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Do financial constraints hamper environmental innovation diffusion? An agent-based approach*

Paola D'Orazio[1] Marco Valente[2]

March 22, 2018

Abstract

We develop a model that combines evolutionary economics concepts and methods with environmental economics concerns. The model is populated by consumers, heterogeneous firms, and a financial sector and is used to investigate the dynamic interactions between the demand and supply side, and the role played by binding financial constraints, in the diffusion of environmental innovations. The aim of the model is to understand how environmental goals can be effectively promoted and achieved in presence of a financial sector whose lending attitude is guided by *long-termism* rather than *short-termism*. We show that financial constraints act as a *deterring barrier* and affect firms' innovation strategies as well as the evolution of technological paradigms. When financial constraints are less binding, firms do not perceive hindrances to the adoption of eco-innovation and, as a result, the presence of the average green technology in the market increases.

Keywords: Environmental Innovation, Agent-based Computational Economics, Financial Barriers, Green Finance, Short-termism, Deterring barriers, Credit constraints.

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1 Introduction

The focus on environmental innovation is of concern for policymakers, not only in the process of adoption and diffusion of eco-innovation at the micro level but also because it is related to the success of macro policies aimed at a low carbon economy transition.

In our model, we focus on financial constraints to environmental innovation and investigate the extent to which financial barriers are a deterrent for the adoption of eco-innovation. This analysis is important because eco-innovation is a key element for the achievement of energy and environmental policy goals and transition toward a sustainable economy.

Our approach combines evolutionary economics concepts and methods, and environmental economics concerns; this methodological choice is based on the evidence that the treatment of environmental innovation in a maximization framework is of limited relevance (Jaffe et al., 2002), while the evolutionary approach proved to be a valid alternative to standard aggregate models (see van den Bergh, 2007, among others). Indeed, as highlighted in (Kiesling et al., 2012, p.2):

"*Aggregate models [...] are not designed for what-if type questions. [...] these models do not explicitly consider consumers' heterogeneity and the complex dynamics of social processes that shape the diffusion and can therefore tackle only a limited set of theoretical issues. Aggregate models have also been criticized for a lack of predictive and explanatory power*".

In this work we contribute to the growing literature adopting the the agent-based modeling methodology. Although being a relatively recent analytical tool, at least in the economics field, its flexibility in dealing with heterogeneity and complex dynamics has attracted many scholars (Tesfatsion, 2006; D'Orazio, 2017), studying issues such as financial markets (Delli Gatti et al., 2005), economic growth (Dosi et al., 2010; Lorentz et al., 2015) and environmental issues (Bleda and Valente, 2009; Faber et al., 2010). The attractiveness of agent-based simulations relies on the possibility to freely choose the assumptions concerning the elements of the model. This is particularly relevant when studying innovations, agents with heterogeneous behaviours and dynamics far from equilibrium, each of them a characteristic preventing the adoption of standard modeling techniques. Moreover, a careful implementation of agent-based model and analysis of its results provides the opportunity to observe in detail the dynamics resulting from every configuration, and therefore providing robust explanations to the simulated phenomena (Valente, 2017).

The motivation for considering the interaction between the financial sector and environmental innovatio is twofold. First of all, external financing (Myers, 1984; Vos et al., 2007) is relevant especially for SMEs and new innovative firms in the case of R&D investments (Schumpeter, 1942; Nelson, 1959; Arrow, 1962). Second, the role of banks is overlooked in existing environmental innovation diffusion models. Third, we claim that the financial sector plays a crucial role in the transition toward a more sustainable economy (Campiglio, 2016), especially because estimates report the current values of green investments to be insufficient to limit the climate change to 2°C, as agreed in COP21[1]. More long-term financial capital is needed for green investments (Mazzucato, 2015), as well as a reform of the current macroprudential regulation (Basel III) which seems to encourage investments towards liquid, short-term less risky high carbon technologies.

The paper is organized as follows. Section 2 presents a literature review on models of eco-innovation diffusion and discusses the motivation for carrying out a research that takes explicitly into account the role of the financial sector. Section 3 presents the model and in section 4 we describe the sequence of the events and the scenarios investigated in the simulations. In section 5 we report and discuss simulations' results. Section 6 provides concluding remarks, discusses policy implications of the investigation carried out in the paper and presents the directions of future research.

2 Background and literature review

Our paper contributes to two streams of research. On one side, our investigation is concerned with ecological innovation processes and market dynamics, where the aggregate demand influenced by consumer preferences plays a crucial role (see Malerba et al., 2007; Nelson and Consoli, 2010; Valente, 2012; Schlaile et al., 2017, among others). Innovation diffusion has been studied by using several different techniques, ranging from mathematical to management approaches, and recently, many researchers have adopted the agent-based simulation approach in that it is very suitable to model the emergence of complex phenomena, thus overcoming many limitations of the standard approaches (see Kiesling et al., 2012, for a review). In particular, investigations on environmental innovation diffusion typically use simple decision rules based on cost minimization or heterogeneous reservation prices; falling prices and the positive externalities of social interactions are also usually assumed. These models put a lot of emphasis on the impact of preferences on technological change[2].

On the other side, our paper contributes to the literature on eco-innovation diffusion by taking into account the impact of financial constraints. Some contributions on the link between innovation and finance can be found in the endogenous growth literature (King and Levine, 1993b,a; Aghion and Howitt, 2008) and in the

[1] For additional information, see (Buchner et al., 2017), which offers a broader overview of how much money is being devoted towards low carbon projects.

[2] Among others, many contributions developed co-evolutionary models of users-producers (Janssen, 2002; Windrum and Birchenhall, 2005; Schwarz and Ernst, 2009), extensions of the Nelson-winter model (Malerba et al., 2007), diffusion models with increasing returns (Frenken et al., 2008; Weisbuch et al., 2008) and network models (Janssen, 2002; Kocsis and Kun, 2008; Hohnisch et al., 2008).

evolutionary economics research that echoes the Schumpeterian approach (Caiani et al., 2014). However, to the best of our knowledge, it is overlooked in existing eco-innovation literature that relies on the ABM approach. Moreover, it worth pointing out that the banking sector is still neglected by other models that deal with climate issues, such as Integrated Assessment Models (IAMs) and ABMs, as well. IAMs are general equilibrium economic models and so far have provided key insights into mitigation options and climate change dynamics; nevertheless, some researchers (see Ackerman et al., 2009; Stanton et al., 2009, among others) have recently raised concerns regarding their ability to capture relevant dynamics (see Balint et al., 2016, for a review). In the ABM literature, many scholars are focusing on climate issues from different perspectives (see Moss, 2002; Haas and Jaeger, 2005; Gerst et al., 2013; Isley et al., 2013; Rengs et al., 2015, among others), but the role of the financial sector is still overlooked.

The motivation for considering the financial sector in our investigation is twofold. First of all, external financing is relevant especially for small and new innovative firms in the case of R&D investments (Schumpeter, 1942; Nelson, 1959; Arrow, 1962). This category of firms usually do not have internal funds available for R&D and have to resort to external financing (Myers, 1984; Vos et al., 2007). Nevertheless, they experience higher costs of capital than larger firms and these costs are only partly mitigated by the presence of venture capital. Additionally, the lack of appropriate resources (internal and/or external) is relevant because this prevents the adoption of green strategies by firms and hinders the implementation of macroeconomic policies at a global level (energy and environmental policies).

