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

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ABSTRACT

Eco-innovation is a complex activity that requires diverse knowledge and an extensive R&D and technology portfolio. This paper investigates the strategies employed by firms and the extent to which green and non-green R&D can influence eco-innovation. We address two research questions: Is investment in green R&D valuable and sufficient for successful eco-innovation? What types of investment are needed for eco-innovation? Our findings provide a better understanding of the mix of knowledge fields required for eco-innovation. To investigate internal firm R&D strategies we use unique data that allow us to identify the influence of the stocks of green and non-green R&D on eco-innovation and the importance of complementarity among specific R&D strategies and knowledge for eco-innovation. Our findings will be relevant for policymakers and firms, to promote investment in R&D to enable eco-innovation and ensure a quick transition to a green society.

KEYWORDS
Eco-innovation; green R&D; non-green R&D; complementarity; knowledge; biotechnology R&D; ICT R&D

JEL CLASSIFICATION
O30; O32; Q55

1. Introduction

Based on its positive influence on pollution reduction and more efficient use of resources, eco-innovation[1] has been touted as lifesaving in terms of facilitating the transition to a sustainable future (Fagerberg, Laestadius, and Martin 2016). As a result, governments worldwide are being pressed by their societies to provide effective and stringent policy measures to incentivise firms to invest in eco-innovation (Garcia-Quevedo, Martinez-Ros, and Tchorzewska 2022). However, tailored regulation requires knowledge about whether investment in green R&D is worthwhile and is sufficient to achieve successful eco-innovation. Despite the importance of identifying the relevance of green R&D for eco-innovation, current empirical findings on the returns to eco-innovation from green R&D are scarce (although see Lanoie et al. 2011; van Leeuwen and Mohnen 2017) as is work on the impact of green and non-green R&D on green innovation and environmental performance (see Lee and Min 2015).

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[1]In this paper, we use eco innovation, sustainable innovation, environmental innovation and green innovation interchangeably (Schiederig, Tietze, Herstatt 2012). Similarly, we refer to both environmental and green R&D.

Thus, eco-innovation can be considered a black box that reveals little about the types of investment required to eco-innovate. Eco-innovation has been described as complex and multi-disciplinary (de Marchi 2012; Igami and Saka 2007) and based on combining knowledge from diverse fields (Barbieri, Marzucchi, and Rizzo 2020; OECD 2011). Existing empirical evidence is derived mostly from studies that use patent data to identify knowledge recombination, based on International Patent Classification (IPC) codes (Barbieri, Marzucchi, and Rizzo 2020; Nemet 2012). However, this strand of work sheds little light on firms' intentional knowledge diversification strategies and decisions to invest in the production of distinct, but complementary knowledge (à la Milgrom and Roberts 1990, 1995).

In this paper, we investigate what resources firms allocate to knowledge creation, using information on internal investment in three types of R&D: green R&D, biotech R&D and Information and Communication Technology (ICT) R&D. We chose these three types since advances in these individual fields have already provided excellent responses to environmental problems. However, combining these fields could increase the potential for solutions with broader application to address complex issues such as climate change. We use unique French data for 2014 to estimate an econometric model to investigate the influence of environmental (green) R&D and non-green R&D on eco-innovation. We examine the complementarity between green R&D and other types of R&D (ICT and biotech R&D) and the potential for producing superior eco-innovations.

Our results confirm that eco-innovation relies on both green and non-green R&D. They show that eco-innovation is more likely to emerge from a combination of green and biotech R&D. The present paper contributes to the eco-innovation literature at the micro-level, by highlighting the knowledge fields driving eco-innovation. We show that eco-innovation depends on investment in non-environmental R&D and the mix between environmental and other types of R&D and that firms combine knowledge production activities in different R&D fields to achieve eco-innovation. Our work shows, also, that decision-makers need to reassess the priorities related to the search for solutions to environmental issues and the formulation of regulation, which contributes to R&D policy debates on the sustainability transition.

The paper is organised as follows. Section 2 provides a review of the literature and presents the hypotheses. Section 3 describes the methodology, the data used and the estimation procedure. Section 4 presents the results and conducts a sensitivity analysis. Section 5 concludes with a discussion of the results and the implications for managers and policymakers.

2. Literature review and hypotheses

2.1. R&D and the eco-innovation literature

The urgency of climate change has triggered extensive research on the factors affecting eco-innovation (Demirel and Kesidou 2011). These factors include market pull (Horbach, Rammer, and Rennings 2012; Triguero, Moreno-Mondéjar, and Davia 2013), policy (Ghisetti and Pontoni 2015), firm size and location (M. Wagner 2008), technology push in the form of internal R&D, acquisition of external knowledge (Galliano and Nadel 2018;

Ghisetti, Marzucchi, and Montresor 2015; Marzucchi and Montresor 2017), organisational capabilities and environmental management schemes (Wagner 2008).

The existing literature focuses on R&D and environmental R&D as the central determinants of environmental innovation. Green R&D provides companies with multiple benefits. It increases the stock of firm knowledge required to eco-innovate and develop new processes and products (Demirel and Kesidou 2011). It enhances absorptive capacity and allows the firm to transform externally acquired knowledge into eco-innovations (Ghisetti, Marzucchi, and Montresor 2015). It enables the firm to exploit its accumulated local knowledge to resolve certain problems and continue to innovate in those specific fields (Battke et al. 2016), although this may result in path dependency (Popp 2019). There is empirical evidence showing that past eco-innovation and patents affect future innovation (Barbieri, Marzucchi, and Rizzo 2020), which suggests there may be both first-mover advantages and barriers to market entry for sustainable products.

However, although some studies show that 10% of firms have a dedicated environmental R&D budget (Lanoie et al. 2011; Stucki and Woerter 2019), most do not distinguish between green R&D and other R&D activities. They tend to use the general R&D budget to proxy for environmental R&D, which mixes non-green and green knowledge production activities (e.g. Horbach 2008). Despite some empirical differences (Cainelli, Mazzanti, and Zoboli 2011), the literature mostly implies that non-green R&D is the main determinant of eco-innovation, an assumption based on several arguments: 1) that serendipity in R&D can lead directly to eco-innovation; 2) that eco-innovation is a windfall from non-green R&D activities; 3) that the knowledge needed for environmental innovation spills over from non-green R&D projects; and 4) that environmental advances emerge unpredictably as a latent property of existing non-green innovations (see Andriani, Ali, and Mastrogiorgio 2017) and activities not aimed explicitly at eco-innovation (see Steger 1993). Disentangling green from other R&D types is essential for two reasons: first, to allow accurate allocation of R&D budgets and subsidies to green R&D activities; and second, to understand the complementarities among R&D fields fashioned deliberately and strategically by firms to promote eco-innovation.

