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Corresponding Author:
johannes.scholz@tugraz.at
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Modelling a Dynamic Forest FuelMarket Focusing on Wood Chips: A Spatial Agent-based Approach to Simulate Competition among Heating Plants in the Province of Carinthia, Austria

Johannes Scholz[1], Florian Breitwieser[1] and Peter Mandl[2]

[1]Institute of Geodesy, Graz University of Technology, Austria
[2]Department of Geography and Regional Studies, Alpen-Adria-University Klagenfurt, Austria

Abstract

Sustainability and renewable resources are attracting increased attention in the energy supply sector. This paper elaborates on the application of agent-based modelling methods to simulate forest fuel markets and supply chains. More precisely, it aims to simulate the market for wood chips for heating purposes, based on a sustainable forest growth and yield model, in conjunction with cognitive agents that act in the market. In the agent-based model, three types of agents are defined: forest owners (supply), biomass heating plant (demand), and 'traders', connecting supply and demand. Forest enterprises can decide on forest operations based on the state of the forest fuel market – e.g. considering the price for wood chips. Each biomass heating plant has an associated 'trader' that tries to fulfil the demand for forest biomass while minimizing the transport distances and the cost for the wood chips. The paper discusses the results of a simulation scenario in the Province of Carinthia, Austria. The simulation results are analysed with respect to space and time concerning biomass transport distance, transport patterns and remaining biomass stock.

Keywords:

agent-based modelling, forest fuels, spatio-temporal modelling

1 Introduction

Sustainability has attracted increased attention in recent years. In the energy supply sector in Europe in particular, sustainable energy production is one of the priorities of politics and administrations (Madlener, Kowalski & Stagl, 2007; IEA, 2003a, 2003b). This is in accordance with the planned reduction of greenhouse gas emissions, as announced as a political goal in the Kyoto Protocol (Grubb, Vrolijk & Brack, 1997). The Kyoto agreement endeavours to achieve a 20% reduction in greenhouse gas emissions between 2013 and 2020 (base year 1990). In Austria, there are a number of initiatives promoting renewable and sustainable energy sources. Nevertheless, there are only a handful of scientific articles that evaluate the spatio-temporal dynamics of renewable energy resource markets (Cintas et al., 2015; Sacchelli, Fagarazzi, & Bernetti, 2013). Most papers dealing with the effects of renewable energy resources in Austria do not consider the spatio-temporal dimension and the inherent dynamics of a forest fuels market (e.g. Arbeitsplattform Wald und Holz in Kärnten, 2009; Schwarzbauer & Stern, 2010; Madlener et al., 2007). In order to simulate the dynamics of the forest fuels market and consider space and time, this paper uses methods from agent-based modelling and simulation (ABM).

ABMs are intended so simulate the activities of agents that act autonomously (Crooks & Heppenstall, 2012). Furthermore, ABM can model and display the behaviour of and dependencies between several agents, and between agents and their environment (Batty, 2009; Mandl, 2003). The intention of ABM is to simulate a system under varying conditions (Macal & North, 2010). Agents act within a defined environment, and are able to interact with the objects present in the environment – e.g. perceive, create, destroy or change them. Agents may be goal-oriented, may be adaptive, and have autonomous behaviour (Kim et al., 2011). The environment mostly remains passive in an ABM, whereas agents (representing population, for example) change dynamically (Batty, 2009). Mandl (2003) stresses that ABMs make use of an environment having a geographical dimension. Hence, ABM and geographical information systems (GISs) have proved to be a powerful combination to simulate real-world problems (Batty et al., 2012; Johnston, 2013; Hofmann et al., 2014; Koch, 2008; Brown et al., 2005; Raubal, 2001; Turner & Penn, 2002; Van Berkel & Verburg, 2012).