Second, several estimates concur in evaluating the current values of green investments insufficient to limit the climate change to 2°C. Indeed, even if the the Climate Policy Initiative[3] reports that total global climate finance was increasing between 2011-2014 (it was 9% higher in 2014 than in 2012; see Figure 1) and that \$ 1.195 trillion were invested in renewable energy and energy efficiency, these resources are still not suffient to meet the goal. It is estimated that about \$ 13.5 trillion is needed over the next 15 years (See Figure 1) to implement the national climate pledges (the so-called "Nationally Determined Contributions, NDCs") countries made at the COP21, and additionally, \$16.5 trillion are necessary over the next 15 years to meet the NDCs plus the additional investment to limit global temperature increase to 2°C. In order to achieve the goals of the COP21, participating countries agreed on three basic measures to be undertaken: (1) Gather appropriate financial flows (2) Set up a new technology framework (3) Develop an enhanced capacity building at global level[4].

[3]For additional information, see `https://climatepolicyinitiative.org/` offers a broader overview of how much money is being devoted towards low carbon projects.

[4]See `http://unfccc.int/documentation/decisions/items/2964.php` for detailed information and an overview of the decisions that led to the last Conference of Parties (COP21). Here `http://www.cop21paris.org/` more details about the objectives and recommendations of the

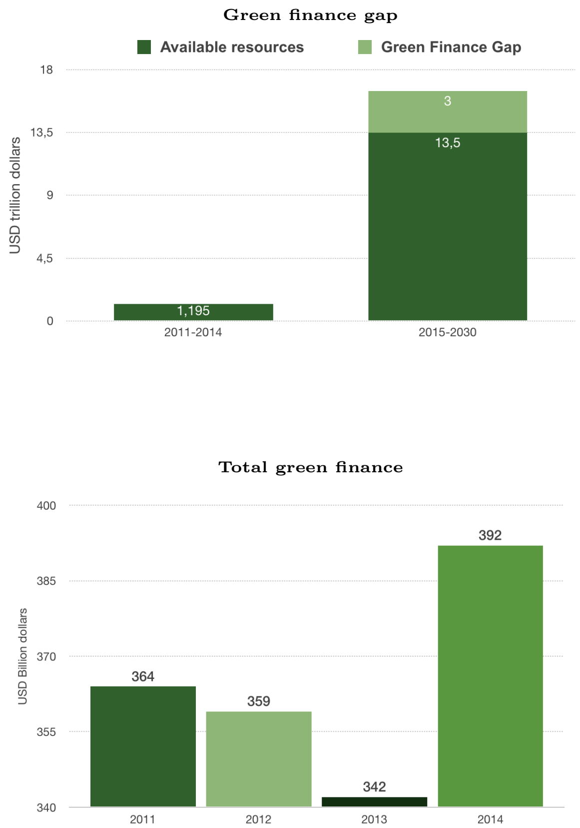

Figure 1: Green financing gap, USD trillion dollars (upper panel). Total Climate Finance, years: 2011-2014, USD billion dollars (lower panel). Source: Authors' elaboration on Climate Policy Initiative data.

Low investments in low-carbon capital are mainly due to the fact that *eco-innovation* is peculiar and fundamentally different from standard non-environmental innovation processes. Environmental innovation entails all the changes in the product portfolio or in the production processes that tackle sustainability targets and any action implemented by firms to reduce their environmental footprint (see Kemp and Pontoglio, 2011; Rennings, 2000, among others). It is characterized by two externalities: it helps to reduce the negative environmental impact of the production process and, at the same time, it entails knowledge spillovers and imitation effects that produce positive externalities (Rennings, 2000). Additionally, it implies higher costs and risky returns on investments. This implies that adverse selection is highly possible in presence of eco-innovation. Moreover, the long-term discounting of low carbon investments requires more patient long-term committed financial capital (Perez, 2004; Mazzucato, 2013, 2015).

The post-crisis macro-financial framework - which is the landscape over which our analysis will be conducted - is characterized by instability of the banking sector and

COP21 that was held in Paris in December 2015.

in particular, by increasing costs of bank's credit and decreased willingness to lend (especially long-term). Banks are indeed more willing to adjust their balance sheet by constraining credit and securing safe assets (Koo, 2013) rather than pursuing the highest rates of return on (necessarily risky) green investments. This results in a higher credit rationing which affects those firms that want to invest in green technologies[5], thus constraining also their full capacity utilization.

3 Model description

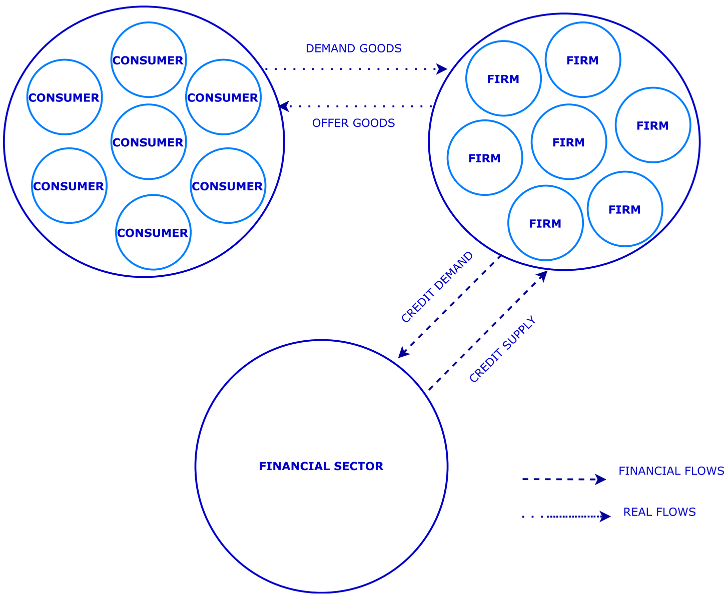

Figure 2: The model: graphical representation

The model is composed of 3 types of actors: heterogeneous households, heterogeneous firms and one banking sector. Figure 2 presents a visualization of the economy and the most important interactions, both real and financial, among the actors[6].

The demand side is composed of one or more consumer classes indexed by $c \in \{1, \ldots, C\}$, defined by their preferences and size (number of members of the class).

The supply side is represented by a collection of firms indexed by $f \in \{1, \ldots, F\}$. Each firm offers a product differentiated along three distinct product characteristics

[5]An important aspect of this conceptual framework is that the focus is on bank lending, rather that market debt or equity, because it represents the most common source of external finance, especially for small and medium size firms.

[6]The model is implemented by using the LSD platform (Laboratory for Simulation Development). See www.labsimdev.org for additional information. The code is available upon request.

or qualities: convenience, $e_f(t)$, user quality, $b_f(t)$, and "green" quality, $g_f(t)$. The first variable, computed as a negative function of the price, express the preference of consumers for cheaper products. The user quality represents the performance of the product as used by consumers. Finally, the green quality is negatively related to the environmental impact caused by the product.

