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Article — Published Version

Policy instruments for green-growth of clusters: Implications from an agent-based model

Environmental Innovation and Societal Transitions

Provided in Cooperation with:

Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle (Saale)

Suggested Citation: Kamath, Ram; Sun, Zhanli; Hermans, Frans (2022) : Policy instruments for green-growth of clusters: Implications from an agent-based model, Environmental Innovation and Societal Transitions, ISSN 2210-4224, Elsevier, Amsterdam [u.a.], Vol. 43, pp. 257-269, <https://doi.org/10.1016/j.eist.2022.04.003> , <https://www.sciencedirect.com/science/article/pii/S2210422422000387>

This Version is available at:

<https://hdl.handle.net/10419/266479>

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Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Environmental Innovation and Societal Transitions

journal homepage: www.elsevier.com/locate/eist

Policy instruments for green-growth of clusters: Implications from an agent-based model

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ARTICLE INFO

Keywords:

Decoupling
Green-clusters
Agent-based modelling
Socio-technical transitions
Policy instruments

ABSTRACT

Green-growth theory asserts that green-innovations will allow us to decouple economic growth from pollution. Policies that promote green-innovations are therefore paramount. Scholarship has become increasingly interested in how green-clusters can contribute to sustainable innovation and decoupled green-growth. In this study, we create an agent-based model that can simulate a cluster's transition, as shaped by different policy instruments. We use this model to explore the effects of a) innovation grants, b) fines for pollution c) financial incentives for entrants, and d) an instrument mix of incentives and fines, on the green-growth of a peripheral-region cluster. Our results indicate that designing instruments for absolutely decoupled growth of peripheral-clusters is close to impossible; and demonstrate the inherent trade-offs in designing policies for relatively decoupled growth. Based on these results, we opine there should be more nuanced deliberation on the potential contribution of green-clusters to sustainable development, with greater focus on the possible trade-offs.

1. Introduction

The notion of green-growth has emerged as a dominant policy response to climate change (Dale et al., 2016). Green-growth theory asserts that green-technological innovation will allow us to relatively or absolutely decouple economic growth from resource use and carbon emissions (Solow, 1973; Hickel & Kallis, 2020). Therefore, policies that promote the creation and adoption of green-innovations are paramount to achieving some level of decoupled green-growth. As a response, over the last decade, innovation policy literature has become increasingly focused on innovations targeting transitions and green-growth (Schot & Steinmueller, 2018). Scholarship has become increasingly interested in how green industrial clusters can contribute to sustainable innovation and green-growth (Hansen & Coenen, 2015; Boschma et al., 2017). Green-clusters grow in a decoupled fashion by developing and selling products or technologies that “reduce carbon emissions and pollution, enhance energy and resource efficiency, and prevent the loss of biodiversity and ecosystem services” (UNEP, 2011:16).

In this study, we explore implications for policies to advance the green-growth of clusters. Here, we are specifically interested in policies for greening of clusters located in peripheral regions. According to the typology introduced by Tödting & Trippel (2005), we can distinguish between metropolitan, specialized and peripheral regions. However, we have limited understanding of the prospects for the development of green-clusters in the various types of regions, and of the differences in required policies. Until recently, research has focused on the evolution of metropolitan or specialised regions, implicitly assuming that there is no innovation in peripheral areas. Growth of any form is difficult in peripheral regions because they are characterized by a lack of critical mass in any industrial

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<https://doi.org/10.1016/j.eist.2022.04.003>

Received 6 September 2021; Received in revised form 22 March 2022; Accepted 4 April 2022

Available online 20 April 2022

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specialization, and by the lack of high-value, knowledge-intensive activities (Isaksen & Trippel, 2014). This view is being increasingly questioned, which is reflected by a rising number of papers, special issues, and edited volumes on innovation outside of agglomerations (Eder, 2019). To fill in the knowledge gap of green-growth in peripheral regions, we address the question, *What policy instruments are most effective in causing green-growth of clusters in a peripheral region?*

To answer this question, we built an agent-based model (ABM) to simulate the transition of a peripheral cluster of firms. With this ABM, we aim to advance understanding of policy instruments that promote green-growth and innovation, and of the emerging practice of modelling socio-technical transitions (Holtz et al., 2015; Köhler et al., 2019). The simulations are based on the idea that the emergence of green-growth in peripheral regions commonly involves the deployment of green-technologies developed elsewhere, i.e. greening through importation (Grillitsch & Hansen, 2019). Mere availability of a green-technology does not guarantee widespread adoption; policy support is often a pivotal catalyst for adoption (del Río González, 2005). In this regard, several studies have argued for the application of different policy instruments (Nauwelaers et al., 2009; IEA, 2011). Using the ABM, we explore the effectiveness of three individual instruments, and an instrument-mix, on the peripheral cluster's green-growth. The instruments are 1) Financial incentives to attract external actors in a green industry, 2) Grants provided to qualifying innovation projects being run by local cluster actors, and 3) Imposition of fines on firms that cross a certain level of pollution. The instrument-mix we explore is a combination of incentives for foreign actors and fines.

In the following section, we introduce the reader to the complex adaptive systems perspective that guides our ABM. In section three, we describe the characteristics of the agents and processes within our agent-based model. In the fourth section, we present and interpret the results of the simulation. In section five, we discuss the strengths and limitations of our model, lessons from our findings, and implications for how scholarship views green-clusters and decoupled growth.

2. Theoretical perspectives

In this section, we discuss the perspective of complex adaptive systems (CAS), which underlies the approach of agent-based modelling. We detail why clusters can be viewed as CAS, and how green-growth can be viewed as the evolution of the cluster-CAS's macro-level properties.

2.1. Clusters as complex adaptive systems

A CAS is composed of a dynamic network of actors that continually (re)act in response to the (re)actions of other actors, and to external stimuli (Waldorp, 1993). In a CAS, aggregate behaviour and various systemic characteristics are seen to emerge from the myriad actions and interactions of its constituent actors (i.e. the process of upward causation) (Gandolfi, 1999). At the same time, these characteristics may guide, and constrain, the actions of the actors making up the CAS (i.e. the process of downward causation).

An industrial cluster is an interconnected, mutually dependant network of actors (such as firms, universities) and institutions, working in a particular field, concentrated in a particular geographical area (Porter, 1998). Industrial clusters exhibit characteristics that make them complex adaptive systems (Martin & Sunley, 2011; Nikolic et al., 2009), such as:

- 1 Emergence: In CAS, macro-level structures and dynamics emerge out of micro-level behaviors and interactions. Cluster-wide properties such as pollution-levels, financial assets emerge from the actions and interactions the cluster's firms, universities etc. These properties then influence the actions of cluster members that (re)produce them.
- 2 Adaptation: CAS can adapt their structures and dynamics. Clusters can adapt (e.g. by reducing pollution-levels) in face of external or internal demands (Martin & Sunley, 2011). This enables clusters to survive, and even thrive, by evolving towards new (more sustainable) set of structures (Klepper, 2006).
- 3 Openness: CAS tend to be dissipative—subject to constant interaction and exchange with their environments. Clusters are open systems that engage in continual exchanges with its environment (Martin & Sunley, 2011).