In this paper, we focus on modelling and simulating the forest fuel market for a given test area, the Province of Carinthia in Austria. In particular, we elaborate on the effect of wood chip heating plants on the availability of biomass for heating purposes. Because biomass is a limited resource, the heating plants compete for the available wood chips on the market. In addition, each heating plant strives to minimize the transport cost (distance) and buying price for the forest fuels. Based on a previous study (Scholz et al., 2014), we model and simulate the forest fuels market with an agent-based approach. In comparison to the previous study, this paper highlights the modelling of the competition of the biomass heating plants in a forest fuel market and presents preliminary results, based on a test scenario (described in section 3).

The paper is organized as follows: section 2 gives a description of the study area and elaborates on the methodological approach. In section 3, we describe an ABM to simulate competition dynamics in forest fuels market. The validation is discussed in section 4, and results are highlighted in section 5. This is followed by a discussion and future research questions.

2 Scientific Approach and Test Area

Test Area: Province of Carinthia

The study was conducted using a specific project area to test the general ABM developed. The Austrian province of Carinthia served as the test area, due to the fact that 57.6% of the area is covered by forests. Additionally, there are several biomass heating plants in operation and/or planned that compete for the available wood chips.

To feed the agent-based simulation with appropriate spatial and non-spatial data, we make use of the following data sets. Forests are represented by a raster data set, with 30m resolution, indicating forests according to the Austrian Forest Act (source: Austrian Research Center for Forests (BFW)). A forest type map and a raster file with the growing forest stock, both with 30m resolution, were also provided by BFW. These data are used to calculate the potential biomass that can be extracted from a forest stand, based on the forest type, tree age, available timber stock and timber growth. A digital elevation model (DEM) at a spatial resolution of 10m is employed to calculate the distance between heating plants and forest stands that are harvested. This is done in conjunction with a road network from the Graph Integration Platform (GIP), a public nationwide transportation graph (Heimbuchner, 2017). In addition, the study utilizes data on the heating plants in Carinthia, notably their position, and the yearly biomass demand. This data set was created by the authors.

Methodology and Approach of the Study

In this study, we used an ABM approach to model and simulate the forest fuels market, with a focus on wood chips. In order to simulate reality, we developed a spatio-temporal model that contains three types of agents: forest owners (supply), biomass heating plant (demand), and 'traders', connecting supply and demand. Additionally, we developed a simple forest growth module and a forest management decision module (i.e. harvesting decisions). The forest management decision module determines the behaviour of forest enterprises. This study aims to feed the ABM model with real-world data, and to evaluate the results of a simulation test scenario.

The rationale behind the model (shown in Figure 1) is as follows. The forest growth module of the model calculates forest growth, based on the spatial data on forests. Hence, each year the forest stock volume increases as forests get older until trees are lost to natural causes. The module utilizes forest yield tables (Marschall, 1975), regarded as a state-of-the art method in forestry.

Based on the growing stock volume and the age of the forest, each forest owner can decide independently on the forest operations, which is modelled in the forest management decision module. Each forest owner follows general forest management guidelines, such as advising on when to perform forest operations (e.g. thinning or clear-cutting an area). We identified three forest-owner types, which serve as agents in the model: smallscale and medium forest owners, and large-scale or federal forests. Each forest owner type may respond and act differently and independently in terms of forest operations. The decisions of the forest enterprises and owners determine the amount of forest fuels available each year on the supply side of the wood chip market. On the demand side of the market are the biomass heating plants. Each heating plant has a defined demand for forest fuel per year, as well as a fixed position.