To our knowledge, only the paper by van Leeuwen and Mohnen (2017) identifies the contribution of green R&D investment to eco-innovation by confirming the positive influence of green R&D on eco-innovation. These authors show that an increase of 1% in eco-R&D intensity increases the likelihood of innovations that allow pollution reductions and resource-savings of 0.36% and 0.24%, respectively. However, they do not investigate the contribution made by multiple R&D fields or their potential complementarities, in terms of achieving eco-innovations. The present article aims to address these points.

2.2. The complexity of eco-innovation

We start from the premise that eco-innovative firms conduct R&D activities in various fields (OECD 2011). Eco-innovation is novel and, compared to other types of innovation, relies on diverse knowledge (de Marchi 2012) from green and non-green domains (Corrocher and Ozman 2019; Dechezlepretre, Martin, and Mohnen 2017; Popp 2019). Such eco-innovation related diversity implies that there are some fields that are crucial for eco-innovations (Barbieri, Marzucchi, and Rizzo 2021) and that it is important to identify their potential contribution to eco-innovation.

Alongside green technologies, which tend to be identified by patent field (e.g. Barbieri, Marzucchi, and Rizzo 2021), the literature also examines green ICT (Faucheux and Nicolaï 2011), which enable greener products and services, for example, ICT systems in cars that allow fuel-efficient driving (OECD 2011). Patent data from large companies can identify green ICT clusters which are more likely to produce eco-innovations (Cecere et al. 2014). Policymakers and institutions also highlight certain General Purpose Technologies (GPTs), such as advanced materials, biotechnologies and nanotechnologies, as important drivers of eco-innovation (OECD 2011, 2012; WIPO 2019). The resulting eco-innovations include those related to waste, agricultural techniques, and pesticide alternatives (e.g. Frietsch et al. 2017).

However, the work in this stream says little about the relative contribution to eco-innovation of these different knowledge fields. The use of patent data can lead to over-estimation of the importance of the knowledge involved in eco-innovation, resulting from the over-emphasis of patent examiners on the contributions made by certain types of knowledge, algorithmic bias in the assignment of IPC codes or inaccurate green technology classifications by scholars and institutions (Angelucci, Hurtado-Albir, and Volpe 2018; Haščič and Johnstone 2011). The body of work not based on patent data tends to focus on R&D collaborations and, thus, provides only indirect insights into the multiplicity of R&D activities driving eco-innovation (Cainelli, Mazzanti, and Zoboli 2011; Galliano and Nadel 2015; Tumelero, Sbragia, and Evans 2019). None of this work examines firms' internal coordinated knowledge production activities or the combination of ICT R&D, biotech R&D or nanotech R&D activities with green R&D, in the creation of eco-innovation.

We draw on studies that underline the strategic and managerial integration of eco-innovation in organisations (e.g. Abbas and Sağsan 2019; Wagner 2008), the complexity involved in eco-innovation (de Marchi 2012) and the share of firms declaring formal R&D activities for environmental purposes (Lanoie et al. 2011; Stucki and Woerter 2019) and hypothesise that firms intentionally allocate and systematically organise their internal knowledge production to eco-innovate. In this case, eco-innovation depends on strategic investment in intentional internal search in multiple fields. This would suggest that eco-R&D is the main driver of eco-innovation. We hypothesise, also, that internal ICT and biotech R&D promote eco-innovation.

H1a: Eco R&D influences eco-innovation positively.

H1b: Non-eco R&D (ICT and biotech R&D) influence eco-innovation positively.

To innovate, firms need to master more than one knowledge field. This technological diversification strategy is used to manage decreasing returns in one area (Cohen and Klepper 1996), to spread the risks among technological opportunities (Garcia-Vega 2006) and to improve absorption of incoming knowledge (Cohen and Levinthal 1989). By combining different technologies, firms are more likely to achieve economies of scope based on some knowledge being available at lower marginal costs and marginal risks, the sharing of the related fixed and sunk costs (Henderson and Cockburn 1996) and better innovation performance (Fleming 2001). In the case of eco-innovation, a portfolio of diverse knowledge, not just green technologies, is required (OECD 2011). Several studies identify the contribution of non-green technologies (e.g. Dechezlepretre, Martin, and Mohnen 2017), confirming that firms use both green (Cunzo et al. 2022) and distant/non-green knowledge to eco-innovate (de Marchi 2012), including GPTs (e.g. biotech, ICTs) (e.g. Santoalha, Consoli, and Castellacci 2021).

This technology diversification behaviour benefits the firm, which, up to a certain threshold is able to derive value from it. Several scholars find an inverted U-shaped relationship between technological diversification and innovation performance (for a survey, see Ceipek et al. 2019). For example, technological diversity can stem from the ability to substitute one technology with another, to enhance yield. Also, some firms might be able to manage and achieve synergies and complementarities (see Milgrom and Roberts 1990, 1995) among technological fields (Granstrand 1998), based on differences among knowledge domains and the ability of the firm to combine them to achieve innovation (Breschi, Lissoni, and Malerba 2003). In this case, the complementarities among technologies will affect the production or adoption of a given technology.

However, the complementarities underlying technological diversification have not been explored. First, most work on diversification is at the output level (for a survey, see Ceipek et al. 2019), whereas identification of strategic complementarity requires analysis at the innovation input level. Second, studies of technology diversification use different complementarity tests for outputs or knowledge types (however, see Kim et al. 2021). Also, despite the finding of an inverted U-shaped curve between eco-innovation and technological diversification, which encompasses a range of knowledge fields (see Cunzo et al. 2022; Ning and Guo 2022), the literature does not provide empirical evidence on the possible complementarities among the different technology fields (such as environmental, biotech and ICT R&D) driving eco-innovation.

Several studies examine possible synergies among knowledge fields that might result in eco-innovation. For instance, the bioeconomy biotech concept (OECD 2009a) has spawned several subfields, such as white biotech which uses biomass as feedstock to develop greener industrial processes with fewer emissions (Lokko et al. 2017; Triguero, Fernández, and Sáez-Martinez 2018; Tylecote 2019). The literature refers, also, to two types of ICTs (Cecere et al. 2014). Green ICTs, which reduce carbon footprints, and ICTs that reduce the environmental impacts of other sectors (Faucheux and Nicolaï 2011). Tylecote (2019) points to examples of ICTs combined with biotech research to enable data analysis and achieve biotech advances in the field of bioinformatics (Lewis, Bartlett, and Atkinson 2016), used to address climate change problems (Appio, Martini, and Fantoni 2017).

