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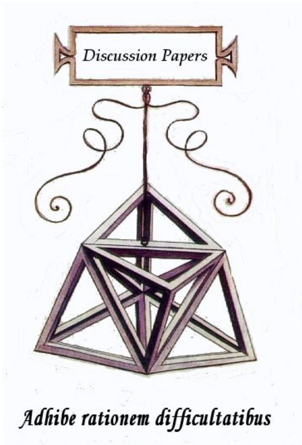

Silvia Leoni, Marco Catola

Green Transition and Environmental Policy in Imperfectly Competitive Markets: Insights from Agent-Based Modelling

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Discussion paper

n. 326

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Keywords: agent-based modelling; pollution abatement; green technology; environmental policy

JEL CLassification: C63; D43; H23; L13; L51

Green Transition and Environmental Policy in Imperfectly Competitive Markets: Insights from Agent-Based Modelling

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The order of authorship was determined randomly since this work would not have been possible without the indispensable contribution of each author.

Abstract

The debate on environmental policy increasingly focuses on aligning private incentives with social objectives in imperfectly competitive markets. While traditional literature has centred on public-based mechanisms like taxes and subsidies, a growing strand emphasizes private-based mechanisms, particularly *green consumerism*, where consumer preferences can drive firms' adoption of clean technologies. Recent game-theoretic analysis shows that consumers' willingness-to-pay can lead to various market equilibria, from all-green to all-brown outcomes. This paper complements this analytical approach by developing an agent-based model (ABM) to study the dynamic evolution of a spatial market where firms, based on relative performance, decide whether to supply brown or green products to heterogeneous consumers. Our computational simulations confirm that all three market structures—all-brown, all-green, and mixed—can endogenously emerge depending on average green consumer preferences. Furthermore, we evaluate the effectiveness of three policy instruments: an environmental tax, a subsidy to green firms, and a subsidy to green consumers. We find that supply-side policies are more effective than demand-side subsidies. Specifically, an environmental tax ensures the fastest convergence to an all-green market, while a production subsidy is most effective at reducing the share of brown firms and consumers in mixed-market scenarios. By bridging game-theoretic insights with agent-based computational analysis, this paper provides a dynamic and policy-relevant perspective on the transition to sustainable markets.

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1 Introduction

Climate change and environmental degradation have renewed interest in the design of policies and mechanisms to stimulate firms' abatement activities. A central question in this debate is how to align private incentives with social objectives in markets that are not perfectly competitive, where strategic interactions and market power play a crucial role. Economists' interest in this topic is evidenced by the vast and heterogeneous literature studying the environmental regulation of imperfectly competitive markets. The range of issues analysed by scholars spans from the traditional problem of optimal environmental taxation (Yin, 2003; Antelo and Loureiro, 2009; Fujiwara, 2009), its combination with production subsidies (Gersbach and Requate, 2004; Li et al., 2016), its impacts on green managerial delegation (Buccella et al., 2022), the use of alternative instruments to correct externalities (Requate, 1993; Heyes, 2000; Sartzetakis, 2004; David, 2005; Goulder and Parry, 2008), to the study of the relationship between environmental regulation and emission-reducing R&D (Poyago-Theotoky, 2007; Ouchida and Goto, 2014), as well as the effects of environmental taxation on firms' location choices and foreign investment (Rauscher, 1995; Dijkstra et al., 2011; Elliott and Zhou, 2013)—and the list is only partial. What all these studies have in common is their reliance on some form of *public-based mechanisms* to correct market outcomes.

More recently, however, a new line of research has emerged that emphasises *private-based mechanisms*, and in particular consumers' preferences for green quality. This strand of the literature, known as *green consumerism* (e.g. Conrad, 2005; Sartzetakis et al., 2012; Ambec and De Donder, 2022; Ceccantoni et al., 2023; Giallonardo and Mulino, 2024), highlights how consumers' pro-environmental preferences can incentivise firms to produce green products that are more costly, even in situations where no public policy is in place.

In a recent contribution, Gori et al. (2024) connected this literature to the one studying the endogenous emergence of Subgame Perfect Nash Equilibrium (SPNE) in non-cooperative games with some form of environmental concern (see, for example Buccella et al., 2021; Xing and Lee, 2024). They show that when abatement enhances the perceived quality of products, demand-side effects alone may induce firms to adopt clean technologies. In particular, they show how private incentives derived from consumers' willingness to pay for green products can induce an SPNE where duopolistic firms decide to both produce a green product. On the other hand, they also show that without a strong willingness to pay by consumers, the SPNE can lead to a mixed market (where only one firm chooses to be green) or even a market where neither firm decides to abate their emissions.

Our work builds on this contribution by studying the dynamics of this market set-up through the use of an Agent-based model (ABM). We develop a relatively simple model of spatial price competition where firms have to decide whether to provide a brown or a green product to a population of consumers that vary in the degree in which they care about the environment. In every period firms can decide whether to revise their decision concerning the quality of the product depending on their relative performance, and we study how the market will evolve over time depending on how much, on average, consumers are willing to pay for a green product. Our results indeed provide evidence in support of the findings that every combination of market outcomes is possible: markets in which there are no green products, markets where there are only green products and markets where both types of products coexist. Finally, we also explore a policy intervention, where we compare three different policies (an environmental tax, a subsidy to green firms and a subsidy to green consumers) to assess whether some instruments may be better than others. We find that policies addressed to the supply side are more effective than those addressed to consumers, despite the assumption that all consumers gain an extra utility from buying green. In particular, while the environmental tax ensures the fastest convergence to a green state, the subsidy instrument is found to be more effective in reducing the share of brown firms and brown consumers in mixed markets (where both green and brown firms operate).

