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Exploring path dependence, policy interactions, and actor behavior in the German biodiesel supply chain

J.A. Moncada [a,b,*], M. Junginger [b], Z. Lukszo [a], A. Faaij [c], M. Weijnen [a]

[a] Faculty of Technology, Policy, and Management, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands
[b] Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
[c] Energy and Sustainability Research Institute, University of Groningen, Nijenborg 4, 9747 AG Groningen, The Netherlands

HIGHLIGHTS

- The effects of both agricultural and bioenergy policy interventions are explored.
- The timing of intervention of bioenergy policies determined the system's evolution.
- A lack of agents' adaptation mechanism led to a decrease in biodiesel production.
- System behavior is influenced by individual behavior which is shaped by institutions.

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ABSTRACT

Biofuel production is not cost competitive and thus requires governmental intervention. The effect of the institutional framework on the development of the biofuel sector is not yet well understood. This paper aims to analyze how biofuel production and production capacity could have evolved in Germany in the period 1992–2014. The effects of an agricultural policy intervention (liberalization of the agricultural market) and a bioenergy policy intervention (a tax on biodiesel after an initial exemption) are explored. Elements of the Modeling Agent systems based on Institutional Analysis (MAIA) framework, complex adaptive systems (CAS) theory, and Neo Institutional Economics (NIE) theory were used to conceptualize and formalize the system in an agent-based model. It was found that an early liberalization of the agricultural market led to an under-production of biodiesel; a late liberalization led to the collapse of biodiesel production. An early introduction of the biodiesel tax led to stagnation in biodiesel production and production capacity; a late introduction led to an increase in sunk costs provided that the biofuel quota is binding. Also, a lack of agents' adaptation mechanism to forecast prices led to a decrease in patterns of biodiesel production when an external shock was introduced in the system. In sum, we argue that system behavior is influenced by individual behavior which is shaped by institutions.

1. Introduction

Concern has grown in the last decades over the issue of climate change. Strategies to tackle this problem include the production of energy from solar, wind, biomass, and other renewable sources. In Europe, the production of liquid fuels from biomass has gained considerable momentum due to its potential to reduce greenhouse gas emissions, to enhance energy security through the substitution of fossil fuels, and to contribute to rural development by increasing employment opportunities[1] and diversifying the activities of farmers [2,3].

Despite the benefits of biofuels, biofuel production is not cost-competitive and thus requires governmental intervention. Policy instruments such as blending mandates, tax credits or tax exemptions, subsidies, and import tariffs are used to stimulate biofuel production and consumption in the world [4]. The literature has focused on reducing the price gap between biofuels and fossil fuels by optimizing the whole supply chain [5–8], by improving the logistics [9,10], and developing more efficient technologies [11–13]. There is clear evidence that biofuel supply chains cannot be created and developed in absence of governmental support[2] [4,15], and yet the scientific literature has focused primarily on technological developments [12,13,16,17] and their optimization [18–20].

* Corresponding author at: Faculty of Technology, Policy, and Management, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands.
E-mail address: j.a.moncadaescudero@tudelft.nl (J.A. Moncada).

[1] Borenstein et al. [1] claims that these arguments, also used to promote renewable electricity generation, are difficult to support.

[2] As it was pointed out by van den Wall et al. [14] bioethanol production in Brazil is a unique biofuel supply chain, as it no longer receives governmental support.

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The impact of policies on biofuels production is mostly analyzed by using an equilibrium framework [6,21–23]. This approach has provided many insights by identifying promising configurations for feedstock, technology, and production capacity required to meet some policy goals. However, there is still a lack of understanding as to: what alternative stories (scenarios) could have unfolded as a result of different policy interventions; what the effects of policy interaction are on biofuel supply chain development and actors' behavior; and what strategies might steer the development of biofuel supply chains in the direction pointed to by the optimization studies.

1.1. Literature review

Support schemes to promote the production and consumption of renewable energy are a key instrument in the decarbonization of the energy mix. The most common support schemes include the competitive auctions, the feed-in tariff scheme, and tradable green certificates [24,25]. Socio-economic policies such as job creation and energy access have also influenced the deployment of renewable energy [26]. In the specific case of biofuels, policies such as: the Renewable Fuel Standard (RFS2) in the USA, the Common Agricultural Policy (CAP) and the Renewable Energy Directive (RED) in the EU have contributed to its deployment [4].

Traditionally, the analysis of the effect of policies on biofuel supply chains has been done by using an equilibrium approach. Luo and Miller [27] used game theory to model biomass and ethanol production decisions and to calculate the incentives required to drive farmers and ethanol producers to participate in cellulosic biofuel industry. Newes et al. [28] used the Biomass Scenario Model to understand the role of incentives on the evolution of the cellulosic ethanol sector. The authors found that multiple points of intervention could accelerate the expansion of that biofuel industry. Rahdar et al. [29] developed a linear programming model to study the competition between biopower generation and biofuel production under the Renewable Portfolio Standards and renewable Fuel Standard in the U.S. The authors found that cellulosic biofuel production will dominate the competition for biomass against biopower generation. Christensen and Hobbs [30] developed a mathematical model of the U.S. biofuel market. The authors argued that compliance with California biofuel policy requires rapid deployment of clean diesel fuels.

The above-mentioned studies do not completely capture the complex nature of biofuel supply chains (BSCs). BSCs are complex adaptive systems and thus they are highly non-linear, exhibit multi-scale behavior and path-dependence, evolve and self-organize making it difficult for an equation-based model to capture their characteristics [31]. By using models that lack this complexity, such as optimization models, is possible to make policy recommendations and to design optimal supply chains. But that optimality only applies in a limited context. As it was pointed out by Simon in his famous Nobel prize lecture: "*decision makers can satisfice either by finding optimum solutions for a simplified world, or by finding satisfactory solutions for a more realistic world*" [32].

Path dependence is one of the interesting properties of complex adaptive systems [33]. The concept of path dependence is defined as a self-reinforcing mechanism [34] and as an outcome (lock-in). Verne and Durand define path dependence "*as a property of a stochastic process which obtains under two conditions (contingency and self-reinforcement) and causes lock-in in the absence of exogenous shock*" [35]. As a theoretical framework, path dependence has been used to explain institutional persistence [36], governance [37], and technology outcomes [38,39]. However, as these are historical case studies it is difficult to provide strong evidence of history dependence [40].

A promising alternative to address these issues is Agent-Based Modeling (ABM). Concepts such as: emergence, adaptation, learning, and feedback mechanisms can be incorporated into ABM [41,42]. As a simulation method, ABM can be employed to "*generate multiple historical trajectories emanating from the same set of initial conditions, thus enabling them to generalize about the mechanisms and processes that produce such histories*" [43]. That is, ABM can be utilized to analyze path dependence.

ABM has been used to address the effects of policies on both agricultural and bioenergy sectors. Brady et al. [44] extended the agent-based agricultural policy simulator (AgriPoliS) to understand the impact of agricultural policies on land use, and biodiversity. Brown et al. [45] assessed the bioenergy crop uptake as a function of farmer types and policy initiatives.