The banking sector is very stylized at this stage of the research. It is meant to provide financial resources to firms that want to innovate. In line with existing literature, in our model we stress the importance of consumers' preferences in shaping the demand. Indeed, an important feature of the model is that innovation decisions towards a specific technology are *demand-driven*, because firms actively search for new market niches since the potentially new characteristic can be perceived differently by consumers. The diffusion of products' characteristics in the market are dependent on the availability of financial resources to fund innovation costs. Rather than focusing on subsidies (Cantono, 2009) or governmental support of R&D, R&D tax incentives , we add a new element to the analysis, i.e. the financial sector and we study the effects of financial constraints on innovation strategies and the evolution of technological paradigms.

3.1 The demand side

The demand side determines the level of sales for each firm using an equation based on the combination of the three qualities of the product produced by each firm: $e_f(t)$, $b_f(t)$, and $g_f(t)$.

Qualities are represented as positive aspects, so that consumers prefer, other things being equal, products with a higher level of one characteristic. The user quality of a product represents the performance of the product when used by the consumer, and the green quality indicates the impact of the product on the environment during its production, use or disposal. The convenience characteristic is a negative function of price of the product, defined as follows:

$$e(t) = \frac{M^e}{1 + e^{\gamma(p(t)-\hat{p})}} \tag{1}$$

where M^e is a parameter that bounds from the top the level of convenience, γ is a parameter regulating the slope of the function and $\hat{p}$ determines the position where price affects the convenience more strongly.

The use of the logistic function permits the determination of a maximum and minimum level of convenience so that even huge price differences beyond certain upper and lower limits do not affect the convenience.

The demand of a product is determined in two stages. Firstly, the utility of each product f for the class of consumer c is computed:

$$U_{f,c}(t) = \alpha_c^e \times e_f(t) + \alpha_c^g \times g_f(t) + \alpha_c^b \times b_f(t) \tag{2}$$

where the α_c^* expresses the consumers' class preferences for each characteristic.

The second stage computes the market shares of the class for each product by normalizing the utility for each product, according to the following expression:

$$ms_{f,c}(t) = \left(\frac{U_{f,c}(t)}{\sum_{j=1}^{F} U_{j,c}(t)} \right)^{\beta} \tag{3}$$

The system parameter β determines the concentration of market shares.

3.2 The supply side

3.2.1 Computation of sales

The total level of sales for each firm f from all class $c \in \{1, ..., C\}$ is computed as follows:

$$S_f(t) = D_c \sum_{c=1}^{C} ms_{f,c}(t) \tag{4}$$

where D_c corresponds to the size of the consumer class, supposed exogenously determined.

3.2.2 Price

Firms are assumed to have variable costs $c_f(t)$ and set their price as a mark-up over the costs:

$$p_f(t) = c_f(t)\,(1 + \mu(t)) \tag{5}$$

Firms compute their profits as:

$$\pi_f(t) = (p_f(t) - c_f(t))S_f(t) \tag{6}$$

3.2.3 Innovation

Firms explore three different potential innovations: decreasing production costs $c(t)$, increasing user quality $b(t)$ or increasing green quality $g(t)$. We assume that the technological landscape is constrained so that it is possible to improve one characteristic only at the cost of reducing the value of the other two. We calibrate the model so that the worsening effect on neglected characteristics is smaller than the improvement effect on the target characteristic. Consequantly, firms may potentially alternate innovation projects concerning the three different characteristics, obtaining as overall results the parallel improvements in all aspects of the product. This strategy, however, reduces the speed of innovation on a single characteristic, which could be improved more quickly by accepting the constant worsening of the others (Bleda and Valente, 2009). The assumption that only one characteristic can be targeted by a single innovation project is clearly a limitation in terms of realism of the model, but does not affect the overall results in terms of aggregate innovation pattern and overall market structure. The reason is that in our model the firms have the possibility to vary the characteristic to improve by means of innovation, and therefore obtain any combination of innovation.

We assume that each firm determines its innovation strategy in terms of probabilities to engage in R&D projects meant to improve one characteristic. These probabilities are determined randomly and do not change during the life time of a firm[7].

3.2.4 Financial resources and innovation financing: firms-bank interaction

Once a firm determines the kind of innovation project, it needs to find a financing institution willing to lend the necessary funds. We assume that the financial sector assesses differently innovation projects depending on which characteristic they aim at improving.

Credit demands differ for the type of innovation (i.e., green, user quality, convenience) the firm wants to carry out. At each time step, firms send their loans' demands to the financial sector; credit rationing and credit risk are accounted for. Regarding the former, for simplicity of implementation and clarity of results, this version of the model assumes that the likelihood for a firm to receive a loan to fund a research project is an exogenously fixed probability identical for all firms, irrespective of their credit conditions. Such radical assumption permits to better appreciate the effect of financing policies on the innovation pattern at system level. In the future we plan to endogenize the probability of receiving financing on the overall credit conditions.

Regarding the latter, to each granted loan, a probability of success has been attached in order to account for possible failures of the innovation project[8].

3.3 Market dynamics: firms' entry and exit

Firms that do not get enough demand, i.e., those that are characterized by market shares below a threshold, τ, are removed from the market. New firms' entrance is

[7] Indicating with P_e, P_b and P_g the probabilities to target R&D innovation projects at reducing costs, increasing user quality or increasing green quality respectively, the innovation process for a firm.

[8] In this version of the model we aimed at reproducing the firms-banks relationship in the simplest way. Even if the building of financial stocks such as loans, bank's equity and deposits as well as the dynamic evolution of firms and banks balance sheets are not explicitly considered, the model does not loose its explicative power.

regulated by a probability, p_{entry} that guarantees a constant rate of new firms in each time period[9].

New entrants, having initially zero markets shares, enjoy a "honeymoon" period during which they will not be removed from the market even if their market share is below the minimum threshold τ.

The probability of directing an innovative project to improve one of the three product characteristics, P_g, P_b and P_e, are randomly assigned drawing from a uniform random function. The assumption of exogenous (random) configuration of new entrants permits to interpret the observed results in terms of the competitive endogenous shaping of the firms exiting the market because of insufficient sales.

The initial cost and quality levels of new entrants are determined as a share of the best value (i.e. lowest cost and highest qualities) among all incumbents, assuming that new entrants can imitate only partly the best practices employed by incumbents.

$$X(t)_{newentrant} = \delta X(t-1)_{Best} \tag{7}$$

where X can be costs c, user quality b or green quality g.

Choosing a value for δ close to, but lower than, 1 allows new entrants to compete with the best firms but not to overcome their quality, requiring them to engage in innovations in order to remain on the market.

4 Simulations

4.1 Sequence of events

In each period of the simulation, the following sequence of events takes place:

1. Firms put their produced (differentiated) goods on the market;
2. Consumer classes choose products according to their preferences for quality, greenness, and convenience;
3. Firms decide whether to carry out an innovation project to improve on one of their products' features with probability P_x;
4. Firms ask for a loan to finance their innovation project, with a probability of success differentiated on the type of project. If the firm is granted the loan then:

[9] New entrants, having initially zero markets shares, enjoy a "honeymoon" period during which they will not be removed from the market even if their market share is below the minimum threshold τ.