The scope of our analysis is not to replace the analytical insights that the game theoretic analysis can provide but rather to enhance them. In fact, we believe that ABM is a natural complement to Game Theory as each method compensates the limitations of the other: Game Theory requires relatively strong assumptions on rationality and a very narrow time horizon while ABM lacks the same degree of analytical rigour and clarity of insights. In this sense, our paper is akin in spirit to the methodological bridge provided by Catola and Leoni (2025), where analytical results obtained in Catola and D'Alessandro (2020) were complemented with computational simulations to assess their robustness and generality, or van Leeuwen and Lijesen (2016) who propose an agent-based version of the Hotelling's game of spatial competition. In addition, the computational approach allow us to test policy tools such that the model results can inform policy makers aiming to green targets.

In general, ABMs have increasingly been used to study game-theoretic environments.[1] For instance, a substantial literature has examined social dilemmas, such as the prisoner's dilemma, and the emergence of cooperation (Axelrod et al., 1987; Ladley et al., 2015; Hales, 2002; Szilagyi, 2012). Other applications include residential segregation (Zhang, 2004, 2011), auction pricing (Bower and Bunn, 2001), and labour market dynamics (Guerrero and Axtell, 2013). More recent studies extend ABMs to incorporate local interactions and spatial frictions in market exchanges with heterogeneous qualities and prices (Di Domenico and Riccetti, 2025), illustrating how bounded rationality and decentralized interactions can generate highly non-linear dynamics that deviate from standard equilibrium predictions.

In industrial organization, ABMs have been applied to a wide range of markets and institutions, including electricity markets (Bower et al., 2001; Sensfuß et al., 2008), carbon emission trading schemes (Tang et al., 2015; Yu et al., 2020), and transaction costs between firms (Klos and Nooteboom, 2001). Applications in environmental and energy economics are particularly prominent, simulating emission trading systems and sustainable transitions in the power sector (Ponta et al., 2018; Lamperti et al., 2018). Efforts to replicate classical oligopoly models, such as Cournot or Bertrand, remain limited and often rely on simplified simultaneous-move specifications (Vriend, 2000; Kimbrough and Murphy, 2009, 2013; Catola and Leoni, 2025).

Our paper contributes to this literature by developing an ABM that embeds oligopolistic interactions and environmental policy considerations within a dynamic, heterogeneous setting, bridging insights from industrial organization, environmental economics, and computational economics.

The rest of the paper is structured as follows: we introduce the model and agent decisional rules in Section 2; in Section 3 we describe the model setup. Simulation results are discussed in Section 4, and policy experiments are presented in Section 5.

[1] In fact, in economics, ABM is a technique traditionally more commonly used in macroeconomics. Notable examples are Delli Gatti et al. (2010); Caiani et al. (2016); Dosi and Roventini (2019).

Finally, in Section 6 we conclude and provide insights for future research developments.

2 The model

We consider a market populated by n firms and m consumers. Firms produce a given product that consumers are interersted in buying and the competition is modelled *à la* Bertrand. Before discussing agents' decisional rules, we briefly introduce the spatial environment and the framework used to model the network.

2.1 The spatial environment

We implement the model in NetLogo (Wilensky, 1999), an open-source platform widely employed for building and analysing agent-based models. NetLogo provides a two-dimensional grid with toroidal topology, such that the horizontal and vertical boundaries are connected and the space effectively "wraps around". Agents are situated on the grid and interact over time. The graphical interface makes it possible to visualise heterogeneous firms directly, to track their behaviour and outcomes step by step, and to connect spatial location with adaptive decision rules. These features are particularly valuable in models of industrial competition, where both geography and local interactions matter.

The structure of information environment is constructed through *social circles*, following Catola and Leoni (2025). This modelling approach – originally introduced by Hamill and Gilbert (2009) – can be seen as a parsimonious alternative to more complex network architectures: each firm is characterised by a radius that defines the set of other firms it can observe. In practice, a firm's competitive neighbourhood is thus determined by spatial proximity, with the radius acting as a cut-off that limits the number of rivals whose performance can be monitored.

2.2 Consumers

Consumers are assumed to purchase one unit of product in each period. On the positive side, they derive utility from obtaining the good *per se* and, in addition, from whether the good is green. On the negative side, they must pay a price and – following the standard model of spatial competition – suffer a disutility from the distance between their own location and that of the supplying firm.

More specifically, consumer utility is given by the following function (where $\mathbb{1}$ denotes the indicator function):

$$U_i = v + \tilde{x}_i \cdot \mathbb{1}_{\{k_j = g\}} - p_j - \alpha \cdot d(i, j), \tag{1}$$

where v is the consumer's baseline utility which is fixed and common for all consumers, $\tilde{x}_i$ is the additional premium from buying a green product (when $k_j = g$) which is a random variable drawn from a normal distribution, p_j is the price charged by firm j, $d(i, j)$ is the Euclidean distance between consumer i and firm j, and α measures the strength of the distance-related disutility. Note that we do not assume the existence of two distinct consumer types (*green* vs. *brown*) as in for example Ambec and De Donder (2022). Instead, each consumer is characterised by a degree of interest in green products, which can be very large (high $\tilde{x}_i$), very small, zero, or potentially even negative.

