Simulating the forest fuel market as a socio-ecological system with spatial agent-based methods: A case study in Carinthia, Austria

Johannes Scholz¹ | Florian Breitwieser¹ | Peter Mandl²

1Graz University of Technology, Institute of Geodesy, Research Group Geoinformation, Graz, Austria
2Department of Geography and Regional Studies, Alpen-Adria University Klagenfurt, Klagenfurt, Austria

Correspondence
Johannes Scholz, Institute of Geodesy, Graz University of Technology, Steyrergasse 30, 8010 Graz, Austria.
Email: johannes.scholz@tugraz.at

Abstract
The paper presents an agent-based modeling and simulation approach to model the forest fuel supply chain for heating purposes (i.e., heating plants). The paper focuses on the simulation of the processes of timber harvesting by forest enterprises and the competition of heating plants for the limited resource of wood chips. In particular, the work identifies different stakeholders having an adaptive behavior—with respect to the overall market conditions and timber prices. The agent-based model developed here—called SimFoMa—uses three types of agents—forest enterprises, heating plants, and traders. The agents are interacting in an environment that has rich information on the forests and road network. The SimFoMa model is applied to a test area, the province of Carinthia, Austria. We defined six different simulation scenarios that cover different market situations—from increasing timber prices, volatile market conditions, or decreasing market conditions—and evaluated the harvest patterns, transport distances and the forest itself. The paper utilizes the agent-based modeling methodology to model the agent’s adaptive behavior of...
the forest fuel supply chain and to model the competition of heating plants for forest fuels. To evaluate this phenomena we mainly analyze transport distances of the simulation runs. For the test area of Carinthia, the experiments show that the behavior of small forest owners influences the supply of forest fuels. Timber prices not meeting the expectations of small forest owners might not motivate them to produce timber and forest fuels. On the long run the overall forest fuel supply does not meet the demand in the test area Carinthia—hence it relies on biomass imports. Furthermore, we witnessed increasing transport distances from harvest site to heating plant.

**Recommendations for Resource Managers**

- The results of the spatial Agent-based simulation of the forest fuel market with agents competing for the limited resource forest biomass show that transport distances for forest fuels can vary and may increase over time. Hence, the planning of the forest fuels supply and the respective transport distances is crucial to reduce the carbon footprint of the timber for heating purposes.

- As small forest owners produce timber on a more irregular basis (based on the price in the market), the motivation of small forest owners is crucial for the steady supply of biomass for heating purposes— for the case of Carinthia.

- In the long run it is not possible to fulfill the demand of biomass for heating purposes for Carinthia, without imports of timber. Again, crucial is the motivation of small forest owners to produce timber.

**KEYWORDS**

agent-based simulation, forest fuel, spatial simulation, spatio-temporal modeling, wood chips
1 | INTRODUCTION

Sustainability has become a buzzword in many contexts. Especially, the energy supply sector is using renewable energy sources to become sustainable in the near future. As clean and sustainable energy production is also one of the main priorities of politics and administration (see IEA, 2003a, 2003b; Madlener, Kowalski, & Stagl, 2007) to reduce the emission of greenhouse gases according to the Kyoto Protocol (Grubb, Vrolijk, & Brack, 1997). The Kyoto agreement tries to achieve a 20% reduction in greenhouse gas emissions between 2013 and 2020—with respect to the base 1990.

In Europe, a number of initiatives promote renewable energy resources. Despite this fact, there are only a handful of scientific papers that discuss spatio-temporal phenomena in energy resource markets (Cintas et al., 2016; Sacchelli, Fagarazzi, & Bernetti, 2013). In fact, the majority of papers in this area neglect spatio-temporal analysis and an evaluation of the forest fuels market (see Arbeitsplattform Wald und Holz in Kärnten—Bilanz und Strategieplan über Aufkommen, Nutzen und Potentiale, 2009; Madlener et al., 2007; Schwarzbauer, Huber, & Stern, 2009).

In this paper, we utilize agent-based modeling (ABM) and simulation to simulate the spatio-temporal dynamics of the forest fuels market. ABMs are capable of simulating activities of autonomous agents and can display the behavior of and the dependencies between agents, and between agents and their environment (Batty, 2009; Crooks & Heppenstall, 2012; Mandl, 2003). Hence, agents act within a defined environment, and are able to interact with the objects in the environment. Any ABM can analyze a system under varying conditions, which helps to understand complex phenomena (Macal & North, 2010). In particular, agents may show different behavior ranging from goal-oriented to adaptive or autonomous one (Kim, Joo, Rothrock, Wysk, & Son, 2011). The combination of ABM and Geographical Information Systems (GIS) has been described in the literature extensively (e.g., Batty, Crooks, See, Heppenstall, 2012; Brown, Riolo, Robinson, North, & Rand, 2005; Hofmann et al., 2014; Johnston, 2013; Koch, 2008; Mandl, 2003; Raubal, 2001; Turner & Penn, 2002; Van Berkel & Verburg, 2012).

The objectives of this paper are the development of a spatial ABM and simulation of the forest fuels market for a test area—the province of Carinthia in Austria for the next four decades. The paper evaluates the spatio-temporal patterns of the forest fuels market (e.g., transport, origin of forest biomass for each heating plant) based on the developed agent-based simulation model. For simplicity reasons we intentionally regarded the test area as “closed” market without any biomass imports. This was done due to three reasons: First, biomass imports would have distorted the spatio-temporal patterns that we are looking for. Second, to model heating pants’ decisions to import biomass would require to model the international market outside of Carinthia and a decision behind, which is out of scope of this paper. Third, imports would counteract the argument that biomass is local and sustainable energy resource—hence, we intentionally simulated local biomass sources without imports.

Based on two previous papers (Scholz, Breitwieser, & Mandl, 2017; Scholz, Mandl, Kogler, & Müller, 2014) we model the forest fuels market utilizing agent-based methodologies. This paper introduces—based on Scholz et al. (2017)—five additional simulation scenarios, and analyzes the obtained results. The paper focuses on the modeling of the competition among the heating plants, under different market conditions (scenarios). Forest Owners react to timber prices, and adapt their forest management strategies (harvest and thinning decisions). Their behavior directly influences the available forest fuel quantity for heating plants.
The paper is organized as follows: Section 2 discusses the relevant literature and in Section 3 we elaborate the methodological approach of the paper. The ABM is described in detail in Section 4, followed by the presentation of the scenarios and experiment in Section 5. This is followed by the results and their validation in Sections 6 and 7, respectively. The paper is closed with conclusions and future research questions.

