of investments in other fields, such as nanotech.

These results confirm the *H1.b* about the role of non-green knowledge in the generation of eco-innovation, validating the assumption about the complexity of knowledge used to eco-innovate. We hierarchise non-green and green knowledge based on the magnitude of their influence on eco-innovation. For eco-process innovation, non-green R&D have a larger impact on innovation probability than green R&D. The image is reversed for eco-product innovation, where green R&D has the most significant influence.

Firm size positively and significantly impacts eco-process and product with a marginal effect of 0.051 and 0.035 at 1%, respectively. This result is consistent with studies of the strong positive impact of labour on eco-innovation (Cainelli et al., 2015). Regulations are great incentives as they increase by 0.247 and 0.178 percentage points eco-process and product innovation, respectively. In contrast, green subsidies are positive but only significant for eco-product innovation. The magnitude is also lower than the green regulation.

Market demand variable has a positive influence on the eco-process and product innovation. The marginal effect is higher for eco-product innovation (0.1964) than for process innovation (0.0724) which is reasonable as it describes the market need and the demand for greener products (Cainelli et al., 2015; Horbach et al., 2012). The influence of collaboration is slightly greater for product innovation (0.0822) than for process innovation (0.0636), indicating that external sources are more helpful in developing product innovation.

Being affiliated with a foreign group has a positive but insignificant impact on both types of eco-innovation, while being an independent firm has a negative and insignificant influence. The three variables describing the different markets have a positive and significant influence on eco-innovation, with national and European markets leading to a greater probability than targeting local markets.

4.2.3 Complementarity test

In Table 2.5, we summarise the result of the complementarity test. We are interested in the complementarity between green, biotech and ICT R&D as these technologies are pervasive with broad economic applications that trigger innovation in other fields. We find complementarity between green and biotech R&D for eco-process innovation and eco-product, confirming our second hypothesis about the synergies between biotech and green R&D.

The complementarity between green and biotech R&D indicates that firms achieve economies of scope when combining the two R&D strategies. Firms using both types of R&D simultaneously are more likely to develop eco-innovation demonstrating the additional gain in performance for firms investing in green and biotech R&D at the same time. The findings align with the literature about biotechnology being increasingly contributing to the development of green technologies as research at the interface between both fields can solve many environmental challenges (Arundel and Sawaya, 2009).

We find neither complementarity nor substitution between the other types of R&D strategies tested in Table 2.5. These results reveal that firms do not benefit from investing in two or three R&D strategies simultaneously, where the marginal returns of one do not change with the more or less investment in other strategies. These findings imply that our second hypothesis is partially supported while the third is not confirmed.

4.2.4 Robustness check

We conduct a robustness check by running alternative estimation to ascertain the robustness of our results. We estimate the model using dummy variables instead of continuous variables describing R&D strategies. We estimate a bivariate probit with Heckman selection to recheck the influence of the various R&D strategies on eco-innovation. The results are consistent with the main specification. Eco-process mainly rely on non-green and R&D. Green R&D is more critical than non-green R&D for eco-product innovation. These results are available upon request.

5 Discussion and conclusion

This study analyses the consequences of knowledge multidisciplinary on French firms' eco-innovation performance and obtains results highlighting the importance of investing in green and non-green R&D. Using a bivariate probit with Heckman sample selection for the data by the Ministry of research on means of R&D and CIS survey for 2014, the paper is based on the initial assumption of three premises. First, this research assumes that one factor that guarantees eco-innovation is the investment in both multidisciplinary knowledge. Based on this assumption, firms should not invest in only green R&D to successfully eco-innovate.

Secondly, the research hypothesises that eco-innovation entails internally mixing and matching R&D strategies. Here, the hypothesis dives further into depicting the complexity of knowledge needed to eco-innovate. Finally, we assume that multidisciplinary has its limitation as investing internally in a very diverse knowledge can be challenging, leading firms to choose which fields they should invest in R&D strategically.

As a first conclusion, the paper confirms that green R&D, indeed, play a crucial role in motivating firms to generate eco-friendly products and services and environmental production processes. The accumulation of green R&D efforts implies that first firms want to benefit from the low carbon product market, which is anticipated to increase yearly until 2050 (Stern, 2006). Second, firms are dedicated to increasing their stock of knowledge in environmental protection despite the risks of green R&D and mobilise this knowledge to devise new applications and processes with long term influence (Demirel and Kesidou, 2011).

The research obtains novel insights about the knowledge base of eco-innovation. Eco-innovation is supposedly complex and departs from firms' local knowledge (de Marchi, 2012; Marzucchi and Montresor, 2017). In a second conclusion, this paper shows that advancements in green technologies do not rely only on momentum in eco-innovation but also incorporate knowledge developed in other fields. These findings indicate the complexity of eco-innovations combining various competencies and knowledge bases and imply that firms have to detain a diverse knowledge portfolio spanning technologies like ICT and biotech.

These technologies are generic, pervasive and have wide economic applications (Gault et al., 2014). These technologies can fasten and contribute to the transition to sustainability (Corrocher and Ozman, 2019; OECD, 2011). Previous literature discussed these benefits in the case of ICT and provided practical examples of products and processes in which biotech, nanotech and advanced materials can develop greener technologies (Cecere et al., 2014; Corrocher and Ozman, 2019; Tylecote, 2019). However, this paper is the first to provide micro-level evidence on how firms allocate their internal resources between different R&D strategies to generate knowledge that will be later used to eco-innovate. This evidence highlights the role of scientific research as the seed that triggers innovation, including eco-innovation.

Third, this paper contributes to the eco-innovation literature by highlighting that the advantages associated with environmental R&D activities and their influence on eco-innovation advancement are more significant when the firm is proactive in non-green R&D activities. This is consistent with previous literature that finds complementarities between resources spent on environmental protection and those paid on organisational innovation, environmental management systems (Antonioli et al., 2018; Wagner and Hansen, 2005) and general innovation strategy (Garcés-Ayerbe and Cañón-de-Francia, 2017).

The complementary between biotech and green R&D arises thanks to combining and reconfiguring resources. Bioeconomy is promoted as a solution to climate change and a lever for transition, where biotechnology will achieve sustainability through greener processes, minimising waste and pollution and increasing energy efficiency (Epicoco et al., 2014). We demonstrate that there are investments in the bioeconomy, and they positively influence innovation development. These findings also support the biotech-bioeconomy vision, where biotechnology is considered central for the transition to the bioeconomy.

Policy actions in this realm should target green R&D, which is a long-term strategy with long term and broader impacts. However, policies should go beyond the narrow categorisation of research and support generic knowledge with general application across technological fields, including green technologies. This paper demonstrates that green technologies depend on a wide range of research like ICT and biotech. Spending to encourage these technologies can be as just as or more important than spending on green R&D.

Moreover, policy and managerial action should consider supporting firms' development of complementarity between the knowledge fields. First, investing in green R&D leads to more benefits thanks to its complementarity with other resources. Identifying these complementarities allows firms to direct their investment for internal and external knowledge search to achieve the best and most cost-effective combination, maximise their innovation output and improve their competitiveness. Second, this multidisciplinary is key to achieving sustainable transition, crystallising new concepts such as the bioeconomy. These combinatory technologies lack private and public R&D spending and more efforts should be directed to support complementarity technologies.

This study is not free from limitations, which can also be an opportunity for future research. Future longitudinal data availability will allow us to deepen our understanding of this topic with dynamic estimation techniques. Future research might account for external sources of knowledge instead of solely focusing on internal R&D. The analysis would have been complete if we also added patent variables to account for all types of innovation. We hope that this avenue can be picked by future research. Finally, one impediment of this study is that the data from the Means of R&D survey is limited to firms that invest in R&D, creating a potential endogeneity problem.

6 Tables

Table 2.1: Variables definition and descriptive statistics:

Variable	Description	Total innovation=1		The total dataset	
		mean	std	mean	std
Dependent variables:					
Eco-process innovation	Equals one if firm introduces at least one eco-innovation throughout the production process between 2012 and 2014 to (1) Reduce material use or water use per unit of output; (2) reduce energy use or CO2 footprint; (3) reduce air, water, noise, or soil pollution; (4) replace a share of materials with less polluting or hazardous substitutes; (5) replace a share of fossil energy with renewable energy sources; and (6) recycle waste, water or materials.	0.679	0.466		
Eco-product innovation	Equals one if firm introduces at least one eco-innovation between 2012 and 2014 generating environmental benefit after the sale and use of goods and services by the end consumers: (1) reduced energy or CO2 footprint; (2) reduced air, water, soil or noise pollution; (3) improved recycling of product after use; and (4) extended product life through longer, more durable products.	0.571	0.494		
Total innovation	Equals one if the firm introduces at least one innovation in product, process, organisational, marketing innovation or any innovative activities.			0.615	0.486
Independent variables					
Market factor	Equals one for firms introducing eco-innovation in response to current or expected demand.	0.184	0.388		

Green regulation	Equals one for firms introducing eco-innovation in response to existing regulations or taxes, expected environmental regulations or taxes to be introduced in the future.	0.341	0.474		
Green subsidies	Equals one for firms introducing eco-innovation in response to government grants, subsidies or other financial incentives.	0.072	0.258		
Cooperation	Equals one for firms cooperating with external actors to introduce innovative activities	0.487	0.499		
Foreign group	Equals one if the firm belongs to a foreign group.	0.244	0.429	0.168	0.374
Independent firms	Equals one if the firm does not belong to an industrial group.	0.226	0.418	0.316	0.465
Local market	Equals one if the firm sells locally.	0.866	0.340	0.896	0.303
National market	Equals one if the firm sells nationally.	0.846	0.360	0.693	0.461
European market	Equals one if the firm sells on the European level.	0.660	0.473	0.458	0.491
Log(Green_R&D stock/L)	Firms green RD stock expenditures were calculated using the RD survey between the years 2008-2014	0.022	0.555		
Log(Biotech_ R&D stock/L)	Firms' biotechnology RD stock expenditures were calculated using the RD survey between the years 2008-2014	0.039	0.445		
Log (ICT_ R&D stock/L)	Firms ICT RD stock expenditures were calculated using the RD survey between the years 2008-2014	0.113	0.757		
Log(Residual_ R&D stock/L)	Firms' residual R&D is calculated as follows: Firms ' total RD stock expenditures - biotech RD stock expenditures+ green and ICT RD stock expenditures. This is to reflect the intensity of R&D investments as well as investments in other fields such as nanotech, advanced materials, social science and humanities.	0.438	1.357		
Log(Total _R&D	Firms ICT RD stock expenditures were calculated			0.314	0.973

stock/L)	using the RD survey between the years 2008-			
	2014			
Log (L)	Number of employees in the firm	4.922	1.637	4.264 1.580