Some studies specifically analyze the impact of policies on biofuel supply chain performance by using the ABM paradigm. Agusdinata et al. [46] developed an agent-based model to understand the dynamics of biofuels supply chain networks. It was found that the network behavior is very sensitive to the rate of information feedback. Shastri et al. [47] analyzed the impact of policies on the evolution of a biofuel supply chain using an agent-based modeling approach. The authors argued that regulatory mechanism such as Biomass Crop Assistance Program led to greater productivity. Other studies have used the agent-based model approach to analyze the path dependence of network industries under different policy regimes [48].

The contribution of this work is to extend the analysis of the effect of policies on the development of biofuel supply chains to account for the path dependence, policy interaction and effects on actor behavior. To achieve this goal, the German biodiesel supply chain was conceptualized and formalized by using an agent-based modeling approach. Biodiesel production in Germany was selected as a study case since it has been heavily influenced by governmental intervention [2,49] as shown in Fig. 1.

The aim of the model is to shed light on how the German biodiesel industry could have evolved under different institutional frameworks and to assess the impact of biofuel policy instruments on biodiesel production and production capacity. Specifically, the research question is: *what patterns in biodiesel production and production capacity are generated as a result of applying different policy interventions in Germany in the period 1992–2014?*

The remainder of the paper is organized as follows. Section 2 describes the development of the agent-based model and the data used in the experiments. Section 3 describes the results obtained which are discussed in Section 4. Conclusions are presented in Section 5.

2. Theory and methods

2.1. Structure of the agent-based model[3]

The construction of the agent based model starts with the formulation of the problem. The problem is formulated using the generative science approach[4], which identifies and describes the problem based on a macroscopic regularity or pattern[5] in the real world. The aim of the agent-based model is to understand how biofuel production and production capacity could have evolved as a result of different agricultural and/or bioenergy policy interventions.

[3] The model development is described in detail in Moncada et al. [50].

[4] To the generativist – concerned with formation dynamics – it does not suffice to establish that, if deposited in some macroconfiguration, the system will stay there. Rather, the generativist wants an account of the configuration's attainment by a decentralized system of heterogeneous autonomous agents [51].

[5] Patterns are defining characteristics of a system and often, therefore, indicators of essential underlying processes and structures. Patterns contain information on the internal organization of a system, but in a "coded" form [52].

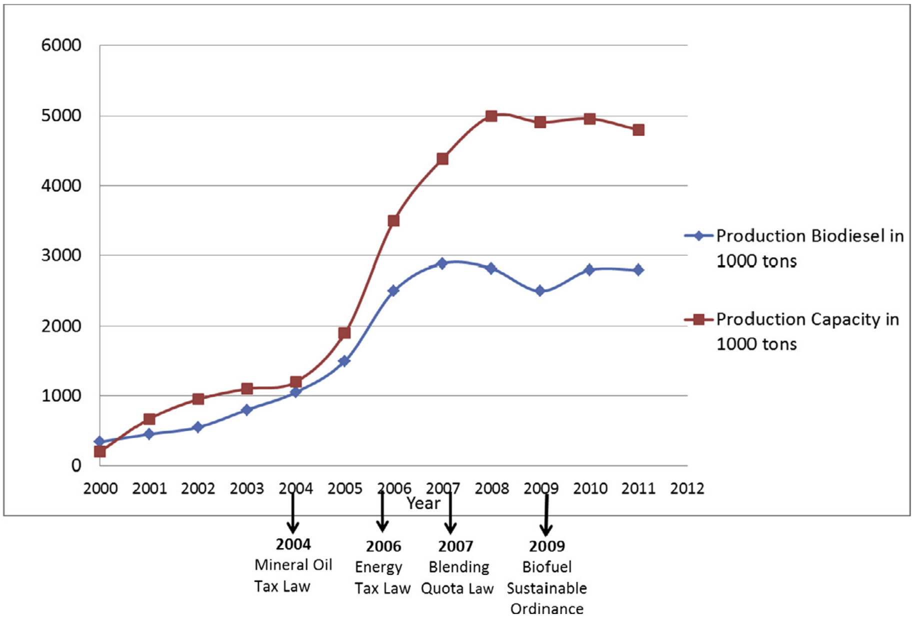

Fig. 1. Effect of different policy interventions on biodiesel capacity and production [49].

The impact of these policies on the different actors involved in the supply chain for biodiesel are to be modeled, replicating not only the currently observed pattern, but also exploring what conditions might lead to different outcomes.

At the core of the modeling framework is the concept of socio-technical systems. Usually, to describe a socio-technical system three elements are required: physical system, network of actors, and institutions [53]. The physical system entails resources (natural resources, information, and technical elements) present in the system. Actors are the agents that perform actions in the system. Institutions are defined as "*the rules of the game in society*" and their "*major role in a society is to reduce uncertainty by establishing a stable (but not necessarily efficient) structure to human interaction*" [36]. Neo institutional Economics (NIE) theory was used to describe the interaction between actors and institutions.

The physical system consists of feedstocks (rapeseed and wheat) and products (diesel and biodiesel); information regarding to prices for rapeseed, wheat, biodiesel, and diesel; and objects such as farms, refineries and distribution centers. The institutions are represented by the different agricultural and biofuel policies that took place in the period 1991–2014. The emergent behavior of the system is the result of the interaction among different actors (farmers, oil mill companies, biodiesel producers, distributors and gas stations), institutions, and the physical system.

Fig. 2 presents a biofuel supply chain conceptual scheme. Agents interact with the objects (technologies) through ownerships (grey line). They interact with other agents by means of physical flows of rapeseed, oil, and biodiesel (solid grey arrow) and through the flow of money (dotted grey arrow). The decision making of different agents is based on the information (prices) provided by different markets (dotted black arrow). The environment is composed of the government. The government can influence the price of the different products and the behavior of the agents through incentives and/or mandates (solid black arrow). To simplify the analysis only three types of agents are included in the model: Farmers, biodiesel producers, and distributors. The environment of the system is composed of the German government which through policies, incentives, and regulations affects some or all of the agents mentioned above.

Fig. 3 outlines the model narrative used in this study. The first year can be considered as a "warm up" period for the simulation. In this year farmers make decisions about land use under endogenous expectations. Biofuel producers and distributors determine theirs bids for rapeseed, and biodiesel, respectively, based on their forecasting. Also, rapeseed is sourced by biofuel producers. In the second year, biodiesel is produced and traded in the biodiesel market between biofuel producers and distributors. Investment decisions in production capacity are made by biofuel producers based on market developments. The activities described in the first year for the rapeseed market are also carried out in parallel during the second year. The cycle is repeated until the simulation reaches the final year.

The agent-based model incorporates typical characteristics of complex adaptive systems such as: adaptation, feedback effects, and heterogeneity. Farmers, biofuel producers, and distributors constantly adapt their forecast about prices for rapeseed, biodiesel producer price, and biodiesel price (consumer prices), respectively, based on feedback received from markets. Agents that share the same properties are assigned different values in those parameters. For instance, biofuel producers are assigned different values of production cost.