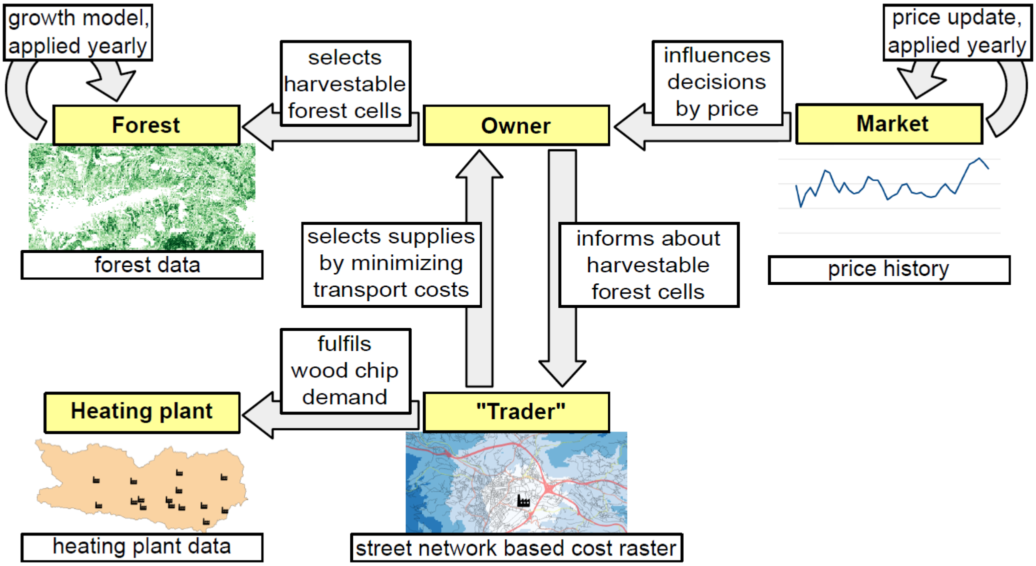

Figure 1: Methodological approach, showing connections between forest, forest owner, markets, 'traders' and biomass heating plants.

Specific agents, called 'traders', connect the supply and demand. As wood chips are a limited resource, the traders compete for the available forest fuel supply, which isaffected by (a) the forest growth model and (b) the forest management operations. The aim is to minimize the transport distances and purchase costs for forest fuel, while fulfilling the demand of the associated heating plant each year.

We evaluated the spatio-temporal effects of the market simulation within the Province of Carinthia. Specifically, we analysed the transport distances and the available/remaining forest stock volume over the simulation period.

3 Agent-based Model for a Competitive Forest Fuel Market: the Experiment

With respect to the agent-based methodology and approach described in section 2.2, this section describes the particular application of the ABM to the forest fuels market. Specifically, we elaborate on the test scenario for the agent-based simulation and the experiment setting.

The forest growth model calculates the forest growth for a one-year period for the two dominant tree species in the test area – spruce and European beech. The annual growth is calculated using forest inventory data provided by BFW, and altitude, which is determined with the help of the DEM of the test area. The result is the standing timber volume in the test area for each year of the agent-based simulation.

The agents on the supply side (i.e. forest enterprises) decide on the forest operations based on the market situation and their own objectives while adhering to general forest management principles. The rationales behind each forest owner type are defined as follows. Large and medium forest owners and enterprises are commercially oriented and so their yearly yield is relatively constant (Arbeitsplattform Wald und Holz in Kärnten, 2009; Jöbstl, 1986a, 1986b). In contrast, the small forest owners show more volatile behaviour than large or medium owners. They harvest either for personal use (firewood) or for monetary reasons (i.e. to make money). Hence, small forest owners harvest and sell timber only if they expect a favourable price, if they need firewood, or if they need money. In the present model we simulate the price expectations of small forest owners and compare them with the market price (Arbeitsplattform Wald und Holz in Kärnten, 2009; Eckmüllner, 1964). However, personal use and personal monetary reasons can hardly be modelled accurately. Hence, we employ a stochastic function (i.e. a random probability function) to help model these issues.

In view of the considerations mentioned above and the literature available (Arbeitsplattform Wald und Holz in Kärnten, 2009; Jöbstl, 1986a, 1986b; Eckmüllner, 1964), we modelled the behaviour of forest enterprises according to their size. Hence, small forest enterprises (< 200 ha) show the following behaviour:

- stochastic harvesting/thinning for personal use on each forest cell every 10–20 years;
- harvesting/thinning if price is equal to or higher than the last timber selling price or if the price is higher than the average price of the last 5 years;
- final clear-cut when the forest cell reaches an age of 110–150 years (stochastically determined);

Medium forest enterprises (200–1000 ha) are modelled as follows:

- thinning (i.e. harvesting) every 9 years;
- thinning operations are only possible in forest aged 20 to 70 years old;
- clear-cut when the forest cell reaches 100 years of age;

Large forest enterprises (> 1000 ha) are modelled as follows:

- thinning (i.e. harvesting) every 7 years;
- thinning operations are only possible in forest aged 20 to 70 years old;
- clear-cut when the forest cell reaches 90 years of age.