Table 2.2: Correlation matrix when total innovation=1

	Eco-process innovation	Eco-product innovation	Log(Green_R&Dstock/L)	Log(Biotech_R&Dstock/L)	Log(ICT_R&Dstock/L)	Log(Residual_R&Dstock/L)	Log (L)	Market factor	Green regulation	Green subsidies	Cooperation	Foreign group	Independent firms	Local market	National market
Eco-process innovation	1.000														
Eco-product innovation	0.584*	1.000													
Log(Green_R&Dstock/L)	0.0263*	0.0677*	1.000												
Log(Biotech_R&Dstock/L)	0.0511*	-0.0780	0.0818*	1.000											
Log(ICT_R&Dstock/L)	0.0478*	0.0478*	0.0679*	0.0296*	1.000										
Log(ResidualR&Dstock/L)	0.1170*	0.1509*	0.319	0.0634*	0.3502*	1.000									
Log (L)	0.2318*	0.1673*	-0.406*	0.0265*	0.2285*	0.2600*	1.000								
Market factor	0.2307*	0.3301*	0.0885*	0.0337*	0.1072*	0.1804*	0.2080*	1.000							
Green regulation	0.4152*	0.3704*	0.0282*	-0.0093	0.0916*	0.1920*	0.2608*	0.3447*	1.000						
Green subsidies	0.1523*	0.1664*	0.0337*	-0.0192*	0.0373*	0.0862*	0.1030*	0.2078*	0.2750*	1.000					
Cooperation	0.2110*	0.2284*	0.0477*	0.0781*	0.1834*	0.2467*	0.3054*	0.1938*	0.1894*	0.0994*	1.000				
Foreign group	0.0610*	0.0485*	0.0051	0.0698*	0.0358*	0.1569*	0.2520*	0.0789*	0.1185*	0.0270*	0.1433*	1.000			
Independent firms	-0.1120*	-0.0697*	0.0172	-0.1166*	-0.0215*	-0.1574*	-0.4436*	-0.1091*	-0.1509*	-0.0382*	-0.2681*	-0.3704*	1.000		
Local market	0.0862*	0.0635*	-0.0192*	-0.0451*	-0.0699*	-0.1081*	-0.1053*	-0.0271*	-0.0396*	0.0496*	-0.0476*	-0.1524*	0.1083*	1.000	
National market	0.0663*	0.0370*	0.0247*	0.0286*	0.1380*	0.1635*	0.2591*	0.0985*	0.1130*	0.0365*	0.1706*	0.1894*	-0.2138*	-0.1283*	1.000
European market	0.0936*	0.0539*	0.0366*	0.0575*	0.1905*	0.2537*	0.2583*	0.1173*	0.1416*	0.0465*	0.2004*	0.2451*	-0.2133*	-0.1111*	0.5358*

Table 2.3: Correlation matrix for selection equation

	Innovation	Log(total R&D/effectif)	Log (L)	Independent firms	Foreign group	National market	European market
Innovation	1.000						
Log(total R&D/effectif)	0.2320*	1.000					
Log (L)	0.2750*	0.2488*	1.000				
Independent firms	-0.1531*	-0.1182*	-0.3293	1.000			
Foreign group	0.1364*	0.1323*	0.2010*	-0.3065*	1.000		
Local market	-0.0536*	-0.1268*	-0.0944*	0.0909*	-0.1529*	1.000	
National market	0.2754*	0.2800*	0.2296*	-0.1391*	0.2280*	-0.1051*	1.000
European market	0.2602*	0.1792*	0.2384*	-0.1513*	0.1789*	-0.1194*	0.5224*

Table 2.4: Bivariate probit regression with sample selection and average marginal effects:

Variables	Eco-process innovation		Eco-product innovation		Innovation
	Coefficient	ME	Coefficient	ME	Coefficient
Log(Green_R&D stock /L)	0.0795** (0.0368)	0.0254** (0.0117)	0.146*** (0.0413)	0.0466*** (0.0135)	
Log(Biotech_R&D stock/L)	0.0970** (0.0470)	0.0310** (0.0150)	-0.0192 (0.0475)	-0.0061 (0.0151)	
Log(ICT_R&D stock /L)	0.00842 (0.0106)	0.0026 (0.0033)	0.0317*** (0.0105)	0.0101*** (0.0033)	
Log(Residual_R&D stock/L)	0.132*** (0.0212)	0.0421*** (0.0067)	0.127*** (0.0220)	0.0404*** (0.0069)	
Size	0.162*** (0.0129)	0.0517*** (0.0040)	0.121*** (0.0133)	0.0356*** (0.0042)	0.155*** (0.00970)
Foreign group	0.0485 (0.0467)	0.0155 (0.0149)	0.0661 (0.0498)	0.0211 (0.0159)	0.0874** (0.0392)
Independent_firms	-0.0546 (0.0441)	-0.0174 (0.0141)	0.0274 (0.0462)	0.0087 (0.0147)	-0.121*** (0.0303)
Green_regulation	0.774*** (0.0420)	0.2477*** (0.0120)	0.558*** (0.0393)	0.1780*** (0.0116)	
Market demand	0.226*** (0.0684)	0.0724*** (0.0215)	0.616*** (0.0618)	0.1964*** (0.0188)	
Green subsidies	0.112 (0.0874)	0.0357 (0.0278)	0.213*** (0.0764)	0.0680*** (0.0242)	
Local market	0.132** (0.0518)	0.0421** (0.0165)	0.122** (0.0571)	0.0389** (0.0182)	0.122*** (0.0432)
European market	0.245*** (0.0451)	0.0785*** (0.0143)	0.136*** (0.0479)	0.0432*** (0.0152)	0.295*** (0.0327)
National market	0.211*** (0.0530)	0.0673*** (0.0170)	0.246*** (0.0550)	0.0784*** (0.0175)	0.312*** (0.0328)
Cooperation	0.199***	0.0636***	0.258***	0.0822***	

	(0.0346)	(0.0109)	(0.0359)	(0.0112)	
Log(Total_R&D/L)					0.308***
					(0.0225)
Constant	-1.654***		-1.775***		-1.017***
	(0.118)		(0.125)	(0.119)	(0.0869)
Complementarity between the two eco-innovation	0.821***				
	(0.013)				
The likelihood-ratio test of equation independence	0.946***		0.944***		
	(0.116)		(0.088)		
Log- pseudolikelihood	-10270.686				
Observations	11,628	5,416	11,628	5,416	11,628

We include in the model sector dummies (2 Nav digit).
The errors are clustered by group identification number
Robust standard errors in parentheses and marginal effect are calculated at the sample mean.
*Significant at 10%; **Significant at 5%; ***Significant at 1%

Table 2.5: Complementarity test results based on bivariate probit regression with sample selection

Eco-innovation	RD fields	t1	t2	Hypothesis	Test results
Eco-process innovation	Green (x1) X Biotech (x2)	3.31 ***	3.43***	Complementarity: $t1 > t_c$ and $t2 > -t_d$ or $t1 > -t_d$ and $t2 > t_c$	Complement
	Green (x1) X ICT (x3)	1.05	0.26	Complementarity: $t1 > t_c$ and $t2 > -t_d$ or $t1 > -t_d$ and $t2 > t_c$	Independent
	Biotech (x2)X ICT (x3)	-1.22	-0.88	Complementarity: $t1 > t_c$ and $t2 > -t_d$ or $t1 > -t_d$ and $t2 > t_c$	Independent
	Green (x1)X Biotech (x2)X ICT (x3)	-0.17		Complementarity: $t1 > t_c$	Independent
Eco-product innovation	Green (x1)X Biotech (x2)	3.01***	3.33***	Complementarity: $t1 > t_c$ and $t2 > -t_d$ or $t1 > -t_d$ and $t2 > t_c$	Complement
	Green (x1)X ICT (x3)	1.83*	0.62	Complementarity: $t1 > t_c$ and $t2 > -t_d$ or $t1 > -t_d$ and $t2 > t_c$	Independent
	Biotech (x2)X ICT (x3)	0.47	0.31	Complementarity: $t1 > t_c$ and $t2 > -t_d$ or $t1 > -t_d$ and $t2 > t_c$	Independent
	Green (x1)X Biotech (x2) X ICT (x3)	-0.11		Complementarity: $t1 > t_c$	Independent

The critical values are 1.96 for t_c and 1.65 for t_d

We added sector dummies as control variables. The error is clustered by group identification number

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Chapter 3 Lost in transition: How to break out from the niche?

The case of micro-algae

Foreword

This chapter is based on a paper with the same title co-authored with Mireille Matt (LISIS) and Nicolas Befort (NEOMA BS).

A version of this paper is currently submitted to the FAERE 2022 conference.

1 Introduction

Bioeconomy is built on using raw materials that will be transformed by biorefineries using complex technologies to produce bioproducts and biofuels to replace petroleum and petrochemicals. First, this biomass can be used as drop-in innovations that have the same functionalities as their unsustainable counterparts. Second, it can be mobilised to develop new products incorporating old and new functionalities. This view of the bioeconomy transition promises, through the usage of biomass, a broad range of applications that are economically and environmentally viable (Vivien et al., 2019). Despite the long history of the bioeconomy and its promised substitution of fossil fuel and petrochemicals, fossil fuel still represents the lion's share in the energy mix (~80% in 2019). Petrochemicals production has been increasing steadily since 2018 and is projected to grow in 2030 (See the World Bank³ and Statistica⁴).

Many innovations developed under the umbrella of bioeconomy did not diffuse successfully and are still in incubation, blocking the achievement of the promised transition towards bioeconomy (Wilde and Hermans, 2021; Wydra et al., 2021). Understanding the processes through which innovations move from a protected niche to a stable, mass-producing industry is thus crucial to completing our understanding of why some innovations succeed while others fail to break out of the niche.

Thanks to the established frameworks of strategic niche management (SNM) (Hoogma et al., 2002; Kemp et al., 1998) and the multi-level perspective (MLP) (Geels, 2019; Geels and Schot, 2007b), we understand, first, process through which a niche (e.g., a bioeconomy innovation) could emerge and challenge the dominant technology in a specific sector. Second, the role of different actors (new entrants and incumbents) in initiating, driving and influencing the development trajectories of a niche innovation (Berggren et al., 2015; Geels et al., 2016). Parallely, the substance work on global value chains explains the coordination of the production process dispersed geographically across actors and how economic activities, including innovation, are governed by studying the role of core actors (e.g., lead firms) in driving global value chains (Gereffi et al., 2006; Gereffi and Korzeniewicz, 1994).

³ <https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS?end=2015&start=2015&view=bar>

⁴ <https://www.statista.com/statistics/407861/forecast-for-annual-growth-in-chemical-industry-worldwide-by-region/>

In this paper, we suppose that the commercial development, expansion, and diffusion of a niche innovation occurs through its integration into the labour division, usually studied through global value chains. For this transition to happen, actors must establish alliances along the main innovation value chain and any adjacent value chains that use the innovation or supply services and products for its production. The type of alliances depends on the actor's position in the value chain, actors' resources, and gaps in competencies.

We explore this hypothesis in the context of the bioeconomy, which is particularly relevant to investigating how a bio-based innovation can successfully diffuse, reach commercial development and eventually dominate. We are using a case study of microalgae as a case of biobased innovations. Microalgae were considered promising biomass. It was expected to transform the existing petrochemicals value chains, which represent a typical example of global value chains with lead firms driving the development of production activities.

The case study of microalgae allows first us to explore how innovation grows into a niche by studying two cycles of promises that developed simultaneously (biofuel and high and medium value-added products). Second, we investigate the relationships established by microalgae firms to integrate and develop cross-linkages between various value chains thanks to its multipurpose characteristics through participation in collective exploration and exploitation activities. These activities aim to gradually confront the innovation in the selection environment, diffuse, expand, and reach the market. Both exploration and exploitation activities privilege different forms of alliances between actors from the main and adjacent value chains at different points in the innovation trajectory. These activities also play a role in restructuration and modifying the existing structure of value chains.

We proceed in three main steps. First, we review the literature and argue for the need to combine the value chain and niche analysis. Second, we use this framework to guide our empirical research. Third, we discuss how the proposed framework reveals the aspect disregarded by the niche analysis. Fourth, we present the case study and analyse the promise cycle. Fifth, we provide a typology of strategies innovative firms can adopt to integrate or develop a value chain and discuss the policy implications of combining the two approaches.

2 Literature Review

2.1 Niche formation

Sustainable innovations are expected to be radical as they are supposed to deviate in their functionalities from the current regime. They emerge in the periphery of the current socio-technical system based on the protagonist's expectations of future performance and functionality of the technology to attract sponsorships (Geels and Raven, 2006a). If these promises are accepted, they lead to shared expectations which are translated into actual projects (Befort, 2020b).