The concept of institution was formalized by using the MAIA framework [54] and the ADICO syntax [63]. ADICO refers to the five elements that an institutional statement can comprise: **A**ttributes (designated roles), **D**eontic (prohibition, obligation, permission), a**I**m, Condition (for the institution to hold), and "**O**r else". Table 1 presents the conceptualization of institutions by applying the ADICO syntax. It was assumed that institutions are exogenous. Both policies, the agricultural reform and the liberalization of the agricultural market, influence farmers' decisions on crop allocation. The biofuel quota act influences biofuel producers' decision making on rapeseed procurement. The energy tax act affects the profitability of the biofuel producer.

The agricultural reform refers to the common agricultural policy (CAP) enacted in 1992. This policy decommissioned a percentage (5–15%) of agricultural land to be earmarked, or set aside, for alternative uses. Farmers were allowed to cultivate non-food crops on those set-aside lands. However, it was forbidden to sell

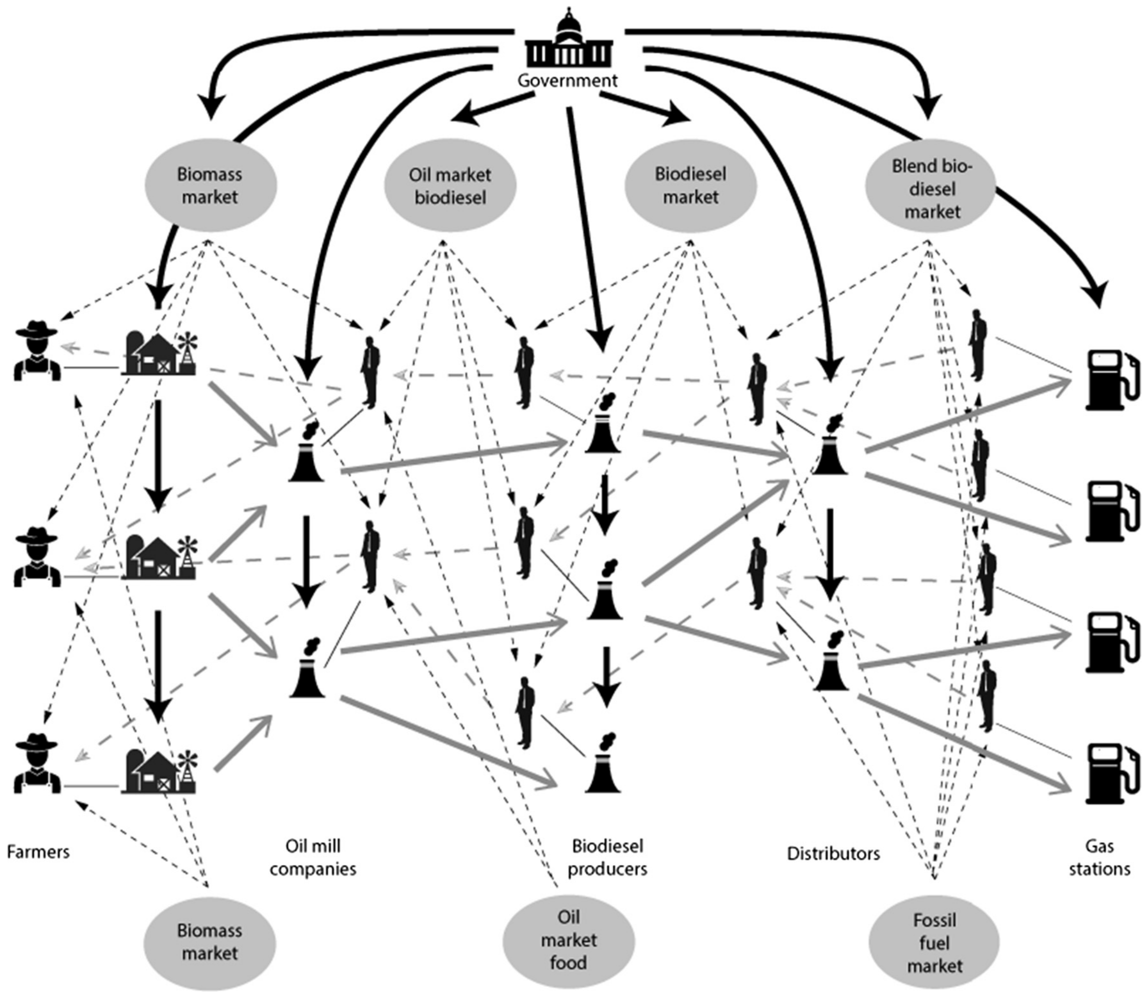

Fig. 2. Biofuel supply chain conceptual scheme.

set-aside rapeseed in the food market. A financial penalty was imposed on farmers who disobeyed this rule. The liberalization of the EU agricultural market prompted (or initiated) the fundamental reform of the CAP in 2003. Production- and volume-focused policies were shifted to area related payments to stimulate a further liberalization of the EU agricultural market.

The energy tax act specifies the energy tax law enacted in 2006. This biofuel policy defined an annual increase of the tax rate on biodiesel. The biofuel quota act refers to the biofuel quota law introduced in 2007. The aim of this policy was to stimulate the biodiesel industry by pressuring biofuel producers and distributors, to meet a biodiesel quota. The policy instrument used to coerce compliance with this regulation was a penalty.

2.2. Data collection

Table 2 summarizes the parameters used to simulate the evolution of the German biodiesel supply chain (base case).[6]

Table 3 presents the institutional chronogram used in the path dependency analysis of the liberalization of the EU agricultural market and energy tax act. The analysis is carried out using as a starting point any year in the period 1995–2010. It is assumed that the agricultural reform expires the year before the liberalization of the EU agricultural market is enacted. However, the earmarked land is only fixed to 0% as of 2008.

[6] For a more detailed overview of the data and assumptions used in the simulations the reader is referred to Moncada et al. [50].

The analysis of the impact of bioenergy policy instruments (tax, and penalty) on biodiesel production, and actor behavior is carried out based on the data presented in Table 4. The range of the values accounts for possible (extreme) departures from those values reported in the base case.

The analysis of the effect of actor behavior on system behavior was conducted based on the adaptation mechanism incorporated in the forecasting of prices. Agents adapt their forecasting based on the following equation [61]:

$$C_t^e = C_{t-1}^a \cdot \left(C_{t-1}^e\right)^{(1-a)} \quad (1)$$

where C_{t-1}^e is the estimate for the previous year, C_{t-1} is the actual value from the past year, and C_t^e is the updated estimate for the current year. a is a parameter that weighs the influence of the actual value of the previous year as compared to the estimate in the forecasting, $0 \leqslant a \leqslant 1$.