Empirically, complementarities behind technological diversification have not been properly explored using adequate estimation techniques (however, see Kim et al. 2021). Moreover, aside from the literature investigating the inverted U-shaped curve between eco-innovation and technological diversification (see Cunzo et al. 2022; Ning and Guo 2022), empirical evidence on the possible complementarities between the different technological knowledge fields driving eco-innovation (environmental, biotech and ICT R&D) is lacking. This is due to the non-availability of data on expenditure on different types of R&D (although see Lanoie et al. 2011; van Leeuwen and Mohnen 2017; Stucki and Woerter 2019). This has led to studies that test indirectly for knowledge complementarities driving eco-innovations. Garcés-Ayerbe and Cañón-de-Francia (2017) provide evidence of complementarity between general R&D stock and green investment, while Antonioli et al. (2018) and Cainelli et al. (2012) respectively provide evidence of complementarity between organisational and environmental management systems and ICT adoption, and ICT adoption and eco-innovation. We hypothesise that eco-innovation is potentially driven by complementarities among diverse R&D fields including ICT R&D:

H2: There are complementarities among internal R&D investments, that is, between green R&D and biotech R&D, between green R&D and ICT R&D and between ICT R&D and biotech R&D.

The search for the most effective knowledge combination from among various technological sets necessitates a strategic and intentional investment decision (Antonelli and Colombelli 2013; Hagedoorn and Wang 2012). The potential combinations of diverse knowledge are vast, and the net benefits are uncertain. The costs tend to be exponential: integrating n different technological knowledge fields in a bundle result in 2^n possible combinations. For binary synergies between two R&D fields, there are $C_n^2 = (n^2 - n)/2$ possible combinations and, in the case of potential synergies among k R&D fields this could reach $C_n^k = n!/k!(n-k)!$ (Fleming 2001; Rahmandad 2019). It is more difficult to search for complementarities in a context of extensive knowledge breadth. A sequential strategy that could be employed by managers would be reducing the number of promising technologies to explore and the identifying the most promising combinations among the selected technologies. The literature proposes many reasons why companies typically explore and exploit a restricted set of knowledge combinations.

One of the main explanations is that the greater the distance among the types of knowledge in the firm's knowledge base, the more difficult it is for researchers and R&D managers with limited cognitive and absorptive capacities (Fleming 2001), to search, identify, coordinate and integrate the different possible dimensions (Carnabuci and Operti 2013; Fleming 2001). A larger distance between R&D fields implies more significant search, codification and transmission costs among interacting specialists (March, 1991; Cohen and Levinthal, 1990; Brusoni, Marsili, and Salter 2005; Galunic and Rodan 1998), as well as additional communication, coordination and integration costs (Hashai 2015; Leten, Belderbos, and van Looy 2007; Zhou 2011). If the interactions concern external R&D sources, additional transaction costs emerge (e.g. Xu and Zeng 2021) from managers' lack of sophisticated portfolio management capabilities (Degener, Maurer, and Bort 2018).

Moreover, knowledge is intrinsically indivisible. Firms cannot combine partial bits of knowledge to achieve synergies (Antonelli 2007; Weitzman 1996). Managers cannot compute the marginal benefits and costs related to interacting R&D investments. Benefits arise only when potential complementary knowledge is fully generated and acquired, incurring high quasi-fixed costs in different technological domains (Warsh 2006). Firms must also consider R&D fields with low returns or high rates of obsolescence (Antonelli and Colombelli 2013) because these can trigger valuable synergies when combined with other top R&D fields.

Consistent with the theory, it has been shown econometrically that both very small and very large knowledge breadth hamper innovation (e.g. Criscuolo et al. 2018; Dahlander, O'Mahony, and Gann 2016; Haus-Reve, Fitjar, and Rodríguez-Pose 2019; Katila and Ahuja 2002; Laursen and Salter 2006). Empirical evidence, using a knowledge complementarity proxy based on the IPC classes of patent portfolios (including backward citations), confirms an inverted U-shaped curve between complementary internal or external knowledge and innovation performance (see Fleming 2001; Hsu and Lim 2014; Keijl et al. 2016; Schillebeeckx et al. 2021).

While firms may manage the complementarities among their main R&D fields of expertise (e.g. within biotech) or derive binary complementarities between biotech and ICT fields, it may be extremely costly and risky to integrate and manage an additional team of researchers specialised in green R&D, within this existing bundle. Nevertheless, firms wanting to benefit from complementarities, will invest a critical mass of R&D resources in unknown and/or distant R&D domains. For instance, green firms must invest in environmental R&D, for instance, to tackle complementarities and synergies between biotech-ICTs. Similarly, firms with initial R&D investment in ICT and Biotech R&D, which are expected to yield high returns, may be keen to invest, also, in low-return environmental R&D (e.g. R&D in bio-based plastics). When exploring multiple possible synergies among different R&D fields, firms will face significant quasi-fixed and often sunk costs because the results of this exploration are uncertain.

In line with arguments about escalating costs and empirical findings on knowledge breadth, we contend that firms are more likely to combine two than three (or even four) sets of R&D fields to achieve green innovations. Very few firms will explore the complementary effects between ICT R&D, green R&D, and biotech R&D fields and even fewer will create innovation from this bundling strategy. Therefore, we hypothesise that:

H3: Firms are unlikely to achieve complementarity among green, biotechnology and ICT R&D inputs in the production of eco-innovation.

3. Methodology

3.1. Data description

To study the complementary relationships among different R&D fields and their impact on environmental innovation, we use data from the 2014 Community Innovation Survey (CIS), which asks firms about environmental innovation. We matched the CIS data with information derived from annual R&D surveys, conducted by the French Ministry of Higher Education and Research (MESRI), for the years 2008 to 2014. The French survey identifies firm-level R&D budgets and different types of R&D expenditure (environmental, biotech, nanotech, ICT, advanced materials, social and human sciences) and public R&D subsidies.

Finally, we matched the CIS data with firm-level data and data on financial links for 2014. The structural (FARE-INSEE and Ministry of Finance) file combines information from tax reports and annual sector surveys, which is used to complement our control variables. The financial link data (Lifi-INSEE) provide information on the groups of enterprises operating in France. Only firms with more than 1.2 million in equity securities, more than 500 employees, or more than €60-million turnover are surveyed. The data allow us also to identify French firms that are part of a foreign business group.