Protected spaces are developed around these innovations to shelter them from environmental pressure, selection criteria and mainstream competition (Kemp et al., 1998; Raven, 2006; Smith and Raven, 2012a). The purpose is to try out (Smith and Raven, 2012a; Turnheim and Geels, 2019), shield, nurture, and empower, whether through a fit and conform strategy in an unchanged selection environment or through stretch and transformation entailing the change in the selection environment (Smith and Raven, 2012).

The main actors in the niche are considered new entrants as the early insights from the niche literature depict incumbents as entrenched in the existing regime, and new entrants are the carrier of the innovation torch (Geels and Schot, 2007a). However, recent evidence considers both incumbents and new entrants as drivers of innovation because of incumbents' strategic expansion and diversification toward niche innovations (Berggren et al., 2015; Geels and Raven, 2006a; Turnheim and Geels, 2019).

Niche actors can face multiple hurdles blocking niche development and progress. Technological, economic, social, cognitive and regulatory lock-in (Geels, 2019) around the existing system makes challenging it an arduous task for niches. Niche failure can also emanate from internal processes on the niche level. These can include: 1) ambiguous formulation of expectations leading to a divergence between niche actors, 2) network fragmentation, 3) narrowed learning processes oriented to technical aspect only of the innovation (Geels and Raven, 2006), 4) uncertainties about user preferences, market development, profitability, 5) lack of cultural legitimacy, and social acceptance. (Geels, 2019). A niche might also face temporal blockage because promises are not satisfied, resulting in disappointment because of commercialisation and demand challenges (Befort,

2021a; Ruef and Markard, 2010). However, this disappointment can lead to formulating a new promise and reorienting expectations to match it (Geels and Raven, 2006a).

A niche has to promote solid learning behaviour and knowledge accumulation to overcome these challenges. Lopolito et al., (2011) argued that the niche actors have to construct networks and linkages to foster knowledge exchange and learning to progress between the different niche statuses (absent, embryonic, proto-niche and full). Actors also need to create communities and social networks that generally advocate for their technology (Hoogma et al., 2002; Schot and Geels, 2008) and manage expectations and visions (Raven et al., 2008; Turnheim and Geels, 2019). To proliferate, expand and consolidate its efforts beyond the boundaries of the niche fostering larger changes (Sengers et al., 2020) and eventually become the dominant rule.

To become the dominant regime, a niche can follow different transition pathways. The choice of the trajectory depends, among other factors, on the type of interactions, in the form of alliances between actors (e.g. new entrants and incumbents) inside and outside the niche (Geels et al., 2016). These alliances play a role in niche diffusion and expansion till they become a dominant regime. However, it is unclear through which processes these coalitions enable the niche innovation to expand and overcome the aforementioned challenges and what form of alliances are needed for a niche to diffuse and reach mass production. In this paper, we will consider the coordination of activities along and cross value chains as one relevant form of alliance to diffuse niche innovation.

2.2 Value chain

Innovation can enhance firms' position in the value chain (Gereffi, 2019). Firms can upgrade their position in the value chain by 1) adopting more efficient technologies, 2) developing new and advanced products, 3) changing the main activities or adding to it by targeting different value chains and sectors with different products and technologies (Gereffi, 2019; Gereffi et al., 2005). Developing new technologies and products can also impact the value chain itself. Some technologies can link multiple value chains in a novel and unexpected way, leading to new value chain emergence (Carrarsi et al., 2018).

In a globalised view of production activities, the literature on value chain studies the coordination of the production and distribution activities (Bair, 2009), the governance of

value-added along the value chain, the management of upgrading trajectories (de Marchi et al., 2013b) and how lead firms drive it as core actors in the cross-border business network. The lead firms mobilise their power and leverage their relationships with suppliers to determine the entry barriers to the value chain and the implications of upgrading trajectories through innovation, for instance (de Marchi et al., 2020).

The relationship between the lead firm and other value chain participants can take various forms. A first categorisation was introduced by (Gereffi and Korzeniewicz, 1994), describing a buyer-driven commodity chain where the lead firms coordinate a highly competent supply base and oblige them to meet specific standards without direct ownership. Another is a producer-driven commodity chain with large integrated firms controlling the production network. Based on this view, lead firms are the driving force behind this structure (Ponte and Sturgeon, 2014).

Continuous research on governance studies governance as the relationships and coordination forms between dispersed firms (de Marchi et al., 2020). Five typologies of governance exist 1) market, 2) modular, 3) relational, 4) captive, and 5) hierarchy. The various types are positioned on an intensity spectrum of three different variables, including the degree of product complexity and specification, the ability to codify it, and suppliers' capabilities to achieve it (Gereffi et al., 2005).

Previous case studies explored how governance plays a role in greening and promoting sustainability in the practices and activities of downstream actors by encouraging innovation activities (de Marchi et al., 2013). The Italian furniture industry case study by de Marchi (2012) highlights that lead firms assumed the responsibility of greening the production activities along the value chain by extending their influence on first-tier and second-tier suppliers. They do so through direct engagement with suppliers by creating incentives to innovate and overcome any costs and by monitoring their suppliers' environmental performance. However, it is worth noting that the greening of the supply chain was only possible because of the deep interactions that took place between lead firms and suppliers in the form of alliances. These alliances were then used to exchange knowledge about quality, standards, and product specifications.

The role of cooperation also arises in the case study of Ponte (2009); Ponte and Gibbon (2005) about quality in wine, clothing and coffee sectors. Lead firms cooperate with suppliers

to develop products that fit the quality demands of lead firms. These products usually require innovative practices and knowledge that suppliers lack but access through alliances with lead firms. In the case of entrepreneurial actions emanating autonomously from suppliers' initiatives, these have to come to answer to lead firms' specifications (de Marchi, 2012), indicating the existence of implicit or explicit collaboration between the two.

2.3 Combining niche and value chain analysis

The successful expansion and proliferation of innovation do not rely only on firms mastering a highly diverse knowledge base or learning and investing in newly emerged technologies and knowledge but also on firms' ability to match their knowledge with products issued from that knowledge and the market altogether. Pavitt (1998) argues that the labour division determines the success or failure of innovative firms. To be successful and commercially produced, any technology needs different constituents produced/assembled by different actors with varying process capabilities (Stephan et al., 2017). The success of technology is hanged upon firms' ability to identify or establish the required alliances and linkages between different processes and the ability of actors to recognise the signals sent by them (Pavitt, 1998).

In a value chain setting, an innovative firm needs to consider the effect of its innovation on the firm's relationships and partnerships with other actors along the value chain (De Marchi et al., 2019, 2013) and maybe other value chains in the case of multi-purpose technologies (Andersen and Gulbrandsen, 2020; Stephan et al., 2017). Lead firms are central in driving value chains. Alliances between them and innovative firms are crucial to match their innovation with lead firms' needs and expectations; otherwise, innovative firms might lose their position in the value chain or abandon the innovation (De Marchi et al., 2019, 2013a; Poulsen et al., 2018). The successful matching results in benefits in terms of market access, competitive advantage, and reinforcing value chain position (de Marchi et al., 2013a; Ponte, 2020). In the niche literature, new entrants and incumbents are both drivers of innovation development. They interact together and build alliances that allow niche innovation to expand and eventually replace the dominant socio-technical regime.

This paper argues that niche innovation needs to integrate a value chain to expand, proliferate, and scale-up. To do so, actors have to develop alliances. Applying the value chain perspective to niche management allows us to include vertical and horizontal alliances in our

conceptualisation of the diffusion of an innovation niche, developing a more integrated approach. Associating the two concepts reveals how actors manage to match their knowledge, products and market to integrate the division of labour and gain more exposure to the selection environment by gradually phasing out the protected space through alliances.

In the case of most modular technological innovations, the confrontation of niche production with mainstream demand in the value chain setting enables the actors to test the compatibility of the innovation with other complementary technological designs. It also allows firms to adapt the innovation to user preferences, find a broader scope of application and utilisation, and explore the possibility of mass production and innovation scale-up. Consequently, the linkages developed vertically contribute to further shaping the innovation, stretching its territory to include more actors, exploring additional applications and gaining legitimacy.

The relationship between the niche and the value chain can take the standard buyer-seller relationship mode, where the value created is tangible and monetary ((Gereffi, 2010; Kaplinsky, 2010; Bröring and Cloutier, 2008). Interaction can also happen through collaborations where value is intangible in the form of new knowledge or new opportunities. For instance, through alliances, firms can access new markets, complementary knowledge and competencies, fulfilling firms' knowledge gaps (Bröring and Cloutier, 2008; Walter et al., 2001). These alliances induce changes at the niche level and in the value chain structure and evolution. Thanks to the new technologies, actors and production activities might be integrated in a novel way linking previously separate industries (Carraresi et al., 2018).

These new linkages can trigger the restructuring of the existing value chains or launch new value chains. The type of the emergent value chain differs based on the innovation characteristics. The new value chain can substitute an existing one (Bröring and Cloutier, 2008), complement another value chain (Bröring, 2010), or create linkages between the steps of value chains, creating value webs. In this paper, we are interested in studying how value chain links can be mobilised by niche innovation to confront it gradually with the selection environment enabling the niche innovation to phase out its protected space, expand, proliferate and gain momentum.

3 Methodology

3.1 Case study selection

We choose microalgae as a case study to answer our question: How do niche innovations in the bioeconomy sectors mobilise value chain links to gain legitimacy, consolidate their position as commercially and economically viable innovations, and diffuse? Bioeconomy is driven by the growing necessity to change our production system (Staffas et al., 2013) by searching for and using new biomass and technologies to substitute non-renewable resources and develop products with the same or new functionalities as their oil-based counterparts (Befort, 2021b).

One promising biomass that received attention in the context of the bioeconomy is microalgae. They are used in their entirety, limiting waste and promoting circularity in the production systems to develop biofuels, biochemicals, and high value-added products in biorefineries using various conversion technologies, closing the production loop (Bauer, 2018; Ubando et al., 2020). They are also being explored for bioremediation and biomonitoring activities (Araújo et al., 2021), wastewater treatment and clean-up of flue gases (Vieira de Mendonça et al., 2021).

This multiplicity of products developed links various sectors, industries, production systems previously distinct such as food, feed, agriculture, energy, cosmetics, pharmaceuticals and nutraceuticals (Fernández et al., 2021), in a new way (B. Golembiewski et al., 2015), as they rely on the same biomass and technologies (Carraresi et al., 2018). Thanks to the technological flexibility, versatility in applications (Rhee et al., 2021), high productivity levels and suitability to grow in different conditions, it became a promising avenue for the development of new sustainable processes and products to mitigate, in an integrated manner, different environmental issues (Vieira de Mendonça et al., 2021).

3.2 Data collection

The data collection for the case study was oriented mainly towards identifying industrial actors to gain information about the date of entry, market segments, products developed, their projects and collaborations with other actors and the latter position in the value chain, main activities and market segments. We rely on multiple datasets to select the main actors explored in this study. First, we gather patent data sets mainly from PATSTAT to

learn about the most innovative actors in the micro-algae sector. The patent data is completed with market research and analysis to identify actors actively engaged in microalgae and incorporate firms that are not necessarily innovative. The information gathered is further strengthened with the project datasets, especially for firms in the EU, where we rely on the CORDIS data, firms' reports, and academic publications. The project database is vital to illustrate how firms collaborate and partner with actors along the value chain to access tangible and intangible value-added. Table 3.1 provides information about the data mobilised for this study and the different periods and sources used to collect it.