Based on these assumptions, decision making processes are modelled which define the annual amount of timber available for heating purposes for each forest cell. Subsequently, the growing stock volume is reduced by the harvest loss (20%), resulting in the gross m^3 of wood available for sale. Of this timber volume, approximately 84.3% is sold as roundwood, and 15.7% can be marketed as forest fuels (Arbeitsplattform Wald und Holz in Kärnten, 2009).

This information is then delivered to the traders, whose task is to meet the demand of each heating plant while minimizing the transport costs. Traders determine the least-cost paths by using a pre-calculated cost surface raster, which is based on the location of heating plants, the road network, the official speed limits, as well as terrain information (i.e. gradient). Based on the transport costs and the gradient of the terrain, the trader evaluates the best harvesting options. In contrast to small heating plants, large facilities also consider more distant forest cells, if the available yield pays off. The modelled trader agents act within a competitive situation based on a first-come first-served principle in the forest cells.

The simulation scenario tested in this study uses an extrapolation of the Austrian price for round timber as it has developed over the last 40 years, during which period the market price of timber increased by 15%. The model mimics the annual behaviour of 15 heating plants and their traders. On the supply side of the supply-and-demand chain are about 23,000 owners. The heating plants have a combined annual demand for forest fuels of approximately 225,600 m^3 of timber. The literature (Arbeitsplattform Wald und Holz in Kärnten, 2009) gives a forecast of a 1.1% annual increase in the demand for forest fuels (from 2010 to 2020). After 2020, the annual increase is gradually reduced until a zero-increase rate is reached. The demand side of the forest fuels supply chain is modelled based on this market scenario.

To initialize the simulation, the following datasets are needed: forest cells (including: timber volume, age, forest type, altitude), cost distance surface (calculation based on the location of the heating plants and the gradient of the terrain), heating plants (including their annual timber demand) and forest owners. In the ABM developed in this study, each point on the graph represents a single year (see Figures 2 and 4). The simulation stops when the timber demand of heating plants cannot be fulfilled by the forest owners or traders.

The experiment conducted in this study used the Repast Simphony ABM platform (North et al., 2013). The model itself and the modules thereof were developed using Java programming language with the help of the Repast Simphony environment. The model is designed to document the state variables of agents, among which are:

- timber stock volume at each forested cell, if it is available for harvesting
- wood price
- owner's timber price expectation
- timber price
- cost distance to each heating plant.

4 Calibration and Validation

Validation and verification of the model is an essential part of ABM (Macal, 2005). The validation process provides information on the accuracy of the simulation by comparing it to a real-world system (Crooks & Heppenstall, 2012; Ngo & See, 2012). For this purpose, continuous real-world data are needed.

The construction of wood chip heating power plants has started to attract attention over the last two decades. Thus the construction of the plants is a fairly recent development and there is only a limited amount of accumulated data available (Österreichischer Biomasseverband, 2015). A data source on timber supply is the Austrian forest inventory survey (Österreichische Waldinventur; ÖWI), which is carried out every 10 years and gives a vast number of statistics on timber harvests (BFW-Bundesforschungs- und Ausbildungszentrum fuer Wald, Naturgefahren und Landschaft, 2017).