2 | RELEVANT LITERATURE

This section discusses the relevant literature in the field of ABM and simulation in general and in the field of agent-based simulation in forestry and forest-based supply chains. Particular focus is given to spatial ABM and simulation, as this is the methodological basis of the paper.

A general overview of ABM is given in a number of publications (e.g., Crooks, Castle, & Batty, 2008; Crooks & Heppenstall, 2012; Goodchild, 2005; Heppenstall, Crooks, See, & Batty, 2011). ABMs simulate the actions of autonomous agents and model the behavior and dependencies between agents. In contrast to earlier Cellular Automata approaches, which model discrete dynamic systems—that is, land use change—ABMs do not reach equilibrium but elaborate on the question how a system reacts to changed situations (Macal & North, 2010). The integration of ABMs and GIS is described in (e.g., Batty et al., 2012; Brown et al., 2005; Gimblett, 2002; Hofmann et al., 2014; Johnston, 2013; Koch, 2008; Mandl, 2003; Minar, Burkhart, Langton, & Askenazi, 1996; Raubal, 2001; Turner & Penn, 2002; Van Berkel & Verburg, 2012).

Bonabeau (2002) discuss the application of ABM to social, economical and ecological problems—referred to as human problems in this article. In addition, ABMs have been used to study social dilemmas (Gotts et al., 2003), such as the prisoner’s dilemma originating from Game Theory. Similarly, Heckbert et al. (2010) argue that ABMs are well suited to model and simulate ecological economic issues, in particular natural resource management, land-use change, market dynamics, or urban systems. The combination of human and ecological systems with the help of ABM has been discussed in An (2012) and Filatova, Verburg, Parker, & Stannard (2013). Whereas Filatova et al. (2013) identify four categorical challenges addressed in the papers of that particular thematic issue: (a) design and parameterizing of agent decision models, (b) verification, validation and sensitivity analysis, (c) integration of socio-demographic, ecological, and biophysical models, and (d) spatial representation.

The application of ABM in forestry is described by Frayret (2011). More specifically, Kostadinov, Holm, Steubing, Thees, & Lemm (2014) developed an agent-based simulation for the biomass supply chain in the Swiss province of Aargau. Similarly, Binder, Hofer, Wiek, & Scholz (2004) published a paper describing the modeling of the material flow with the help of an ABM approach. Similarly, Scholz et al. (2014, 2017) applied spatial ABM to evaluate the biomass supply chain in a defined test area in Austria. In particular, they analyzed spatio-temporal patterns of supply and demand—for a given simulation scenario. Lemieux et al. (2009) integrate an advanced planning and scheduling approach to evaluate the capacity of the forest-based supply chain with respect to different planning scenarios. Simon and Etienne (2010) present an ABM supporting local forest management. This project is capable of comparing two simulation scenarios which helps local stakeholders in decision making. Another paper by Bone and Dragičević (2009) describes the simulation of effects of forest management decisions on land cover. In particular, the ABM in this paper focuses on behavior of agents concerning changes in timber price and harvest costs in a North American context (USA and Canada).
Marques et al. (2014) employ a combined simulation-optimization approach for short-term decision making in forest management (i.e., forest operations).

In the field of bioenergy simulation there are some recent papers that utilize ABM methodologies (Rammer & Seidl, 2015; Rouleau, 2016; Rouleau & Zupko, 2019; Seidl, Rammer, Scheller, & Spies, 2012; Zupko & Rouleau, 2019). Rouleau (2016) elaborate on a framework for using ABM to assess the sustainability of bioenergy production, similar to Zupko and Rouleau (2019)—who concentrate on nonindustrial forest production. A review of coupled human and natural systems (CHANS) using ABM is given in An (2012). Forest ecosystem dynamics modeling and simulation with ABM technologies are covered by Seidl et al. (2012) and Rammer and Seidl (2015). Their platform “iLand” is focuses on forest landscape dynamics, simulating individual trees (i.e., competition, growth, mortality, and regeneration). In addition, the interactions between climate (change), disturbance regimes, vegetation dynamics, and forest management are modeled in this platform. Nevertheless, the interactions between demand and supply in the forest fuels market has never been addressed. The papers mentioned above model forest management decisions under different circumstances (e.g., climate change) and their effects for the forests itself. Hence, there is a gap to connect the forest owner decisions with the forest fuels market. Combining demand and supply, and integrating some kind of competition for the limited resource timber and evaluating the spatio-temporal effects and results has not been published to date.

3 | METHODOLOGICAL APPROACH

This study is methodologically based on an ABM approach. We modeled the forest fuel market with particular focus on the wood chip market for energy purposes. The model is called “Simulation Model of the Forest Fuel Market” (SimFoMa).

To mimic reality, we developed a model that is capable of simulating the spatio-temporal behavior and relationships of agents. The model contains three types of agents: forest owners (supply), biomass heating plants (demand), and “traders” (connecting supply and demand). A forest growth module estimates the annual increase of growing timber stock, whereas a harvest model mimics the behavior of forest owners and enterprises in terms of their forest management decisions (i.e., harvesting and thinning operations).

The general set-up of SimFoMa is shown in Figure 1. Basically, the ABM approach models reality with two building blocks: environment and agents. The environment and the agents make use of generic modules that have a defined functionality (e.g., calculating forest growth, select cells for harvesting). The environment contains of the Forest, the Market, and the Road Network, each having specific modules: the Forest Growth Module and the Market Module. The agents in SimFoMa comprise of the Forest Owners, the Traders and the Heating Plants. The agent class “Forest Owner” makes use of the Harvest Module, whereas the “Traders” utilize the Trading Module.

In general, we distinguish four forest owner types based on the size of their enterprise: small-scale (smaller than 200 ha), medium (200–1,000 ha), and large-scale (greater than 1,000 ha) forest owners as well as federal forest enterprises. Each forest owner type can perform different forest operations with respect to the forest and the forest fuel market (i.e., price level for roundwood timber). The forest owners’ decisions determine the potential available amount of biomass (i.e., wood chips) on the supply side of the forest fuel market. The modules and their
respective functionalities—denoted as methods here—are briefly discussed in the following paragraphs and in Section 4.