3.3 Data analysis

We adopt a single case study approach as it is suitable to conduct an in-depth analysis of the micro-algae niche (Thomas, 2021; Yin, 2008). The in-depth analysis enables us to reconstruct the long term development trajectory of the micro-algae by intertwining the proposed theoretical approach with the empirical evidence to demonstrate the closeness between the two (Eisenhardt and Graebner, 2007). To analyse the data, we develop a multi-layered analysis. First, patents, publications, and projects data were chronologically classified to build a timeline of microalgae niche emergence, niche expansion by promise formulation and consolidation, exploration and evaluation of the viability of the promise, disappointments and recovery phase. Using previous literature and reports, we build a second layer where we identify the political, economic and societal factors contributing to the emergence of the niche to investigate the enabling environment triggering innovations and lock-ins that might trap the innovation inside its protected space. In the two first layers, we rely on historical events analysis as a method, which is a fine-grained analysis that dives into details to gauge theoretical implications from empirical observations (Langley, 1999). The historical event analysis equips us with the correct elements to characterise the promises cycle.

In the third layer, we mobilise a dynamic value chain analysis to identify and differentiate between the value chain segments targeted by niche actors using the value-added by firms to the product development process (Gereffi and Fernandez-Stark, 2011). In this layer, we privilege the project and firms' data to explore firms' business strategies and positions in the value chain to understand how firms' positions in the value chain evolve and change over time following changes on the niche level. We do so by matching firms' supply with existing or future demand for their product. The value chain lens adds to the historical

analysis by focusing on the linkages developed by actors to gradually leave the protected space and reach a place in between the niche and regime where they confront their innovation with some of the selection environment

The final layer of the analysis mobilises all information collected on previous layers to study the implication of niche emergence and evolution on the overall value chain structure. This enables us to identify the different strategies that a niche innovation can follow to become something more and surpass the niche frontiers and to shed light on the complex process by which innovation comes to exist, evolve, and stabilise.

4 Results

4.1 From the nineteenth century to 1975

4.1.1 Discovery of algae and niche formation (1889-1950)

Algae was part of the traditional diet of many civilisations worldwide in Africa, Latin America and Asia, specifically in countries like Mexico Chad dating back to the fifteenth and the sixteenth century (Habib and Ahsan, 2008). Research evidence shows that the interest in algal research started in Japan in 1889, but these efforts crystallised in the 1920s (Coaldrake, 2021). Researchers believe that Second World War was perhaps the catalyst for research in micro-algae to secure lipid sources for the production of fuel and food (Burlew John S., 1953; Coaldrake, 2021). In parallel, leading US institutions conducted algal research in the 1930s, including Harvard University and the California Institute of Technology. However, it was only in the 1940s that algal research gained momentum in the US. Scientists at the Carnegie Institution of Washington picked the scientific interest in *Chlorella* as a part of the project related to understanding the process of plants' photosynthesis (Burlew John S., 1953). Around the same time, European researchers (French and German) discovered micro-algal.

In 1943, the Carnegie Institute's work focused on algae for the war effort; instead of exploring algae as a potential source of food or fuel at this stage, they began to research the production of an antibiotic, chlorellin, from *Chlorella*, but the results were inconclusive. After the war, fuel and food security were recognised as a post-war priority reorienting the research and applying algae to food and fuel production. This shift led to the first patent filled in 1950 by the Carnegie Institute of Washington and granted in 1953 about the cultivation methods of micro-algae (Carnegie Institution of Washington, 1950). This patent, as shown in

Figure 3.1, which depicts the three main stepping-stones that the microalgae niche went through, marks the first step in the formalising trajectory of microalgae and niche construction. The patent indicated the potential commercial value of micro-algae because it is rich in vitamins, vitamin complexes, antibiotics, steroids, protein, fat and carbohydrates. The discovery of the institute also led to the collaboration with Japanese researchers in the 1950s and the Stanford Research Institute led by Arthur D. Little to build the first pilot unit for the cultivation of chlorella between 1948 and 1950.

4.1.2 Knowledge base expansion (1950-1975)

In the '50s, interest in micro-algae rose in different areas around the world simultaneously but in a disconnected manner. These disconnected efforts established their first connection in the Algal Mass Culture Symposium in 1952 (Borowitzka, 2013), representing the second step in connecting efforts on microalgae, as shown in Figure 3.1. The conference included researchers from the US, Japan, Europe, and other countries to survey world knowledge and aid those wanting to cultivate and establish pilot plants. One of the repercussions of this Symposium is the development of various technologies for the mass cultivation of microalgae, such as open ponds, photobioreactors and others.

The primary interest in microalgae as energy sources was recorded during this period. According to Sheehan et al. (1978), Meier is the one who proposed the production of methane gas from the carbohydrate fraction cells using algae in 1955. Oswald and Golueke (1960) further developed this idea by conducting a techno-economic engineering analysis of microalgae biomass to produce methane gas.

In Europe, the French National Scientific Research Centre (CNRS) filled the first French and European patent about algae's accelerated growth and potential application in 1962. Five years later, different species of algae received international attention, primarily due to their potential benefits for food applications. The international association of applied microbiology claimed Spirulina as a "wonderful future food source" (Habib and Ahsan, 2008). The United Nations World Food Conference in 1974 considered Spirulina as the new weapon to fight malnutrition (García et al., 2017). A few years later, the FDA recognised the benefit of spirulina in the book titled "Consumer" (FDA, 1982).

The 70s were specifically crucial for microalgae applications. The oil embargo in 1973 and the slowed research and innovation efforts in chemistry motivated the search for alternative energy sources, especially from algal lipids. The department of Energy in the US launched the Aquatic Species Program, which is considered the most comprehensive effort in algal fuel research. The program was established in 1978 with a 25MUS\$ budget and ended in 1996, yielding scientific advances in algal strain isolation, characterisation, algae genetic engineering, biochemistry, physiology and culture, and conducting techno-economic analyses and resource assessments (Hu et al., 2008).

Still, in the 70s commercial interest grew substantially for micro-algae, the cultivation of micro-algae, which was already happening on a large scale in Japan in the 1960s, reached the USA, China, Israel and other countries with emphasis on *Spirulina* and *Chlorella* (Camacho et al., 2019), especially for food and fuel purposes. Also, 1970 marks the first patent filed by Hitachi LTD, the only industrial player with patents, until 1975, when *Chlorella* Industry Co Ltd filed their first patent for *Chlorella* cultivation. This marks another important step in the microalgae trajectory that gradually evolves to include industrial and academic actors, as shown in Figure 3.1.

4.2 Industrial exploration (1976-to 2001)

4.2.1 First sign of exploration by chemical industry giants (1976-1990)

The economic and political environment in the mid-70s provided the right incentive for using and chasing alternative biomass for energy and bio-based product. The increase in fossil fuel prices, President Carter's famous energy speech about the decreased fossil fuel reserves, and the urgency of alternative fuel sources are just a few examples. These external factors, combined with the rising interest in bio-based products and advancement achieved in the genetic engineering of plants, were the needed trigger to start the industrial exploration of microalgae. Thanks to these incentives, it was not long after the academic discovery of microalgae that industrial corporations joined the race.

Many chemistry firms were on the hunt for new raw materials and biomass to recover the glorious years of the chemical industry suffering from a slow-down in innovation during the mid-'70s. The search for new biomass rich in carbon compounds to produce a wide range of bio-products such as polysaccharides, lipids, pigments, proteins, vitamins, bioactive compounds, antioxidants, and high value-added molecules sparked the curiosity of firms like

Bayer AG, DSM, Du Pont, BASF that started to explore micro-algae in the second half of the 70s and the '80s leading to multiple patent filling in this period by these companies.

The direction of exploration behaviour of these firms differed. DSM's portfolio in the '70s was mainly directed to petrochemicals, pharma, plastic products and energy. However, the first patent filed by DSM in microalgae was meant to explore algal strains with high concentrations of omega 3 for the production of algal DocosaHexaenoic Acid (DHA), an omega3 fatty acid. The earlier motivation of firms like BASF and Dupont focused on using microalgae for biofuel, the substitution of petrochemical-based products, and the development of new functional bio-products.

4.2.2 Materialisation of chemical firms' efforts and new entrants (1990-2001)

The multitude of applications and the promising commercial value of microalgae paved the way for the emergence of firms wholly dedicated to exploiting microalgae. In contrast with the previous period, the interest of chemical corporations crystallised in a different form by financing the creation of subsidiaries devoted to microalgae, such as E.I.D Parry with Parry nutraceuticals; Fuji chemicals created AstaReal. Besides the diversification trend of old chemical firms, new biotech firms emerged. Most firms in our dataset emerged in the 1990s except for two. The first is Martek bioscience, which developed in 1980 as a spinoff of the NASA program exploring micro-algae as a food, oxygen source and waste disposal catalysts in interplanetary missions. The second is Cyanotech corporation, founded in 1983, specialised in cultivating microalgae and producing astaxanthin; the rest of the firms emerged at the beginning of the 1990s. These companies centred their business strategy around specific algal strains that can be mobilised to develop particular applications. These differentiated business decisions indicate that firms think about which market segment and value chain to target.

Some firms that emerged in this period focused on cultivating microalgae, drying and extracting molecules sold for applications in nutraceuticals, human health, skincare and others. They also produce ready to use products that do not need further processing. Examples include AstaReal, specialising in astaxanthin from *Haematococcus Pluvialis*, directed to the production of feed for pets, livestock, aquaculture, and horses. The astaxanthin is also sold to external firms wishing to use it for human health applications and skincare,

such as Now foods which buy astaxanthin supplied by AstaReal to produce skincare products sells tablets and capsules.

Other firms are oriented to only cultivating and selling complete microalgae for direct human consumption. Australian Spirulina cultivates Spirulina and produces spirulina powder and tablets for human consumption. At the same time, a different group of firms are the suppliers of equipment and machinery for algae cultivation, such as Subitec, a producer of photobioreactors. A last group of firms targeted fuel such as Green fuel technology, which grows algae using emissions emitted from a plant to produce biofuel from algae.

These different firms' categories illustrate the foundation of the microalgae niche. Actors started to stream in and strategically choose their position in the value chain. This choice involved the type of product produced (e.g., algal strain, equipment, extracted molecules, final products). In the case of firms cultivating algae, the strain choice implied deciding on the applications to target and the market segment for which the product is intended to shape the innovation and its expectations.

This phase concludes the first stage of microalgae trajectory mainly oriented to knowledge formation and expansion, the early effort of niche construction and network formation as illustrated in Figure 3.1. The microalgae trajectory then evolves to reach the hype and mass entry period (stage 2). The promise fails in stage 3, which describes the disappointment, the reformulation of expectations and innovation survival until it reaches the market. These last two stepping-stones will be discussed in detail below.

4.3 From 2002-to 2015- the formation of a strong promise

This period is characterised by a continuous increase in patents filed, reaching its peak in 2011. It also witnessed a rise in publications after an almost constant publication rate between the 1990s and 2001, as mentioned in Figure 3.1.

4.3.1 Biofuel promise network (2002-2015)

The microalgae journey reached a new stepping-stone in 2002-2015. In this period, the exploitation of microalgae for biofuel received substantial attention triggering the hype stage in the microalgae promise cycle. Algal fuel was considered the solution to energy problems by providing a third-generation alternative biofuel. To develop it, firms need to identify the

strains with a high concentration of lipids⁵ or genetically engineer a cultivated strain to increase its lipid content. This lipid can be later extracted and converted to biofuel (Demirbas and Fatih Demirbas, 2011; Liu et al., 2011).

Considered the “next big thing”, firms were thus built on a bundle of promises. First is the hope of finding the right strain, cheaply mass-producing it. The second is developing the right conversion techniques to scale up to tens of millions of gallons of algal fuel in the span of a few years at prices competitive with fossil fuel. The third is the use of non-arable land and a wide variety of water sources and a substantial reduction in greenhouse gas emissions (Bošnjaković and Sinaga, 2020; Pienkos et al., 2011).