2.2. Green-growth is the transition of a cluster CAS

Green-growth implies that, amongst other changes, the cluster's financial standing should improve as pollution-levels decrease. When we view a cluster as a CAS, its green-growth can be perceived as a transition of its macro-level properties (such as pollution, financial assets etc.); where these properties become more sustainable, and guide actor behaviour that drives further transition. These changes at the cluster-level will only emerge through the adoption and creation of green-technologies at the actor-level (i.e. upward causation). In parallel, cluster-level structures (such as the availability of grants) will attempt to shape actors' choices that advance (or retard) decoupled growth (i.e. downward causation). Essentially, what we model in our ABM are these processes of upward and downward causation, and how they possibly lead to green-growth of the cluster.

2.3. Peripheral regions and green-growth

Peripheral regions are characterised by low-levels of clustering, and a lack of industrial specialisation (Isaksen & Trippel, 2014; Grillitsch & Hansen, 2019). These regions are dominated by small-and medium-sized enterprises. They can host a few large firms (Grillitsch & Hansen, 2019). Peripheral firms engage in low-levels of collaboration, leading to little knowledge-exchange (Isaksen & Trippel, 2014; Grillitsch & Nilsson, 2015). Amongst the various types of regions, innovation rates are lowest in peripheral regions.

Furthermore, innovation by peripheral firms is mostly of an incremental nature (Shearmur, 2011; Isaksen & Trippel, 2014).

Owing to the relatively weak support system for innovation, peripheral firms are unlikely to find all the resources necessary for innovation, within these regions. Consequently, to create green-growth paths, they must collaborate, with extra-regional actors, or use imported knowledge and technologies. Studies such as Grillitsch & Nilsson (2015), Grillitsch & Hansen (2019) argue that (green) growth in the periphery will be centred on the activities of a few innovative firms in the region, attracting foreign agents, and importing (green) knowledge and technologies.

2.4. Sustainability treadmill

In our ABM, the agents are essentially on a type of technological treadmill (Cochrane, 1958). In its original form, the treadmill theory refers to a race to continually update technology in possession, to lower production costs. Failure to update technology leads to relatively higher costs, and to bankruptcy.

In our model, we apply this idea with a modification – agents are in a race to continually innovate, update green-knowledge and green-technologies, lower pollution and become more sustainable (while becoming financially richer). If they fail to innovate, their pollution rises (on both a relative and absolute basis), as the performance of their green-technologies deteriorates with time. With failure to innovate, the agents become (relatively) dirtier, fall behind in the sustainability treadmill, and eventually, fall off and perish (as their dirtier products lose share in the market).

3. Methodology

The most effective and accurate model of a CAS is one which is itself, a CAS. Therefore, the most suitable option to model cluster evolution is agent-based models. To answer our research question, we created an ABM in the Netlogo 6.1 modelling environment. Netlogo has an easy-to-use GUI, and does not require a lot of programming effort, letting us focus on the model's logic.

ABMs can be relied upon to examine how a system will respond to developments such as the introduction of new policy. There are multiple instances of ABMs being used to explore various emergent phenomena in industrial clusters. Dilaver et al. (2014) investigated the relationship between the entrepreneurial character of a region and the emergence of clusters. Agents in the model run innovation projects to create new knowledge. When these projects succeed, agents reap financial rewards. Successful projects can also lead to the creation of spin-offs. Experiments revealed a positive correlation between the entrepreneurial nature of the region and cluster development (because of higher spin-off formation). Canals et al. (2008) investigated the link between the willingness of actors to collaborate (to share knowledge, resources), and the intensity of clustering in a region. In the model, firms randomly collaborate. Experiments revealed that spatial clustering was more intense when the willingness to collaborate was high. Vermeulen & Pyka (2014) simulated the mediating effects of agents being able to collaborate with extra-regional actors. Agents in this ABM collaborate and share inputs for innovation. Rewards from successful innovation, which are abilities to create more advanced technological artefacts, are equally shared amongst the collaborators. The model demonstrated that when agents are able to collaborate with external actors, the artefacts created are much more radical. Finally, Zhang (2004) modelled how the emergence of clusters begins with the appearance of some inspiring entrepreneurial agents. In the model, an entrepreneurial firm randomly appears and makes a large profit, which inspires other firms to enter the landscape. Each firm is given some level of technological assets. Firms that fail to make a profit fail to innovate, leading to their exit. These processes combine to cause spatial clustering of firms.

While our model has been inspired by the features of these models, unlike preceding ABMs, we do not model for innovation that merely leads to richer agents; rather, we model for innovation that makes the agents (and the cluster) not only richer, but also greener. Moving away from extant models of cluster-based innovation, we simulate processes of environmentally-sustainable innovation. Firm-agents collaborate and contribute resources to projects aimed at effecting incremental or radical green-innovation. Successful projects help agents not only reap financial rewards but also new green-knowledge and improved green-technologies; which help agents lower their pollution, and become more sustainable. Additionally, we make a further contribution to the field of modelling cluster-based innovation - by conducting experiments to determine which instruments can effectively stimulate green-growth.

3.1. Structure of the agent-based model

We describe below, the variables in the ABM; the main agent behaviours, and processes, within the ABM; and the macro-level parameters that we track. For greater detail on the ABM, we welcome the reader to view the Overview, Design concepts, Details (ODD) protocol in the supplementary materials.

Agent-properties and global variables

In our ABM, there are a number of agents (i.e. firms), clustered in a landscape with characteristics of a peripheral region. The behaviours of these agents are governed by two sets of variables - agents' own and global. The main agent variables are 1) Financial capital, 2) Knowledge capital, 3) Reputational capital, 4) Pollution-levels, 5) Radical project experience, and 6) Incremental project experience. The main global variables are 1) Probability of collaboration 2) Probability of radicalness 3) Probability of innovating 4) Innovation potential 5) Cluster-size 6) Decay rate. The first five global variables are informed by the postulations of Tödting & Trippel (2005) and Isaksen & Trippel (2014), and data from the European Innovation scoreboard for 2019–2020. The definitions of these variables are given in Table 1 below.

We can use this model to simulate cluster-transition in any region, by controlling the global variables. To answer our research

question, we simulate the greening of a cluster in a peripheral region. We operationalise the features of the periphery, as detailed in Section 2.3, by controlling values for the following global variables:

- Percentage of large firms: we only have a small percentage of large firms in the cluster, at initialisation.
- Probability of collaboration: we have used the range of values for modest regions (0 to 27%) from the European RIS scoreboard.
- Probability of radicalness: we have used the range of values for modest regions (0 to 55%) from the European RIS scoreboard.
- Probability of innovation: At initialisation, we have used the lowest value for modest regions (2.2%) from the European RIS scoreboard.