3. Results

3.1. Experiment A: Policy analysis

3.1.1. Path dependency analysis

To study the effect of institutional change on the German biodiesel value chain, a path dependency analysis was carried out. The experiments were set out to explore the impact of the year of enactment of the liberalization of the EU agricultural market,

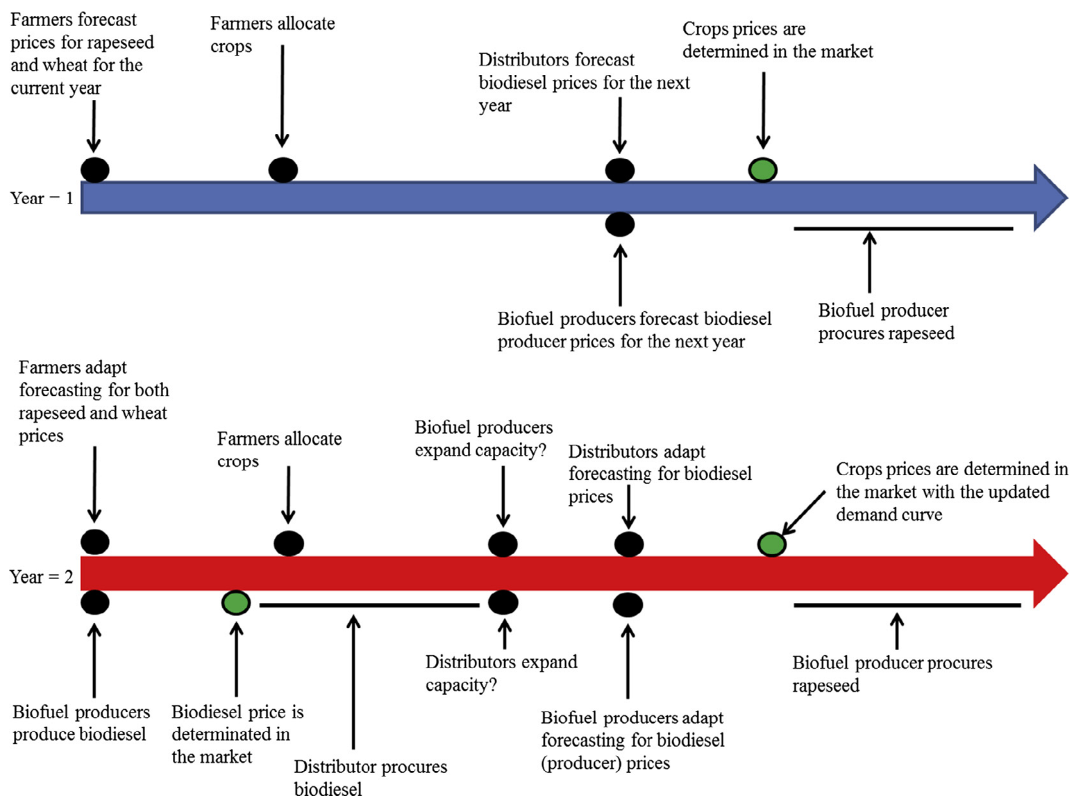

Fig. 3. Model narrative.

Table 1
Institutional table for the biodiesel energy system (adapted from Moncada et al. [50]).

Institution						
Name	Attribute	Deontic type	Aim	Condition	Or else	Type
Agricultural reform	Farmer	Must	Sells crops to the energy market	If crops were grown in the earmarked land	Fine selling	Rule[a]
Liberalization of the EU agricultural market	Farmer		Sells crops to the energy market	If prices in the energy market are equal or high to those prices in the food market regardless of the land type		Shared strategy[b]
Energy Tax act	Biofuel producer	Must	Pays tax	If energy tax is binding	Fine producing	Rule
Biofuel quota act	Biofuel producer	Must	Produce the amount of biodiesel assigned to meet the demand	If biofuel quota is binding	Fine producing	Rule
	Biofuel distributor	Must	Distributes the amount of biodiesel assigned to meet the demand	If biofuel quota is binding	Fine distributing	Rule

[a] Rule: it includes all the elements of the ADICO syntax. That is, "attribute", "deontic type", "aim", "condition", and "or else".
[b] Shared strategy: it includes all the elements of the ADICO syntax but "deontic type", and "or else".

and the energy tax act on biodiesel production and production capacity. The institutional chronogram used is presented in Table 3. Simulations were run for each permutation 100 times, and 1000 times for the analysis of the effect of timing of the introduction of liberalization of the EU agricultural market and the energy tax act, respectively.

3.1.1.1. Effect of the liberalization of the EU agricultural market on biodiesel production and production capacity. Fig. 4 presents the mean of biodiesel production (top) and production capacity (bottom) in the period 1992–2014 under different years of enactment of the liberalization of the EU agricultural market. The base case refers to the year 2003 as year of enactment of the agricultural policy. Fig. 4 shows that the introduction of the policy prior to the year 2001 led to the stagnation of biofuel production with respect to the base case as the biodiesel market was not mature enough to compete for the feedstock. A sudden increase in biodiesel production took place upon the introduction of bioenergy policy in 2000. The production approximately matched that reported in the base case when the agricultural policy was introduced at any year of the period 2001–2004. As of 2005, the biodiesel production gradually decreases with reference to the base case as a late liberalization of the agricultural market inhibits its expansion. As of 2008, the biodiesel market collapsed as a consequence of the introduction of the tax in 2006 and a limited feedstock supply.

Fig. 4 also indicates that the introduction of the policy prior to the year 2000 led to an overinvestment in production capacity. This is explained by the fact that an early liberalization of the rapeseed market increased the supply to biofuel producers. As a secure provision of feedstock is crucial in decision making about

Table 2
Techno-economic, logistic, and policy parameters.

Parameter	Value	Unit	Reference
Rapeseed production cost	240–278	euro/t	[55]
Wheat production cost	80–130	euro/t	[56]
Biodiesel fixed production cost	0.08–0.11	euro/liter	[57]
Yield rapeseed oil	0.4	kg oil/kg rapeseed	[58]
Yield biodiesel	0.97	kg oil/kg biodiesel	[58]
Yield glycerol	0.11	kg glycerol/kg biodiesel	[58]
Yield rapeseed meal	0.56	kg rape meal/kg rapeseed	[58]
Rapeseed transportation cost	0.05	euro/(t km)	[59]
Biodiesel transportation cost	3.74e-4	euro/(liter km)	[59]
Premium agricultural land	301	euro/ha	[60]
Premium grass land	79	euro/ha	[60]
Standard agricultural premium	301	euro/ha	[60]
Extra fee energy crops	45	euro/ha	[60]
Tax biodiesel	0.3	euro/liter	[58]
Penalty	0.5	euro/liter	[58]
Ratio quota/total capacity	0.65		[49]

Table 3
Institutional chronogram used in the path dependency analysis.

Institution	Period	
	Starts	Expires
Agricultural reform	1992	1994–2009[a]
Liberalization of the EU agricultural market	1995–2010	2015
Energy Tax act	1995–2010	2015
Biofuel quota act	2007	2015

[a] It is assumed that the agricultural reform expires one year before the liberalization of the agricultural markets is enacted.

Table 4
Parameters used in both policy interaction and actor behavior analysis.

Parameter	Range	Base Case	Unit
Tax biodiesel	0.2–1	0.3	euro/liter
Penalty	0.2–1	0.5	euro/liter

investment, an increase in the feedstock supply led to early investments. Values for production capacity roughly matched the data reported in the base case in the period 2003–2005. The negative effect of the tax on production capacity is enhanced when the liberalization of the agricultural market is enacted as of 2006.