An extensive network was gradually constructed around microalgae in general and algal fuel in particular to support the promise. Many associations and non-profits started advocating for algal biofuel, such as the International Air Transport Association that, led discussions, published reports and organised conferences about alternative aviation fuel, including algal fuel. The purpose of conferences, organised by associations or academics such as Alga Europe and AlgalBBB2023, is to work as a catalyst for synergies and foster alliance building between scientists, industries, and decision-makers to promote and facilitate knowledge exchange and project implementation.

Microalgae received stimulus public funding from entities such as the European Commission and the Department of Energy in the US for research and demonstration programmes. These were carried out by industrials and academics to develop the technology needed to increase algal lipid production. Famous examples include the Framework Programmes since 1985 and Horizon 2020. The hope was to promote biofuel from non-food materials to achieve various climate and energy targets by 2020 (IEA Bioenergy, 2017). Some of the largest projects include the AQUAFUELS project (2009), which resulted in the creation of the European Algae Biomass Association; the Algae Cluster projects with a budget of 31 million euros to demonstrate the production of algal fuel starting by the selection of algae strain to cultivation and production, algal oil extraction, biofuel production and biofuel testing in transportation applications.

In the context of the energy independence and Security Act of 2007 in the US (IEA Bioenergy, 2017) and the DoE top 10 (Bozell and Petersen, 2010), there has been

⁵ A lipid is fatty, oil-containing acid molecule.

considerable support for algal fuel by the Department of Energy (Pienkos and Darzins, 2009) that financed a multi-year program to reach an economically viable algal biorefinery industry. National Alliance for Algal Biofuels and Bioproducts (NAABB) was funded for \$44M as a result. Other consequences of this multi-year program included the funding of three integrated biorefinery demonstration plants with a budget of \$97M. The DoE also financed some firms directly like Solazyme, Algaenol biotech LLC., Sapphire Energy Inc., where the primary purpose was to develop demonstrations and pilot sites (Menetrez, 2012). In other countries, such as Japan, the Kyoto protocol included a biofuel program focusing on second and third-generation biofuel (Herrador, 2016). One of the main goals in Japan is to produce commercially viable jet fuel from algae.

Besides public funds, millions of dollars were mobilised in private investments. The particularity of these partnerships is that it illustrates how actors gradually attempt to confront their protected technologies with the selection environment by building collaboration and alliances with actors situated along the microalgae value chains and parallel value chains. This confrontation is driven by the desire to test the compatibility of the innovation with the existing complementary technological design, the attempt at market and demand creation, and taking the innovation to the “next level” by trying to reach large production levels.

In the case of algal fuel, actors established links with actors situated in different steps of the value chains. Firms emitting CO₂ and wastewater can benefit from these by-products by partnering with microalgae firms. Microalgae firms can build their cultivation unit at the stream of the effluents supplying microalgae with the needed nutrients creating a link between two previously distinct value chains through the cascading usage of by-products.

Still upstream, firms would need specific equipment and machinery sourced from firms such as SCHOTT that supplies glass tubes to Heliae and Algatech. The alliances between algal firms and SCHOTT provides the latter with new applications for its products and enables it to upgrade to a different value chain. These alliances allow the innovation to reinforce its footing by expanding and linking with suppliers from other value chains.

Alliances occurred between algal fuel firms and their supposed competitors: the incumbents' energy firms. These cross-linkages between the energy value chain and microalgae were mainly oriented to demonstration projects to research how to grow and convert microalgae into fuel and study the commercial viability and its capacity to compete

with alternative fuel and energy sources. Chevron partnered with Solazyme to produce and test algal biodiesel. Algenol Biofuels Inc. and Valor Energy collaborated using each other expertise to explore algal fuel for transportation.

To transform the promise into actual production, firms established commercial agreements based on the promise of future firms' ability to produce fuel at a commercial scale. Shell, HR petroleum and Aurora biofuels developed a joint venture called Cellena for algal biofuel production. Cellena established a commercial agreement based on its future production level with NESTE oil for biodiesel production. These linkages are clear examples of niche actors attempting to transform the promises into production by investigating if the innovation can be massively produced or scaled up to the desired level to substitute fossil fuel in the transport sector.

To test the compatibility of algal fuel with engines and motors, algal fuel firms (e.g. Helia; Euglena) sought alliances with transport (e.g., Toyota Prius, Isuzu) and aviation firms (Boeing, SkyNRG) (Menetrez, 2012). These alliances benefit algal fuel firms by accessing complementary knowledge to enhance further and shape the innovations to fit the requirements of future users.

The value chain was mobilised to establish linkages with suppliers, future buyers and users and to identify and invest in actors developing similar technologies. Algal fuel firms invested in each other, pooling their resources and knowledge to achieve a common goal. These alliances include technology licensing, direct investment, and collaboration on demonstrations and pilot plants. These alliances reinforced the niche innovation by allowing actors to work together on enhancing and optimising it.

4.3.2 High value-added product promise (2002-2015)

Concurrently to the algal fuel promise, the development of medium and high value-added products from microalgae emerged as a parallel promise. Micro-algae offers a natural alternative, environmentally sustainable, plant-based substitute to develop nutraceuticals, pharmaceuticals, cosmetics, food and feed products. It was perceived as an alternative to chemically synthesised products and products produced from biomass that have repercussions on food security, water consumption and arable land footprint.

The predicted growth of the bioproduct market developed from microalgae was 53.43 billion USD by 2026, attracting new and old actors. Dyeing agents (e.g., Chlorophylls, Carotenoids, Phycobiliproteins) market reached 300 million USD in 2009, whereas astaxanthin was projected to reach 770 million USD in 2024. The market share of PUFAs, in particular omega 3, was 2.4 billion USD, with the US being a major player. The commercial potential of high value-added molecules attracted many start-ups such as Microphyt, AstaReal, Algisys LLC, Bioprocess alga, Fermentalg SAS. Some incumbents also diversified in these sectors since the mid-70s, such as DSM and BASF, while others joined during the hype period, such as Roquette Frères, that started their algal research in 2006.

Besides the market valuation, the promise of high value-added was reinforced by The FDA publishing the Generally Recognized As Safe (GRAS) list in the US and reviewing it between 1998-2012, encompassing seven algae food-based ingredients (Enzing et al., 2014). This GRAS was the green light on producing novel food products by microalgae firms, which played a crucial role in driving the production of high value-added products from microalgae.

To scale up and expand the innovation, firms established relationships along the value chain. Relationships existed between microalgae suppliers and buyers of raw materials, including cosmetics, nutraceuticals, food, and feed products. Solix sells its microalgae to BASF. Algatech supplies its natural astaxanthin to FujiFilm Corp, which distributes and uses astaxanthin in cosmetics and dietary supplement products.

The alliances between buyers and suppliers took a more integrative approach with the establishment of joint ventures. Roquette Frères partnered with Solazyme in a joint venture to produce and commercialise nutritional and dietary products derived from microalgae. The collaboration aims to provide Solazyme with speedy market entry, access to large agri-food firms, and financial support. Other joint ventures emerged to commercialise the technology used to grow microalgae. IGV GmbH, a producer of microalgae and Bioalgotral specialised in tubular photobioreactors, established a JV where IGV is supposed to use their technology to produce multiple microalgae strains for potential application in food, cosmetics and fuel.

In some cases, actors acquired firms cultivating microalgae and producing high value-added products. For example, DSM acquired Martek in 2011, a pioneer in the microalgae market. However, it is worth noting that acquisition and joint ventures were more common during the survival period.

These linkages illustrate the gradual orientation of niche actors to the production and commercialisation of their products and technologies instead of only focusing on research and development activities. This behaviour indicates how firms with new technologies try to integrate into the existing value chains or develop a new value chain by choosing and positioning their business strategy in different steps of the production activities. Moreover, it shows that upstream firms' collaboration with downstream actors benefits actors upstream as it enables market access and knowledge transfer.

4.4 From 2011-to 2021: the disappointment and the rebound

4.4.1 Biofuel disappointment 2011-2015

Decades of research about algal fuel finally reveal the disappointing reality. The production level aspired by the industry and the cost reduction remains a distant dream. This disappointment was limited to algal fuel and materialised in algal fuel firms' exit from the algal fuel market, as mentioned in Figure 3.1. Many firms went bankrupt, including SBAE industries NV, Algaestream, A2BE Carbon Capture, LLC, Aquavirids, Inc, Sapphire Energy Inc, and Aurora biofuel. The projects conceived with industrial partners stopped and were sometimes deemed unsuccessful. Many conferences were permanently cancelled, and NGOs were dissolved, such as EABA Expo and conference, International Algae conference, and Trimatec.

Many bottlenecks block the development of algal fuel from a technical point of view. (Saad et al., 2019). The difficulty lies in identifying a microalgae strain with high biomass production and high oil content. This strain must be cost-effective, suitable for cultivation in the chosen location and easy to harvest. The cultivation of microalgae using Co₂ emitted from power plants entails the problem of toxic compounds such as NO_x and SO_x. Growing microalgae in an open pond system lead to low productivity, high cost of harvesting, and potential contaminations compared to photobioreactors. It might be true that microalgae cultivation does not need arable land (Leite et al., 2013). However, it requires flat terrains for pond systems. Most harvesting techniques are costly and inefficient in separation leading to low quality of the oil. The production process from collection, concentration, and drying leads to high energy charges and significant greenhouse gas impacts. Despite the research efforts, there are still constraints in achieving high lipid productivity commercially.

From a techno-economic point of view, all these technical challenges entail that the production cost is substantially higher than fossil fuels. To reach the needed production level of algal fuel, cultivation would require higher fertilisers than lignocellulosic raw materials, which requires fewer fertilisers, pesticides, and energy and is cheaper with a lower Co₂ footprint (Bošnjaković and Sinaga, 2020; Singh et al., 2011). Studies show that replacing 5% of diesel with algal fuel requires 123 billion to 143 trillion litres of water (Saad et al., 2005). Using wastewater can be a potential solution with significant drawbacks such as contamination, pathogens predators, and heavy metals. Moreover, wastewater streams can be located far from the cultivation unit rendering their transportation costly and energy-intensive.

The competition with other energy sources made it hard for algal fuel to survive, in the case of cars such as battery-powered electric vehicles and hydrogen-electric vehicles, leaving biodiesel from algae with no market advantage (Bošnjaković and Sinaga, 2020). Electric cars are already more accessible with many governmental directives to facilitate their spread on the European and global levels in the near future. These factors, coupled with the drastic decline of fossil fuel prices between 2008-2011, made it even harder for algal fuel to survive. Climate emergency calls for solutions that can be deployed right now. Algal biofuel has a very long road ahead to overcome the multiple hurdles facing it.

4.4.2 Survival 2015-2021

Despite the disappointment, multiple algal fuel firms survived by shifting their business strategy, production activities, and rebranding to target high value-added products. Only Exxon mobile is still attached to the biofuel promise by continuing funding research with Viridos (formerly Synthetic Genomics, Inc.). The two companies announced that they are using the CRISPR gene-editing technology to develop algal strains that will lead the way to achieve a low carbon fuel. In 2021, Total energies announced its cooperation with Veolia in a four-year research project to cultivate microalgae using Co₂ in la Mede biorefinery with the long term goal of producing biofuel.

Moreover, the idea of exploiting the full potential of microalgae was reinforced in this period to obtain different products simultaneously, leading to a higher market value than the production cost and potentially offsetting the high cost of the algal fuel (Vanthoor-Koopmans et al., 2013). Microalgae biorefineries can transform biomass into fuel, cosmetics, chemicals,

food, feed, and value-added compounds (Chew et al., 2017). These novel applications, along with the old applications in food, feed, cosmetics, and pharmaceuticals, continue to attract new start-ups, but entry is slowed compared to the 2001-2011 period. This biorefinery approach to microalgae implies the possibility of linking the algal fuel value chain to high and medium value-added products.