The general methodological approach followed in this paper is as follows (see Figure 2). We defined a test area, the Province of Carinthia in Austria, due to the availability of spatial data serving the purpose of the paper. The approach produces six simulation scenarios, which are defined in Section 5. Two of the simulation scenarios—denoted as resource-oriented—are grounded on the assumption of an “optimal” use of the natural resources available, whereas four market-oriented scenarios model the adaptive behavior of agents regarding different market conditions (i.e., timber price). Based on a given set of data for the test area, describing forest, heating plants, road network, and a market situation we conducted 10 simulation runs for each scenario. For each simulation scenario we evaluate the spatio-temporal effects of the market situation. In particular, we analyze the transport distances, remaining growing timber stock volume and the harvest pattern over the simulation period.

The results of the simulation are evaluated with the help of historic data sets from the Austrian forest inventory survey (called Österreichische Waldinventur, ÖWI). This is done, due to the fact that the construction of new heating plants increased during the last two decades. Hence, there is only a limited amount of data available Österreichischer Biomasse-Verband (2017). In addition, the market model is an extrapolation of the timber price development over
the last 40 years. Thus we compare the results of our model with observed data from ÖWI—in particular the overall quantity of harvested timber.

4 | SPATIAL ABM TO MODEL A COMPETITIVE FOREST FUEL MARKET

The ABM SimFoMa developed in this paper follows previous work of Scholz et al. (2014) and Kostadinov et al. (2014). The model simulates a Forest-based Supply Chain of forest biomass for heating purposes. The model starts at the forest and models the processes until the forested biomass reaches the heating plant. The model itself is intended to deliver results on the macro level. Hence, we do not model the material flow of the Forest-based Supply Chain.

The ABM model SimFoMa utilizes the agents, a given environment, and the relationships between agents, environment, and among agents. The agents are:

- forest owner
- timber agent (trader)
- heating plant

The environment comprises of the forest itself and the market that forms the context for each agent. We devote a sub-section describing each agent and member of the environment.

4.1 | Environment

4.1.1 | Forest

Forest in Austria is basically defined by the Austrian Forest Act 1975 (Republic of Austria, 1975). Forest in Austria fulfills four different functions:
- Economic function: forests having this main function are predominantly intended to produce timber in a sustainable manner.
- Protective function: these forests should protect people, infrastructure, and soil from natural hazards and erosion.
- Welfare function: these forests are intended to provide clean air and as water resource.
- Recreational function: forests having a recreational function serve for recreation and touristic usage.

Forest management in Austria is dominated by age-grouped forest. Hence, forest owners manage such age-grouped patches of several hectares forest in a similar way. These patches are called forest stands (Weinfurter, 2013). Thus, we represent the forest with the help of regular tessellated cells having 100 m resolution. Every cell can be regarded as static agent, with the following attributes: Timber stock volume, Age, Forest type, Elevation (meters above sea level), Slope, Forest Owner (type). Each forest cell itself can make use of the Grow Module. The Grow Module estimates the growth of the trees in m³ wood per hectare. This estimation is based on the attributes of each forest cell data originating from the Austrian forest inventory survey (called Österreichische Waldinventur, OWI). The annual yield is added to the current growing stock volume of each stand (see Table 3).

The yield tables used here (Amt der Tiroler Landesregierung, Abt. Forstplanung, 2004; Marschall, 1975) are dependent on the age of the forest, the place, altitude, and forest type (Hasenauer, 1994; Kilians, Müller, & Starlinger, 1994). For coniferous forests up to an altitude of 700 m we used “Fichte Bruck EK 10” (Kilians et al., 1994; Marschall, 1975), for altitudes above 1,700 m “Fichte Hochgebirge EK 10,” and between 700 and 1,700 m we calculate the mean values between “Fichte Bruck EK 10” and “Fichte Hochgebirge EK 10” as there is no appropriate yield table available. In addition, for broad-leaved stands and mixed stands we utilized yield tables developed by the state Tyrol (Amt der Tiroler Landesregierung, Abt. Forstplanung, 2004). The broad-leaved yield tables are developed for an altitude up to 700 m. For higher altitudes we use 2/3 (from 700 to 1,400 m) and 1/3 (above 1,700 m) of the original yield value.

### 4.2 Forest owner

Forest owners manage the forests they own. Mainly, they decide if a forest cell (see Section 4.1.1) should be thinned or harvested. The ability of forest owners to decide on harvesting/thinning is implemented in the Harvest Module. The module evaluates the context of the forest owner, the market and the forest itself and suggests a forest operation, that may be realized if and only if a trader (see Section 4.4) buys the timber to fulfill the demand of a heating plant. Hence, if no trader buys the timber, the respective forest cell remains not harvested/not thinned—and the timber is available in the next simulation year.

Generally, we have implemented two different behavior patterns in the Harvest Module of forest owner agents—either acting based on general resource-oriented rules (for resource-oriented scenarios in Section 5.3.1) or on the other hand an adaptive and context-oriented behavior (see market-oriented scenarios in Section 5.3.2).

The general resource-oriented rules—similar to Scholz et al. (2014)—strive to utilize the existing timber resources in an optimal way. Literature suggests thinning operations every 5–10 years, after the stand has reached a certain tree height or age (Landwirtschaftskammer Oberösterreich, 2015;
For spruce we assume minimum age for thinning operations to be 20 years and for beech to be 30 years. The rotation time is between 80 and 120 years for spruce and 60–100 years for beech. At the end of the rotation cycle the stand is harvested with a clear-cutting operation (Bundesforschungszentrum für Wald [BFW], 2016; Fichtner, 1955). The forest owners select the forest cells to be harvested (either being a thinning operation or clear cutting) randomly within the given time intervals (i.e., time between thinning operation or clear cutting).