In each period, consumers *search* among the available firms and select the option that provides the highest utility. In this framework, the choice balances three factors: low price, short distance, and the product being green—the latter being more relevant the larger the value of $\tilde{x}_i$. To reflect the large size of the market, we further assume that consumers cannot search among all active firms, but only among those lying within a search radius r from their location.

2.3 Firms

The firms in the market produce a product that is homogenous in its consumption qualities, but can be produced in a way that is environmentally friendly (which we label as a *green* product) or in a standard polluting way (which we label as a *brown* product). We model the production of the green product as an end-of pipe cleaning technology. Therefore, the unitary cost of producing the good is sustained to produce both the brown and the green version – and it is normalised to 0 – but the production of the green product requires an additional unit cost of c to abate emissions (this cost function is in line with Catola and D'Alessandro, 2020).

The profit function is therefore:

$$\pi_j = (p_j - c \cdot \mathbb{1}_{\{k_j=g\}})q_j \tag{2}$$

In terms of time structure, firms have to choose firstly whether they want to produce a green or a brown product, and secondarily the price at which they want to sell their product. We present the model in this order.

2.3.1 Choice of the Type

At the beginning of each period, firms decide which kind of good to produce. We assume that this choice is made by comparing their own profits with those of their competitors, and by imitating the type that performs better. In practice, however, switching production lines is not straightforward—it requires effort and money—and it is also difficult for firms to gather information about all competitors, especially in relatively large markets such as the one modelled here.

To capture this process, we follow the same approach used in Catola and Leoni (2025), which was designed to take into account the nuances of switching behaviour. At the beginning of every time step, firms compare their own profits with the average profits of their local competitors of the opposite type within radius R_j.[2] If π_j is below the local mean $\bar{\pi}_{-j}$, firm j considers switching its production. To better capture the costs of changing the production process, we add a preliminary step: not every firm evaluates the possibility of switching type in every period. Instead, at the beginning of each time step, a firm has a probability ρ of entering this procedure. This probability can be interpreted as a parsimonious way to capture inertia in firms'

[2] In its original formulation by Hamill and Gilbert (2009), social circles required reciprocity in linking two agents. In our setting though we relax this assumption to capture the idea that different firms may have different information about competitors, and that such information is not necessarily reciprocal. Thus firm radii are heterogeneous.

behaviour, reflecting the fact that switching production technologies is costly and rarely reconsidered at every period.[3]

In game-theoretic terms, at the beginning of each period t, firms that are selected to evaluate their type choose whether to keep their type $k \in \{g, b\}$ from the previous period or to switch to the other type $(-k)$, according to the following rule:

$$\begin{aligned}
&\text{if} \quad \pi^{t-1} \geq \bar{\pi}_{-k}^{t-1} \quad \text{then} \quad k^t = k^{t-1}, \\
&\text{if} \quad \pi^{t-1} < \bar{\pi}_{-k}^{t-1} \quad \text{then} \quad \begin{cases} k^t = -k^{t-1} & \text{with probability} \quad \theta, \\ k^t = k^{t-1} & \text{with probability} \quad 1-\theta, \end{cases} \\
&\text{where} \quad \bar{\pi}_{-k}^{t-1} \text{ is the average profit of rivals within firm } j\text{'s circle.}
\end{aligned} \tag{3}$$

The switching probability is defined as:

$$\theta = \Pr(switch) \;=\; \max\left\{0,\; \exp\left(\lambda \frac{\bar{\pi}_{-k} - \pi_j}{\bar{\pi}_{-k}}\right) \;-\; 1\right\}, \tag{4}$$

where $\lambda > 0$ is a parameter measuring the "intensity of choice", i.e., the sensitivity of firms to relative profit disadvantages.[4]

2.4 Pricing

Rather than assuming full profit maximisation, we model firm pricing through a simple heuristic rule. This assumption is consistent with evidence from management and industrial organisation showing that firms often rely on rule-of-thumb strategies instead of complex optimisation (e.g. Artinger and Gigerenzer, 2025; Gigerenzer and Brighton, 2009; Gahler and Hruschka, 2022).

Each firm adjusts its price based on the relative performance obtained in the previous period. In line with theories of the firm in industrial organisation, we assume that each firm measures its performance in terms of profits and uses as a reference point its competitors in the same sub–market (i.e. firms of the same type). In other words, both decisions of the firm are based on profits, but the relevant comparison group differs: when deciding the type, the firm compares its performance to firms of the other type, while when deciding the price, the firm compares its performance to firms of the same type. Such profit–based adjustment rules are consistent with the evolutionary and agent–based industrial organisation literature, which departs from exact profit maximisation and models firms as adapting their strategies in response to realised profits (e.g. Cyert and March, 1963; Vriend, 2000; Alkemade et al., 2007).[5]

Formally, after the choice of type, each firm j of type k updates its price according to its last-period profits π_j^{t-1} relative to the mean profit of firms of the same type

[3] An alternative assumption would be that each firm considers switching type every fixed number of periods. However, since the model is simulated with a Monte Carlo approach, our formulation implies that on average each firm considers switching every $1/\rho$ periods.

[4] As stated in Catola and Leoni (2025), this formulation was originally adapted from the standard ABM literature in macroeconomics (see, e.g., Delli Gatti et al., 2010; Riccetti et al., 2013).