The idea of maximising the utilisation of microalgae to produce a variety of products along with the fuel was further reinforced when the DoE announced the financing of 11 projects with a budget of 34\$M in 2021. The purpose of the projects was to produce and improve biofuels, biopower and bioproducts for sectors where electrification is still not possible, like aviation and marine using municipal solid waste and algae. The Japanese government and companies also adopted this same strategy focused on jet fuel. Euglena Co., Ltd is a Japanese company that grows the microalgae euglena for cosmetics and food products. In 2010, the company started its biofuel research journey, and in 2018, it opened the first demonstration plant for bio-jet production and biodiesel.

The marine and the aviation sectors are considered a better fit for algal fuel as there is a need for drop-in fuel compatible with the engine and does not require its alternation or replacement. Moreover, the shift included the focus on using microalgae in sectors such as agriculture. Since 2015, the number of agriculture-related patents filed increased significantly, focusing on plant growth and health, biofertilisers, resistance elicitors, weed management, and post-harvest (Murata et al., 2021). Other novel applications of microalgae are environmentally friendly biotechnology processes for wastewater treatment, bioabsorption, and nutrient recovery (Yap et al., 2021).

In this period, actors' alliances took the previously discussed forms, but in addition to it, some actors developed marketing alliances. Some retailers (e.g., Carrefour and Amazon) buy high value-added products in the form of capsules and tablets and sell them to the end consumers. Other supermarkets such as Cora and Supermarché Match push their suppliers to use these molecules as feed, as is the case of salmon suppliers for retailers Match and Cora in France. Many more firms were acquired and joint ventures established, mainly oriented to exploiting high and medium value-added products. Solabia Group in France acquired Algatech LTD, Corbion acquired TerraVia, NextStage AM acquires stakes in Fermentalg. Parry (India) Limited signed a joint venture with Synthite Industries Ltd with an aim to grow

value-added algae-based products. DSM establish a joint venture with Evonik for the same purpose.

Other agreements took the form of marketing and commercial alliances to collaborate in R&D, manufacturing, marketing and sales. AlgaEnergy signs a commercial and marketing agreement with Yokogawa. Fermentalg signs a similar agreement with DDW. These alliances clearly indicate actors' orientation towards exploitation activities by focusing on the commercialisation and marketing of microalgae.

The innovation and its induced alliances influence the structure of petrochemicals' value chains. Thanks to the integrative character of microalgae, it links different products and functions into one system. As industrial boundaries spanner biomass, the line between previously distinct sectors and value chains are gradually blurred (Bröring, 2010; B. Golembiewski et al., 2015). Microalgae create linkages between different steps in various value chains, making it difficult to pin a start or an ending point. In this case, many value chains are meshed together in the form of value webs.

5 Discussion

5.1 How does the value chain enable understanding the diffusion of niche innovation?

In the case of multipurpose innovations, combining the value chain approach with niche analysis highlights the complexity of dynamics resulting from the emergence of a niche innovation linking different sectors. Figure 3.2 illustrates the interdependencies between the main value chain (e.g., microalgae) and adjacent value chains and sectors. As shown in Figure 3.2, the value chain analysis first enables us to survey and include all actors involved in niche innovation through the study of the upstream of the main value chain and the adjacent sectors supplying, producing inputs and delivering services needed for the production in the upstream of the main value chain. At the same time, we also study the different downstream sectors (main and adjacent) using niche innovation to create different products or services. Therefore, this framework underlines that innovation relies on the combinations of existing knowledge and technologies and is usually used and produced by various actors coming from diverse sectors.

Second, the framework shows the interactions between the niche actors and incumbents situated in the main value chains and adjacent industries and sectors. These interactions lead to niche expansion and development where actors participate in exploration and exploitation activities through collaborations shaping the development and the restructuring of value chains and governing the flow of knowledge and products. Exploitation and exploration activities enable firms, through the development of alliances, to subscribe to the labour division, integrate value chains, or develop a new one. Based on the case study findings, we can then argue that the development of alliances among actors situated in different steps of the main and adjacent value chain is the strategy used by niche to surpass the protected space, diffusing and gradually heading towards mass production.

From our empirical case study, we identified different types of alliances that emerge under the exploitation and exploration activities (March, 1991) as these two types of activities deal with the question of value creation and capture in an organisational context (Wilden et al., 2018). First, the exploration activities are centred around risk-taking, discovery, innovation, and flexibility (March, 1991). **Research alliances** mainly characterise exploration activities. These partnerships can include a wide set of actors (niche actors, incumbents, universities, NGOs...) working collectively to experiment, develop and test new technologies. The purpose of these alliances is to share risks between firms through collaborative research and development activities, explore the viability of innovation and bring together diversity in views and approaches and complementary knowledge (de Faria et al., 2010; Hall et al., 2001). The research alliances can take the form of research projects conceived through public and private investments.

While, exploitation activities focus on embedding the innovation into production processes, refining the innovation to increase efficiency, implementation and production (March, 1991). The empirical findings allow gauging different types of alliances that can fall under exploitation activities. They clearly show niche actors attempt to surpass the niche and reorient their efforts from promises to actual production by phasing out the protected space gradually:

- **Conformity alliances:** The aim is to test the compatibility of the innovation against any complementary technological design, reduce technical risks, increase efficiency along value chains, develop standards, access to users' know-how and experiences, seek to

influence their preferences and receive feedback from them and policymakers. Alliances can be in the form of demonstration and pilot projects or joint declarations of intent. Firms might gain exposure, reduce technical risks, improve performance, and gain operating experience based on the type.

- **Buyer-supplier alliances downstream:** Niche actors directly sell their products to intermediate firms/retailers/consumers. If the niche innovation were meant to substitute an existing technology, the introduction of the innovation in the value chain would impact existing suppliers who will have to compete with the new entrant (Geels and Schot, 2007). It is also worth noting that the existing suppliers can diversify by including niche innovation in their production activities. This type of alliance also illustrates the intersectoral linkages. A niche innovation can be multi-purposed, connecting different sectors; therefore, the labour needed to produce an end product is divided between firms with different capabilities and know-how.

- **Buyer-supplier alliances upstream:** These alliances are between the input suppliers delivering products and services needed by producers located upstream of the main value chain assembling and producing the innovation. The niche innovation provides input suppliers with the possibility to upgrade by targeting a new market (Gereffi, 2019; Gereffi et al., 2005). The outsourcing of inputs enables firms to focus on their core capabilities and acquire the needed inputs for the production from specialised suppliers with expertise in the required input (Gereffi et al., 2005).

- **Marketing alliances:** Firms can more easily identify technological gaps, but it is harder to recognise missing capabilities and gaps in market understanding as they are more difficult to measure and identify. Missing market capabilities might lead to innovation failure and eventually abandonment. Moreover, the market partnership contributes to building cultural legitimacy and social acceptance. They also reduce uncertainties about user preferences and help firms gain and keep customers, which is a hard task for new entrants.

- **Reinforcing alliances:** Niche actors collaborate together in different steps from idea generation to product development and launch, implying the existence of a collective process where firms pool together their knowledge and resources in various forms for a common goal through licensing in and licensing out technologies, project collaborations, direct investments, demonstration and pilot projects and even acquisitions. These alliances reinforce the niche as they are mainly between new entrants and enable the unification of internal standards guiding innovation production activities.

• ***Joint ventures (JV) between niche firms and incumbents:*** “JV is created by two or more firms pooling a part of their resources within a common legal organisation” (Kogut, 1988) to produce and sell a given product or service. New entrants can benefit from access to skills, resources, new markets, distribution networks, funds and support from incumbents. However, there are also downsides to JVs. First, both actors have asymmetric goals (Das, 2000). Some incumbents consider JV as just a business investment. Therefore their involvement in technology development and learning processes is limited. Start-ups and incumbents have different organisational cultures, leading to clashes and eventually failure of the JV (Brouthers et al., 1995; Das, 2000).

• ***The acquisition between niche and incumbents:*** It is an opportunity for incumbents to consolidate their integration. Through these relationships, incumbents acquire external knowledge, new manufacturing technologies, and skills, explore new markets, penetrate new technology domains, and generate new products (Hagedoorn and Duysters, 2002). The benefit of an acquisition depends on the firm’s internal knowledge base and its capacity to absorb new knowledge.

• ***Commercial with or without marketing agreements:*** Niche actors and incumbents also developed alliances extending from R&D, manufacturing, and marketing. Each firm will leverage its core competencies. Start-ups mobilise their expertise in niche innovation while incumbents provide knowledge related to increasing efficiency, scaling up production, and any missing capabilities.

Third, this approach reveals the repercussion of a niche innovation emergence and diffusion on constructing new value chain links or modifying existing links. The bioeconomy related niche innovation can induce change and restructure sectors and industries that were once considered stable and mature such as petrochemical value chains. Innovations in the upstream value chain through the usage of new biomass can generate opportunities downstream, while the introduction of innovation downstream will have repercussions on the upstream. In any case, the innovation activities will be distributed unevenly between a heterogeneous set of actors whose alignment is essential for production.

In our case of the bioeconomy, the final form of the value chain is a value web which is very common in the bioeconomy. The new technologies connect various value chains by using by-products or new biomass as a source of novel applications to substitute synthetics and petrochemicals. The established linkages between different value chains do not

necessarily lead to developing a new value chain. These linkages are between specific steps of value chains and not the entirety of the value chain. Therefore, the structure that emerges from the cross-linkage is a value web where many value chains mesh together.

5.2 A dynamics lens of alliances:

Analysing the niche innovation through the promise cycle equips us with enough information to follow actors and study the change in collaboration behaviour in the different periods. Figure 3.3 depicts the various steps of niche emergence and promise cycle and the type of partnership that is most likely to prevail. The figure shows using colour intensity if exploration or exploitation activities are more likely to characterise a given period. A niche innovation starts with the revelation period, where knowledge is discovered at a particular moment in time and in a controlled and intentional environment or through serendipity. The revelation triggers a knowledge formulation and expansion period. At the beginning of this phase, actors (emblematic actors, new entrants, universities, research organisations..) are disconnected, working separately on advancing the knowledge.

The initial attempts at network formation happened through conferences, collaboration for academic publication and research projects with exploration goals commenced by public and academic entities. Therefore, Figure 3.3 shows the isolation and a light green colour for early exploration activities that were mainly between academics and scientists. The alliances between new entrants and incumbents did not crystallise until the mass entry-hype period. Before that, firms worked in an almost isolated manner. The knowledge formulation and expansion phase also emphasises the role of incumbents as early explorers of promising innovations, particularly diversifying firms that move from one sector to another bringing along resources and knowledge that can play an essential role in a technology development trajectory.

The hype period is characterised by 1) the entry of new actors (start-ups and incumbents), and 2) the mobilisation of more funds and resources in the form of private and public alliances between the different actors to conduct exploration and exploitation activities. Figure 3.3 reflects the increase in alliances through the deployment of intensive exploration activities (dark green) and large efforts in exploitation activities (blue). The type of alliance sought by actors differs based on the application of a multi-purpose innovation in a given sector or industry and the position of firms in the central and adjacent value chains.

The disparity in alliances strategy depends on the maturity and stabilisation of the niche innovation in a given sector for multipurpose innovations. For instance, in the case of high value-added promise, actors developed buyer-supplier downstream relationships and joint venture partnerships, while firms working on the algal fuel promise established conformity partnerships and research partnerships.

The exploration and exploitation activities pushed all technical and economic obstacles to innovation diffusion and expansion to the surface. The disappointment is expressed through exits and cessation of firms, projects, and networking events and entities. Both types of activities are ceased; therefore, the heat map shows them in white. However, the factor that contributed to the disappointment will trigger new promises. The innovation survives by orienting actors' expectations to other functionalities to formulate new promises. The new promises require a new type of organisation and a new type of resource allocation. Exploration activities take a back seat, freeing space for more intensive exploitation activities in comparison with the hype period (darker blue), especially partnerships oriented towards production, marketing and commercialisation activities, and through the stabilisation of buyer-supplier relationships along the main and adjacent value chains, joint ventures, acquisitions, marketing and commercial agreements. Finally, exploitation activities dominate entirely in the Market stage.