We use data for “modest innovator regions” because they resemble most closely, peripheral regions. They are regions whose overall innovation scores are below 50% of the European average. The ranges for probabilities for collaboration, innovation, radicalness are lowest for modest regions. To simulate conditions of metropolitan or specialized regions, we simply change the range of values for the above global variables (using data for “strong innovators” or “innovation leaders” from the scoreboard).

As the model runs, the ranges for probability of collaboration and probability of radicalness are always adhered to. This way, the agents always collaborate and engage in radical innovation at rates that are characteristic of peripheral firms. We do not maintain a range for the probability of innovating, and for the percentage of large firms, as we treat them as an emergent variables shaped by agents’ innovation activities.

Agents’ action-space

The objective of the agents in the simulation is to survive, and grow, for as long as possible. The agents exist in an environment where demand for their products is positively correlated with their sustainability (applying the idea of the sustainability treadmill from Section 2.4). Consequently, each agent’s survival depends on its ability to increase knowledge-capital, financial capital, and reputational capital. The challenge facing agents is that with time, the capital stocks they hold diminish, while pollution climbs. In the model, assets decrease by the formula $C(1 - dr)^t$ while the pollution increases by the formula $P(1 + dr)^t$. “C” is the value of the capital-asset in the prior time-step, “P” is the pollution-level of the agent in the prior time-step, and “dr” is the decay rate.

The agents’ knowledge capital (which is green-knowledge, green-technologies and associated machinery and equipment possessed by an agent) decreases with each time-step. As the sustainability performance of its green-technologies decreases with time (due to deterioration of machinery and equipment), the agent’s knowledge capital loses value. With their physical technology assets deteriorating, and the technology becoming relatively inefficient, agents’ products and processes become dirtier, as the pollution-level of each agent increases (both in relation to other agents’ products and processes, and on an absolute basis). When an agent’s pollution-level crosses 100, the agent will cease to exist (an emulation of the government forcing a highly polluting firm to close).

Agents’ financial capital decreases when demand for their products comes down. As agents’ knowledge capital decreases, the sustainability of their products and processes come down. This causes the relative competitiveness of products to go down, reducing demand for them. Lower demand forces agents to use their reserves to survive; hence the reduction in financial capital each time-step. When the financial capital for an agent falls under 10, the agent will cease to exist. With declining value of green-technology and knowledge, declining sustainability for their products, the reputational capital of the agents decreases each time-step. When the reputational capital for an agent falls under 10, the agent will cease to exist.

Agent survival and growth requires innovation at a rate that staves off rising pollution and decreasing assets. New knowledge and

Table 1

The agents’ own and global variables that guide agent behaviour.

Variable	Definition
Agents’ own	
Financial capital	Financial capital in possession of an agent.
Knowledge capital	Green-knowledge and green-technologies possessed by an agent.
Reputational capital	Reputation, sustainability credentials of an agent.
Pollution-level	Represents how polluting an agent’s operations are.
Radical project experience	The number of successful radical innovation projects an agent has participated in.
Incrementalproject experience	The number of successful incremental innovation projects an agent has participated in.
Global	
Probability of collaboration	This is the probability of firms collaborating for a (green) innovation project. Defined as ratio of number of firms collaborating in an innovation project to the total number of firms. The range of values for this variable is obtained from the range of values for “Innovative SMEs collaborating with others” for modest regions, from the European RIS 2019–2020 scoreboard.
Probability of radicalness	The probability of a (green) innovation project being a radical one. Defined as the ratio of number of successful radical innovation projects to total number of successful projects. The range of values for this variable is obtained from the range of values for “Sales of new-to-market and new-to-firm innovations” for modest regions, from the European RIS 2019–2020 scoreboard.
Probability of innovating	The probability of a (green) innovation project succeeding. Defined as the ratio of number of successful projects to total number of projects. The initial value for this variable is obtained from the lowest value for “Product or process innovators” for modest regions, from the European RIS 2019–2020 scoreboard. There is no range used for this variable.
Innovation potential	This is the ratio of the number of successful projects to the total number of firms at a point time.
Cluster-size	This is the number of agents in the cluster, at any given point in time (note: split agents are counted as one agent).
Decay rate	This is the rate at which the agents’ three capital asset stocks decline with each time-step, and also the rate at which the agents’ pollution rises with each time-step.

technology assets are created or adopted through green-innovation projects. Successful projects endow agents with rewards in the form of capital assets and lower pollution. Initially, most projects are incremental in nature, and green-technologies are assumed to be available “off-the-shelf” (applying the idea of greening through importation (Grillitsch & Hansen, 2019)). After multiple instances of incremental innovation, the peripheral agents can develop more advanced green-technologies through radical innovation projects. Through (incremental) innovation projects, agents can obtain new knowledge and tech, which help them (slightly) lower pollution. While innovation lowers pollution on an absolute basis, it can also make them cleaner in comparison to other agents; which increases demand for the agent-firms’ products. So agents also reap financial asset rewards through innovation. Along with green-innovation success, comes greater reputation. So, the agents also gain reputational capital. With successful radical projects, the firm-agent moves onto a new green-technology that surpasses the sustainability of technologies in possession. The asset rewards and pollution-reduction in this case, therefore, are higher than from incremental innovation. However, radical innovation is rarer, with lower chance of success. Engaging in radical innovation projects requires agents to first succeed in several incremental innovation projects. Without green-innovation, agents turn dirty, with higher levels of pollution and lower levels of capital. This leads to firm-agents ceasing to exist, and the cluster dying. Green-innovation in the model has three steps – initiating projects, innovating, and reaping rewards for successful innovation.

Initiating green-innovation projects

To start an innovation project, an initiator agent collaborates with between one and five agents that possess the highest levels of knowledge capital. Once a project is initiated, links are formed between the project partners. Any firm-agent can initiate a green-innovation project. At a time, an agent can only be a member of one project (unless it splits into two divisions, in which case the agent can participate in two projects simultaneously). For this exploratory model, we have not factored in the effects of any proximity dimensions (such as geographical, social, institutional, cognitive or organisational (Boschma, 2005)) in the collaborative process; we aim to incorporate these dimensions in future versions.

The number of projects successfully initiated in a time-step is the product of probability of collaboration and a random positive integer below the variable “number of projects in a tick”, which is input by the observer. Some of the projects are randomly chosen to be radical innovation projects. In the beginning stages, most projects are incremental innovation projects. The chances of an initiated project being a radical project are positively correlated with the innovation potential. With time, if there are several successful incremental innovations, the innovation potential rises, and so can the number of radical projects.

The act of innovation

After the agents have collaborated on a project, they innovate using green-technologies that present the possibility of new capital rewards, and reduction in pollution. To execute the project, project-partners commit capital to the project. The chances of project success are directly proportional to the total knowledge, financial, and reputational capital committed to the project, the total number of successful radical/incremental projects that the partners have been a part of, and the global variable probability of innovating. Chances of project success are lower when the project is a radical one. The capital an agent commits to the project is proportional to its capital stocks, and the number of successful projects it has been part of. This way, richer, more experienced agents are able to commit more capital.