(a) the research project lasts a number of periods, during which no other projects can be initiated;

(b) at the end of the research period a new innovation succeeds with a given probability;

(c) in case of success, the firm improves the features targeted by the research projects and worsen the other two;

(d) Firms update their specific convenience, quality and/or greenness;

5. Firms with $ms_f(t) < \tau$ exit the market;

6. A new firm enters the market with a probability p_{entry}.

4.2 Scenarios

Using the above-described model, in this paper we study the impact of demand and the availability of green financial resources on the diffusion of green technologies. In particular, we focus on the distribution of preferences of consumers and their interactions with the behavior (more/less "pro-green") of the financial sector. The analysis is conducted over three different scenarios:

1. *Demand neglecting green quality*: the configuration investigated in the first test considers a market where consumers care exclusively for the convenience, i.e. the price level, and user quality, disregarding the environmental properties of products.

2. *Demand caring for green quality*: in this configuration, we replicate the same exercise of scenario 1 but in this case consumers assign to green quality the same relevance as user quality.

3. *Financing green technology*: in this scenario we investigate the effect of increasing the probability for the financial sector to accept a loan request to finance R&D in green technologies.

5 Model results

The model is designed to study the effects of different credit conditions onto the capacity of firms to pursue a technological trajectory balancing three targets: 1) convenience (by means of reducing production costs), 2) user quality, and 3) green quality. The setting for the model we are going to use, besides the parameters we explicitly comment in the main text, are reported in appendix 7.1. This setting produces some common properties replicated throughout all the exercises presented below.

Figure 3 shows that the number of firms rapidly climbs as new entrants face little competition by the few incumbents, so that even poorly performing firms enjoy a market share above the threshold set for the exit. This stage reaches a sudden stop when the number of firms is such that small firms find themselves below the threshold, hence exiting. The exogenous rate of entry and endogenous rate of exit determine a more stable set of active firms. Indeed, in this period the competition starts to be relevant, so that better performing firms, even if tiny because of their young age, quickly replace incumbents offering poor products. At any one time, the cross sectional analysis of firms' size reproduces the well-established power law pattern, reproduced in Figure 4.

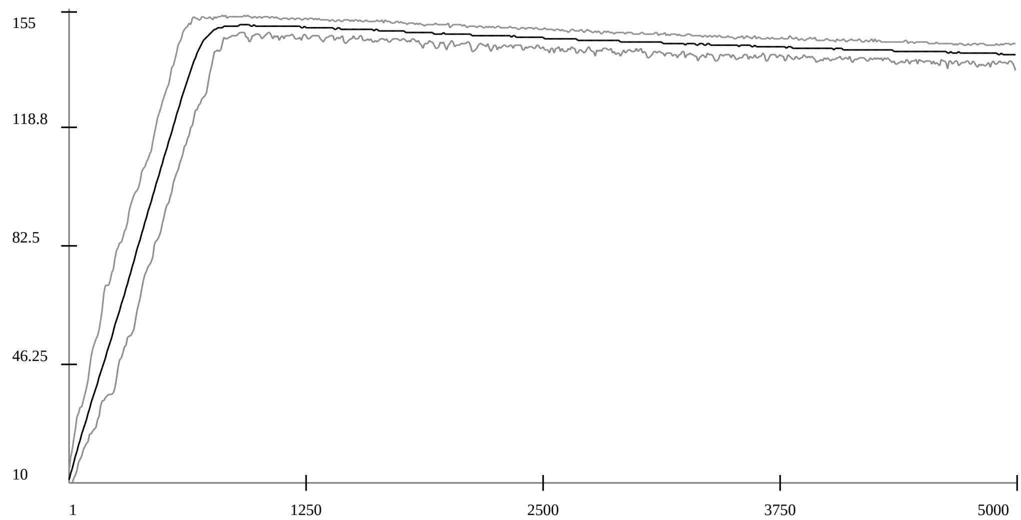

Figure 3: Number of firms. Average values over 100 simulations (grey lines indicate the minimum and the maximum value across simulations).

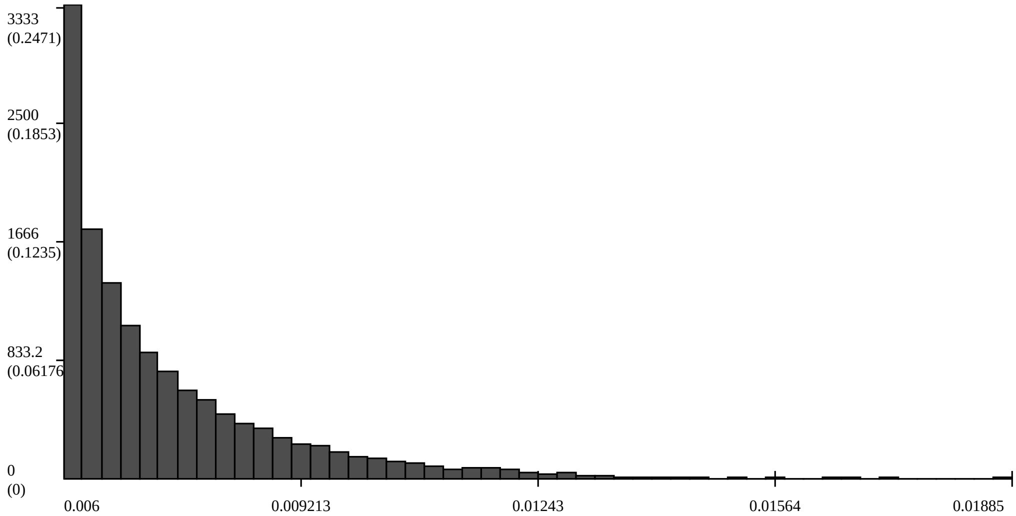

Figure 4: Individual firms' market share distribution. Data computed over the cumulated values from 100 distinct simulation runs. The horizontal axis reports the size of firms and the vertical axis the absolute and, between parentheses, relative frequency.

These general properties support our claim that the overall structure of the model provides a suitable instrument to analyse the effects of credit availability on the innovation strategies of firms, and consequently on the overall technological pattern shown by the market. Notice also that the model does not enter into cyclical patterns, but, on the contrary, adjust quickly to a continuous pattern. This feature of the model derives from the exogenous assumption that an infinite amount of innovation is always available, rather than exhausting the space for innovations within a given technological trajectory. Innovation cycles, and related industry life cycles are beyond the scope of the present exercise though being fully compatible with the overall framework.

We start by presenting the results produced by assuming equal credit conditions, independent on the type of innovation a firm is pursuing. We can therefore appreciate the extent to which demand conditions affect the competitive environment and therefore shape the technological profile of emerging successful firms. For this purpose we analyze two sets of results generated assuming two extreme types of demand, one giving no relevance to environmental quality and the second giving the same relevance as to the other two aspects.