The adaptive behavior of forest owners and enterprises is based on the context of each enterprise. As the sizes of forest enterprises in Austria differ widely (Landesregierung, 2015; Wald in Österreich—Das Portal zu Wald und Holz, 2016), their behavior is and their objectives are different. Based on the Austrian Forest Inventory (Austrian Research Center for Forests, 2016), we differentiate the following enterprise categories:

- Small forest owners (<200 ha)
- Large forest owners (200–1,000 ha)
- Forest enterprises (>1,000 ha)
- Federal forest enterprise (e.g., Austrian Federal Forests)

In Austria the share of these four categories is as follows. According to Austrian Ministry for Sustainability and Tourism (2017) 54% of the forested area is owned by small forest owners, 28% of forested area is owned by large owners and forest enterprises, whereas 18% of the forested area is managed by federal forest enterprises.

The agents representing small forest owners are modeled with respect to Eckmüllner (1964). There the behavior of these owners is described as being influenced by stochastic events—like cash or timber requirements—and the timber market (i.e., average roundwood timber price per m³). Hence we assume the following rationale for agents representing small forest owners:

- agents have a self-consumption of timber of 21% (Arbeitsplattform Wald und Holz in Kärnten—Bilanz und Strategieplan über Aufkommen, Nutzen und Potentiale, 2009);
- agents mostly have little or no connection to forest management (see Hogl et al., 2005)—hence, we apply a random time period between 5 and 25 years between two consecutive thinning operations;
- agents harvest/thin if the average roundwood price is “good”—that is, if the timber price is above the expectations of the agent (see Table 1);

| Ratio expected vs. real timber price | Harvest probability (%) |
|--------------------------------------|-------------------------|
| >1.2                                 | 100                     |
| 1.1–1.2                              | 70                      |
| 1.05–1.1                             | 50                      |
| 1.025–1.05                           | 40                      |
| 0.975–1.025                          | 30                      |
| 0.95–0.975                           | 20                      |

TABLE 1 Assumed price expectations (average roundwood price) and harvest probability values for agents representing small forest owners (developed based on Brazee & Mendelsohn, 1988)
• each currently cell that had a thinning operation cannot have another thinning or harvest operation within the next 5 years;
• agents tend to manage their forests so that they are over-mature (Büchsenmeister, 2011); thus, the final harvesting (clear cut) is done randomly between 90 and 150 years of tree age;

Large forest owners, forest enterprises and federal forest enterprises behave differently from small forest owners, as they have to plan forest operations on an annual basis—as they have to cover their costs (Arbeitsplattform Wald und Holz in Kärnten—Bilanz und Strategieplan über Aufkommen, Nutzen und Potentiale, 2009; Jöbstl, 1986a, 1986b; Schwarzbauer et al., 2009). Table 2 lists the decision parameters for large forest owners, enterprises and federal forest enterprises.

Concluding, the resource-oriented scenarios are intended to test if there are enough biomass resources available. The market-oriented scenarios are modeled with a behavior of the forest owner agents, that mimics their real-world behavior. Hence, large forest owners/enterprises/federal forests show a more “resource-oriented” behavior with the objective to sell timber to utilize their resources. For small forest owners the objective is different. They sell timber if the price meets their expectations or if they need money (for what reason ever). Hence, their behavior is more volatile and/or based on the timber price in the market.

4.3 | Market

The market is predominantly important for market-oriented simulation scenarios, described in Section 5.3. In SimFoMa, the market is influencing timber supply and price. As the demand remains relatively constant each year, the supply side of the market reacts to the market.

Small forest owners tend to react to average roundwood timber prices, and harvest more timber if the price is high (Arbeitsplattform Wald und Holz in Kärnten—Bilanz und Strategieplan über Aufkommen, Nutzen und Potentiale, 2009). Thus, the average roundwood timber price in the market is influencing the timber supply provided by small forest owners. For all other forest owners timber for energy purposes is not the main product (Binder et al., 2004; Schwarzbauer et al., 2009). As small forest owners own 70% of the forested area of Carinthia (Bundesforschungszentrum für Wald, 2019), the timber price for roundwood has the highest influence on their harvest and thinning decisions.

**TABLE 2** Decision parameters for harvest operations of large forest owners, forest enterprises, and federal forest enterprises

| Parameter                                      | Values       | Nature   |
|------------------------------------------------|--------------|----------|
| Period between harvesting (large owners/enterprises and federal for.) | 6–9/5–7      | Random   |
| Forest age required for thinning operations    |              | Constant |
| Coniferous forest                              | 20           |          |
| Deciduous forest                               | 30           |          |
| Forest age required for clear cut              |              | Random   |
| Coniferous forest                              | 80–120       |          |
| Deciduous forest                               | 60–100       |          |
To simulate the timber price, we utilize the Market Module. The module defines the timber price for each simulation year. The module makes use of historic roundwood timber prices ranging from 1994 to 2016 (Holzmarktbericht der LK Österreich, 2016). The historic roundwood prices have a positive trend, and can thus be used for market scenarios having an increasing timber price. For simulation scenarios having a decreasing timber price we flip the curve around the y axis (see e.g., Figures 9 and 11—timber price).

### 4.4 Timber agent (Trader)

The timber agent—denoted as Trader hereafter—connects the forest owners and the Heating Plants (see Section 4.5). In the model each Trader is associated with a single Heating Plant, and has to purchase enough timber to fulfill the demands of the Heating Plant. As the share of timber for heating purposes per m³ harvested timber is at 6.2% (Arbeitsplattform Wald und Holz in Kärnten—Bilanz und Strategieplan über Aufkommen, Nutzen und Potentiale, 2009), the remaining 93.8% timber are used as roundwood, for paper or pulp industry. For sake of simplicity, the Trader only consumes the timber for heating purposes, whereas the remaining timber (i.e., roundwood) is not available for heating purposes or other Traders.

Basically, Traders try to minimize the transport cost to deliver the biomass to the heating plant. In addition, each Trader strives to reduce the purchase price for the biomass. The Trader agent acts as follows. The agent visits the forest cells and checks if they offer timber for heating purposes. Having visited all Forest Owner’s forest cells the Traders decides which timber to buy with respect to cost minimization, mentioned above. To realize a cost minimization in terms of transport cost, cost rasters for each heating plant containing the transport cost to each forest cell are developed. As there are several Traders—one for each heating plant—purchasing timber in parallel, the Traders compete for the available timber. SimFoMa uses a first come, first serve principle. The first Trader at a cell can buy all available timber for heating purposes. If forest fuel at a forest cell is left over, it is open to be purchased by another Trader.