The model is based on an extrapolation of the price development over the last 40 years, which makes it possible to match the outcomes of the model to the observed data of the ÖWI. In particular, the model outputs for the quantity of harvested timber are compared to the quantity given in the corresponding ÖWI period. A schematic depiction of this process is given in Figure 2. The comparison of the data derived from the simulation and from the ÖWI is done by using relative values, because of a difference in absolute timber harvesting quantity. In addition, the following operations are carried out during pre-validation:

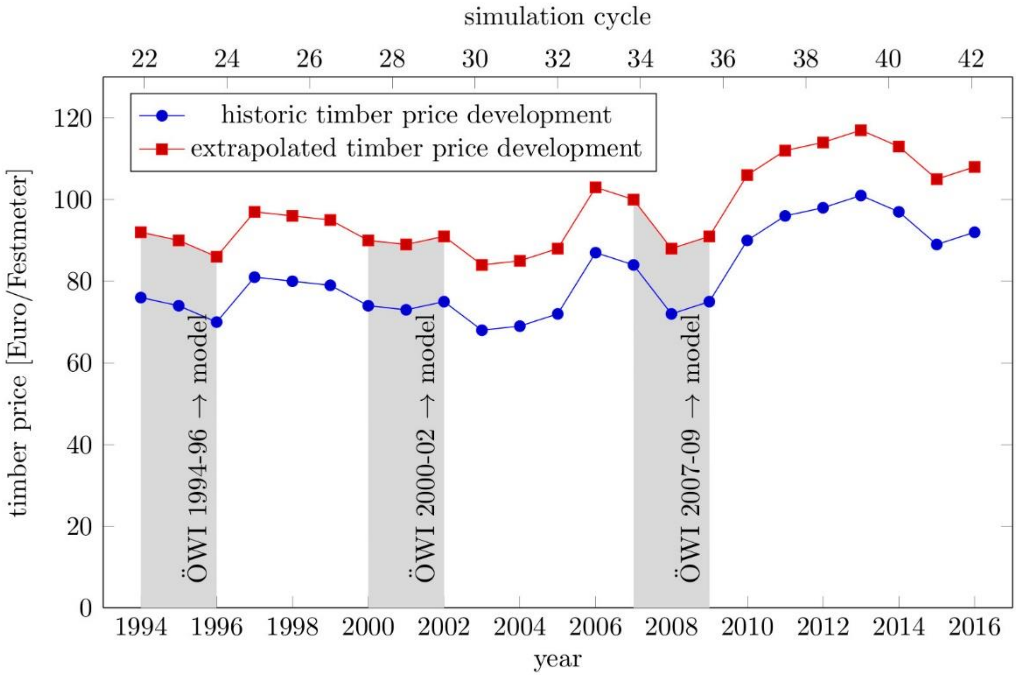

Figure 2: Validation process based on related price development. The Model outcome is compared to ÖWI data in the corresponding ÖWI-survey timeslots (1994–98, 2000–02 and 2007–09).

- sensitivity analysis to determine which parameters would deliver relevant modifications to the model;

- empirical calibration to identify the best fit to the reference data provided by the ÖWI.

Figure 3 shows that the model is a good overall match to the data provided by the ÖWI. The greatest divergence (26.2% ÖWI to 19.9% modelled results) can be observed in the comparison of the harvesting rate of the forest companies in the ÖWI for 2000–02. The other values show a difference of about 3% to the reference data provided by the ÖWI.