[5] In the ABM macroeconomic literature the most common pricing heuristics are mark-up rules where the updates happen according to evolution of market shares (e.g. Delli Gatti et al., 2010; Riccetti et al., 2013; Delli Gatti et al., 2025). We chose the approach closer to the literature of microeconomics and industrial organisation.

$\overline{\pi}_k^{t-1}$ within its group of competitors:

$$p_j^t = \begin{cases} p_j^{t-1} + \varepsilon & \text{if } \pi_j^{t-1} > \overline{\pi}_k^{t-1}, \\ p_j^{t-1} - \varepsilon & \text{if } \pi_j^{t-1} < \overline{\pi}_k^{t-1}, \\ p_j^{t-1} & \text{otherwise,} \end{cases} \qquad \text{where } \varepsilon \sim \mathcal{U}[0, 0.05]. \tag{5}$$

Thus, firms performing better than the average increase their price by a random amount between 0 and 5%, while firms performing worse reduce it by the same random amount.[6] To avoid negative payoffs, we also impose a control condition ensuring that the new price p_j^t is implemented only if it is higher than the unit cost. If this is not the case, the firm instead sets a price equal to its unit cost (0 for a brown firm and c for a green firm), which results in zero profits for that period.

Note that firms that have switched type in the previous step adopt as initial post-switch values the average price of their new competitors of the same type, and then apply Equation (5). In this way, the firm immediately aligns its pricing strategy with that of its rivals of the same kind and capture the idea that since the firm decided to switch because it was over-performed, it will try to mimic the competitors after the switch.

3 Model Setup

We simulate a market composed by 1000 consumers and 50 firms. At the initialisation ($t = 0$), each firm is assigned a random position and a random radius for its social circle in the range $[5, 25]$. 25 firms are randomly assigned the green type and the other 25 the brown type. To determine the initial price, each firm is assigned a random value for the initial mark-up $\mu^0 \in [0, 2)$ to add to its unit cost.[7]

Consumers are also randomly placed in the space and are assigned their baseline utility v and the random green premium x_i which they will retain for the entire simulation. The radius for consumers is homogeneous. Then each consumer decides whether and from which firm to buy the product, thus determining the market shares of every firm. At this point, all the relevant quantities for the decision in round 1 ($t = 1$) are computed. We select a fairly large value for v to ensure that every consumer will buy in every round.

Finally, in terms of firms' probability, we chose a value of $\rho = 0.4$ meaning that on average a firm will consider switching every 2.5 time steps and $\lambda = 0.5$, to ensure that the switching probability is always well defined.

An overview of the values used at the model setup is reported in Table 1.

[6] The random change is intentionally small to keep the dynamics smooth, especially as we do not impose an upper bound on prices.

[7] In NetLogo the command `random-float 2` draws a random number in the interval $[0, 2)$, i.e. it can take any value greater than or equal to 0 and strictly less than 2.

Variable	Symbol	Input
Number of firms	N	50 (25 green, 25 brown)
Number of consumers	M	1000
Unit abatement cost	c	5
Initial mark-up	μ_0	$\sim \mathcal{U}[0, 2)$
Imitation sensitivity	λ	0.5
Probability of entering switch	ρ	0.4
Firm competitor radius	R	$\sim \mathcal{U}[5, 25]$
Consumer search radius	r	10
Baseline utility	v	50
Green premium	x	$\mathcal{N}(\overline{x}, 0.4\overline{x}^2)$
Distance penalty	α	2

Table 1: Baseline parameters and initialisation

The model is iterated for 500 time steps or until the market converges to either all firms are of the same type (green or brown). As in Gori et al. (2024), we use the utility green premium x as the main control variable for running a comparative analysis on whether the market will always converge to either states or mixed *equilibria* will emerge.

Therefore, we test 10 values of $\overline{x}$, starting from 1 to 10, and for each value we run 1000 simulations. We calibrate the standard deviation of the green premium x at 20% of its mean. This choice ensures a coefficient of variation equal to 0.2, so that roughly 95% of the distribution falls within ±40% of the mean value. The resulting dispersion provides sufficient variability in consumers' willingness to pay for green products while keeping the distribution reasonably concentrated around the mean.

Finally, to measure market concentration we compute the Herfindahl–Hirschman Index (HHI), which increases as market shares become more uneven across firms. Formally, if s_i denotes the market share of firm i and $\sum_i s_i = 1$, then:

$$HHI = \sum_{i=1}^{N} s_i^2. \tag{6}$$

The index takes values in $[1/N,\, 1]$: it is minimized at $1/N$ when all N firms have equal market shares (perfect competition) and equals 1 when a single firm monopolizes the market. In our case the minimum value is $1/50 = 2\%$.

4 Results

Results of the Monte Carlo simulations are summarised in Table 2.