### 4.5 Heating plant

Heating plants are static agents that represent real biomass heating plants. The heating plants under review in this paper are biomass heating plants, that use timber to generate energy for heating purposes. Each heating plant has a defined annual timber demand that measured in m³ wood chips. According to Arbeitsplattform Wald und Holz in Kärnten—Bilanz und Strategieplan über Aufkommen, Nutzen und Potentiale (2009) the annual demand in Carinthia is about 239,400 m³ wood chips, having an expected annual demand increase of 1.1%. We expect the annual demand increase to be stable for the next 10 years, and thereafter to gradually converge toward 0.

### 4.6 Simulation procedure

The agent-based simulation consists of procedures that are carried out at each simulation cycle. A simulation cycle in this context represents a single year. Generally, the simulation starts with an initialization of the agents and their environment, with the help of spatial and nonspatial
data. On the basis of the initialized objects the agent-based simulation is carried out for each year in a specific order—as depicted in Table 3.

The process starts with updating the forest cells using the Forest Growth Module, that results in the current age and growing stock of the forest under review (Step 1). Under specific scenarios—that is, market-oriented scenarios—Step 1A is carried out. This step comprises of the update on the timber price by the Market Module. Step 2 requires the Harvest Module, that defines the potentially available timber (i.e., timber marked for harvesting) at each forest cell. In addition, the Harvest Module is responsible to model the final harvest decisions of each forest owner agent. Please note, that the timber needs to be purchased by a Trader agent and delivered to the heating plant before it is used for heating purposes. Step 3 involves the creation of one Trader agent per Heating Plant agent. Subsequently, the Trader agents try to fulfill the timber demand of their associated Heating Plant. In addition, they try to minimize the transport distances of the biomass and parallel try to minimize the timber purchase price. The functionalities are implemented in the Trading Module. Finally, the results are written into specific output files for analysis purposes.

The simulation terminates if the timber demand by the Heating Plants cannot be fulfilled. This is the case, when less timber is marked for harvesting by the forest owners than timber demand by the heating plants.

5 | EXPERIMENT

The section elaborates on the test area and the relevant data necessary for conducting the simulation experiments. In addition, the parameters of simulation scenarios are discussed—alongside with a description of the scenarios itself.

5.1 | Test area: Province of Carinthia

The study was conducted in the province of Carinthia, Austria. This specific test area was chosen, due to the data availability for the purpose. In addition, 57.6% of the Carinthia’s area is covered by forests. During the last 20 years several biomass heating plants have been constructed which are still in operation. The Province of Carinthia has a forested area of 584,000 ha. The annual cut is approximately 3.6 mio m$^3$, with an annual yield of 5.2 mio m$^3$ (Austrian Research Center for Forests, 2016; Landesregierung, 2015). The Forest Association Carinthia reports that there is a timber demand in Carinthia of approximately 6 mio m$^3$ wood, from which only 6.2%—that is, 250,000 m$^3$ wood—are used for biomass heating plants (Arbeitsplattform Wald und Holz in Kärnten—Bilanz und Strategieplan über Aufkommen, Nutzen und Potentiale, 2009) (Figure 3).

5.2 | Base data

Data are the basis of the agent-based simulation. We utilize the following spatial and nonspatial data sets. We represent forest by a 30 m raster data set. We use data from the Austrian Research Centre for Forests (BFW) to describe the forest in the test area:
TABLE 3  Procedure of one simulation cycle—that is, 1 year—of the agent-based modeling

| Temporal sequence per year | Agent class or environment class | Contextual information | Module or method involved | Output |
|---------------------------|----------------------------------|------------------------|---------------------------|--------|
| 1                         | Forest                           |                        | Forest growth module      | Updated data on forest cells (age, growing stock) |
| 1A                        | Market                           |                        | Market module             | Updated timber prices |
| 2                         | Forest owner                     | • Market               | Harvest module            | Available timber for heating purposes per forest cell |
|                           |                                  | • Forest               |                           |                    |
|                           |                                  | • Forest owner         |                           |                    |
| 3                         | Heating plant                    |                        | Create_Trader() method    | Trader agents |
| 4                         | Trader                            | • Available timber at forest cells | Trading module | Collected timber at each cell for a specific heating plant |
|                           |                                  | • Road network         |                           |                    |

Note: The temporal sequence of the actions, as well as the involved agent and environment classes, their necessary contextual information and utilized module/method is given. In addition, the output of each simulation step is given in the rightmost column.
• Forest map: Defines cells with forest according to the Austrian forest act (Republic of Austria, 1975).
• Standing timber stock volume: Represents the standing timber stock in m$^3$/ha. The standing timber is described based on a 30 m raster from BFW—hence we have no information on forest stands.
• Forest type: Defines the forest type for each raster cell. Values in the rasters range from broad-leaved, broad-leaved dominated, coniferous dominated, coniferous, or no forest.

To represent the topography in the test area Carinthia we utilized a digital elevation model (DEM) with a resolution of 10 m, that got aggregated to 30 m resolution. The DEM was provided by the government of Carinthia.

The data on biomass heating plants were collected directly from the operating companies. We collected the position and the annual biomass demand of each heating plant. In total a demand of approximately 239,400 m$^3$.

According to the Austrian Forest act (Republic of Austria, 1975) the main function of each forest is defined and described in the Forest Development Plan (WEP). This spatial data set is available on the Austrian open data platform. To calculate travel distances between forests and heating plants we utilize a road network originating from the Graph Integration Platform Austria (GIP.at) (Österreichisches Institut für Verkehrsdateninfrastruktur [ÖVDAT], 2016a, 2016b). This data set is developed by governmental bodies in Austria and contains a nationwide seamless navigable road network for Austria.

SimFoMa, defined in Section 4, requires to know which forest cell belongs to which type of forest owner. As there is no spatial data set on the forest enterprises available in Austria, we created such a data set using a stochastic methodology. Based on the share of each forest enterprise type of the forested area in each county of Carinthia we randomly assigned 20 ha hexagonal patches to the forest owner types. So in each county the share of forest enterprise types is remains fixed, but the spatial allocation might be not accurate. This might result in
inaccuracies on a micro scale, but on a macro scale the structure of forest enterprise types and their spatial allocation remains intact (see Figure 4)—especially for the Province of Carinthia.