A project succeeds or fails within one time-step. When a project succeeds, a few things happen. Firstly, the probability of collaboration increases (by the ratio of the number of partners in the project to total number of agents). The increment occurs as long as the probability of collaboration stays under the upper limit of its range (see Table 3). Secondly, the probability of innovating is updated (by calculating ratio of successful projects to total number of projects undertaken), as long as it stays under the value of one. Thirdly, the radical project experience or incremental project experience for each partner is increased by one. Next, if the project that succeeded is a radical one, probability of radicalness is updated (by calculating ratio of successful radical projects to total number of successful projects). The updating occurs as long as the probability stays under the upper limit of its range (see Table 3). By maintaining the ranges for probability of collaboration and radicalness, we ensure that the agents always behave as peripheral firms. Fifth, if the successful project is a radical one, a spin-off firm-agent is created from the initiator agent (like in Dilaver et al. (2014)). This spin-off will have 25% of the parent’s knowledge and financial capital, pollution-level, and past experience with successful projects; and 50% of reputational capital. Finally, the links that were formed between the project-partners are removed (which is the first event that occurs when a project fails).

Rewards from green-innovation

Successful innovation immediately rewards all participating agents equally (like in Vermeulen & Pyka (2014)), with capital-assets and lower pollution. After each successful project, the agents will have their financial, knowledge and reputational capital doubled (in case of a radical project), or rise by 25% (in case of an incremental project). Pollution is halved (in case of a radical project), or decreases by 25% (in case of an incremental project). See Table 4, for the equations that govern capital increments, and pollution decrements.

As firms become richer, they can be involved in multiple innovation projects. If any of an agent’s three capital-stocks go above 100, the agent is allowed to participate in two innovation projects within the same time step. The model enables this by splitting the agent into two separate agents that represent internal divisions that can independently carry out innovation-projects (conceptually, we think of this splitting as a rich, large firm reorganising into independent divisions that are focused on one particular product-line, or a certain market). The parent agent’s financial and knowledge capital, its pollution, and its past experience with successful projects are split into two, and each half is inherited by the two divisions. Since there are no new firms being created, but rather independent internal

divisions, the two new agents are counted as one when the model calculates cluster-size.

Agent death

Rewards are tempered by decreasing capital and increasing pollution in each time-step. See [Table 4](#), for the equations that govern capital decrements, and pollution increments. If the financial or reputational capital falls under the value of 10, or if the pollution-level for an agent goes above 100, the agent will cease to exist. With the death of an agent, the innovation potential of the cluster is updated (as the ratio of the number of successful projects surviving agents have executed, to the number of agents).

Macro-level patterns and end-state of interest

We track the following macro-level variables, to gauge the progress of the cluster's green-growth:

- 1 Pollution-levels: This is the sum of the pollution-levels of all the agents that make up the cluster.
- 2 Cluster-size: This is the number of agents existing at any point in time (note: split agents are counted as one agent).
- 3 Knowledge capital: This is the sum of the knowledge capital stock of every agent in the cluster.
- 4 Financial capital: This is the sum of the financial capital stock of every agent in the cluster.
- 5 Reputational capital: This is the sum of the reputational capital stock of every agent in the cluster.
- 6 Ratio of pollution to financial capital: Green-growth requires economic growth to decouple from pollution. We track this ratio to see if as the cluster's pollution-levels go down, its financial capital stock goes up.

Besides these six parameters, we also track the number of successful projects and the number of successful radical projects. The desired end state, where the simulated cluster has transitioned and decoupled, is one where pollution has declined, cluster-size has increased or at least remained the same, capital stocks have increased, and the ratio of pollution to financial capital is trending down. The least desired state is when the agents have died out as pollution increased and capital stocks have been depleted.

3.2. Experiments with instruments shaping green-growth

In the ABM, we conducted experiments to simulate the effects of three individual instruments, and an instrument-mix, on peripheral agents' innovating behaviour, and on the green-growth of the cluster. The three instruments were 1) Financial incentives used to attract external actors having experience with the imported green-technologies, 2) Grants provided to qualifying innovation projects being run by cluster actors, and 3) Imposition of fines on cluster actors that cross a certain level of pollution. We chose these instruments because we wanted a group of instruments with different purposes. While grants and incentives for foreign actors are both economic instruments for technology-push, fines are a regulatory instrument for demand-pull. The instrument-mix we explored is incentives and fines being applied simultaneously. This combination ensured that while our study did not analyse the effect of so-called "sermons" (i.e. communicative policy tools that stimulate stakeholder participation, learning and collaboration ([Wieczorek & Hekert, 2012](#))), we covered the "carrots" and "sticks" of innovation policy. Incorporating communicative tools is something we aim to explore in future research. The four experiments we conducted are summarised in [Table 5](#).

Model initialisation for experiments

For each of the experiments, we initialised the model with a total of 50 agents, with 3% of the firm-agents being "large" firms. For the large firms, financial capital and reputational capital were assigned random initial values between 50 and 100. For the small firms, financial and reputational capitals were random values between 10 and 50. The model was initialised with agents having random pollution-levels between 0 and 100. For agents with a pollution-level of under 50, knowledge capital is a random value between 25 and 75. These greener agents are given the colour green. For all other agents, knowledge capital is 25. These "dirtier" agents were given the colour red.

At initialisation, the radical project experience and incremental project experience for each agent was set to 0. We assigned probability of collaboration a value of 14% (roughly mid-point of the range) and probability of radicalness, a value of 28% (roughly mid-point of the range). At initialisation, the model gave probability of innovating a value of 0.022 (lowest possible value), and innovation potential, value of 0.01 (meaning only 1 out of 100 agents can come up with a successful innovation). The number of projects initiated in a tick is the product of probability of collaboration and a random positive integer below five (number of projects in a tick). A project could have between 2 and 6 partners (we chose to use this range based on an overview of projects in a cluster we previously studied. Between 2014 and 2019, there were 27 collaborative projects in this cluster, only four of which included 6 or more partners). We set the decay rate at which assets decline and pollution rises at 0.1%. For the range of possible variable values at initialisation, see [Table 3](#). Once started, the simulation runs till either of two conditions is met - when the number of agents in the cluster is less than the number of projects in a tick (5), or when the number of ticks is greater than 300.

Imposition of fines on polluting firms

Fines refer to financial capital that is instantly reduced from an agent's stock when its pollution-level is equal to, or crosses, 33. Every time-step, the model finds agents that do not satisfy this criterion, and fines them. Fine levels range from 0% to 25% of each agent's financial capital. For this scenario, we varied fine levels from 0% to 25%, with jumps of 5%. At each fine level, we executed 100 simulation runs, for each of the macro-level patterns of interest.