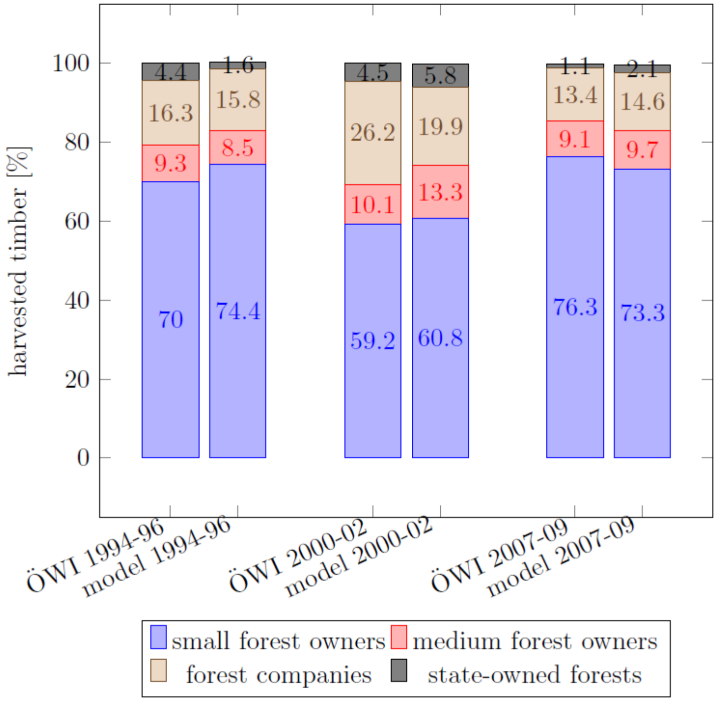

Figure 3: Relative harvesting quantities of the 4 owner types in the ÖWI-survey timeslots compared and the corresponding simulation cycles. Over all 3 timespans of the ÖWI, a maximal discrepancy of 4% could be observed.

5 Results

The results of the agent-based simulation are discussed in this section. First, we elaborate on the transport distances for the timber for each heating plant. Secondly, we elaborate on the market – i.e. how the timber price influences the availability of forest fuels. This is followed by a set of maps depicting the state of the forest at specific points in time representing 5, 10, 20, 30 and 43 years from now respectively.

In the ABM described in this paper and the simulation scenario, timber price fluctuations are present (see Figure 4, line for 'round wood price'). The timber price seems to have a relation to the mean transport distances per year. If the price rises, transport distances decrease. This is due to the fact that the price is one trigger for small forest owners to harvest timber. This is shown in Figure 4 around years 6 and 7. The opposite happens at years 29 and 34. Timber supply gets scarce, because the price is below the price expectation for several years in a row. Thus only a few small forest owners, who manage the majority of forested areas, are willing to harvest timber. As a consequence, traders have to rely on timber sources further away from the heating plant, resulting in increased transport distances. The next rise of timber prices results in a lowering of the mean transport distance within 1–2 years.

The evolution of the growing timber stock is shown in Figure 5. Due to the volatile behaviour of the small forest owners, the process of over-aging forests can be seen. This is based on the fact that the members of this owner type sometimes regard their forests as a piggy bank, which they don't touch. The commercially cultivated forest (i.e. owned by middle to large forest owners) is depicted as lighter spots at year 30, and at year 43 as partly re-afforested areas (red) and therefore not available for harvest. This aligns with the fact that commercial forest owners tend to over-cultivate their forests (see Büchsenmeister, 2011, p. 6). Overall, the simulation shows that the harvested areas tend to be grouped around the central valley, where most bigger heating plants are located. This might be due to the fact that traders try to reduce the transport distances for the forest fuels.

The abort criterion of the simulation process is seen at year 43. This can be explained by the fact that the owners were not willing to sell at the prevailing timber price, which resulted in inadequate supply for the heating plants.