5.3 Simulation scenarios

The simulation of the forest fuel market in the Province of Carinthia, is done with respect to six different scenarios that are outlined below. Basically, there are two scenarios that focus on the optimal utilization of the resource timber, and four other scenarios that involve the market that influences the decisions of the Forest Owners.

The scenarios are as follows:

- 2 resource-oriented scenarios
  - Basic scenario
  - WEP scenario
- 4 market-oriented scenarios
  - Positive market development
  - Negative market development
  - Constant market development
  - Volatile market development

Each simulation scenario is described in detail in Sections 5.3.1 and 5.3.2. For each simulation scenario, a total of 10 simulation runs are calculated.

In all scenarios, we modeled an annual increase of the biomass demand. The annual increase is defined to be 1.1% (Arbeitsplattform Wald und Holz in Kärnten—Bilanz und Strategieplan über Aufkommen, Nutzen und Potentiale-, 2009), until simulation cycle # 30. From this time on the increase is gradually lowered toward a zero increase. In absolute numbers the annual demand starts at 237,000 m³ and reaches a maximum of 310,000 m³.

FIGURE 4 Modeled map of forest enterprise types in the Province of Carinthia—Hexagonal 20 ha patches were assigned to forest owner types
### Table 4: Simulation parameter of the resource-oriented scenarios—Basic scenario and WEP scenario

| **Harvesting module rules** |  
|-----------------------------|
| General resource-oriented rules (see Section 4.2) |
| + WEP harvesting limitations for WEP scenario |

| **Data** | 
|----------------|
| Standing timber stock |
| Biomass heating plants |
| Forest owners |

| **Simulation parameter** | **Value** |
|-------------------------|---------|
| Share of timber for heating purposes (%) | 6.2 |
| Annual increase of biomass demand (%) | 1.1 |
| Imported biomass (%) | 37 |
| Thinning operations intensity (% of standing timber that is harvested) | 19.6 |

| **Timber harvesting selection criteria** | 
|-------------------------------|
| Time between harvesting operations (year) | 5–10 |
| Harvesting loss (%) | 
| Coniferous trees | 5–10 |
| Broadleaved trees | 10–15 |

| **Minimum harvesting age (year)** | 
|-----------------------------|
| Coniferous trees | 20 |
| Broadleaved trees | 30 |

| **Maximum harvesting age** | 
|-------------------------|
| Coniferous trees | Final cut |
| Broadleaved trees | 80–120 |

| **5.3.1 | Resource-oriented scenarios** |

In both resource-oriented scenarios—basic and WEP scenario—we assume one single harvesting behavior, for all Forest Owner agents. Hence, these scenarios should evaluate the general availability of biomass for heating purposes in Carinthia’s forests, similar to Scholz et al. (2014).

The WEP scenario considers the limitations in terms of harvesting induced by the Austrian Forest Development Plan (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft [BMLFUW—Lebensministerium], 2006; Republic of Austria, 1975). In this plan, each forested area is categorized according to the four main functions of a forest (see Section 4.1.1). Hence, forests with economic function are intended for intensive forest management, whereas all other forests with the remaining functions shall be used in an extensive manner. This is reflected in an extended period between two harvesting or thinning operations, which lasts between 5 and 10 years compared with the values of economic forest (see Table 2). The parameters are given in Table 4. In this table, parameters having a value range are determined by the random principle but have to be within the given value range.
Market-oriented scenarios

All four market-oriented scenarios are based on the specific behavior of the forest owner agents (small forest owners, large forest owners, forest enterprises, federal forest enterprise). The agents react to market conditions, in particular the timber price, and their own behavior (in combination with certain stochastic parameters). The simulation parameters are listed in Table 5—where the ones with stochastic nature are given as value ranges.

For the market-oriented scenarios we define four different scenarios according to Bone and Dragićević (2009). We define the following price and market developments:

- **Positive market**: Is based on an extrapolation of the timber market 1994–2016.
- **Negative market**: The market/price development is calculated as an inverted positive market situation.
- **Stable market**: In the stable market situation the timber prices are modeled to change at a small rate—±1%.
- **Volatile market**: This market situation is characterized by timber price changes by ±10% annually. The timber price is modeled with a stochastic function, but the annual change needs to be within the range of ±10%.

### 5.3.2 Market-oriented scenarios

This section presents the relevant results of the simulation scenarios, defined in Section 5.3. The results analyze the transport distances (average and maximum), available timber stock, and harvest patterns. Each result documented in this section represents the average of 10 simulation runs.

| **TABLE 5** Simulation parameter of harvest module for the market-oriented scenarios |
| --- |
| **Harvesting module rules** |
| Adaptive behavior (see Section 4.2) |
| **Data** |
| Standing timber stock |
| Biomass heating plants |
| Cost raster layers from each heating plant to forest cell |
| Forest owners |
| Timber prices per simulation cycle and scenario |
| **Simulation parameter** | **Value** |
| Share of timber for heating purposes (%) | 6.2 |
| Annual increase of biomass demand (%) | 1.1 |
| Imported biomass (%) | 37 |
| Thinning operations intensity (% of standing timber that is harvested) | 19.6 |
| Harvesting loss [%] | |
| Coniferous trees | 5–10 |
| Broadleaved trees | 10–15 |
| **Timber selection criteria** |
| Small forest owner, large forest owner, forest enterprise, federal forest enterprise | see Subsection 4.2 |
runs per scenario—except for the stop criterion. The reported iteration numbers of the simulation stops are the highest number of running iterations of the 10 simulation runs for each scenario.

6.1 Base scenario

The base scenario is strongly related to the approach of Scholz et al. (2014). Again, all forest owner types share the same behavior. Hence, this scenario is regarded to evaluate the biomass supply potential present in the Province of Carinthia.