3.1.1.2. Effect of the energy tax act on biodiesel production and production capacity. Fig. 5 presents the mean of biodiesel production (top) and production capacity (bottom) in the period 1992–2014 under different years of enactment of the energy tax act. The base case refers to the year 2006 as the year of enactment of the bioenergy policy. The introduction of the energy tax act prior to the year 2001 led to stagnation of biofuel production. A slight increase in biodiesel production took place when the bioenergy policy was introduced in 2002, although its production was lower than the one reported in the base case. As of 2002, production gradually increased along with the year of enactment to match the values reported in the base case in 2006. As of 2008, biodiesel production was higher than production levels reported in the base case, as a late introduction of the tax led to major investments in capacity as seen in the patterns for production capacity.

A similar pattern to that described for biodiesel production was observed for production capacity. A premature enactment of the energy tax led to stagnation. As of 2002, investment in production capacity increased. A late introduction of the tax led to major investments in capacity as it was assumed that investments in production capacity depend on the biodiesel tax. The perception that the biodiesel market will grow increases in the absence of the tax.

3.1.2. Bioenergy policies instruments interaction

The experiments were set out to explore the impact of the biodiesel tax and penalty on biodiesel production and adoption of rapeseed by farmers. Permutations of the data reported in Table 4 were used in the simulations. 1000 simulations were carried out per each combination of parameters.

3.1.2.1. Effect of the biodiesel tax and penalty on biodiesel production. Fig. 6 presents biodiesel production as a function of time. The horizontal shift represents a change in the penalty for non-compliance with the biodiesel quota and the vertical shift represents a change in the tax levied on biodiesel production. These policy instruments were introduced in the biofuel quota act and energy tax act, respectively.

As shown in Fig. 6**,** an increase in the value of the penalty led to an increase in biodiesel production for values of the biodiesel tax less than, or equal to, 0.6 euro/liter. The penalty had no effect on biodiesel production for values greater than 0.6 euro/liter for the biodiesel tax. This is due to the fact that biodiesel production is not profitable at all above this level of taxation. In contrast, biodiesel production decreased with an increase in the biodiesel tax. Overall, the effect of the biodiesel tax was greater than the penalty. This can be explained by the fact that a tax directly affects biodiesel producers whereas a penalty can be avoided. In fact, the penalty only offset the negative effect of the biodiesel tax when this tax had a value of 0.2 euro/liter. The penalty became an effective coercive policy instrument only at lower values of taxation. For the most part, patterns in biodiesel production for different scenarios are below that reported by the base case. Values of the biodiesel tax above 0.6 euro/liter led to a collapse in the biodiesel production.

3.1.2.2. Effect of biodiesel tax and penalty on adoption of rapeseed by farmers. Fig. 7 presents the percentage of farmers adopting rapeseed as a function of time for different combinations of penalty and biodiesel tax. The horizontal shift represents a change in the penalty for non-compliance with the biodiesel quota and the vertical shift represents a change in the tax levied on biodiesel production. The figure shows that an increase in the biodiesel tax led to lower adoption of rapeseed compared with the base case. In contrast, an increase in the penalty led to a slight increase in the adoption of rapeseed. For values of the biodiesel tax above 0.4 euro/liter the adoption of rapeseed was below of that reported in the base case at any value of the penalty. In fact, the adoption of rapeseed collapsed when the biodiesel tax was greater or equal to 0.8 euro/liter.

The link between bioenergy policies and farmers' behavior arises from the introduction of the biodiesel tax in 2006 which caused the shutdown of many biodiesel production facilities leading to a decrease in the demand for rapeseed. Thus, the higher the biodiesel tax, the higher the number of plants that need to be shut down and the lower the demand for rapeseed.

3.2. Experiment B: Effect of actor behavior on system behavior

3.2.1. Effect of agents' adaptation mechanism to forecast prices on biodiesel production

Fig. 8 shows biodiesel production patterns as a function of time at different values of the parameter a in Eq. (1). Values of parameter a close to the unity provide a forecasting of the price that takes

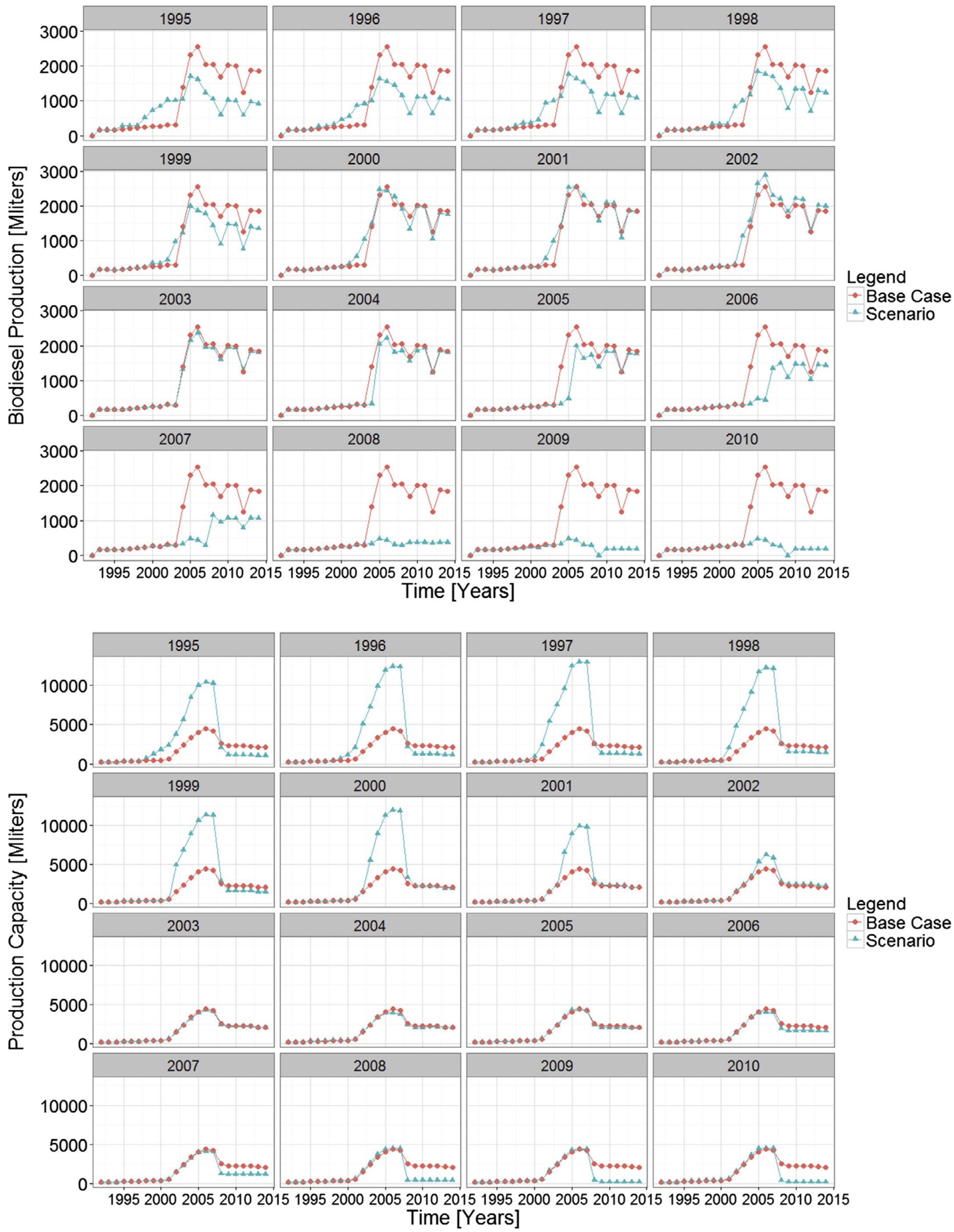

Fig. 4. Biodiesel production (top) and production capacity (bottom) patterns at different years of enactment of the liberalization of the EU agricultural market.