5.1 Demand neglecting green quality

In order to control for possible distortions due to randomness, we ran 100 simulations and report, for each variable, the average value computed over each run and the relative maximum and minimum levels at each time step. Figure 5 shows that after a short initial chaotic period, where firms are few and randomly initialized, firms pursue a consistent strategy in two stages. First, they focus on reducing costs, which provides the most effective competitive advantage [10]. Due to the imposed technological restrictions, reducing production costs requires necessarily the worsening of the other two qualities. This early stage is however short-lived, lasting a few hundreds of time steps, since further cost reductions become increasingly less efficient in increasing the convenience perceived by users. Firms thus turn to a different competitive tool, "discovering" the sensitivity of consumers to the user quality. As a result, we observe a reversal of the direction for average user quality that starts a never ending ascending path.

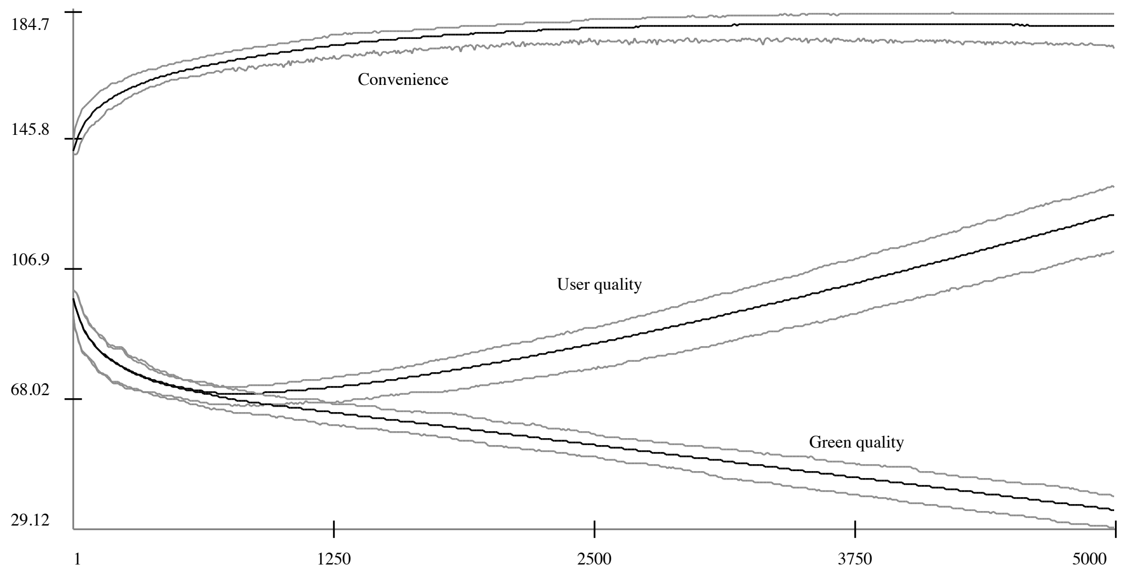

Figure 5: Baseline scenario with consumers' preferences neglecting green quality: average values of the three qualities. Average values over 100 simulations (grey lines indicate minimum and maximum value across simulations)

Given the assumption concerning the technological paradigm, postulating that an increment in one quality requires the worsening of the others, the green quality continues its descending path, reflecting the complete disregard of firms concerning innovations on this dimension.

[10]This is possible given the functional shape we impose on the relation between price and the convenience function.

Figure 6 reports the firms' strategies by which the quality values are produced. The series indicate the average values of the firms' Pe, Pg and Pq that are the probabilities to initiate a research project aiming, respectively, at decreasing costs, increasing green quality or increasing user quality. These parameters are exogenously determined at the entry of a new firm, but the average value is endogenously determined by the market since the exit of firms depends on their relative competitiveness. As a result, inadequate innovation profiles are discarded.

Results show that at the initial stage both research projects aimed at cost reductions and at improving user quality are more likely to be pursued. However, the relevance of cost-reducing innovation quickly shows to be inferior to the need to improve user quality. Nevertheless, firms cannot afford to completely neglect innovations concerning the convenience of consumers, since, by assumption, costs increases any time an innovation aimed at improving user quality is introduced. Consequently, from time to time, firms need to keep on investing on cost reductions, so as to avoid falls in their price competitiveness. The final outcome is that innovations aimed at improving user quality are by far the most frequent, concerning about 2/3 of all innovations at the end of the simulation run. The remaining share of innovations concerns almost exclusively cost-reducing projects, meant to maintain a constant level of price, i.e. hampering cost's increments due to the first type of innovation.

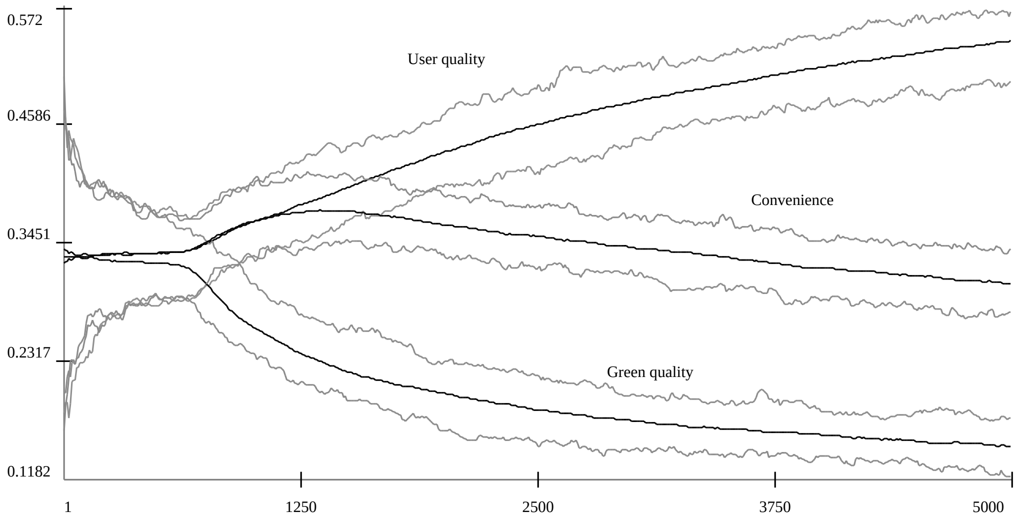

Figure 6: Baseline scenario with consumers' preferences neglecting green quality: average values of the innovation strategies of firms. Average values over 100 simulations (grey lines indicate minimum and maximum value across simulations)

Innovations concerning green quality get rarer, with a constant falling share until well below 10% of all innovations; this is due to the choice of configuring new firms with random values[11].

5.2 Demand caring for green quality

We replicate the same exercise described above but in this case consumers assign to the green quality the same preference of user quality.