The simulation stops after 36 simulation cycles (i.e., years), due to the fact that the harvested timber volume does not meet the demand of the heating plants. In Figure 5 we depict the wood stock and the average transport distances for all heating plants in the test area over the simulation runs. The average transport distances (of all transport processes) increase over time (see Figure 5). Table A1 lists the average timber transport distances over 10 simulation runs per year averaged for

![FIGURE 5 Base scenario: Average transport distances of each heating plant for each simulation year/cycle. The black dash-dotted line represents the total wood stock in m³ and the blue dash-dotted line represents the wood stock available for harvesting/thinning operations](image-url)
all heating plants. The table also shows the maximum timber transport distance of the 10 simulation runs for each heating plant per simulation year. The average transport distances start at a value of 11.9 km and reach a level of 41.5 km at simulation cycle 36. The mean average transport distances over all years has a value of 17.92 km ± 6.87, whereas the mean maximum distance over all simulation years is 34.56 km ± 11.36. The average and maximum transportation distances show a statistically significant positive correlation $\rho_{\text{avg}} = 0.74$ and $\rho_{\text{max}} = 0.78$ with the simulation year (with $p_{\text{avg}} = 0.00000002$ and $p_{\text{max}} = 0.00000003$). Hence, in this simulation scenario the transport distances increase with an increasing simulation year. This is also visible in the available wood stock amount in simulation year 36. There the non-harvestable cells dominate the map, which requires timber to be transported over longer distances to arrive at the heating plants.

The harvest patterns for each heating plant underpins the argument of increasing transport distances, that the harvest patterns are concentrated around the heating plants at the beginning of the simulation. In later stages of the simulation, the harvested cells are spatially dispersed. Where several heating plants compete for the available timber, the harvest pattern is spatially dispersed—even in the beginning (see e.g., heating plants Villach, Treffen, Weissenstein in Figure A2).

6.2 | WEP scenario

The WEP scenario is similar to the base scenario, but amended by the restrictions induced by the Austrian Forest Development Plan (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft [BMLFUW—Lebensministerium], 2006; Republic of Austria, 1975). Hence, the owners share a similar behavior, regarding forest operations, and less timber is potentially available. Thus, the termination criterion of the simulation is reached earlier compared with the base scenario—at year 33. The average transport distances are higher compared to the base scenario. Wood stock reveals that non-harvestable cells are visually dominant, even at simulation cycle 33.

In Appendix B, we depict the wood stock and the average transport distances for all heating plants in the test area over the simulation runs. The average transport distances (of all transport processes) increase over time (see Figure B1). Table B1 lists the average timber transport distances over 10 simulation runs per year averaged for all heating plants. The table also shows the maximum timber transport distance of the 10 simulation runs for each heating plant per simulation year. The average transport distances start at a value of 14.2 km and reach a maximum of 47.6 km at simulation cycle 32. The mean average transport distances over all years has a value of 17.56 km ± 7.12, whereas the mean maximum distance over all simulation years is 33.64 km ± 12.55. The average and maximum transportation distances show a statistically significant positive correlation $\rho_{\text{avg}} = 0.73$ and $\rho_{\text{max}} = 0.71$ with the simulation year (with $p_{\text{avg}} = 0.000001$ and $p_{\text{max}} = 0.000003$). Hence, in this simulation scenario the transport distances increase with an increasing simulation year. This is also visible in the available wood stock amount in simulation year 33. There the non-harvestable cells dominate the map, which requires timber to be transported over longer distances to arrive at the heating plants (see Figure B2).

6.3 | Positive market scenario

The market-oriented scenarios are the advanced simulation scenarios described in this paper. As described in Sections 4 and 5 each agent shows a different behavior, based in the market situation.
In addition, the limitations induced by the Austrian Forest Development Act are applied to this scenario. This scenario comprises of 21 simulation cycles until the stop criterion is met. As the behavior of agents is depending on the price level, Figure 6 shows the higher transport distances, timber prices, price expectations, wood stock and available timber in the forest. Visually, increasing timber prices in comparison to the price expectations lead to decreasing timber transport distances. Table C1 lists the average timber transport distances over 10 simulation runs per year averaged for all heating plants. The table also shows the maximum timber transport distance of the 10 simulation runs for each heating plant per simulation year. The average transport distances start at a value of 8.1 km and reach a maximum of 26.3 km at simulation cycle 15. The mean average transport distances over all years has a value of 17.94 km ± 5.82, whereas the mean maximum distance over all simulation years is 35.41 km ± 9.8. The average and maximum transportation distances do not show a statistically significant correlation with the simulation year. In Figure C2 shows the harvesting pattern, with harvested cells evenly dispersed over the test area. The timber stock (see Figure C1) shows that there is enough timber available in the forest, but it seems that some forest owners seem to decide not to harvest at all. This can be justified by the timber production of the small forest owners which is depicted in Figure 7. The figure shows the timber

**FIGURE 6** Positive market scenario: Average transport distances of each heating plant for each simulation year/cycle. The black dash-dotted line represents the total wood stock in m³ and the blue dash-dotted line represents the wood stock available for harvesting/thinning operations.
price, the price expectations and the produced timber by each forest owner category. Apparently, the small forest owners respond to timber prices above their price expectations by an increase of timber production. Contrary, they decrease their timber production if the timber price decreases. The correlation coefficient between produced timber volume of small forest owners and timber price—abbreviated as $\rho_{\text{prod}−\text{price}}$ and the correlation coefficient between the timber price and difference between timber price and price expectation—abbreviated as $\rho_{\text{prod}−(\text{price−expect})}$—justifies the visual analysis. The $\rho_{\text{prod}−\text{price}}$ has a value of 0.57 with a $p = .0064$. The $\rho_{\text{prod}−(\text{price−expect})}$ has a value of 0.56 with a $p = 0.0084$. Hence, the correlations between (a) price and timber production of small forest owners as well as (b) the difference between price and price expectation and timber production of small forest owners are statistically significant.

6.4 | Negative market scenario

The negative market scenario simulates the effect of decreasing timber prices on the forest fuels market. Due to the fact that forest owner agents react to timber prices—especially if the price situation does not meet the expectations—not enough timber is harvested to fulfill the demand.

**FIGURE 7** Price expectations and harvest volumes of the positive market scenario. The dashed blue line shows the timber price, the blue fine-dotted line the price expectations and the solid lines the timber production of each forest owner type for each simulation year.
Hence, after eight simulation steps the stop criterion is met. The shortage of offered biomass for heating purposes is depicted in Figure 8 showing the average transport distances for each heating plant, alongside the timber price, price expectation, wood stock in the forest, and available wood in the forest. Table D1 lists the average timber transport distances over 10 simulation runs per year averaged for all heating plants are. This table also shows the maximum timber transport distance of the 10 simulation runs for each heating plant per simulation year. The average transport distances start at a value of 7.97 km and reach a maximum of 28.4 km at simulation cycle 8. The mean average transport distances over all years has a value of 18.54 km ±6.08, whereas the mean maximum distance over all simulation years is 36.13 km ±10.88. The average and maximum transportation distances do not show a linear correlation with the simulation year.