Table 2: Simulations results

x	brown	mixed	green	time to all brown	time to all green	brown firms in mixed	brown consumers in mixed
1	956	44	0	39.59	-	42.62	832.90
				(38.36)		(1.67)	(46.70)
2	964	35	1	57.08	400.00	40.31	778.72
				(53.07)	(-)	(2.60)	(63.07)
3	960	40	0	69.40	-	37.44	712.88
				(58.34)		(2.55)	(65.59)
4	959	34	7	87.84	362.43	33.20	628.06
				(70.13)	(80.34)	(3.15)	(78.21)
5	875	48	77	114.42	317.71	28.42	546.38
				(85.64)	(89.39)	(2.54)	(57.74)
6	481	115	404	154.47	291.57	24.24	483.00
				(95.31)	(89.38)	(3.63)	(86.93)
7	139	86	775	183.01	270.62	19.98	424.86
				(95.26)	(87.84)	(2.60)	(73.75)
8	31	77	892	208.77	248.55	16.62	366.50
				(93.64)	(88.77)	(3.06)	(76.17)
9	4	51	945	235.00	200.53	13.83	314.82
				(126.70)	(111.28)	(2.37)	(60.38)
10	0	46	954	-	120.58	10.75	273.08
					(102.51)	(3.06)	(63.62)

For each value of x, we report the number of runs for which the model converges to a *brown* state (i.e., all firms turn brown), *green* state (i.e. all firms turn green) or does not converge and generates a *mixed* equilibrium; for convergent simulations, the average time to converge across simulations (s.d. in parentheses); for non-convergent simulations, the composition: average number of *brown firms in mixed* and *brown consumers in mixed* (s.d. in parentheses) across time steps and runs.

The Monte Carlo results in Table 2 reveal a clear transition in system dynamics as the parameter x increases.

For low values of x, the system almost exclusively converges to the *brown* state, with relatively short convergence times. As x increases, the frequency of *green* outcomes rises steadily: starting from $x = 4$, the number of runs in which the market converges to green is still small, but steadily increases until becoming prevalent from $x \geq 7$ onward.

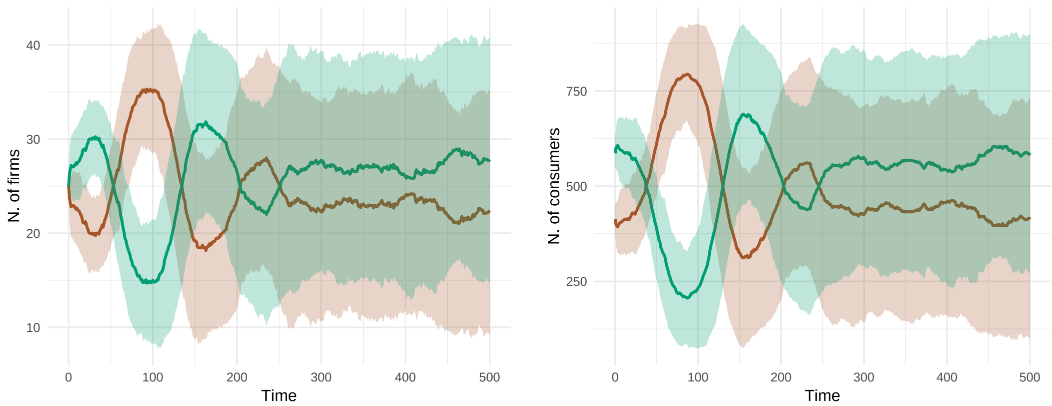
It is worth noting that the values are also in line with the unitary abatement cost: as long as the average willingness to pay for green products is lower or equal to the cost of producing them (i.e., $\overline{x} \leq 5$), the average profit premium of green firms will be negative. Accordingly, in the vast majority of cases the market converges to brown, with a few instances where the spatial component of the market and the randomness in the distribution of x provide a "lucky environment" for the green product. It is only when the average profit premium for green firms becomes positive that green firms are able to take over the market. It is then not surprising that the most mixed case is indeed $x = 6$. The average green premium is positive, but small in magnitude and with a large share of consumers for whom it is still negative; in this case the spatial component of the market plays a crucial role, leading to a very balanced outcome.

Average convergence times show an increasing trend for brown trajectories, whereas green trajectories initially display very large mean values, followed by a decline as x increases. The mixed outcomes indicate that, whenever coexistence persists, the average number of brown firms and brown consumers decreases monotonically with x, signalling a gradual rebalancing in favour of green firms and green consumers. Overall, the model exhibits a sharp regime shift: low values of x lead to brown monopolization, while high values induce full green adoption, with an intermediate region characterized by mixed outcomes and more heterogeneous, longer convergence times. Again, the case $x = 6$ stands out as the most balanced in terms of shares, with brown firms and consumers accounting for about 50% of the market.

4.1 Mixed markets

In this section, we separately analyse the cases in which the market remains mixed after 500 time steps. In the following figures, we show the evolution of the market along the simulated time span in terms of share of firms and consumers by type, firm prices and profits; and market concentration. We select the case of $x = 6$ since it provides the largest number of observations for mixed outcomes.

Figure 1 displays the average number of firms (panel a) and the average number of consumers (panel b) across simulations. The figure shows that, although the market does not reach full convergence within the simulated time span, there is a persistent dominance of green firms and consumers for a large part of the period, after initial substantial oscillations before the model stabilizes.