5.3 Transition policy

At the niche level, innovations are supported by supply-side policies to protect the niche from the current selection environment through subsidies and regulatory adaptations (Verborg et al., 2008). In the case of bioeconomy in general and microalgae in specific, these policies are motivated by the innovation's closeness to the existing regime to find a drop-in alternative for fossil fuel to fit in the current design of vehicles. The same logic was also noticeable in the case of high value-added products that come to provide the same functionalities as their chemical and unsustainable counterparts favouring those that fit into the existing regime, rules, practices and principles (Smith and Raven, 2012b).

This narrative of politicians and the innovation champions consistently downplayed the commercial feasibility red flags present from the start of the niche. The primary focus of public funds and policies was on R&D and demonstration projects and building a vast, diverse network of start-ups, incumbents from outside and inside the regime, universities, and

NGOs that worked on advancing the knowledge and accumulating the necessary know-how (Hellsmark et al., 2016). This focus lacked interest in commercialisation, developing social acceptance and challenging existing cognitive barriers.

To tackle these shortages, there is a need for deployment and procurement policies that focus on a given technology locked-in niche to work on building market demand for the technologies. These policies aim to enable technologies to diffuse and overcome any issue related to cost, uncertainty, and externalities (Schmidt et al., 2016). In other words, the demand side policies fulfil the gaps in technology push policies (Montmartin and Massard, 2015) related to market creation and commercialisation. However, this type of policy was lacking in the case of microalgae and would not have been sufficient for the case of platform biomass such as microalgae.

Besides technology push and demand-pull policies, multi-purpose innovations spanning various sectors require the coordination and the alignment of sectors and industries involved through the development of intersectoral policies or the coordination of sectoral policies (Boon and Edler, 2018; Weber and Rohrer, 2012). Coordination and alignment policies are thus needed to manage innovation with intersectoral applications to avoid bottlenecks and inefficiency while supporting the new technology's diffusion and the proliferation (Stephan et al., 2017). It will also manage knowledge exchange, labour division among actors in the different value chains, boost network formation market and demand creation. Indeed, intersectoral policies that consider the interplay between the innovation and complementary technologies, upstream and downstream, and actors from other value chains are thus crucial to support and incentivise intersectoral technologies to achieve a successful transition.

6 Conclusion

This paper assumes that a niche's commercial development, diffusion and expansion transpire through its integration into labour division and the global value chain. This integration is attained by developing alliances along the innovation value chain (main value chain) and adjacent value chains. We use microalgae as a case study to support the endeavour of our assumption in the development and shaping of the bioeconomy. This seems particularly pertinent for bioeconomy innovation since their underlying innovation dynamics involve transforming the existing petrochemicals value chains to develop sustainable bioproducts to substitute fossil fuel and petrochemical products.

Our findings illustrate that niche innovation integrates the value chain through collective exploration and exploitation activities. Exploration and exploitation activities require different types of alliances between actors from the main and adjacent value chains at different points in the innovation trajectory. The alliances established along the various value chains have repercussions on existing value chains as they lead to restructuring and modifying current value chains. The crossing of the two frameworks is thus useful in understanding how niche innovation diffuses and develops commercially and finally replaces the existing sociotechnical regime. However, for these linkages to transpire, there is a need for policies beyond demand-pull and technology-push to coordinate the innovation-related sectors and industries and facilitate change in the case of multipurpose technologies.

However, our investigation has its limitations. We only cover the case of microalgae; similar studies in other fields might help to validate and improve our conceptual approach. Furthermore, we do not conduct expert interviews, which yields two caveats. First, investigating the experiences and perspectives of the interviewees contribute to establishing a better understanding of the phenomena under study. Second, individual views and knowledge which is essential for shaping social practices.

The current analysis investigates the internal tool used by niche actors. However, it will also be relevant to identify and describe the moment in the innovation trajectory where it becomes a competitive player in the market. The description of these turning points and the mechanisms deployed by innovation actors internally and externally to reach them is thus crucial to complete our understanding of bioeconomy innovation trajectories. Moreover, many bioeconomy innovations rely on by-products to develop new solutions, linking new segments of the value chain where by-products and waste become products produced, transported, distributed and sold on markets. In this context, further questions arise about the circularity of the value chain and to what extent geographic aspects because of the potential difficulty of waste re-localisation drive the development of clusters.

7 Tables and Figures

Table 3.1: Data sources and type

Data Type	Period	Source and purpose
Patent data	1950-1995	<ul style="list-style-type: none"> - Internet research to identify the first patent application by academics and the first patent application by industrial actors/ Reports - The search yielded 35 patents. These patents are used to identify the first actors and their first concrete contribution to the field.
	1995-2017	<ul style="list-style-type: none"> -PATSTAT/ Grey literature/ reports by various organizations -The number of patent filled identified in this period are 8118. -The purpose is to identify the general trend in patent filling in microalgae. This analysis will also enable us to determine and study the promise cycle for microalgae.
	2017-2021	<ul style="list-style-type: none"> -Grey literature/ Reports -The aim is to identify the current state of the microalgae, the main area of interest of firms and actors actively generating knowledge in the field.
Firms	1970-2020	<ul style="list-style-type: none"> Market analysis/ Top 20 inventors from patent data/ online reports by organizations such as WIPO -The total number of firms studied is 75 firms. We took a deep dive in their business strategy, their targeted market segment and product developed. We also based the analysis on the report and newsletters published by the firms. -The analysis is also interested in the collaboration and the alliances built between the different firms and how the actors constructed links along different value chains.
Publication	1995-2017	<ul style="list-style-type: none"> -SCOPUS/Reports -To identify the promise cycle by following the general trend of publications. -To identify the actors who are actively publishing.
Projects	1980-2021	<ul style="list-style-type: none"> -CORDIS EU/ Department of Energy US/ Reports -We collected 833 project funded by the European Commission. The project database is important to map what type of alliances are built, between which types of firms based on their position in the value chain. -For the US, we find the information in reports, grey literature as well as firms' newsletters.