Our final dataset includes 18,419 firms 11,591 innovators and 5,416 eco-innovators.

3.1.1. Dependent variable

The definition of eco-innovation varies (Ghisetti, Marzucchi, and Montresor 2015). Kemp and Pearson (2007, 7) define it as '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 are new to the firm adopting them, which is in line with the Oslo Manual definition (OECD/Eurostat 2018)

CIS 2014 defines eco-innovation similarly. It includes two eco-innovation related questions. First, it asks the firm if it has developed an innovative production process which has environmental benefits such as reducing materials use, energy use, air pollution, water, soil, and noise pollution, replacing materials with less polluting types, substituting fossil fuels with renewable energy, or enabling waste recycling. Second, it asks the firm if it has produced new products and/or services whose consumption leads to environmental benefits such as smaller carbon footprint, reduced air, water, noise or soil pollution or more durable and more easily recyclable products. Our dependent variables are based on the responses to these two questions.

3.1.2. Explanatory variables

Our explanatory variables include the different R&D stocks, as defined in the 2008 to 2014 annual R&D surveys conducted by MESRI. Environmental R&D involves R&D activities to reduce air, soil, noise and water pollution, enable better waste management and enable protection of biodiversity and habitats. The survey use the OECD (2009b, p. 9) definition of Biotech R&D which 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.' Nanotech R&D refers to the study, manipulation, and exploitation of very small-sized (less than 100 nanometres) structures and systems. ICT R&D activities generally focus on software and simulations for research purposes. Advanced materials R&D refers to research into materials that are unique to the firm or new to the market. Finally, social, and human sciences R&D involves economics, management, marketing, and others.

The redistribution of internal R&D expenditure among the different R&D fields may sum to more than 100% due to multipurpose investments. For instance, in the case of a firm declaring investment in ICT R&D, the research may be focused only on ICT, or on ICT used to benefit the environment. In this case the ICT R&D expenditure might be declared as aimed at ICT research and, also, environmental R&D, which can result in double counting.

To estimate R&D stocks, we use R&D survey data for 2008 to 2014 and, since knowledge takes time to generate innovations or patents, employ the perpetual inventory method. We use a depreciation rate for R&D of 0.15, although amortisation rates across technological fields might not be constant and could be higher than 15% (Li and Hall 2020). We add green, biotech and ICT R&D as separate inputs. We build a variable called 'Other R&D' to include nanotech, advanced materials and social sciences and humanities R&D. These four items are used to compute four

R&D intensities (see Table 1). Using R&D stocks instead of R&D flows allows us to approximate the firm's experience in the different R&D fields. Experience enables increased absorptive capacity and lower search and integration costs among fields, which facilitate the recombination of new knowledge (Baker and Nelson 2005).

3.1.3. Control variables

The first set of control variables includes firm-specific factors, such as firm size and sector. Firm size is measured as the natural logarithm of the number of employees. According to the literature, firm size has a positive and significant impact on eco-innovation since small and medium sized firms face higher financial and technological constraints than larger firms and might be less incentivised to eco-innovate (Cainelli, De Marchi, and Grandinetti 2015). We control for sectoral differences (according to the NACE[2] classification) because sectors vary in their technological intensity, which leads to different sectoral innovation dynamics (Gilli, Mancinelli, and Mazzanti 2014; Rammer and Rexhauser 2012). Firms affiliated to a French or a foreign group are considered to have better access than independent firms to information and financial resources which have an influence eco-innovation (Chassagnon and Haned 2015; Mairesse and Mohnen 2004). We control for affiliation using three dummy variables with French group the reference group. In addition, market scope has been shown to influence eco-innovation and, according to Hashi and Stojčić (2013), firms oriented towards local and national markets will invest less in innovation, implying that the intensity of competition affects the firm's innovation decision. We include three dummy variables for market scope (local, national, European, with international the reference group). In addition to internal R&D investment, firms also search external sources for knowledge that will complement their internal knowledge. Therefore, we include a dummy variable for firm cooperation to control for collaboration with external knowledge sources (Cassiman and Veugelers 2006). Finally, in the two-core equations only, we control for policy and market pull factors. We include variables for whether or not the firm considers regulation, market demand and green subsidies to be important drivers of the decision to introduce eco-innovations (Chassagnon and Haned 2015). These latter variables are Likert scales (importance that is null, weak, fair, or high) and are assumed not to be observable for non-green innovators. We retained them because they do not perfectly predict the likelihood to eco-innovate. There is a framing effect caused by a previous question in the CIS, which asked those firms that failed to innovate what hampered their innovation activity. Several firms that did not produce any eco-innovations, listed the factors hampering green innovation as regulation, market demand and green subsidies. While these responses might bias the parameters for the three control variables, they are unlikely to affect the issues of interest regarding our core green and non-green R&D variables.

3.2. Econometric estimation

We estimate the impact of R&D field on eco-innovation, by employing a knowledge production function (Griliches 1979; Hall, Mairesse, and Mohnen 2010). We

[2]NACE is the statistical classification of economic activities in the European Community and is used uniformly by all member states.

Table 1. Variables definition and descriptive statistics.

Variable	Description	Innovative firms mean	Innovative firms std	All firms mean	All firms std
Dependent variables					
Eco-process innovation	Equals 1 if the firm introduced at least one eco-innovation between 2012 and 2014 to (1) reduce materials 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. Set to 0 otherwise.	0.679	0.466		
Eco-product innovation	Equals 1 if the firm introduced at least one eco-innovation between 2012 and 2014 generating environmental benefits after the sale and use of goods and services by 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. Set to 0 otherwise.	0.571	0.494		
Total Innovation	Equals 1 if the firm introduced at least one product, process, organisational or marketing innovation or engaged in any other innovative activity. Set to 0 otherwise.			0.615	0.486
Independent variables					
Green R&D intensity	Firm's green R&D stock expenditure in 2008–2014, per employee, in logarithm.	0.022	0.555		
Non-Green R&D intensity	Firm's non-green R&D stock expenditure in 2008–2014, per employee, in logarithm.	0.240	0.957		
Biotech R&D intensity	Firm's biotechnology R&D stock expenditure in 2008–2014, per employee, in logarithm.	0.039	0.445		
ICT R&D intensity	Firm's ICT R&D stock expenditure in 2008–2014, per employee, in logarithm.	0.113	0.757		
Other fields R&D intensity	Firm's residual R&D calculated as R&D stock in other fields (e.g. nanotech, advanced materials, social sciences and humanities), per employee, in logarithm.	0.438	1.357		
R&D intensity	Firm's R&D stock expenditure in 2008–2014, per employee, in logarithm.			0.314	0.973
Cooperation	Equals 1 for firms cooperating with external actors for innovation activities. Set to 0 otherwise.	0.487	0.499		
Market demand	Equals 1 for firms considering market factors a highly important driver of the decision to introduce innovations with environmental benefits. Set to 0 otherwise.	0.184	0.388		
Green regulation	Equals 1 for firms considering existing regulation or taxes or future environmental regulation or taxes as highly important drivers of the decisions to introduce innovations with environmental benefits. Set to 0 otherwise.	0.341	0.474		
Green subsidies	Equals 1 for firms considering government grants, subsidies or other financial incentives as highly important drivers of the decision to introduce innovations with environmental benefits. Set to 0 otherwise.	0.072	0.258		
Size	Number of employees, in logarithm.	4.922	1.637	4.264	1.580
Foreign group	Equals 1 if the firm belongs to a foreign group. Set to 0 otherwise.	0.244	0.429	0.168	0.374
French group	Equals 1 if the firm belongs to a French business group. Set to 0 otherwise.	0.530	0.499	0.516	0.499