into account the actual price endogenously calculated in the system. That is, when the parameter *a* is close to unity, agents adapt their forecasting to the patterns (prices) generated in the macro-behavior. On the contrary, a value of the parameter *a* close to zero implies no adaptation of the agents in their decisions. This non-adaptive behavior is due to unavailability of the information rather than lack of the intelligence of the actors. The fundamental behavioral assumption was that agents aim to improve their economic situation by making rational decisions with the information available. For the cases (a = 0.1; a = 0.9), it was assumed that all agents had the same value for this parameter.

Fig. 8 shows that the impact of the parameter *a* is regime-dependent. Before the agricultural market was liberalized in 2003, the effect of the parameter on biodiesel production is negligible. However, as of 2003 biodiesel production considerably increases at higher values of the parameter *a*. When a = 0.1 biodiesel production is considerably affected; notably, after the energy tax is enacted in 2006.

The influence of the parameter *a* on biodiesel production can be explained by the fact that the introduction of the agricultural policy shocked the system by expanding the production of rapeseed in arable land for energy applications. An adaptation mechanism

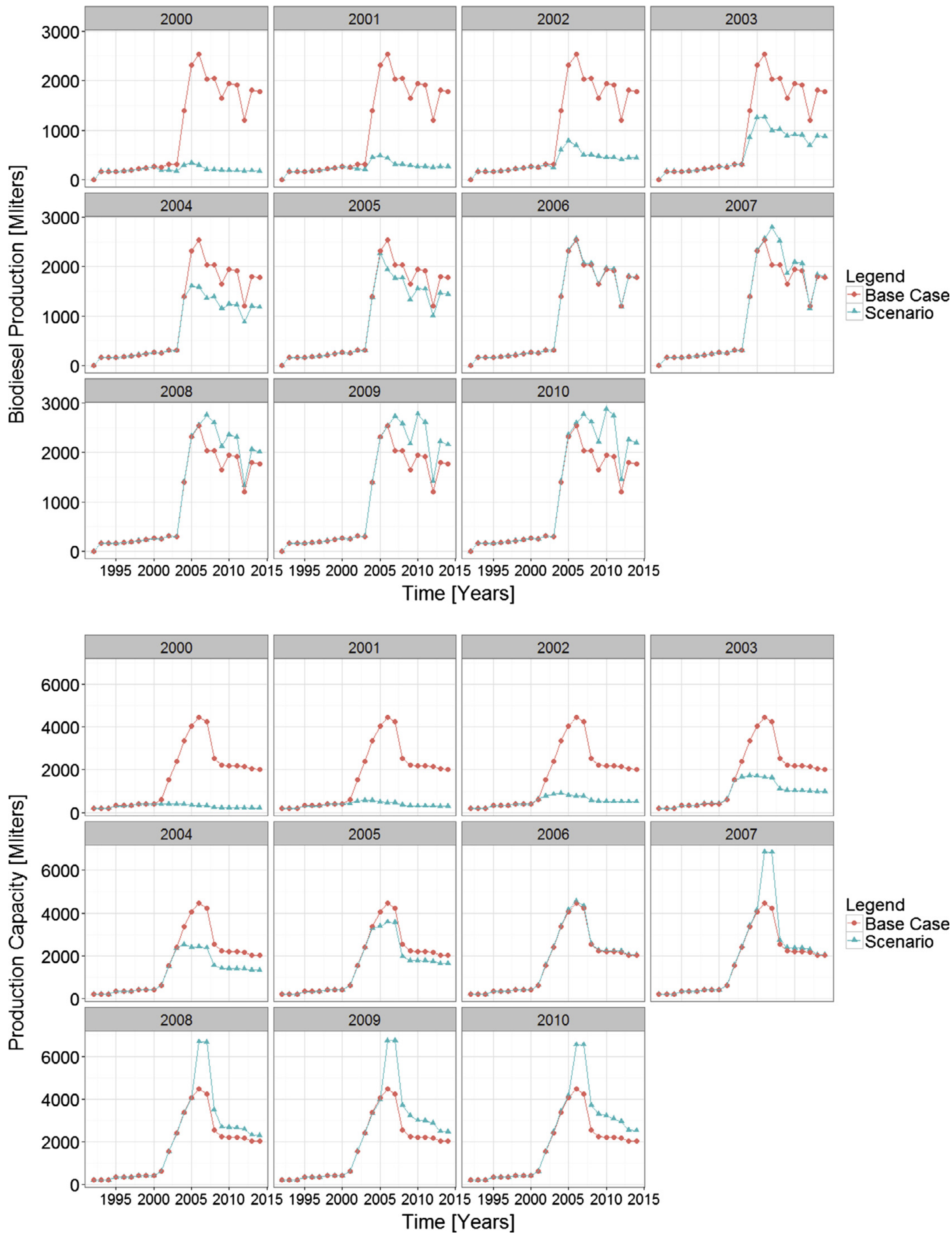

Fig. 5. Biodiesel production (top) and production capacity (bottom) patterns at different years of enactment of the energy tax law.

allowed agents to adapt their decision making to the new system macro-behavior. Specifically, agents expanded production of rapeseed and invested in production capacity. A similar observation can be made when the energy tax law is enacted. In general, a more limited adaptation mechanism led to lower biodiesel production.

4. Discussion

The results on path dependency suggest that the timing of intervention of agricultural and biofuel policies determines the evolution of the system. Model results on policy instruments interaction and actor behavior indicate that the biodiesel energy tax is the dominant policy instrument. Only the penalty could offset the negative effects of the tax on biodiesel production and adoption of rapeseed by farmers when the latter had a low value. Finally, the results about the influence of adaptation mechanisms for forecasting prices on biodiesel production suggest that poor adaptation mechanisms caused by lack of information lead to lower biodiesel production.