Introducing grants for local innovation projects

Grants refer to financial capital that is given to a particular project, which is added to the financial capital that has already been committed to a project, by project partners. Grant levels range from 0% to 25% of the financial capital possessed by the project. In each time-step, during the act of innovation, the model will check if particular projects can receive grants. The chances of a project receiving a grant are positively correlated with capital stocks committed to it, and the number of successful incremental/radical projects that the partners have been part of (following Banal-Estanol et al. (2016)). For this scenario, we varied grant levels from 0% to 25%, with jumps of 5%. At each grant level, we executed 100 simulation runs, for each of the macro-level patterns of interest.

Incentives for attracting entrants

Incentives refer to financial capital that is bestowed to the entrant, immediately upon entrance. Incentives range from 0% to 25% of the financial capital an entrant possesses at entry. The probability of a new agent entering the cluster is positively correlated to the incentives set. Only one entrant may enter the cluster in each tick, and it may be a large or small agent. Entrants upgrade the knowledge capital of the cluster by bringing in new, higher-value green-technology and knowledge. Entrants' knowledge capital, ranging between 75 and 100, is higher than of cluster agents. An entrant's pollution-level is the same as the lowest pollution-level amongst cluster-agents. Entrants' experience with successful incremental and radical innovation is random values between the mean and maximum experience amongst the cluster-agents. Once they enter the cluster, entrants will behave like any other cluster agent. If they fail to innovate, they can turn dirty, become asset poor, and cease to exist. For this scenario, we varied incentive levels from 0 to 25%, with jumps of 5%. At each incentive level, we executed 100 simulation runs, for each of the macro-level patterns of interest.

Introducing an instrument-mix of incentives and fines

In this final scenario, every time-step, some entrants may enter the cluster and receive incentives, and some agents may get fined. For this scenario, we varied both incentive and fine levels from 0 to 25%, with jumps of 5%. At each combination of incentives and fines, we executed 100 simulation runs, for each of the macro-level patterns of interest.

4. Results

We now present the variations of the macro-level patterns of interest for each scenario. We first discuss results for the individual instruments, then for the instrument-mix.

Agent-based modelling often entails, as in our case, stochastic settings, and may generate rich and complex patterns. To investigate the uncertainty of the modelling results and how the uncertainty or variations of the model outputs can be attributed to various input variables, a sensitivity analysis needs to be conducted symmetrically (Ten Broeke et al., 2016). We used RNetLogo, and its extended R packages, *nlexperiment* and *nlr*, to execute a sensitivity analysis. We welcome the reader to view the setup and results of this analysis in the supplementary data.

4.1. Green-growth shaped by fines, grants, incentives

We started off our experiments by first analysing the effects of the three policy instruments individually. In the simulation where we imposed fines on polluting firms, we saw that as fines increase, the number of successful (radical) projects decline. We also saw that the cluster-size drops below the initial value at all fine levels, with the reduction in size trending slightly up with fine-levels. Asset-stocks stay below initial levels at all fine-levels, with the reduction in stock trending up with fines. Decreasing innovation success causes a decline in asset values, leading to a shrinking cluster. Pollution stays below initial values, and drops more with increasing fines. However, with declining innovation, this drop in pollution has to be attributed to shrinkage in cluster size. Decreasing pollution causes the ratio of pollution to financial capital to trend down. Overall, fines seem to retard the green-growth of the cluster by failing to encourage green-innovation.

In the simulation of grants for qualifying projects, we saw that increasing grant levels lead to higher levels of innovation (unlike with fines). Like with fines, asset values and cluster-size drop below their initial values at all grant-levels. However, we saw that with rising grants, the magnitude of reduction in size and assets diminish. We observed that with rising grants, the drops in pollution levels increase. With cluster-size increasing with grants, we can attribute this increasing reduction in pollution to rising levels of innovation. We also saw that rising grants causes the ratio of pollution to financial capital to decline. For this scenario, we ran another set of simulations, with a larger grant range of between 0 and 200%. We did see a positive effect where the magnitude of reduction in cluster-size and assets decreases; but even with a grant-level of 200%, an inflection to rising cluster-size and stock-levels does not occur. This tells us that simple financial grants alone are not sufficient to cause a richer, decoupled cluster (unless perhaps when they reach extraordinary levels that dwarf private investment).

In the simulation of incentives for entrants, what we saw is that with increasing incentives, the number of successful (radical) projects increase. Rising innovation leads to cluster-size and capital assets moving up from their initial values. However, this is only after incentives cross certain threshold. Below these thresholds, innovation is not high enough to lead to increasing size and capital stocks. Although pollution drops below initial values at all incentive-levels, raising incentive levels diminishes the amount of reduction in pollution. This demonstrates that we cannot optimise for pollution-reduction and capital-augmentation simultaneously. We will have to either give up a bit of capital or some pollution-reduction, in choosing one of many states where pollution has dropped, and capital stock has risen. High incentives seem to aid decoupling, as the ratio of pollution to financial capital fall with increasing incentives. We also ran a second set of simulations for this scenario, where entrants' experience with successful innovation was the same

as the maximum experience amongst the cluster-agents. What we saw was that with more experienced entrants, the inflection points where asset-values and cluster-size start increasing from initial values, are at lower incentive-levels than in the first case. This is because of higher innovation levels, which also lead to higher magnitude of asset and cluster-size augmentation.

We welcome the reader to view the graphs we have provided in the supplementary data, which depict the variation of the macro-variables of interest in each of the above scenarios.

4.2. Green-growth shaped by an instrument-mix of incentives and fines

We now come to the scenario where entrants are incentivised to come into the cluster, and where agents can be fined. Fig. 1 depicts how pollution in the cluster varies with increasing levels of incentives and fines. Fig. 2 depicts how the ratio of pollution to financial capital of the cluster varies. Fig. 3 depicts the variation of cluster-size, knowledge capital of the cluster, financial capital of the cluster, reputational capital of the cluster, the number of successful radical projects, and the number of successful projects.

From Fig. 1, we see that the pollution has dropped below its initial value throughout, but the reduction in pollution increases significantly after the fine-level of 2.5%. Above this level of fines, incentives do not have a major effect on the magnitude of pollution-reduction. Below this level, we see increasing incentives lead to lower reduction in pollution. The figure suggests we keep fines above 2.5% for optimum reduction in pollution. Looking at changes in the cluster’s capital-assets, graphs b, c, d in Fig. 3, we see that capital-stocks are maximised when fines are kept below 2.5%, and incentives are kept at the highest level. Coming to innovation rates, looking at graph f in Fig. 3, we see total innovation success is highest when fines are kept at zero, and incentives at 25%. This combination of incentives and fines also maximises cluster-size, as per graph a. For radical project success, it is better to keep both fines and incentives high (see graph e in Fig. 3). Finally, increasing fines and incentives both cause the ratio of pollution to financial capital to decline. The decline due to increasing incentives is more gradual than due to increasing fines. Fig. 2 suggests we keep both incentives and fines at the highest level to optimise for this ratio.