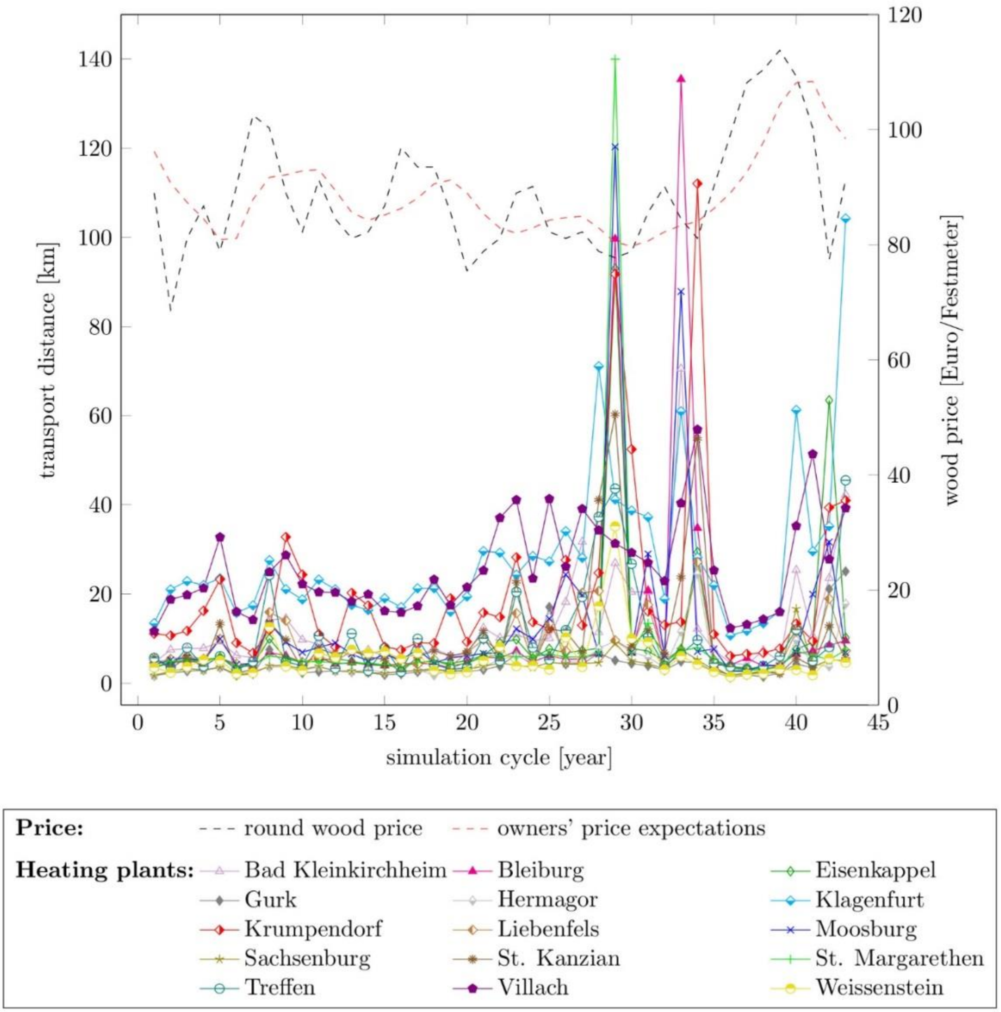

Figure 4: Results of the simulation scenario: simulated average transport distances for each heating plant by simulation cycle (year). The development of price expectations and the simulated timber price are also shown.