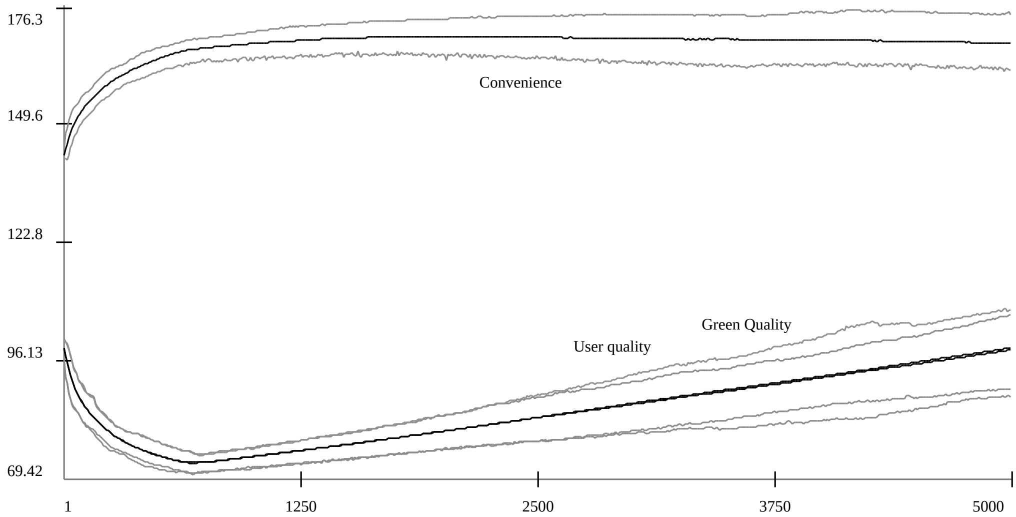

Figure 7: Baseline scenario with consumers' preferences giving the same relevance to green and user quality: average values of the three qualities. Average values over 100 simulations (grey lines indicate minimum and maximum value across simulations)

Reported results presented in Figure 7 highlight that firms engage in more varied strategies following consumers' preferences[12]. Under this different condition, we see that demand considers equivalent the two characteristics, and therefore firms to cater to more varied consumer preferences. The results presented show that the model easily adapts to the new conditions. Firms can no longer afford to neglect the green quality; as a result, its average value follows the same pattern as the

[11] For clarity of interpretation of results we are assuming, rather unrealistically, that new entrants pick randomly their innovation strategy, i.e. the probability to carry on the different types of innovations. A more rapid convergence to the optimal innovation strategy would be produced by allowing new entrants to imitate the innovation strategy dominant on the market at the time of their entry. Such assumption, however reasonable in economic terms, would, however, constitute an advantage for new entrants we prefer to avoid, considering more relevant the role of systemic learning reached through selection among purely random choice rather than exploiting imitative mechanisms. The results presented should therefore be considered *a fortiori*, as more robust than those that could be produced with more realistic assumptions of imitation.

[12] Figure 8 confirms that the competitive environment represented in the model adapts to the consumer preferences by selecting firms with the same probability to innovate on green and user quality.

user quality[13]. Similarly to the previous results, we observe an initial decrease in costs that lead to a quick rise of the convenience. Once the ceiling on this aspect is reached, firms turn their attention to the other two qualities which, being equally relevant, enter an identical pattern of continuous increments[14].

Notice that firms need to focus on the innovation of two qualities, besides maintaining low costs. The result is that the absolute levels of the two qualities reached in this scenario is drastically reduced with respect to the previous scenario where firms could concentrate all quality-improving innovations only on the user quality.

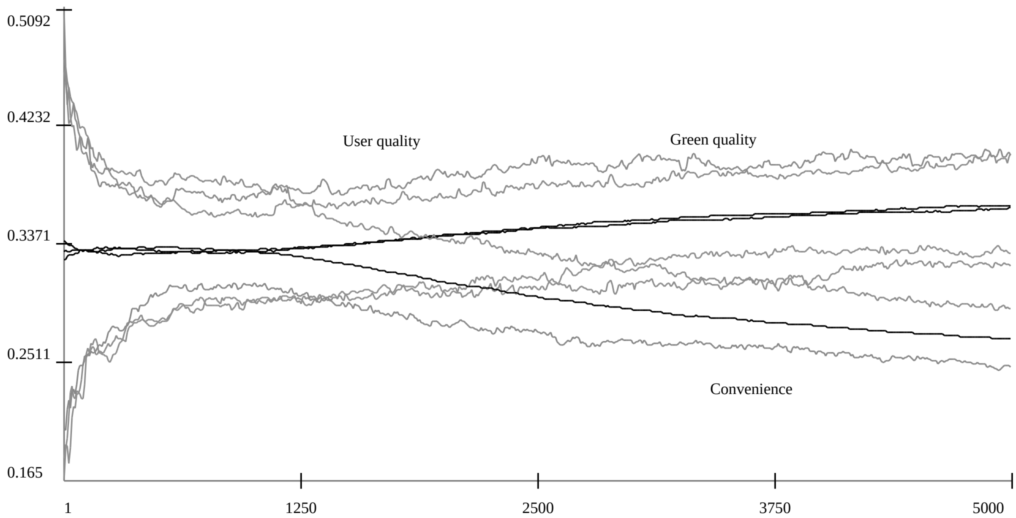

Figure 8: Baseline scenario with consumers' preferences giving the same relevance to green and user quality: average values of the innovation strategies of firms. Average values over 100 simulations (grey lines indicate minimum and maximum value across simulations)

Figure 8 confirms that the competitive environment represented in the model adapts to the consumer preferences by selecting firms with the same probability to innovate on green and user quality.

These two preliminary exercises show that the competitive setting responds to consumers' preferences by retaining randomly configured new entrants suited to the features of demand. In the following, we exploit this property of the model to investigate the role of financing.

[13]The differences due to random conditions, and is statistically insignificant.

[14]Notice that firms need to focus on the innovation of two qualities, besides maintaining low costs. The result is that the absolute levels of the two qualities reached in this scenario are drastically reduced with respect to the previous scenario where firms could concentrate all quality-improving innovations only on the user quality.

5.3 Financing green technologies

We consider a configuration where consumers' preferences are set to a more likely profile. We set the weight of the green technology as 20% of the overall utility, while the two remaining characteristics, convenience and user quality, split evenly the remaining 80%. Under these conditions the overall pattern falls in between the two extreme cases presented above.

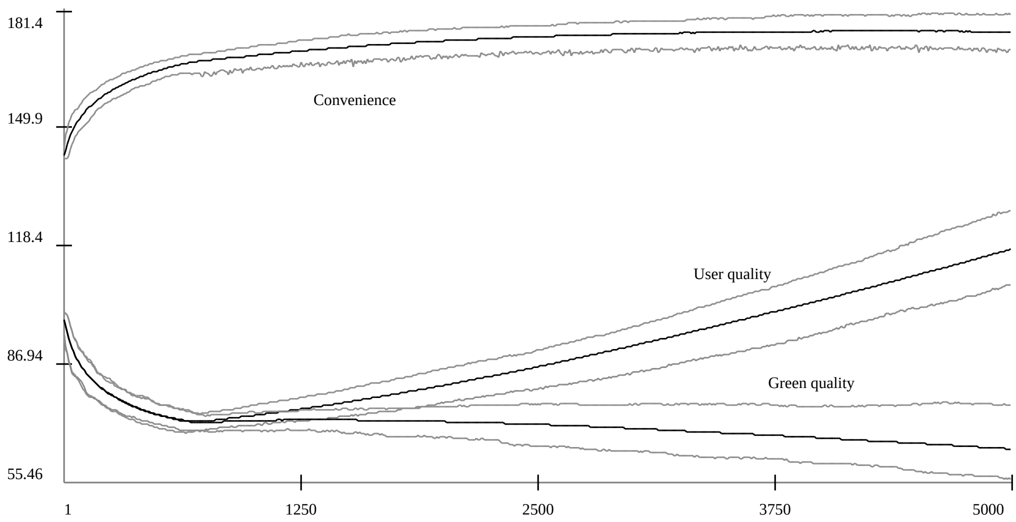

Figure 9: Consumers' preferences weighting green quality for 20% of the utility: average values of the qualities. Average values over 100 simulations (grey lines indicate minimum and maximum value across simulations)

As for the case where green quality is irrelevant to consumers, its value falls systematically with competition based on convenience at the early stage, and user quality in the long term. However, Figure 9 shows that the decreasing rate is sensibly slower (compared to Figure 5), indicating that the consumers' low, but still positive, attention to environmental issues is sufficient to force firms to direct some of their innovative efforts also on this aspect.