The path dependence analysis of the effect of the liberalization of the EU agricultural market on biodiesel production identifies a policy window. This policy window refers to a period in which the policy should be enacted to increase the performance of the

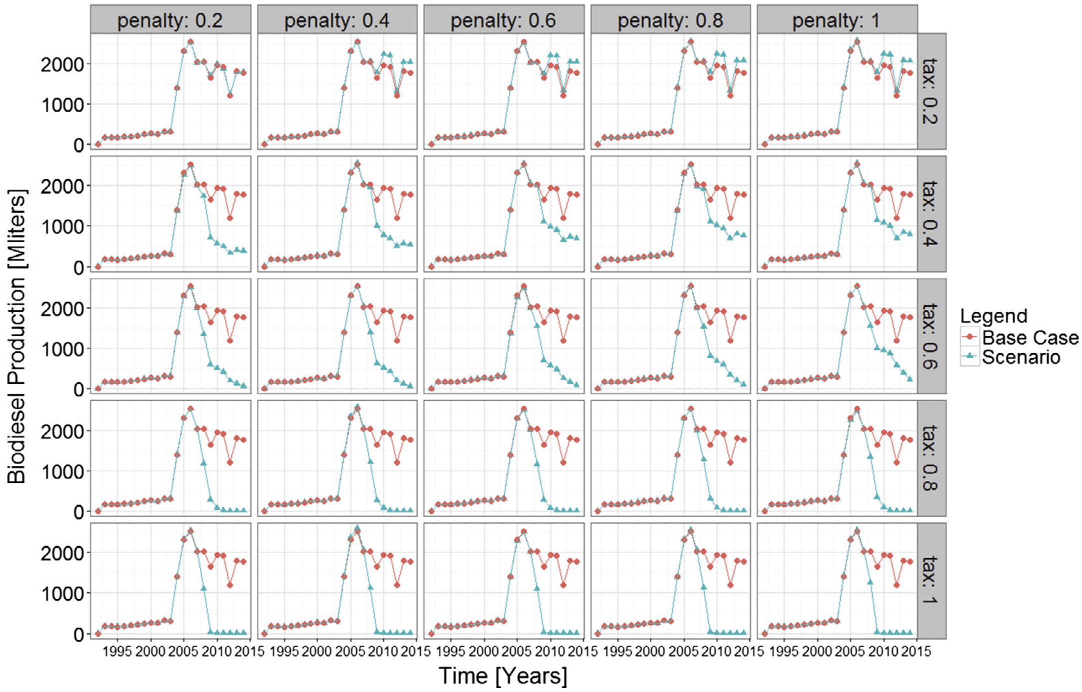

Fig. 6. Biodiesel production as a function of time for different combinations of penalty for not producing the biodiesel quota (top) and biodiesel tax (right). Biodiesel penalty and biodiesel tax in euro/liter.

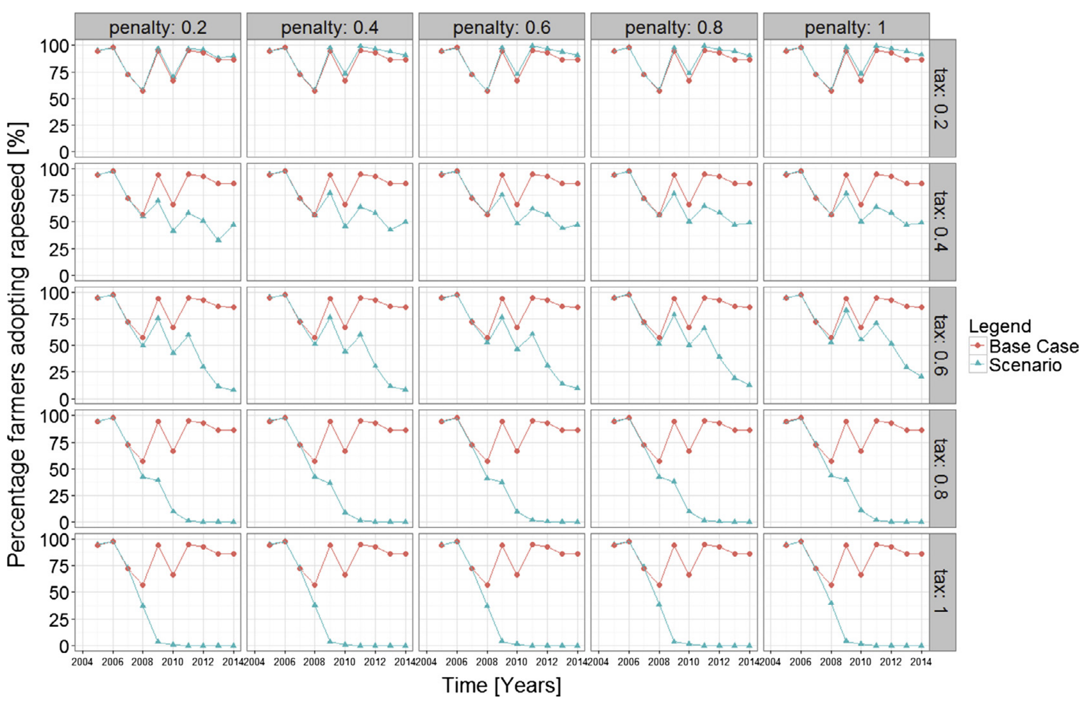

Fig. 7. Percentage of farmers adopting rapeseed as a function of time for different combinations of penalty for not producing the biodiesel quota (top) and biodiesel tax (right). Biodiesel penalty and biodiesel tax in euro/liter.

system. An execution of the agricultural policy either before or after the policy window would lead the system to an under production of biodiesel or the collapse of the biodiesel market. The formation of the policy window can be explained as follows: an early liberalization of the agricultural market would entail an increase in feedstock production as well as in the competition for feedstock. As the biodiesel market is not mature enough to compete for the feedstock with other sectors, the biodiesel production is limited. On the other hand, a late liberalization of the agricultural market inhibits the expansion of the market provided that import tariffs for rapeseed oil are too high to capture the gains from international trade.

In the case of investment in production capacity, an early introduction of the agricultural policy leads to an increase in production capacity as a consequence of the increase in rapeseed supply. The reason why investment in production capacity keeps increasing even though biodiesel production is limited, is due to the