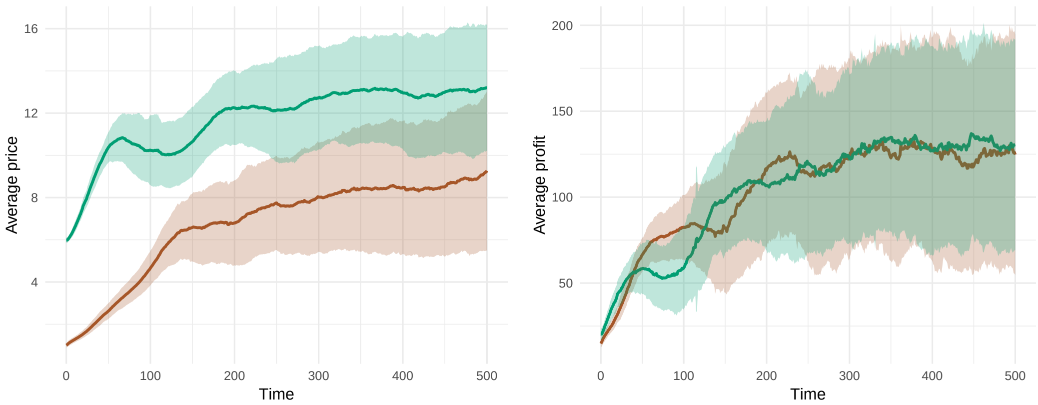


(a) Average number of firms

(b) Average number of consumers

Figure 1: Average number of firms and average number of consumers by type (green and brown) across 500 Monte Carlo simulations. Shaded area indicates ±1 one standard deviation across simulations

Figure 2 report the average evolution of prices and profits for green and brown firms across simulations. Green firms tend to charge higher prices than brown firms, which is consistent with their cost structure and the price updating rule reported in Equation (5). However, the gap between green and brown prices narrows over time as the share of green firms increases and competition among them intensifies. Turning to profits, the dynamics are less clear-cut: despite higher average prices, green firms do not systematically earn higher profits than brown firms. In fact, the similar profitability of the two types is what keep the market mixed. Instead, their long-run sustainability appears to derive from the expanding base of green consumers, while brown firms maintain relatively stable but non-increasing profits and gradually decline in number.

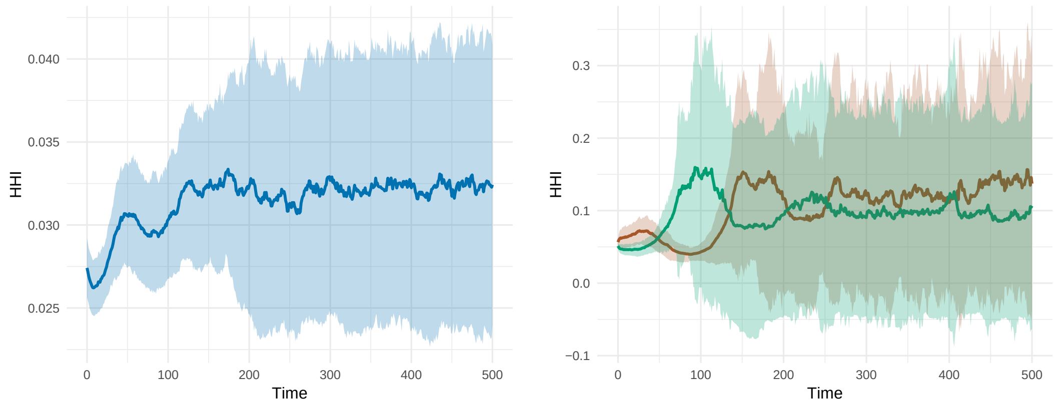


(a) Prices

(b) Profits

Figure 2: Average prices and profits of green and brown firms across simulations. Shaded areas indicate ±1 standard deviation.

Figure 3 reports the evolution of market concentration. Overall concentration remains very low throughout the simulation, with the Herfindahl–Hirschman Index (HHI) fluctuating between 0.025 and 0.04. This reflects the relatively large number of firms active in the market and the intense price competition, which prevents any individual firm from capturing a dominant share. The absence of capacity constraints does not alter this result, since spatial segregation naturally limits firms' local reach. Although the aggregate HHI suggests a highly competitive market, this measure combines both brown and green firms. When we compute local HHIs for green and brown firms, Figure 3b shows that the average HHI among brown firms is slightly higher than the HHI among green firms. This could reflect the formation of localized "pockets" of brown dominance: spatial segregation allows a handful of brown firms to retain a relatively large base of nearby consumers who remain insulated from wider competition. Overall, though, considering that on average firms are evenly split between the types, both local markets remain highly competitive.



(a) Whole Market

(b) Green and brown submarkets

Figure 3: HHI Index. Shaded areas indicate ±1 standard deviation.

5 Policy experiment

In this section, we use our model to conduct a policy experiment aimed at identifying which instruments are most effective in increasing the number of firms that choose to adopt green practices.

We analyse three different policy instruments. The first is a traditional Pigouvian tax, where the government imposes a unit tax on firms producing a brown product. The second is a green subsidy for producers, where the government grants a unit subsidy to each firm that chooses to produce a green product. The third is a green subsidy for consumers, in which the government provides a unit subsidy to each consumer who opts to purchase a green product. For the sake of the comparison, we chose the three policy to be equal in magnitude, therefore we introduce a firm subsidy of the value of 1 (which account for 20% of the production cost) and then we compare it with a green tax or a consumer subsidy of the same value.

We again set $x = 6$ and run 1000 simulations for each policy scenario and compare them with the baseline model in Table 3.