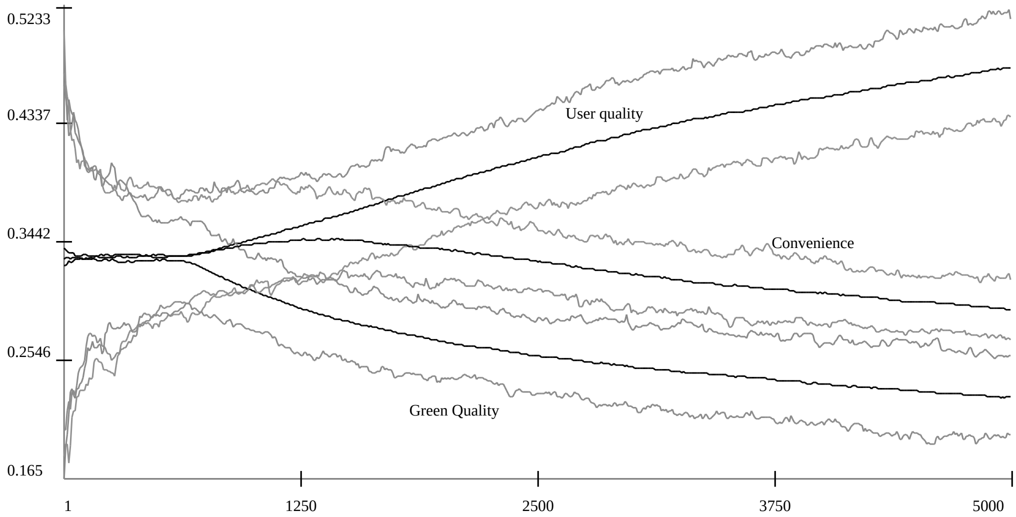

Figure 10: Consumers' preferences weighting green quality for 20% of the utility: average values of innovation strategies. Average values over 100 simulations (grey lines indicate minimum and maximum value across simulations)

Such result is supported by the results shown in Figure 10, reporting the average values of the probabilities determining the innovation strategies (P_g, P_e and P_b). Again, as compared to Figure 6 we see that the average probability of innovating in the environmental dimension is much higher than in the case where consumers pay no attention to the green quality.

So far we have presented results based on the assumption that innovating firms face identical conditions to finance innovations directed to any of the three possible directions, i.e. cost reduction and improvement of user or green quality. However, the empirical literature supports the conjecture that this is not the case. Innovations on green quality appeal to a smaller base of consumers and entails more ambitious innovations than improving quality or production processes. As a consequence, green quality faces far higher uncertainty in both attaining positive results and obtaining competitive success. Not surprisingly the banking system refrains, if possible, from these uncertainties providing loans preferably to finance innovations with more promising expectations.

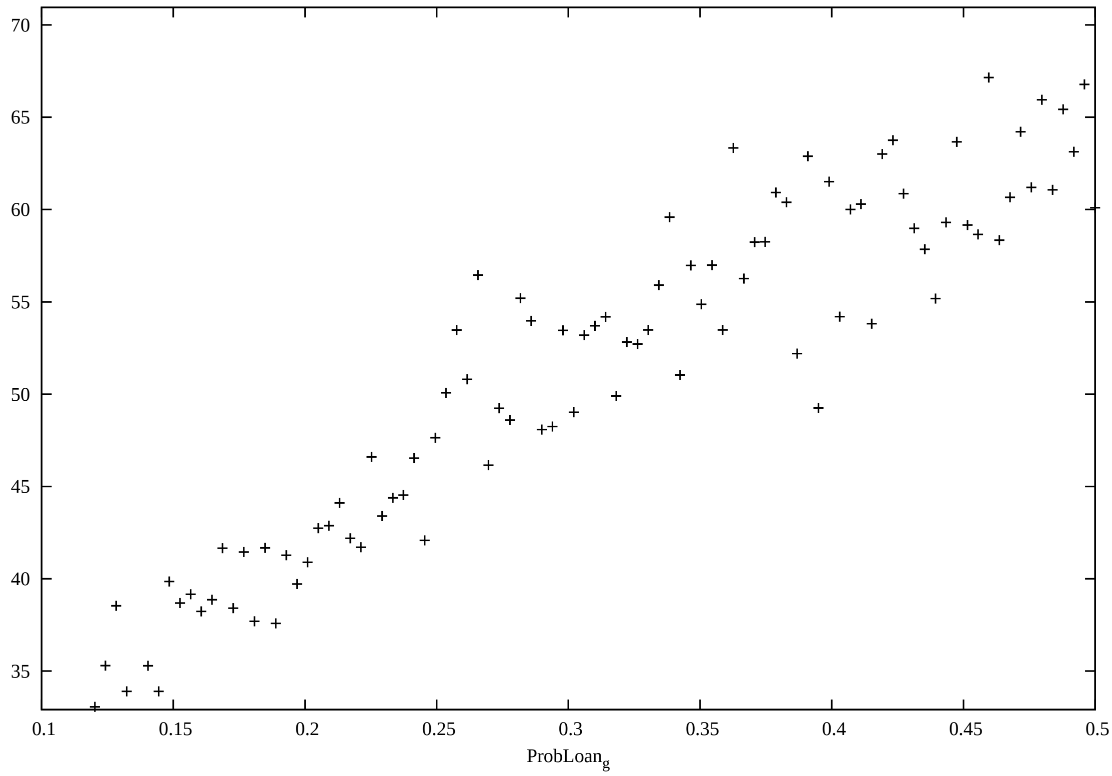

Figure 11: Average values of $g(t)$ of existing firms across 100 simulations differing for the probability that firms receive financing innovations meant to improve green quality. Probabilities ranging from 10% up to 50% (values used in the baseline scenarios). Values collected at time $t = 5000$.

Our model allows studying the effects of the reluctance by credit suppliers to finance these innovations. For this purpose Figure 11 reports the average value of the green quality computed at the time step 5000 for configurations identical to the one used above (i.e. positive but low consumer' sensitivity to green quality) but for one feature. When a firm seeks an innovation, the probability of receiving the funding to pursue the research project varies with the nature of its aim. For innovations meant to reduce costs or to increase user quality, the financial sector grants loans with a probability of 50%, as used in the previous exercises, while the probability to borrow for green innovation projects is lower. To study the effects of this parameter we run simulations with values ranging from 10% to 50%.