(*Continued*)

Table 1. (Continued).

Variable	Description	Innovative firms mean	std	All firms mean	std
Independent firms	Equals 1 if the firm does not belong to an industrial group. Set to 0 otherwise.	0.226	0.418	0.316	0.465
Local market	Equals 1 if the firm sells locally. Set to 0 otherwise.	0.866	0.340	0.896	0.303
National market	Equals 1 if the firm sells nationally. Set to 0 otherwise.	0.846	0.360	0.693	0.461
European market	Equals 1 if the firm sells in the European markets. Set to 0 otherwise.	0.660	0.473	0.458	0.491
Other countries	Equals 1 if the firm sells in the Non European markets. Set to 0 otherwise.	0.451	0.498	0350	0.477

European markets are the UE market countries plus Albania, Bosnia and Herzegovina, Kosovo, Liechtenstein, Macedonia, Montenegro, Norway, Serbia, Switzerland, Turkey.

NACE dummies are not listed in Table 1. They are defined at 2-digit NACE code level (Nace Rev 2) for the following industries: Food, Beverages and Tobacco (10–12), Textile (13–15), Wood, paper and furniture (16–17, 31), Printing (18), Petroleum and Chemistry (19–20), Pharmaceutical (21), Rubber and non-metals (22–23), Metal (24–25), Manufacturing (26–30, 32), Reparation (33), Electricity and gas (35) Wastewater (36–39), Construction (41–43), Trade (45–47), Hotels & Restaurants (55–56), Transport services (49–53), Information and communication (58–63), Financial and insurance services (64–66), Scientific Activities (69–75), Other services (77–81).

consider that risky investments in knowledge production, primarily R&D activities, will lead to innovative outputs. Following this logic, risky investments in green R&D activities should lead to green innovative outputs whereas non-green R&D activities will be likely to lead to non-green innovation. We follow the R&D spillovers literature and consider both types of R&D in the same production function: R&D investment leads to intra-firm cross spillovers, typically through inter-projects, inter-plants and inter-divisions. In this case, green R&D is likely to enable firms to develop non-green innovation while non-green R&D is expected to help firms achieve green innovations (e.g. Dechezlepretre, Martin, and Mohnen 2017). In addition to investigating cross spillovers, we need to examine the mechanisms at play if we consider both green and non-green R&D activities. A critical aspect is the identification of complementarities between green R&D and non-green R&D, where non-green R&D includes biotech R&D, ICT R&D and other R&D fields.

First, we implement equation (1) using a bivariate probit model where Y_i^*, the two interdependent latent variables, are product and process eco-innovations with observed values 1 or 0. This controls for possible correlation between the error terms, measuring the complementarity between two types of eco-innovation (Bönte and Dienes 2013).

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

We assume that only innovative firms responded to the eco-innovation part of the CIS. To control for potential bias due to eco-innovation being observed only for innovative firms, we implemented a Heckman probit selection equation with R&D investment as the main driver of innovation.

The selection equation specification is similar to the two outcome equations. Innovative firms are more likely to invest in R&D even if such formalised expenditure is not always observed for marketing and organisational innovation. The effort to produce knowledge is approximated by the stock of internal R&D expenditure, which we split further into green R&D intensity and non-green R&D intensity. We consider that green R&D may trigger product and process innovation as well as innovation in marketing (packaging, logistics, etc.) or the organisation of firm processes. Non-green R&D is likely, also, to influence the types of innovation which could be green or non-green. We include control variables for firm size and NACE 2-digit industry, which explain a large part of the variance. As already mentioned, we introduce additional variables to control for firm's market scope, which influences the spread of fixed costs and the market and learning opportunities. We control, also, for lack of R&D investment by foreign groups located in France compared to their usual level of R&D, and the fact that independent firms do not benefit from intra-group externalities.

We add a fourth equation which includes an instrument variable, as a robustness check, to address the possible endogeneity of green R&D investment. Estimation of multivariate probit models with sample selection also requires an exclusion variable, which is difficult to identify since the selection variable determinants are similar to the determinants used in the outcome equation (see Cameron and Trivedi 2005). As a robustness check, we consider the variable French DoD Direction Generale de l'Armement (DGA) R&D contract as likely to trigger innovation, but unlikely to explain a positive or negative influence on environmental innovations related to defence products or processes or products or processes introduced by firms operating in commercial markets. The share of DoD R&D contracts in internal R&D budgets is found to be significantly ($Pr < 1\%$) and positively related to the probability of being innovative, controlling for other observed variables. In the overall model (available upon request), the coefficients listed do not change and the standard errors of our core green and non-green R&D variables are not deflated, suggesting proper identification in our core model.