5. Discussion

Over the past decade, the field of innovation policy has seen increasing emphasis on studying the design of policies promoting green-clusters, clusters that undergo decoupled green-growth. There is however, limited knowledge on which policies can instigate green-growth in clusters. To contribute to this knowledge gap, we created an agent-based model.

This ABM stitches macro-level and micro-level perspectives together, enabling us to see how a cluster decouples through agents’ green-innovation. Our model is a virtual laboratory that allows for experimentation and projection – by modifying the set-ups of extant instruments or through the introduction of new instruments. We can for instance, explore the effects of reducing the pollution threshold above which agents are fined. We can also, with some changes in the model, explore the effects of other instruments such as

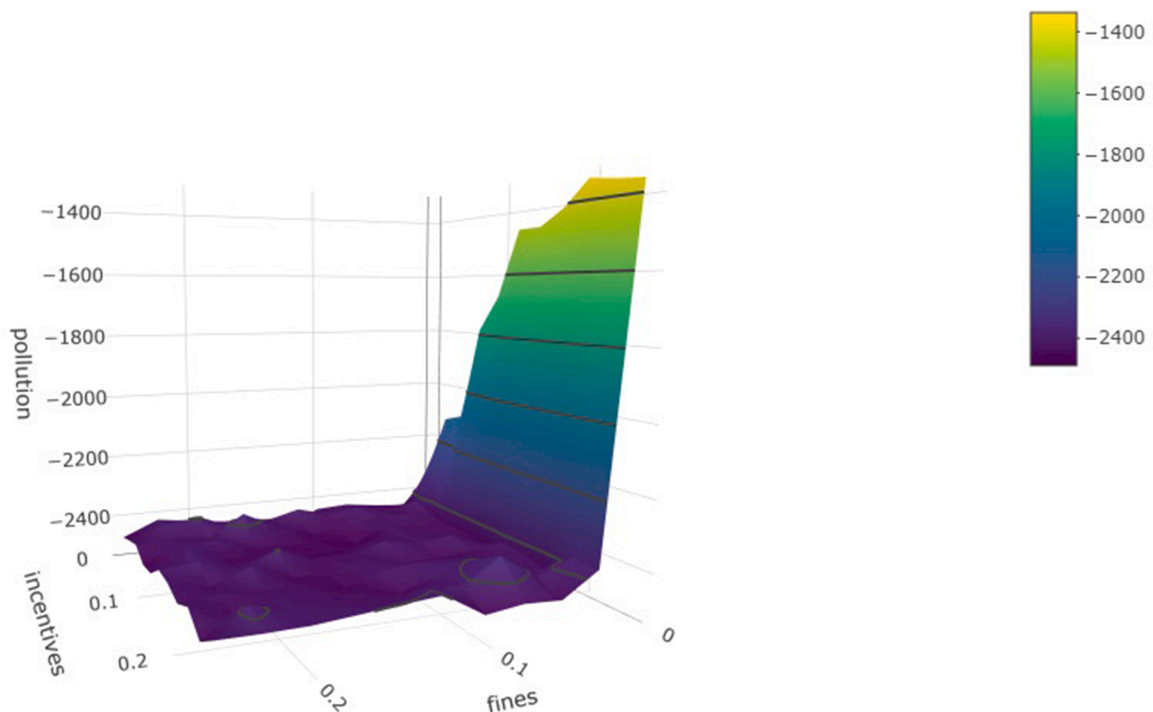


Fig. 1. Variation of pollution in the cluster, with increasing levels of incentives and fines.

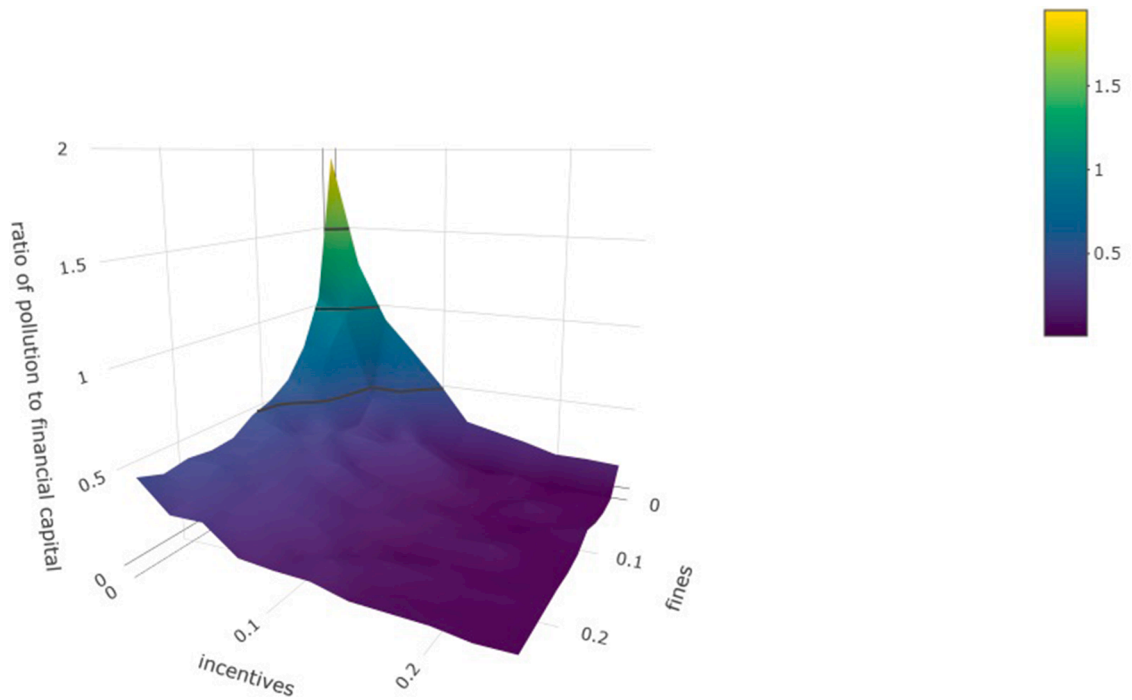


Fig. 2. Variation of the ratio of pollution levels to financial capital of the cluster, with increasing levels of incentives and fines.