Figure 3.1: Micro-algae emergence timeline

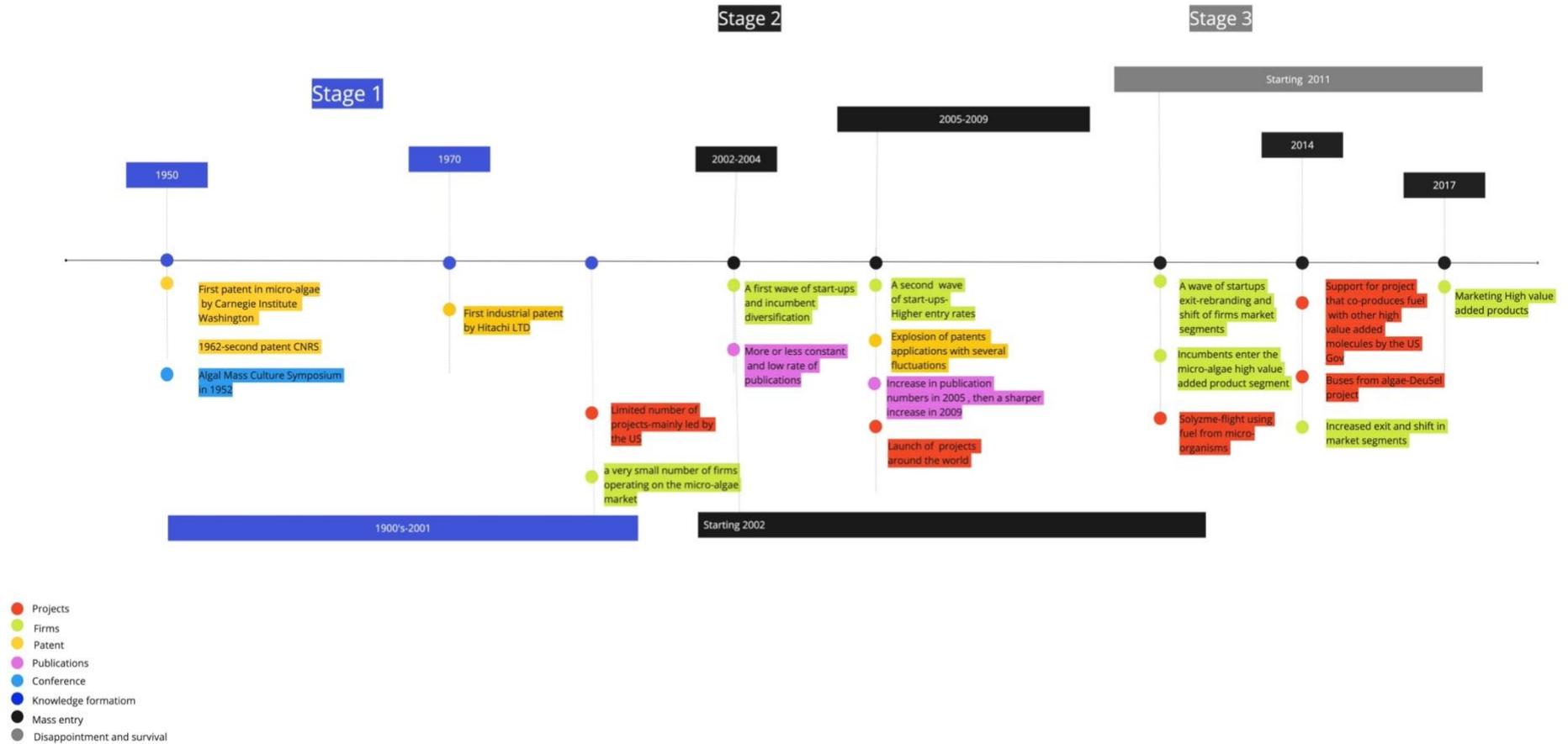


Figure 3.2: Value chain emergence and dynamics

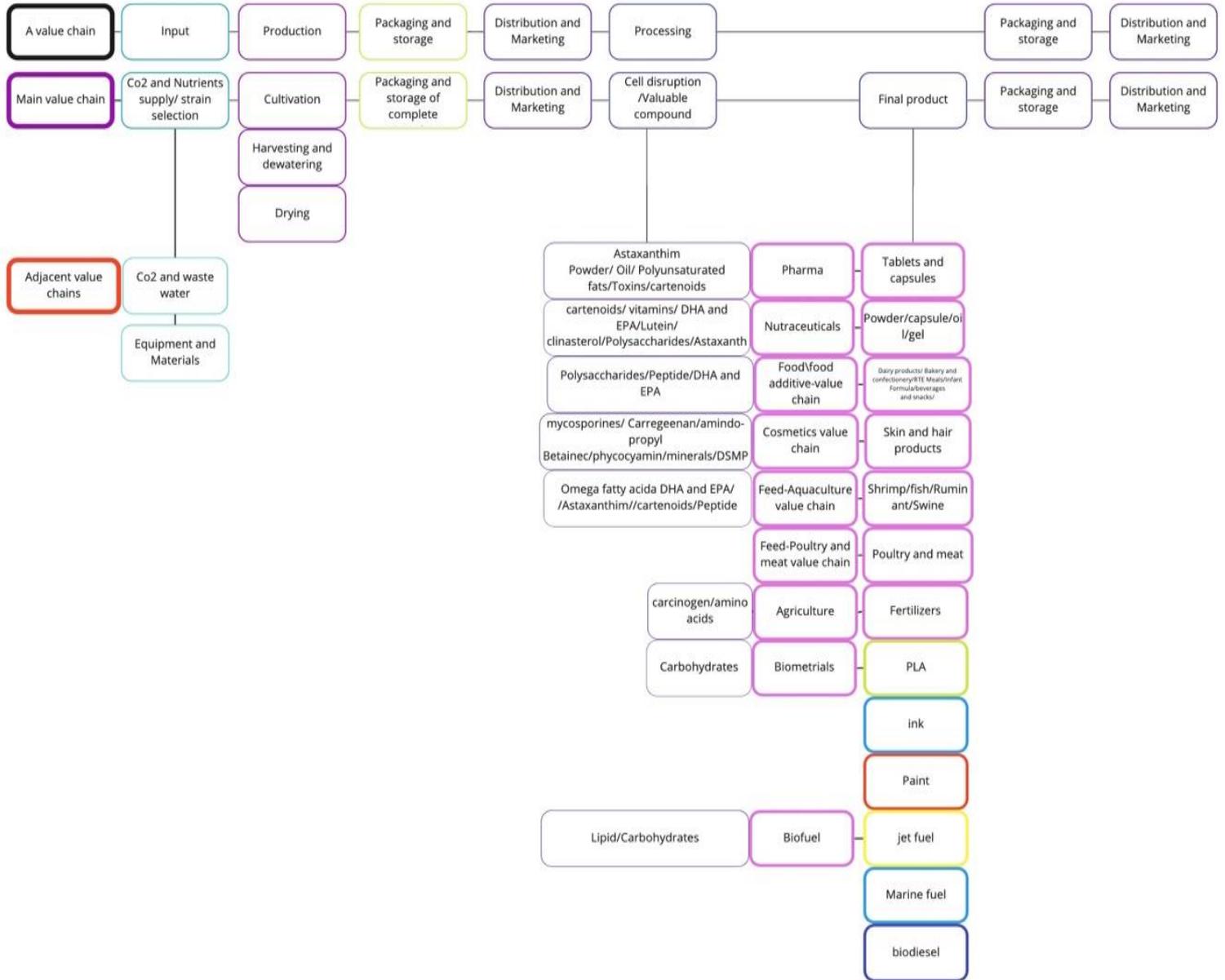
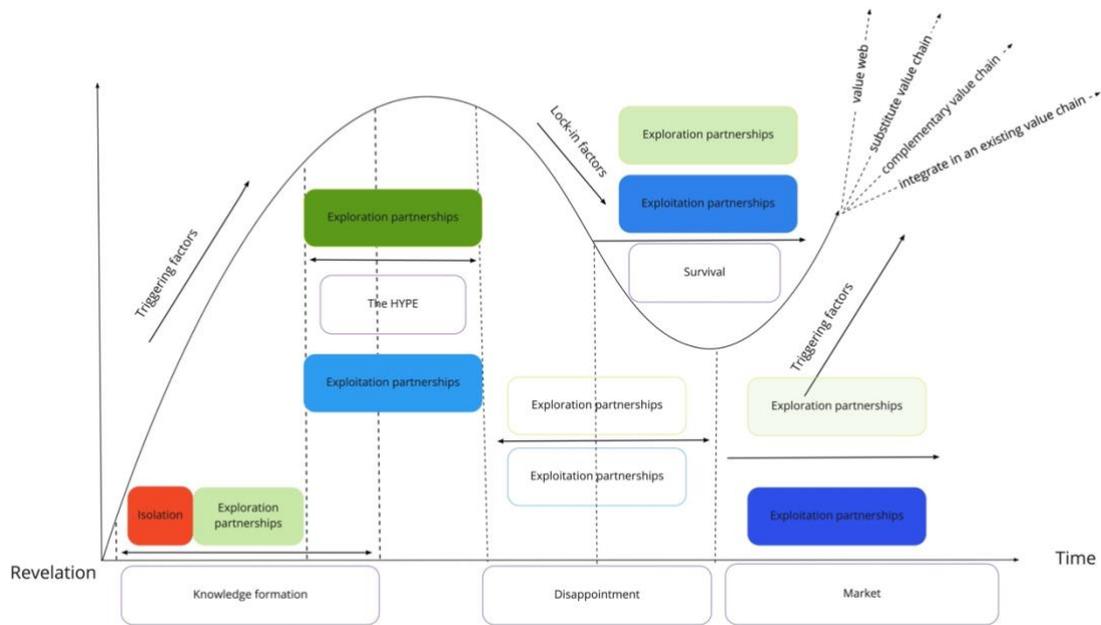


Figure 3.3: Map of alliances intensity in promise cycle



General Conclusion

In this dissertation, we tackle the four challenges identified in the literature by Birte Golembiewski et al., (2015) and van Lancker et al., (2016). The first two challenges are related to the feature and the nature of innovation inputs (e.g., knowledge). While the last two are about the commercialisation and the repercussion of the innovation of the value chain structure. We aimed to study the strategies that actors developed to overcome these hurdles. We do so by adopting an analysis that accounts for actors' sectoral position.

In this spirit, we mobilise a three-level analysis. In the first level, we focus on agriculture as it is the main producer of biomass that will contribute to the bioeconomy (e.g., upstream). At this level, we are interested in exploring challenges related to knowledge complexity and the variety of sources needed to acquire this knowledge. Agriculture industrialisation rendered it reliant on standardised inputs, including knowledge. This knowledge uniformity disrupted the previously intimate and close connection between farmers and their land (Pretty, 1995; Šūmane et al., 2018b). The shift to sustainable farming calls upon relinquishing standard knowledge for plural, diverse and heterogeneous knowledge that comes from a variety of sources. We explore the diversity of knowledge sourcing strategies implemented by farmers to grow different crop types in the first chapter.

We exploit a survey about sustainable agricultural practices and knowledge sources. We use a multivariate probit with a marginal effect calculation. The results enable us to rank the knowledge sources based on their relevance for each crop and practice. It highlights the need for internal and external knowledge sources to innovate in sustainable farming. It shows that knowledge can be used to develop multiple products thanks to farmers' capacity to derive commonalities.

For agriculture in specific and bioeconomy in general, advocacy for a sustainable bioeconomy needs to account for the diversity of knowledge, its complexity and the plurality of strategies that actors can develop to acquire it. In summary, there is not a one size fit all strategy as it depends on farmers' context, objectives and goals. This analysis brings some understanding to the first challenge facing the bioeconomy related to knowledge complexity and the variety of sources needed. This coincides with Levidow et al., (2013) views on how farmers and external actors can come together to develop new knowledge relying on intimate and local knowledge and biological resources.

The second level of analysis focuses on actors downstream engaged in the transformation of inputs and the development of the environmental products and production processes. In the second chapter, we examine the knowledge needed to develop greener production processes and products by investigating the inputs of eco-innovations. In this chapter, we tackle the challenge related to knowledge complementarity. Our reading of the eco-innovation literature describes eco-innovation as complex and multi-disciplinary (OECD, 2011). We inspect this complexity by exploring the contribution of different R&D fields to the generation of eco-innovation. We also inspect the complementarity using Carree et al., (2011) between the different knowledge fields to find evidence of the second challenge of the green and bioeconomy innovation.

We use the community innovation survey for 2014 and data about R&D expenditure developed by the Ministry of Higher Education and Research. We mobilise a bivariate probit with Heckman selection to test our assumptions. We find that different R&D domains contribute to eco-innovation. We also find complementarity between green and biotechnology R&D, which most likely drive a superior eco-innovation. These results highlight the ingredients and the mixing between the different components to eco-innovate. Moreover, it demonstrates the prominent role of biotechnology in the development of eco-innovation.

The diffusion of eco-innovation, including bioeconomy, requires targeted R&D policies to support firms' investment in green R&D. However, these policies should promote green innovation and extend to support the basic sciences that lead to the development of general-purpose technologies (GPTs) like biotechnologies and ICTs. Thanks to their pervasive feature and the increasing synergies between the different technologies, the GPTs can enable environmental and green applications across many sectors, accelerating transition to sustainability and decarbonisation.

The third level of analysis focuses on the whole value chain and examines microalgae as a case study. The value chain lens is useful in the case of the bioeconomy as it has a cross-industry nature linking various industries using the same raw materials for their production activities (Carraresi et al., 2018). In this level (the third chapter), we address the challenges related to commercialisation and the repercussions of innovation on value chain restructuring. This chapter aims to examine the strategies adopted by actors to mobilise value chain links to diffuse, expand and commercialise their innovation.

We adopt a case study approach, and we collect data from heterogeneous sources such as patents, projects, firms, and publications. The findings of this chapter highlight that actors engage in collective exploration and exploitation activities. These activities demand different types of alliances between actors situated in the main value chain of microalgae and actors positioned in adjacent value chains at different points in time in the innovation trajectories. These alliances lead to restructuring the existing value chains and modifying previous relationships along the value chains.

The challenges facing the bioeconomy of commercialisation diffusion can be solved by establishing alliances. If actors engage in alliances, they will access knowledge and practices that they lack, enhance their innovation, find a new application for it, and market it. In other words, these alliances will help them break outside the niche to expand and eventually replace the existing establishments.

The dissertation has several contributions to the literature, which can be seen as follow. First, the complexity of knowledge can be overcome by developing strategic knowledge sourcing strategies. These strategies are not, however, uniform. They are highly dependent on the actors' context, objectives, previous knowledge, and the gaps in competencies to be filled. Second is the need for policies that account for these heterogeneities in knowledge sourcing strategies and facilitate their occurrence, especially in agriculture, where policymakers must work closely with farmers to develop adequate tools for their needs. Third, we contribute to the ongoing debates related to public resource allocations. Eco-innovation has to come first on the policy agenda, but also, we should not neglect that eco-innovation does not happen in a vacuum. Eco-innovation needs other scientific domains for its progress, and these domains require equal attention if we want to achieve and accelerate the transition to sustainability. Fourth, we contribute to transition literature by emphasising the role of alliances as a tool to integrate the labour division and hence the value chain. This integration enables firms to commercialise their innovative products and reach the market. We also show how innovation developed in niches diffuse and the consequences of this diffusion of the form of the value chain.

Our work is not free from limitations. For instance, cross-sectional data constrain our understanding of the different strategies developed by actors to acquire the necessary knowledge to innovate. This is particularly relevant for the first and the second chapter. We also found limitations related to the firm-level surveys where the data did not allow us to

integrate all sources of knowledge (first chapter) or study collaboration behaviour in details (the second chapter). The methodological tools and the data used represented another limitation of the dissertation. We do not account for the endogeneity emanating from the survey sampling in the second chapter, as the data set was restricted to firms with R&D activities. However, it is worth noting that we are solving this issue for the publishable version of the chapter. The final limitation is using one case study (the third chapter). To ensure the validity of our results, we need to apply the framework to other case studies, which can also improve our conceptual approach.

We can also derive multiple policy implications for the bioeconomy specifically and eco-innovation generally. First, policies must facilitate networking and knowledge sourcing. This can happen through developing policies that answer actors' needs and account for actors' the context in which this knowledge exchange occurs. Agricultural policies must be formulated in close collaboration with farmers to integrate best and support their needs. Policies need to provide platforms for face to face interactions and rely less on online knowledge exchange tools because online tools do not function as intended (see the first chapter)

Second, eco-innovation policies must be a top priority; however, policymakers must understand the components and ingredients of eco-innovation to promote eco-innovation. Supporting green R&D is essential, but it is not enough. Policies should also support investments in basic science and encourage synergies between knowledge fields because knowledge recombination is a primary driver of innovation. Finally, the cross-industry nature of the bioeconomy calls for intersectoral policies that account for multi-purpose and industry spanning innovations.

Finally, this dissertation highlighted the need for transition policies. Most policies are supply oriented. However, for green innovation to diffuse, we need more demand-oriented policies. These policies should work on market creation and expansion. We also emphasise that some innovations have a cross-industry nature. Therefore, policies should account for this intersectoral dimension to facilitate the exchange of knowledge and practices, coordinate, and align the different activities needs of actors involved.

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