Finally, we test the complementarity among our three variables: green, biotech, and ICT R&D intensity, implementing Carree et al.'s (2011) approach. The test is written in equation (2) and its transformation is presented in equation (3):

$$Y_i = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_{12} x_1 x_2 + \alpha_{13} x_1 x_3 + \alpha_{23} x_2 x_3 + \alpha_{123} x_1 x_2 x_3 + \varepsilon_i \tag{2}$$

$$\begin{aligned} Y_i = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_{12}(x_1 x_2 - x_1 x_2 x_3) + \alpha_{13} x_1 x_3 + \alpha_{23} x_2 x_3 \\ + (\alpha_{12} + \alpha_{123}) x_1 x_2 x_3 + \varepsilon_i \end{aligned} \tag{3}$$

We are interested in the significance of the coefficients α_{12} or the $(x_1 x_2 - x_1 x_2 x_3)$ variable and $(\alpha_{12} + \alpha_{123})$ for the $x_1 x_2 x_3$ variable. The t-values of the former is t_1 and 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 with either $t_1 > t_c$ and $t_2 > -t_d$ or $t_1 > -t_d$ and $t_2 > t_c$ where t_c and t_d are critical t-values. The critical t-values are $t_c = 1.96$ and $t_d = 1.65$ at 10% for a significant two-sided level test.

4. Results

4.1. Descriptive statistics

Firms involved in market, organisational, product or processes innovations or involved in some other type of innovation activity represent more than half (61%) of the dataset (see Table 1 and Appendix Tables A1 and A2). More than half (68%) of innovating firms also developed process eco-innovations while 57% developed product or service eco-innovations. The highest R&D intensity is for ICT, followed by biotech and then green R&D. Around 50% of innovative firms cooperate with external actors to access the competencies needed for their innovation activities.

Among innovating firms, around 34% declared regulation to be an incentive for introducing environmental measures and eco-innovation while 18% reported market demand to be an important driver of eco-innovation. Only 7% of firms considered subsidies a strong driver of the decision to eco-innovate. Most firms target and sell their products in the national market (around 85%) compared with 66% who sell in the European market. Roughly the same percentage (ca 24%) of firms are independent or are affiliated to a foreign industrial group. Table 1 reports other descriptive statistics.

4.2. Econometric results

Tables 2 and 3 report the results of the bivariate probit with Heckman selection. Table 2 includes the variables for green and non-green R&D and Table 3 reports the results for different subcategories of non-green R&D.

The findings show that green R&D has a positive influence on the probability of eco-innovation. It is significant for eco-product and process innovations at the 5% p-value. Table 2 shows that a 1% increase in green R&D increases the probability of eco-product innovation by 5.6% (e.g. an increase of 5.6 percentage points of the probability at the average point) and the probability of eco-process innovation by 3.9%. In Tables 2 and 3, eco-process and eco-product innovations are complements (correlation among residuals significant at $p < 1\%$).

The results support *H1a* about the role of green R&D in eco-innovation. Apart from the positive influence identified, the findings suggest that green R&D is more relevant for eco-product than for eco-process innovation. The results in the literature are mixed due to the different measures used for eco-innovation and green R&D. Our results are close to those obtained by Frondel et al. (2007) and are compatible with van Leeuwen and Mohnen (2017). The variable non-green R&D reveals, also, that a 1% increase in non-green R&D increases the probabilities of eco-product and eco-process innovation by respectively 3% and 4%. As expected, the magnitude for non-green parameters is lower than for green R&D as in Lee and Min (2015).

If we break non-green R&D down into its different categories (see Table 3), we find that biotech R&D has also a positive and significant effect on eco-process innovation at a p-value of 5% and increases the probability by 5.3%. However, for eco-product innovation the impact is negative and insignificant. This might be due to the use of biotech to develop greener technologies and incorporate them into production processes, as in the case of white biotech (see examples in Triguero, Fernández, and Sáez-Martinez 2018; Tylecote 2019).

ICT R&D contributes to eco-product innovation, increasing its probability by 1.7% at the 1% level. However, the impact of ICT R&D is not significant for eco-process innovation. The findings are in line with the literature on ICT firms diversifying into eco-innovation (Corrocher and Ozman 2019) and the importance of ICT adoption for driving eco-innovation (Antonioli et al. 2018). The variable Other R&D has a positive and significant impact on both eco-innovation types, increasing their probability by 7%.

Table 2. Bivariate probit regression with sample selection.

	Eco-process innovation		Eco-product innovation		Total Innovation
Variables	Coefficient	ME	Coefficient	ME	Coefficient
Green R&D intensity	0.0712***	0.0390	0.103***	0.0560	0.123***
	(0.0126)		(0.0126)		(0.0177)
Non-green R&D intensity	0.0746***	0.0409	0.0549**	0.0299	0.193***
	(0.0219)		(0.0216)		(0.0221)
Cooperation	0.193***	0.0615	0.249***	0.079	
	(0.0348)		(0.0364)		
Size	0.171***	0.0940	0.116***	0.0634	0.168***
	(0.0132)		(0.0135)		(0.00974)
Foreign group	0.0541		0.0698		0.100***
	(0.0463)		(0.0496)		(0.0388)
Independent firms	−0.0431		0.0339		−0.115***
	(0.0436)		(0.0469)		(0.0298)
Green regulation	0.775***	0.2474	0.558***	0.1771	
	(0.0423)		(0.0398)		
Market demand	0.218***	0.0698	0.627***	0.1990	
	(0.0716)		(0.0664)		
Green subsidies	0.117		0.207***	0.0656	
	(0.0908)		(0.0787)		
Local market	0.133**	0.0425	0.119**	0.0377	0.113***
	(0.0518)		(0.0568)		(0.0430)
National market	0.204***	0.0652	0.246***	0.0784	0.307***
	(0.0530)		(0.0542)		(0.0329)
European market	0.239***	0.0764	0.132***	0.0420	0.301***
	(0.0453)		(0.0481)		(0.0326)
Log- pseudolikelihood		10257.26			
ρ innovation equations		0.8183***			
		(0.013)			
ρ with selection eq. residuals	0.946***		0.942***		
	(0.013)		(0.012)		

*, **, *** respectively 10%, 5%, 1% level of significance.
N = 11591 observations with 5416 innovative firms.
Sector dummies are included and defined at *2-digit* NACE code *level* (Nace Rev 2).
French groups and other countries' market are taken as a reference.
Errors clustered by group identification number.
Marginal effects (ME) calculated at the sample mean.

This finding highlights the importance of investment in other fields, such as nanotech, materials or social sciences.

These findings support *H1b* about the role of non-green knowledge for generating eco-innovation. In the case of eco-innovation in processes, non-green compared to green R&D has a larger influence on the innovation probability and vice versa for eco-product innovation, where green R&D has a stronger influence.