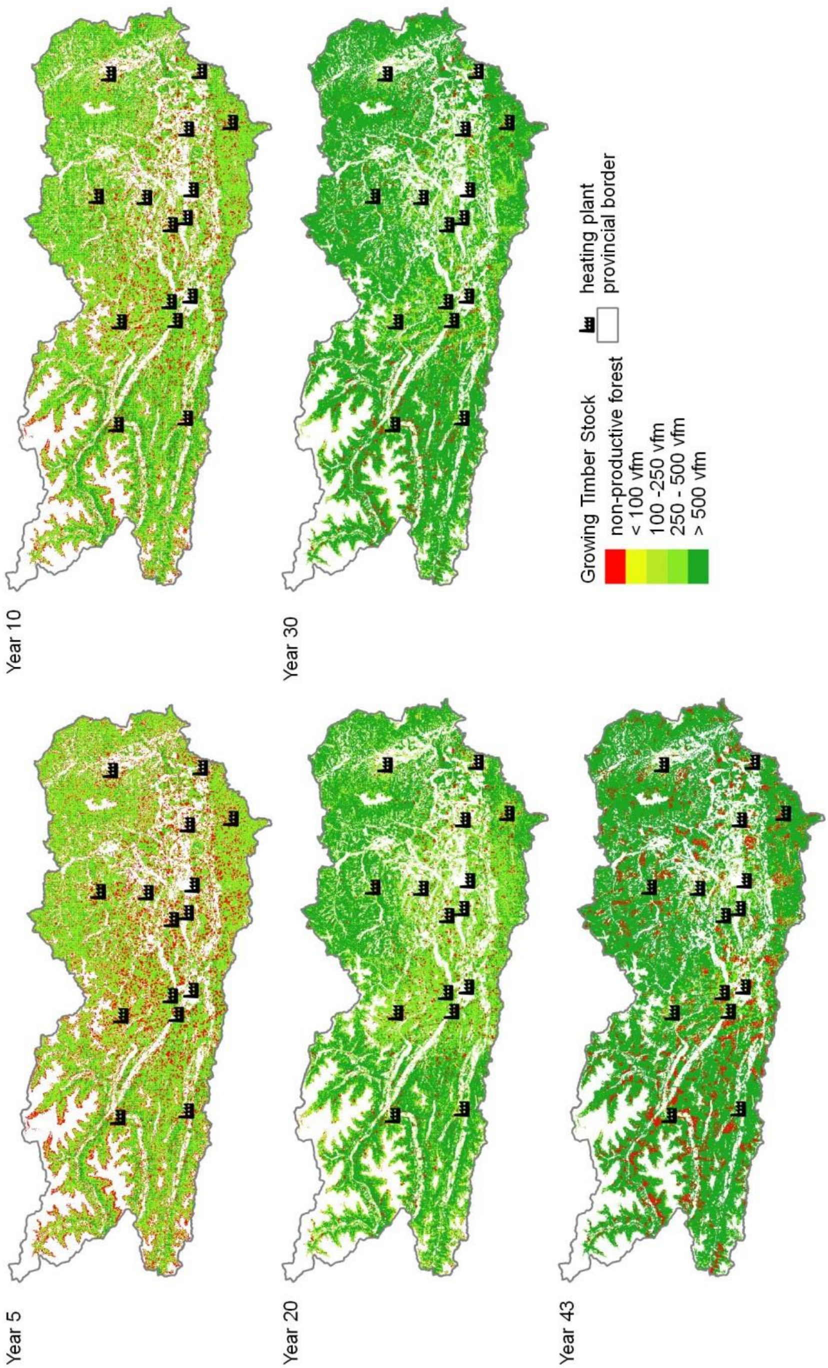

Figure 5: Growing timber stock volume per forest cell at specific points in time (year 5, 10, 20, 30 and 43). Cells are colour-coded with respect to the available timber (see the legend). Cells coloured red are unavailable for harvesting. Green cells show available timber. The locations of heating plants are shown using specific symbols.

6 Conclusions

The model presented here was developed over the last four years (2013–2017) in several steps. The overriding objective was to create a simulation model for the supply of biomass heating plants with wood chips, and the resulting temporal and spatial patterns of the supply areas. The model developed in an earlier publication (Scholz et al., 2014) was simpler: it did not consider the forest owners or the market dynamics and covered a shorter simulation period. The ABM simulation presented in the current paper includes a model of the forest fuels market. The scenario discussed here represents a standard market situation, which is calibrated using real data for the states of the forests and for economic development which has taken place in recent years. The results presented here show the benefits of a spatial ABM approach for modelling the forest fuels market. The spatial dimension is essential to simulate local competition between heating plants and to reveal spatio-temporal patterns of timber usage. In comparison to standard GIS analyses, the ABM approach enables the simulation of individual agents' behaviour, reflecting quite accurately a free market in which participants make their own decisions.

Future research directions involve the simulation of different market scenarios. One scenario could include the Austrian forest development plan, which considers forest conservation as well as avalanche and torrent control measures. This scenario limits timber extraction from forests in specific places. Other possible scenarios include an increasing or decreasing timber price, or a volatile price situation. Furthermore, influences on a more global scale, such as climate change, could also be simulated. The consequences of the aforementioned processes, like global warming, resulting in changed forest cultivation styles or damage to forests would definitely have an impact on the forest fuels market. Additionally, it could also be possible to assess the influence on the supply situation of large new heating plants which are currently being planned.

The present model is thus just the first of a series of agent-based models for the use and supply of renewable energy sources for electricity production, heating and traffic, which will be developed and tested as a laboratory for sustainable resources management.

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