Table 3: Simulation results of policy scenarios

Policy	brown	mixed	green	time to brown	time to green	brown firms in mixed	brown consumers in mixed
Baseline	481	115	404	154.47	291.57	24.24	483.00
				(95.31)	(89.38)	(3.63)	(86.93)
Consumer subsidy	147	76	777	177.26	262.02	20.38	434.44
				(88.34)	(87.66)	(2.58)	(70.73)
Firm subsidy	123	79	798	204.47	258.56	19.35	405.33
				(93.86)	(85.76)	(2.38)	(68.96)
Green tax	60	51	889	218.27	228.21	19.71	415.78
				(108.22)	(87.30)	(3.37)	(78.03)

We report the number of simulations that converge to either *brown* or *green* (i.e. all firms of either type) and cases of non-convergence (*mixed* state). For convergent simulations, the table displays the average time to converge (s.d. in parentheses); for non-convergent simulations, the composition: average number of *brown firms in mixed* and *brown consumers in mixed* (s.d. in parentheses).

The Monte Carlo simulations highlight the Green tax as the most effective policy in fostering a transition toward green firms and consumers, with 889 out of 1000 converging to a green state (vs. 404 in the baseline) and the shortest average time to green convergence (228.21). Both Firm subsidy and Consumer subsidy also significantly increase convergence to green, but with a higher persistence of mixed systems. Notably, the Firm subsidy reduces the average brown firms across simulations in mixed systems to 19.35, the lowest value among policies with the lowest variability although the difference with respect to the green tax scenario is very small. The Firm subsidy scenario also results in the lowest average share of brown consumers. These results suggest that tax-based instruments may be more effective in accelerating green convergence, but subsidy-based policies may be preferable where gradual adaptation and social acceptance are priorities. However, while the former would generate governmental revenue, the latter represents a costly policy for the policy-maker.

Either the case, our policy experiment suggests that despite the green preference characterizes all consumers in the market, policies addressed to buyers are not as effective as those acting on the supply side.

In Table 3 we report the average number of brown firms and consumers along the simulation period (i.e. for all 500 time steps) across runs. However, we were also interested in checking what is happening at the end of the simulation rather than on average over the entire run, since this could actually provide a better information of the effectiveness of the policies when we do not reach convergence. Thus we analyse the average numbers of brown (or green) agents at the end of the simulation period (i.e. at $t = 500$) for the runs that do not converge to either state (i.e. the mixed markets). In Figure 4 we show the market outcomes through the use of a box-plot of the distribution of the green consumers and green firms in the last time step of the simulations. A box-plot provides a compact representation of the distribution of a variable, reporting the median, the interquartile range, and the presence of extreme values. In this case, the figure compares the shares of green consumers and green firms across different policy scenarios.

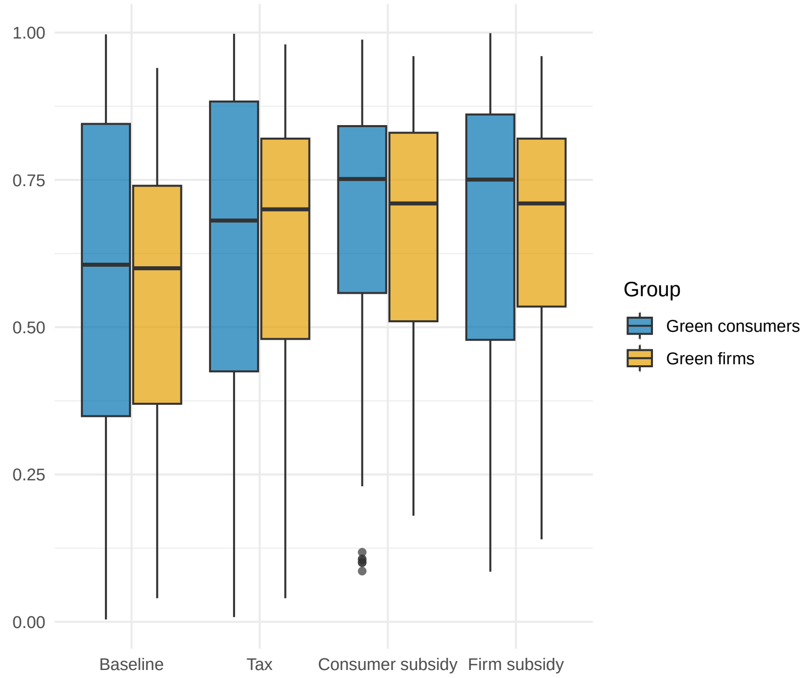


Figure 4: Box-plots of the distribution of green consumers (blue) and green firms (orange) across the baseline and the policy scenarios.

The plot indicates that policy instruments significantly affect the extent of green adoption. Relative to the baseline, both taxes and subsidies shift the distribution upward, although the magnitude and dispersion differ between consumers and firms. Subsidies, in particular, are associated with higher and more consistent adoption among firms, whereas consumers respond less uniformly, showing greater variability across scenarios.

To have a more rigorous evidence of any potential effect, we also runs the Wilcoxon test among the four treatments, as well as pairwise comparison for both the share of green consumers and the share of green firms. The significance levels for the Wilcoxon test reported in Table 4 show that the distributions of the share of green consumers and green firms (baseline and three policy scenarios) are statistically different. In Table 5 and Table 6 we test instead the pairwise differences.

Table 4: Wilcoxon rank-sum test: baseline vs. all scenarios combined.