The Figure shows a strongly positive effects of financing on the average level green quality, supporting the hypothesis that financing is a necessary, if not sufficient, component of a successful system pursuing environmental innovations. Without adequate financing firms will be prevented from pursuing innovations towards improving the environmental record of their activity, that could only worsen as a by product by different types of innovation.

However, devoting resources to finance environment-related innovations should be designed with care to prevent undesirable results and unexpected obstacles. Innovations on “green” projects can be expected to be more risky and related investments to have a longer payback periods. Thus financial institutions may find themselves at risk because of their lending to this class of projects, and macro-prudential policies designed to curb the exuberance of financial markets may turn out to reduce the amount of credit available for “green” innovation. From the results of the present work we conclude that a more careful analysis of the interdependecy between innovation and financial sectors are required to assess the viability of environmental friendly investments and to design adequate policies.

6 Conclusions and policy implications

The model developed in this paper shows that innovation decisions towards a specific technology are *demand-driven* and emerge because of firms' active search for new market niches. We focus in particular on eco-innovation diffusion because of the political and environmental concerns related to it.

We discussed the extent to which, according to both theoretical and empirical literature, eco-innovation diffusion faces both *deterring* and *revealed* barriers (D'Este et al., 2012); our model explicitly focuses on financial constraints, which are usually perceived as deterring barriers (Ghisetti et al., 2017). They arise because of eco-innovation peculiarities; namely, risk and uncertain long-term returns which constitute important hindrances for adoption and diffusion of environmental technologies in the market. To study the extent to which financial barriers are a deterrent for the adoption of eco-innovation, we build up an agent-based model populated by consumers with different preferences for products' qualities, heterogeneous firms with different innovation profiles and a financial sector which exhibits different “propensities” to lend with respect to the type of innovation project for which the loan is requested.

Our setting stresses the importance of demand, on one side, and the crucial role played by the financial sector's lending attitudes, on the other. In particular, we show that innovation decisions towards a specific technology are *demand-driven* and emerge because of firms' active search for new market niches since the potentially new products' characteristic can be perceived differently by consumers. Additionally, the diffusion of products' characteristics in the market is dependent on the availability of financial resources to fund innovation costs.

Simulations' results point out the crucial role played by the financial sector in the emerging dynamics of the model: when the financial sector adopts a more ”patient” (i.e., long-term perspective) lending attitude towards green innovative firms, a higher diffusion of environmental innovation is recorded in the economy. This is in line with recent empirical evidence according to which the perception of financial barriers by

SMEs and the stringency of financial constraints, constitute a deterrent for the eco-innovative capacity of firms[15].

One policy implication that arises from our analysis is that, in order to fill the so-called "green finance gap" it is thus important, on one side, to solve the allocation problem and direct resources to green projects and, on the other side, to provide and employ more resources on "environmental-friendly" projects.
Additionally, we claim that a policy that enables the provision of adequate resources from the financial sector is more effective, compared to carbon pricing (see Campiglio, 2016, for a detailed discussion on the pros and cons of the implementation of carbon pricing) or to a lump-sum transfer, in triggering the diffusion of innovation. Regarding the former, the introduction of a carbon price may not be sufficient in order to stimulate green investment, because carbon pricing directly affects existing capital value and, via price adjustments, the patterns of consumption. This generates a financial transfer from carbon-intensive capital holders to low-carbon capital holders, implying a short term distributive effect, which is difficult to manage politically. Moreover, the introduction of a tax on the carbon content of goods and services will face strong political and social resistance, because of increased costs of production and, as a consequence, increased costs for consumers.

Regarding the latter, a lump sum transfer (e.g., subsidies, either to the demand- or to the supply-side) is not enough to solve the issue and can have only temporary effects: it is indeed difficult to establish a self-sustained process of innovation diffusion, even in presence of long-term subsidies (Cantono, 2009; Metcalf, 2009). Applying an environmental tax could results instead in a win-win strategy because it would enhance fiscal consolidation and affect consumption and production choices.

Taking into account these concerns, a different framework is thus needed to understand how the environmental goals the international community has agreed upon can be effectively promoted and achieved. We claim that considering the role of green finance, both private and public is of utmost importance for enhancing the transition towards a low carbon economy. There are however a number of issues related to the *long-termism* of the financial sector. This lending attitude implies that banks hold more long-term risky loans on their balance sheets which in turn means that banks are potentially not able to meet the capital and liquidity requirements of the macroprudential regulation set under Basel III. Additionally, the presence of long term assets in the banks' balance sheets requires them to have a more stable source of funding, which in turn implies costs of refinancing and, as a consequence, an increased risk perception of the project. The impact of the macroprudential regulation is thus relevant for the expansion of green finance since the current framework seems to discourage the financing of investment in long-term

[15] See (Savignac, 2008; Mancusi and Vezzulli, 2010; Ghisetti et al., 2017; Czarnitzki and Hottenrott, 2017) for an empirical analysis on French, Italian, EU and OECD firms respectively, and (Marin et al., 2015) for a cluster analysis on the barriers to eco-innovation for EU SMEs.

risky green technologies while encouraging investments towards liquid, short-term less risky high carbon technologies.

The model developed in this paper could be further extended to include a more detailed banking sector, different macroprudential regulations and alternative financial channels, such as state investment banks (Mazzucato and Penna, 2016). The extended version of the model could also be included in a fully-fledged macro model which can help in performing richer policy analysis and assist policymakers in some crucial decisions regarding green policies. This is left for future work.

7 Appendix

7.1 Parameters setting

In the following, we report the numerical values used to generate the results presented in the paper. The values are chosen to allow the investigation at the core of this work, and they do not reflect a calibration to a specific empirical case. This type of exercise would be unfeasible because the parameters, though well-defined according to economic theory, could not be observed in reality or, when they could be collected, they present highly volatile values differing through cases and time periods.

Our model does not claim to be a realistic representation of markets, nor to show universal properties. Rather, the model aims to provide a useful benchmark for grasping the main implications of a specific set of assumptions. Therefore, the numerical values assigned to the parameters of the model are merely required to not lead to extreme conditions, and to allow us to understand the interplay among the core elements implemented in the model.

Parameter	**Description**	**Value**	**In equation(s)**
H	Number of consumers	100000	
F	Initial number of firms	10	
α_e	weight of convenience	(explored)	(2)
α_g	weight of green quality	(explored)	(2)
α_b	weight of user quality	(explored)	(2)
β	sales' coefficient	3	(4)
M^e	maximum of the logistic function	200	(1)
γ	slope of the logistic function	0.03	(1)
$\hat{p}$	position of the logistic function	100	(1)
δ	best quality imitated	84%	(7)
wt	waiting time steps before innovation	10	
$p_{success}$	probability of success of innovation projects	50%	
τ	threshold exit	0.006	
$minAge$	minimum age for exit	10	
p_{entry}	probability new firm entrance	20%	

Table 1: Parameters' setting for the simulations runs presented.

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