The influence of collaboration is slightly greater for product innovation (8%) compared to process innovation (6%), suggesting that external sources contribute more to product innovation. Bearing in mind our reference to possible biases in the regulation, subsidies and market demand coefficients, our results suggests that firms that report regulation as important for promoting environmental innovation are more likely to eco-innovate, with a 25% and 18% increase in the respective probabilities of eco-process and eco-product innovation. Firms that consider green subsidies to be important are more likely to develop eco-product innovation while those that consider market demand to be an important driver of green innovation are more likely to be involved in both eco-process and eco-product innovation. The marginal effect is higher for eco-product innovation (20%) compared to eco-process innovation (7%),

Table 3. Bivariate probit regression with sample selection.

	Eco-process innovation		Eco-product innovation	
Variables	Coefficient	ME	Coefficient	ME
Green R&D intensity	0.0795**	0.0436	0.146***	0.0801
	(0.0368)		(0.0413)	
Biotech R&D intensity	0.0970**	0.0533	−0.0001	
	(0.0470)		(0.0169)	
ICT R&D intensity	0.00842		0.0317***	0.0174
	(0.0106)		(0.0105)	
Other fields R&D intensity	0.132***	0.0723	0.127***	0.0694
	(0.0212)		(0.0220)	
Cooperation	0.199***	0.0636	0.258***	0.0822
	(0.0346)		(0.0359)	
Size	0.162***	0.0888	0.121***	0.0612
	(0.0129)		(0.0133)	
Foreign group	0.0485		0.0654	
	(0.0467)		(0.0498)	
Independent firms	−0.0546		0.0290	
	(0.0441)		(0.0463)	
Green regulation	0.774***	0.2477	0.558***	0.1780
	(0.0420)		(0.0393)	
Market demand	0.226***	0.0724	0.616***	0.1964
	(0.0684)		(0.0618)	
Green subsidies	0.112		0.213***	0.0680
	(0.0874)		(0.0764)	
Local market	0.132**	0.0421	0.122**	0.0389
	(0.0518)		(0.0571)	
National market	0.211***	0.0673	0.246***	0.0784
	(0.0530)		(0.0550)	
European market	0.245***	0.0785	0.136***	0.0432
	(0.0451)		(0.0479)	
Log- pseudolikelihood		−10270.69		
ρ innovation equations		0.821***		
		(0.013)		
ρ with selection eq. residuals	0.946***		0.944***	
	(0.116)		(0.088)	

*, **, *** respectively 10%, 5%, 1% level of significance.
$N = 11591$ observations with 5416 innovative firms.
Sector dummies are included and defined at 2-digit NACE code level (Nace Rev 2).
French groups and other countries' market are taken as a reference.
Errors clustered by group identification number.
Robust standard errors in parentheses and marginal effect (ME) calculated at the sample mean.
The sample selection equation is not reported.

which is as expected since it refers to market demand for greener products (Cainelli, De Marchi, and Grandinetti 2015; Horbach, Rammer, and Rennings 2012).

In the case of the other control variables (see Table 3), firm size has a positive and significant impact on eco-process and eco-product innovation with respective marginal effects of 8% and 6% at the 1% level. Affiliation to 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, in line with previous literature (Chassagnon and Haned 2015). Firms targeting local, national, and European markets are more likely to innovate, with a larger impact for firms targeting European markets, which is consistent with Hashi and Stojčić's (2013) findings. As expected, in this selection equation, large and intensive R&D firms are more likely to innovate (Cainelli, Mazzanti, and Montresor 2012; Chassagnon and Haned 2015; Mairesse and Mohnen 2004).

4.3. Complementarity tests

Table 4 reports the results of the complementarity tests. We find complementarity between green and biotech R&D for eco-process and eco-product innovation, which supports *H2* about the synergies between biotech and green R&D. Firms using both types of R&D simultaneously are more likely to develop eco-innovation, which is evidence of the performance gains to be derived from simultaneous investment in green and biotech R&D. These findings are in line with work that suggests that biotechnology is contributing increasingly to the development of green technologies and that research at the interface of these fields is responding to many environmental challenges (OECD 2009a).

Among the other types of R&D strategy tested in Table 4, we found neither complementarity nor substitution effects. Synergies are limited to the combination of two R&D strategies, where the marginal returns from one strategy are unaffected by more or less investment in the other strategy. These findings provide partial support for *H2* and fully support *H3*. It should be noted that the findings for *H3* might be due to the fact that, the results of the R&D survey show that only 33 firms declared simultaneous investment in ICT, biotech and environmental R&D and even fewer firms declared investment in four fields simultaneously.

Table 4. Complementarity tests.

Eco-innovation	RD fields	t_1	t_2	Test results
Eco-process innovation	Green X Biotech	3.31***	3.43***	Complement
	Green X ICT	1.05	0.26	Independent
	Biotech X ICT	−1.22	−0.88	Independent
Eco-product innovation	Green X Biotech	3.01***	3.33***	Complement
	Green X ICT	1.83*	0.62	Independent
	Biotech X ICT	0.47	0.31	Independent

*, **, *** respectively 10%, 5%, 1% level of significance.
Complementarity occurs when either $t_1 > t_c$ and $t_2 > -t_d$ or $t_1 > -t_d$ and $t_2 > t_c$.
where t_c and t_d are critical t-values. 1.96 and 1.64 at $p < 5\%$ and $p < 10\%$ for example.
Sector dummies are included as control variables. Errors clustered by group identification number.

4.4. Robustness checks

Table 5 reports the robustness checks. To deal with the endogeneity of R&D investment, we instrumented green and non-green R&D using two R&D subsidy variables, although we recognise that R&D subsidy could also be endogenous (see Mina et al. 2021). The first instrument refers to green subsidies or funds received by firms; the second refers to non-green subsidies to develop non-green innovations. We tested only for the impact of green and non-green R&D on eco-innovation, adding two more R&D equations to our core model. The impacts of green R&D on eco-innovation are similar to the results in Table 2, but the size of non-green R&D is more than twice as large (impact of green R&D on eco-process innovation becomes significantly different from 0 only at the 11% level), confirming the critical role of non-green R&D for eco-innovation.

Table 5. Bivariate probit with sample selection and instrumental variables (Core variables only).