Variable	W	p-value
Green consumers (%)	9838.0	0.086*
Green firms (%)	8784.5	0.0019***

Note. Wilcoxon rank-sum test with continuity correction; observations with share = 0 or = 1 were excluded. Significance levels: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Table 5: Pairwise Wilcoxon rank-sum tests for green consumers (%).

	tax	consumers subsidy	firms subsidy
baseline	1.000	0.600	0.600
tax	–	1.000	1.000
consumer subsidy	–	–	1.000

Note. Holm-adjusted p-values. No pairwise comparison reached significance. Observations with share = 0 or = 1 were excluded. Significance levels: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Table 6: Pairwise Wilcoxon rank-sum tests for firms green firms (%).

	tax	consumers subsidy	firms subsidy
baseline	0.303	0.055*	0.055*
tax	–	1.000	1.000
consumer subsidy	–	–	1.000

Note. Holm-adjusted p-values. Subsidies show borderline significance ($p < 0.1$) relative to the baseline. Observations with share = 0 or = 1 were excluded. Significance levels: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Within the mixed cases, the policies tested had no measurable impact on consumers, as the share of green consumers did not differ significantly across scenarios. By contrast, the policies did affect firms: relative to the baseline, all treatments increased the share of green firms. Among them, the two subsidy schemes appear more effective than the tax, as they produced the largest differences with respect to the baseline, although the two subsidies performed similarly to each other. These results suggest that while consumer behaviour remained largely unaffected, policy interventions were successful in shifting firms towards greener choices, with subsidies emerging as the most promising instruments. This is in line with the results displayed in Table 3 confirming that policy action on the demand side may not be effective even in the presence of specific green preference of consumers.

In addition, Figure 5 shows that the profit difference between green and brown firms is on average larger in all three policy scenarios compared to the baseline. This outcome is consistent with the reduced presence of brown firms observed under the three policies. This pattern reflects both the reduced profitability of brown firms when green-oriented measures are introduced, which limits their competitiveness relative to green firms. By contrast, green firms are able to improve their performance since the very initial time steps of the simulation run. The results therefore indicate that the policies are effective in shifting relative profitability in favor of green firms, not only by reducing the survival of brown firms but also by constraining their economic returns.

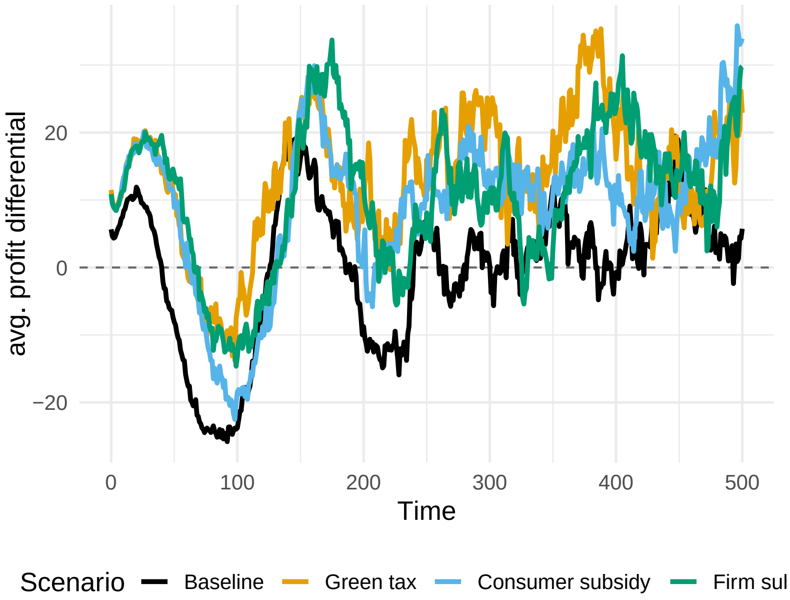


Figure 5: Average difference in profits between green and brown firm per treatment.

6 Conclusions

This paper has explored the dynamics of green technology adoption in an oligopolistic market using an agent-based modelling approach. By moving beyond the static equilibrium predictions of game theory, we have been able to capture the evolutionary process through which firms, responding to profitability signals and interacting with a heterogeneous population of consumers, converge on different market structures. Our results broadly validate the findings of analytical models, such as Gori et al. (2024), by showing that a market can indeed endogenously evolve into an all-brown, all-green, or mixed state, contingent primarily on the average intensity of consumers' environmental preferences.

Our analysis yields clear and policy-relevant insights. While green consumerism provides a foundational incentive for firms to abate, our policy experiments indicate that it may be an insufficient driver for a rapid and complete transition on its own. The comparative assessment of policy instruments reveals a distinct advantage for supply-side interventions. The environmental tax emerged as the most powerful tool for accelerating the convergence to a fully green market. Conversely, the subsidy directly granted to green firms proved most effective in shifting the composition of mixed markets towards green firms and green consumers. The relative ineffectiveness of the consumer subsidy highlights a critical point: even when consumers value green products, channelling support directly to the supply side appears to be a more efficient lever for change in this strategic context.

Methodologically, this study underscores the value of agent-based modelling as an important complement to game theory in industrial organization and environmental economics. The ABM framework allowed us to incorporate heterogeneity and spatial competition in a way that would be intractable for a purely analytical solution. Furthermore, it provides a "laboratory" to test the impact of different policy instruments.

Naturally, this work opens several avenues for future research. The model could be enriched by allowing firms to choose not just a binary "brown/green" technology but a continuous level of abatement investment, or by introducing more sophisticated consumer learning and social network effects. Furthermore, exploring the implications of firm entry and exit, or de-localization, would add another layer of realism. In conclusion, by bridging computational and analytical methods, this paper offers a dynamic understanding of the transition to sustainable markets, providing both a theoretical contribution and practical guidance for policymakers aiming to design effective environmental regulations.

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