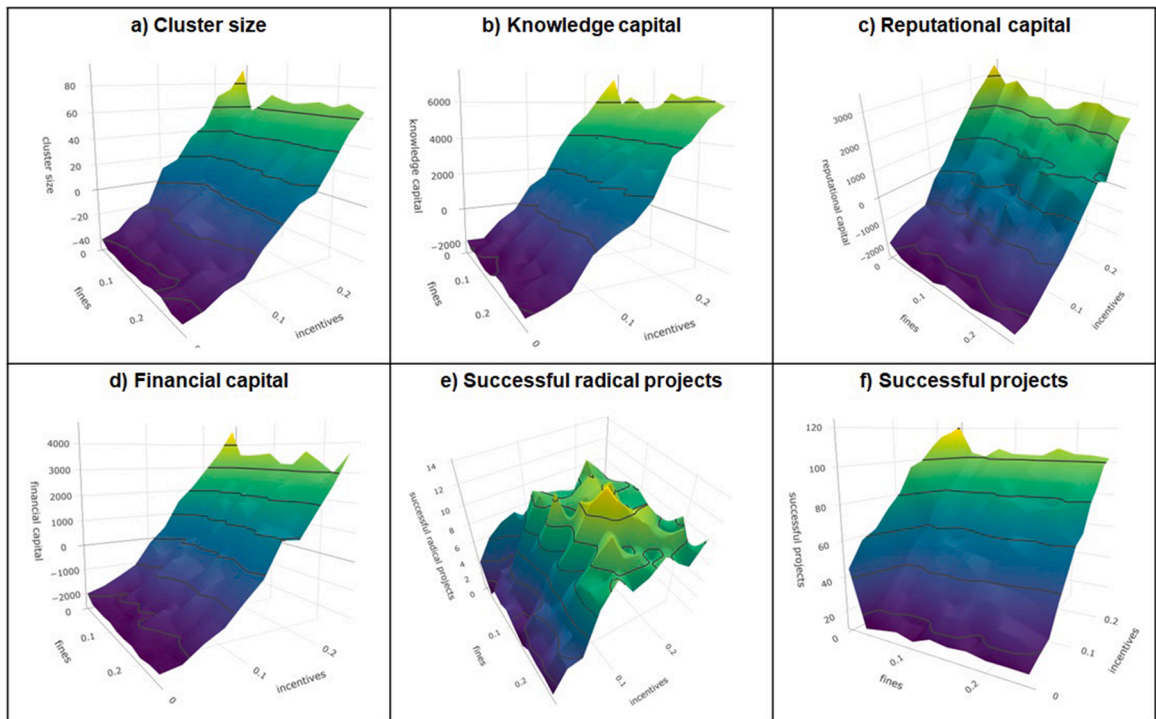


Fig. 3. Variation of cluster-size, knowledge capital of the cluster, financial capital of the cluster, reputational capital of the cluster, the number of successful radical projects, and the number of successful projects, with increasing levels of incentives and fines.

public procurement guarantees, technology standards on the cluster’s decoupling. In spite of these strengths, the model also has some limitations that present avenues for future research. As an exploratory model, its rules and agents are somewhat simplistic and abstract. Agent behaviour can be further developed by, for instance, factoring in the effects of different proximity dimensions, such as geographical, social, institutional, cognitive or organisational, in the process of agents collaborating. We also have the opportunity to refine rules and agent-behaviours, and to validate simulation results, using empirical data (which is the temporal dynamics of global variables such as probability of collaboration, and of macro-level parameters such as pollution (the dynamics of which may be shaped by instruments)) from real-life clusters, in future versions of the model.

While our ABM can model the transition of clusters in any region (by controlling for global variables), we used the model to explore how green-growth of a peripheral-region cluster is shaped by different instruments. To operationalise the characteristics of peripheral regions, we use data for “modest innovator regions” from European Innovation scoreboard for 2019–2020. In this section, we discuss the lessons from our findings, results, and implications for how scholarship views green-clusters and decoupled growth.

5.1. The effectiveness of different instruments

From our simulations, we saw that fines are the least effective of all instruments. The model suggests that fines retard the green-growth of the cluster by failing to encourage green-innovation. The model also showed us that while grants encourage innovation, innovation rates are not high enough to cause the emergence of a decoupled cluster. This is true even for grant-levels of 200%. This tells us simple financial injection is not enough to spur cluster transition, unless they are raised to extra-ordinary levels several orders of magnitude larger than private investment. However, raising grants to such levels may be out of reach for most peripheral-region governments.

From the simulation of incentive-driven green-growth, we saw that incentives are able to cause a richer, more sustainable cluster to emerge, after a certain incentive threshold. An exploratory process is required to find the thresholds for different conditions. We found that higher the experience of the entrants, lower the incentive levels required for the decoupling to begin. That incentives were the most effective in driving the transition of a peripheral cluster conforms to the postulations of [Isaksen & Trippi \(2014\)](#), [Grillitsch & Nilsson \(2015\)](#), [Grillitsch & Hansen \(2019\)](#), which call for green-growth policies focussed on attracting foreign actors and knowledge into the periphery. It is important to note here that unlike grants, incentives introduce into the cluster not just financial capital, but also advanced knowledge-capital, and reputational capital.

5.2. Implications for decoupled growth of clusters

Our intention in this study was to create an exploratory ABM to simulate the green-growth of a cluster in any type of region. We did not intend this to be an advanced predictive model. We envision for predictive powers to be incorporated in future iterations. From the results of our exploration, we can infer certain implications for how we think about green-clusters and sustainable development.

What we saw from the simulation of green-growth shaped by the instrument-mix is that it can be optimized for each macro-variable (see [Table 2](#) below); there is no one combination of incentives and fines that optimises for all of the macro-variables simultaneously. These results indicate that absolutely decoupled growth of peripheral-region clusters is close to impossible. Rather, it is possible to achieve various states of relative decoupling. However, optimising for decoupling (low ratio of pollution to financial capital) requires foregoing optimisation of some other macro-variables. For instance, maximizing innovation rates requires a mix of high incentive-levels and low fine-levels, but if we want to minimise the ratio of pollution to financial capital, the model suggests we keep both incentives and fines high.

Our results demonstrate how complex the nature of designing an effective instrument-mix for the green-growth of clusters is. We see the inherent trade-offs in designing an instrument-mix for relatively decoupled growth of clusters. There is no way to maximise reduction in pollution, or augmentation of assets, without sacrificing some capital, or some pollution-reduction.

Even green-clusters working with sustainable technologies will have some level of pollution. Pollution-levels for sustainable technologies will be less than those for non-sustainable ones, but the second law of thermodynamics will still apply on the former as well. In this regard, our results confirm some of the criticism of the decoupled growth theory, that it under theorizes the contested notion of sustainable development in the “greening” process (see [Hickel & Kallis, 2020](#); [Ward et al., 2016](#)). Based on our simulations, we opine that there should be more nuanced deliberation, with greater focus on possible trade-offs, on the potential contribution of green-clusters to sustainable development (see [Hansen & Coenen \(2015\)](#), [Wilde & Hermans \(2021\)](#)).

5.3. A landscape of possibilities

Because complex-adaptive systems are indeterministic, ABMs cannot be prescriptive tools; rather, they provide us with a landscape of possibilities. The results of our instrument-mix simulation show that there is a landscape of several possible states of relative-

Table 2
How various instrument combinations optimise for different macro-variables.