	Eco-process innovation		Eco-product innovation		Green R&D intensity		Dirty R&D intensity	
Variables	Coefficient	ME	Coefficient	ME	Coefficient	ME	Coefficient	ME
Green R&D intensity	0.0900	0.0285	0.105**	0.033**				
	(0.0557)	(0. 0173)	(0.0439)	(0.0135)				
Non-green R&D intensity	0.150***	0.0474	0.130***	0.0412***				
	(0.0463)	(0.0146)	(0.0474)	(0.0150)				
Green Public subsidies					0.743***	0.0014***		
					(0.0762)	(0.0005)		
Non-green Public subsidies							0.252***	0.0907***
							(0.0116)	(0.0039)

*, **, *** respectively 10%, 5%, 1% level of significance.
Green subsidies and non-green subsidies are used to control for endogeneity of Green R&D and Dirty R&D respectively.
Other variables for eco-process and eco-product innovation are as in Table 2.
For the two R&D equations, explanatory variables include size and the instrument variables (Green fund and non-green fund).
The sample selection equation is not reported.
Errors clustered by group identification number.
Robust standard errors in parentheses and marginal effect (ME) calculated at the sample mean.

5. Discussion and conclusion

In this paper we studied investment in green and non-green R&D using econometric methods. We made three assumptions. First, firms should not invest only in green R&D in order to achieve successful eco-innovation. Second, eco-innovation requires some internal mixing and matching of R&D strategies. Third, knowledge diversification strategies have limitations due to the characteristics of knowledge and the costs of diversification.

We showed that green R&D is crucial for producing eco-products and services and environmental production processes. Involvement in green R&D activities implies that the firm is keen to benefit from the low-carbon product market, which is forecast to increase yearly up to 2050 (Stern 2007). It implies, also, that firms are willing to increase their stocks of environmental protection knowledge despite the risks related to green R&D. This knowledge can be mobilised to produce new applications and processes (Demirel and Kesidou 2011).

We contribute some novel insights about the eco-innovation knowledge base. Eco-innovation is complex and requires diverse knowledge (de Marchi 2012; Marzucchi and Montresor 2017). We have shown that advancements in green technologies rely not only on momentum in eco-innovation but also incorporate knowledge developed in non-environmental fields. These findings indicate the complexity of eco-innovation, which combines various competencies and knowledge bases and imply that firms have to maintain a portfolio of diverse knowledge spanning technologies such as ICT and biotech.

ICTs and biotechnologies are generic, pervasive and have wide economic application (Gault et al. 2014). They can contribute to and accelerate transition to a sustainable society (Corrocher and Ozman 2019; OECD 2011). The literature discusses these benefits in the context of ICTs and provides practical examples of products and processes that use biotech, nanotech and advanced materials to develop greener technologies (Cecere et al. 2014; Corrocher and Ozman 2019; Tylecote 2019). Our paper is novel in providing the first micro-level evidence of how firms allocate their internal resources among different R&D strategies to generate knowledge that can be used subsequently to eco-innovate.

We demonstrated that the influence of green R&D on eco-innovation advances is more significant for firms that are also involved in non-green R&D. This is consistent with studies that provide evidence of complementarities among resources invested in environmental protection and investment in organisational innovation, environmental management systems (Antonioli et al. 2018; E. R. Wagner and Hansen 2005) and general innovation strategies (Garcés-Ayerbe and Cañón-de-Francia 2017).

We found evidence of complementarity between green R&D and biotech R&D, but no evidence of complementarities among other R&D fields. Our results suggest that a bioeconomy, based on greener processes, less waste and pollution and increased energy efficiency enabled by biotechnology applications, could be the solution to climate change and the sustainability transition (Epicoco, Oltra, and Saint Jean 2014).

Despite the limitations imposed by use of cross-sectional data and lack of variables for an open innovation strategy, we believe that our results have important implications for decision makers. We showed that green technologies depend on a wide range of R&D activities that can be as or more important than spending solely on green R&D. Green innovation strategies and policies should go beyond a narrow categorisations of research and should include generic knowledge with broad application across technological fields, including green technologies, and/or should strive for cross-sectoral and cross-institutional coordination among a range of innovation fields and policies (see Mazzucato, Kattel, and Ryan-Collins 2020).

Policymakers and managers should consider supporting firms' development of complementarity among knowledge fields because: 1) investing in green R&D provides increased benefits thanks to complementarity with other resources; 2) identifying these complementarities would allow firms and policymakers to direct their investments and resources to internal and external knowledge search to achieve the best and most cost-effective combinations to promote innovation and improve firm competitiveness; 3) multidisciplinarity is key to achieving a sustainable transition and crystalising new concepts such as the bioeconomy; and 4) these combinatory technologies require private and public R&D spending, and more effort should be directed to supporting the development of synergies among knowledge fields.

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Appendix:

Table A1. Correlation matrix when total innovation = 1.

	Eco-process innovation	Eco-product innovation	Green R&D intensity	Biotech R&D intensity	ICT R&D intensity	Other fields R&D intensity	Log (L)	Market factor	Green regulation	Green subsidies	Cooperation	Foreign group	Independent firms	Local market	National market
Eco-process innovation	1														
Eco-product innovation	0.584*	1													
Green R&D intensity	0.0263*	0.0677*	1												
Biotech R&D intensity	0.0511*	−0.0780	0.0818*	1											
ICT R&D intensity	0.0478*	0.0478*	0.0679*	0.0296*	1										
Other fields R&D intensity	0.1170*	0.1509*	0.319	0.0634*	0.3502*	1									
Log (L)	0.2318*	0.1673*	−0.406*	0.0265*	0.2285*	0.2600*	1								
Market factor	0.2307*	0.3301*	0.0885*	0.0337*	0.1072*	0.1804*	0.2080*	1							
Green regulation	0.4152*	0.3704*	0.0282*	−0.0093	0.0916*	0.1920*	0.2608*	0.3447*	1						
Green subsidies	0.1523*	0.1664*	0.0337*	−0.0192*	0.0373*	0.0862*	0.1030*	0.2078*	0.2750*	1					
Cooperation	0.2110*	0.2284*	0.0477*	0.0781*	0.1834*	0.2467*	0.3054*	0.1938*	0.1894*	0.0994*	1				
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			
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		
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	
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
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*

*: 1% level of significance.

Table A2. Correlation matrix for selection equation.

	Innovation	Total R&D intensity	Log (L)	Independent firms	Foreign group	National market	European market
Innovation	1						
Total R&D intensity	0.2320*	1					
Log (L)	0.2750*	0.2488*	1				
Independent firms	−01531*	−0.1182*	−0.3293	1			
Foreign group	0.1364*	0.1323*	0.2010*	−0.3065*	1		
Local market	−0.0536*	−0.1268*	−0.0944*	0.0909*	−0.1529*	1	
National market	0.2754*	0.2800*	0.2296*	−0.1391*	0.2280*	−0.1051*	1
European market	0.2602*	0.1792*	0.2384*	−0.1513*	0.1789*	−0.1194*	0.5224*

*: 1% level of significance.