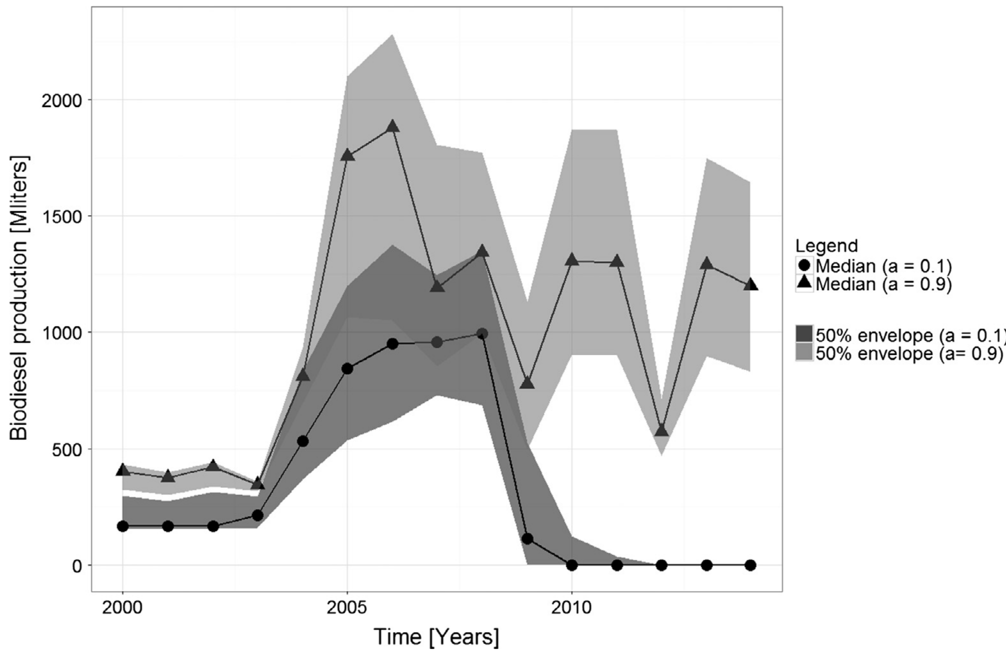

Fig. 8. Biodiesel production as a function of time at different values of the parameter used in the forecasting of prices for rapeseed and biodiesel (see Eq. (1)).

assumption that the perception of agents about expansion capacity is exclusively a function of the institutional framework. In reality, agents' perceptions about expansion capacity also co-evolve with the macro-behavior of the system (biodiesel production, prices, etc.). This model flaw could be addressed by incorporating a feedback mechanism between agents' perceptions about expansion capacity and system behavior.

The path dependence analysis of the effect of the energy tax on biodiesel production and investment in production capacity indicates, as it was expected, that an early taxation of biodiesel leads to lower biodiesel production and investment in production capacity. On the other hand, a late introduction of the tax leads to an increase in production capacity that eventually decreases as a consequence of enacting the biodiesel tax and the quota. It is important to realize that this decrease in production capacity can be utilized as a proxy for sunk costs as it is assumed that when a plant is shut down its capacity cannot be re-used. The increase in production capacity arises from the assumption that producers' expectations of sudden market growth increases in the absence of a biodiesel tax. In short, a late introduction of the tax leads to an increase in sunk costs provided that a biofuel quota is binding.

In the study of the effect of the interaction of bioenergy policy on biodiesel production, production capacity and adoption of rapeseed by farmers, two policy regimes are identified. In the first regime (biodiesel tax <0.3 euro/liter), the penalty can offset the negative effects of the tax. Conversely, in the second regime (biodiesel tax $\geq$0.4 euro/liter), the tax is the dominant policy instrument. In this regime, biodiesel production and production capacity considerably decrease.

The analysis of the effect of agents' adaptation mechanism to forecast prices on biodiesel production suggests that system performance depends on the ability of agents to adapt to it in the event that an external shock (the introduction of a new policy) is introduced in the system. As pointed out by Arthur: "*behavior creates pattern; and pattern in turn influences behavior*" [62]. This interplay between the micro-system (individual behavior) and the macro-system (system behavior) has been recognized by economists since Adam Smith. Unlike an optimization approach, this feedback mechanism can be incorporated in agent-based models as demonstrated in this study.

The analysis carried out in this study extends the literature on path dependency, where analysis has been limited to qualitative analysis of historical case studies, by incorporating a quantitative analysis. Moreover, this study extends the analysis done by Kaup and Selbmann [49] by identifying different policy regimes with their respective dominant policy instruments, and by shedding light on new mechanisms that drive the behavior of the system such as the co-evolution between individual behavior and system behavior. Understanding the path dependency of different policy interventions and identifying their policy regimes with their respective dominant policy instruments on existing biofuel supply chains might provide insights on how to efficiently develop new biofuel supply chains such as bio jet fuel supply chains.

The study neglects organizational structures of farmers and biofuel producers. Future research should explore the effect of policies on organizational structures. These structures can have a considerable effect in the performance of the system as they determine the transaction costs. An increase in the transaction costs might reduce the amount of capital available to invest.

Still, the analysis carried out in this study should give more evidence of the potential application of agent-based Modeling (ABM) in the analysis of (bio) energy systems. Unlike conventional models, ABM allows the exploration of actor behavior as a function of different policy interventions, the incorporation of feedback mechanisms (adaptation), and allows a more realistic description of the actors and their decision making (bounded rationality). Even further, ABM can be used along with optimization approaches to assess what policy strategies are more effective in leading the system to its optimum and to explain what mechanisms play an important role.

5. Summary and conclusions

The study was conducted to answer the following research question: What patterns in biodiesel production and production capacity are generated as a result of applying different policy interventions in Germany in the period 1992–2014? To answer that question, an agent-based model was developed. The model was used to explore the impact of the timing of the enactment of specific agricultural and bioenergy policies (path dependence) on patterns in biodiesel production and production capacity. The model was also used to analyze the impact of policy instruments such as biodiesel tax and penalty on patterns in biodiesel production and adoption of rapeseed by farmers. Finally, the influence of agents' adaptation mechanisms to forecast prices on patterns in biodiesel production was studied.

Based on the path dependency analysis, we find that the timing of intervention of agricultural and biofuel policies determines the evolution of the system. An early (late) liberalization of the agricultural market leads to a under production of biodiesel (collapse of the market). Hence, to stimulate production of biodiesel, the agricultural market should be enacted within a policy window. On the other hand, an early introduction of the biodiesel tax leads to stagnation in biodiesel production and investment in production capacity. A late introduction of the tax leads to an increase in sunk costs provided that the biofuel quota is binding.

Considering the results of the interaction of bioenergy policy instruments, we argue that patterns in biodiesel production and rapeseed adoption depend on the policy regime and its dominant policy instrument. When the biodiesel tax is the dominant policy instrument biodiesel production and rapeseed adoption patterns decrease following an increase in the level of taxation. This negative effect can be offset by the penalty only if the biodiesel tax is not dominant.

In light of the analysis of the effect of agents' adaptation mechanism to forecast prices on biodiesel production, we argue that poor adaptation mechanisms caused by lack of information lead to a decrease in biodiesel production upon introduction of an external shock to the system. The implications of this insight are twofold. First, it gives evidence that system behavior is influenced by individual behavior. Second, the unstable nature of the institutional framework to stimulate the production and consumption of bioenergy, the limited information available, and the limited processing information capacity of the actors, point to the need for mechanisms that improve the accessibility of pertinent information to the agents. One alternative could be to increase the transparency in trade statistics for both agricultural and bioenergy markets.

The insights of this study might underpin policy making for the creation of new biofuel supply chains. A better understanding of the role of institutions on existing biofuel supply chains might accelerate the implementation of new biofuel supply chains, such as the biojet fuel supply chain, in other countries.

Given these points, we argue that the incorporation of the influence of institutions on the performance of bioenergy systems should be a fundamental part of the research agenda. Institutions influence behavior, which in turn determines the properties of the system. Unlike optimization approaches, agent-based modeling is suitable to incorporate these types of feedback mechanisms as this study has demonstrated. Particularly, it is of interest to analyze the co-evolution of formal institutions (policies) and system behavior. That issue will be the subject of analysis in future work.

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