	High Incentives	Low Incentives
Low Fines	Optimise for augmentation of capital and cluster-size, total innovation success	
High Fines	Optimise for pollution-reduction, pollution to financial capital ratio, and radical innovation success	Optimise for pollution-reduction

Table 3
Possible values of variables, and the values at time of initialisation.

Variable	Possible values
Agents' own Financial capital	Model sets to any random value between 50 and 100 for large firms. Model sets to any random value between 10 and 50 for small or medium firms
Knowledge capital	Model sets to 25 if pollution greater than 50. Model sets to some random value between 25 and 75 if pollution is lower than 50
Reputational capital	Model sets to any random value between 50 and 100 for large firms. Model sets to any random value between 10 and 50 for small or medium firms
Pollution-level	Model sets to any random value under 100
Radical project experience	Model sets to zero at initialisation
Incremental project experience	Model sets to zero at initialisation
Colour	Green for agents with pollution-levels lower than 25. Red for agents with pollution higher than 25
Size	Model sets size at 5% of financial capital
Shape	Extant agents are circular in shape, Spin-offs are triangular, Entrants are pentagonal
Global	
Probability of collaboration	Any value between 1% and 27%. For our experiments, we set initial value as 14% (roughly mid-point of the range)
Probability of radicalness	Any value between 1% and 55%. For our experiments, we set initial value as 28% (roughly mid-point of the range)
Probability of innovating	Model sets Initial value at 2.2%
Innovation potential	Initial value is 0.01
Cluster-size	Any value between 30 and 100. For our experiments, We set initial value as 50
Percentage of large firms	Any value between 0% and 5%. For our experiments, we set initial value as 3%
Decay rate	Can be any value between 0 and 1%. For our experiments, we set a rate of 0.1%
Maximum possible project size	For our experiments, projects have between 2 and 6 members
Number of projects in one tick	Can be any value between 5 and 8. For our experiments, we use a value 8
Grants for innovation projects	For our experiments, we set a range of between 0% and 25%
Fines for polluters	For our experiments, we set a range of between 0% and 25%
Incentives for entrants	For our experiments, we set a range of between 0% and 25%

Table 4
How capital assets and pollution decrease/increase with time, or increase/decrease with successful green-innovation.

Variable	Decrement (each time-step)	Rewards (from innovation)
Financial capital	Decreases at a rate between 0 and 1% (as set by user). We use a rate of 0.1%	Increases by 25% with incremental innovation. Doubles with radical innovation.
Knowledge capital	Decreases at a rate between 0 and 1% (as set by user). We use a rate of 0.1%	Increases by 25% with incremental innovation. Doubles with radical innovation.
Reputational capital	Decreases at a rate between 0 and 1% (as set by user). We use a rate of 0.1%	Increases by 25% with incremental innovation. Doubles with radical innovation.
Pollution-level	Increases at a rate between 0 and 1% (as set by user). We use a rate of 0.1%	Decreases by 25% with incremental innovation. Halves with radical innovation.

Table 5
The experiments conducted in the model, by introducing different instruments.

Experiments	Description	Instrument settings
Imposing fines on polluting firms	Fines refer to financial capital that is instantly reduced from an agent's stock when its pollution-level is equal to, or crosses, 33.	Fine levels range from 0% to 25% of an agent's financial capital.
Introducing grants for innovation projects	Grants refer to financial capital that is given to a qualifying project.	Grant levels range from 0% to 25% of the financial capital that has already been committed to the project
Introducing incentives for attracting entrants	Incentives refer to financial capital that is bestowed to the entrant, immediately upon entrance.	Incentives range from 0% to 25% of the financial capital held by the entrant
Introducing instrument-mix of incentives and fines	Every time-step, some entrants may enter the cluster and receive incentives, and some agents may get fined.	Incentive levels range from 0% to 25% of the financial capital that has already been committed to the project. Fine levels range from 0% to 25% of each agent's financial capital.

decoupling (beyond the inflection points where cluster-size and assets start rising above initial values). Policy makers will first have to figure out what the inflection points are for their region. The next challenge is to gauge if there is a better local optimum, or a global optimum. This determination can be done by closely studying, and comparing with, other peripheral clusters that have enjoyed relatively greater decoupling. [Alkemade et al., 2009](#) recommend that while attempting to move through such landscapes, authorities

should be mindful of modifying instrument combinations, once information indicating policy-ineffectiveness becomes available. Without timely modification, the cluster may get locked into a particular growth path and find it very difficult to move to better optima. Authorities must, for instance, avoid progressively concentrating grants into projects innovating with one particular technology, because future performance and externalities can be unclear.

6. Conclusion

In this study, we investigated implications for policy instruments to advance green-growth of clusters. To conduct this analysis, we created an agent-based model in Netlogo 6.1. While the model can be used to explore the decoupled growth of clusters in any region, we used it to simulate the transition of a peripheral-region cluster. We conducted four *in silico* experiments, where we investigated how a cluster's transition is shaped by financial incentives used to attract external actors, by grants provided to qualifying innovation projects, by the imposition of fines on cluster actors, and by an instrument-mix of incentives and fines. The experiments looked at how the instruments shaped the evolution of different macro-variables: cluster-size, pollution-levels, financial capital, knowledge capital, and ratio of pollution to financial capital (which represented the level of decoupling achieved).

In scrutinising the effects of these instruments on green-growth of clusters located in peripheral regions, we found that fines are the least effective of all singular instruments; grants encourage innovation, but simple financial injection (even at extremely high levels) into projects is not able to cause a decoupled cluster to emerge; incentives can cause a richer, more sustainable cluster to emerge, but only after certain thresholds are crossed. Incentives' superior effect can be attributed to the fact that entrants not only bring financial capital into the cluster, but also but also advanced knowledge-capital, and reputational capital. With the simulation of the instrument-mix, we saw that there was no one combination of incentives and fines that optimises for all of the macro-variables simultaneously. There is no way to maximise reduction in pollution, or augmentation of assets, without sacrificing some capital, or some pollution-reduction. Our results demonstrate how complex it is, to design effective instruments for the green-growth of peripheral-clusters. In short, this study indicates that it might be quite impossible for policy makers "to have their sustainability cake and eat it too".

Our results show that even green-clusters cannot be completely free of pollution (though pollution-levels will be lower than that for non-sustainable clusters), and that absolutely decoupled growth of clusters is close to impossible. This calls for greater nuance in defining the role of green-clusters in sustainable development and decoupled-growth, with greater focus on the possible trade-offs involved. Our experiments with the instrument-mix point to a landscape of several possible states of relative-decoupling. The challenge for policymakers is in undertaking an exploratory process that moves the cluster along the landscape, to a better local optimum, or to global optimum. This exploratory process may incur high costs and may cause reversal of decoupling. To avoid such reversal, policy-makers should monitor the effectiveness of instruments and modify them if required, on a timely basis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the German Federal Ministry of Education and Research (BMBF) under grant number 031B0020.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.eist.2022.04.003](https://doi.org/10.1016/j.eist.2022.04.003).

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