The timber stock (see Figure D1) shows that there is enough timber available in the forest, but it seems that some forest owners seem to decide not to harvest at all. This can be justified by the timber production of the small forest owners which is depicted in Figure 9. The figure shows the timber price, the price expectations and the produced timber by each forest owner category. Apparently, the small forest owners respond to timber prices above their price expectations by an increase of timber production. Contrary, they decrease their timber production if the timber price decreases. The correlation coefficient between produced timber volume of small forest owners and timber price—abbreviated as $\rho_{\text{prod-price}}$ and the correlation coefficient between the timber price and difference between timber price and price expectation—abbreviated as $\rho_{\text{prod-(price-expect)}}$ shows mixed results. The $\rho_{\text{prod-price}}$ has a value of 0.46 with a $p = .255$ and shows a weak linear correlation, which is not significant. The $\rho_{\text{prod-(price-expect)}}$ has a value of 0.67 with a $p = .0674$. Hence, the correlation coefficients here are hint that there is a correlation between the difference of price & price expectation and timber production of small forest owners which is no statistically significant. Here, one has to be aware that we have only 8 simulation years as data basis. Nevertheless, from Figure 9 it becomes visually obvious that there might be a connection between timber price (and the difference between timber price and price expectation) and the produced timber volume of small forest owners.

### 6.5 Stable market scenario

The stable market scenario simulation results in a quite stable average and maximum transport distance in comparison to the other scenarios, due to the non-volatile character of the timber market (see Figure E1). Nevertheless, the simulation stop criterion is met after 20 simulation cycles, although the wood stock reveals that timber is still available.

Table E1 lists the average timber transport distances over 10 simulation runs per year averaged for all heating plants. The table also shows the maximum timber transport distance of the 10 simulation runs for each heating plant per simulation year. The mean average transport distances over all years has a value of 16.34 km ±3.95, whereas the mean maximum distance over all simulation years is 32.97 km ±6.78. The average and maximum transportation distances do not show a linear correlation with the simulation year. The mean average transport distance is concentrated around the mean value, which is justified by the low standard deviation of only ±3.95.

The timber stock (see Figure E2) shows that there is enough timber available in the forest, but it seems that some forest owners seem to decide not to harvest at all. This can be justified by the timber production of the small forest owners. The correlation coefficient between produced
FIGURE 8  Negative market scenario: average transport distances of each heating plant for each simulation year/cycle. The black dash-dotted line represents the total wood stock in m$^3$ and the blue dash-dotted line represents the wood stock available for harvesting/thinning operations.
timber volume of small forest owners and timber price—abbreviated as $\rho_{\text{prod-price}}$ and the correlation coefficient between the timber price and difference between timber price and price expectation—abbreviated as $\rho_{\text{prod-(price-expect)}}$ shows mixed results. The $\rho_{\text{prod-price}}$ has a value of 0.67 with a $p = .0011$ and shows a linear correlation, which is significant. The $\rho_{\text{prod-(price-expect)}}$ has a value of 0.27 with a $p = .25$ (weak linear correlation and not significant). Hence, the correlation coefficients here are hint that there is a correlation between the price and timber production of small forest owners which is statistically significant. This is also justified by the Figure E3, where the harvest patterns of the simulation cycles 1–3 and cycles 19–21 show that the harvested cells are centered around each respective heating plant.

6.6 | Volatile market scenario

The volatile market scenario simulation results in a quite unstable maximum transport distance, which can be justified by the volatile character of the timber market (see Figure F1).
Nevertheless, the simulation stop criterion is met after 20 simulation cycles, although the wood stock reveals that timber for heating purposes is still available in the forests.

Table F1 lists the average timber transport distances over 10 simulation runs per year averaged for all heating plants. The table also shows the maximum timber transport distance of the 10 simulation runs for each heating plant per simulation year. The mean average transport distances over all years has a value of 19.77 km ±7.5, whereas the mean maximum distance over all simulation years is 37.95 km ±11.53. The average and maximum transportation distances do not show a linear correlation with the simulation year.

The timber stock (see Figure F2) shows that there is enough timber available in the forest, but it seems that some forest owners seem to decide not to harvest enough. The correlation coefficient between produced timber volume of small forest owners and timber price—abbreviated as $\rho_{\text{prod-price}}$ and the correlation coefficient between the timber price and difference between timber price and price expectation—abbreviated as $\rho_{\text{prod-(price-expect)}}$ show no significant linear correlation at all. The harvest patterns of the simulation cycles 1–3 and cycles 19–21 show harvested was concentrated around each respective heating plant (see Figure F3). This is not true for the heating plants Klagenfurt and Villach. Those two heating plants are the ones with the highest annual biomass demand and compete for the available biomass.

7  Validation

According to Macal (2005) model validation and verification is an essential part of any ABM. Any validation process shall evaluate the accuracy of the simulation in comparison to real-world data (Crooks & Heppenstall, 2012; Ngo & See, 2012). In addition, Zeigler et al. (2000) denote this as replicative validity.

In this particular case, real-world data on biomass heating plants and the forest fuel supply chain is still scarce, as construction and operation of such heating plants started approximately two decades ago. Hence, only a limited amount of accumulated data is available (Österreichischer Biomasse-Verband, 2017). A fruitful data source for validation purposes is the Austrian forest inventory (ÖWI) (Austrian Research Center for Forests, 2016), that evaluates several parameters of Austria’s forest. The in-situ data collection of ÖWI is carried out every 10 years and detailed statistics are published thereafter by the Austrian Research Centre for Forests (BFW).

7.1  Validation of the resource-oriented scenarios

As SimFoMa is based on an extrapolation of the market situation of the last 40 years, it is possible to match the results of the simulation to the observed data of the ÖWI. We use the simulation results of the harvested timber and compare them with the quantity listed in the ÖWI in the same time period. The validation of the resource-oriented simulation scenarios is primarily done via a comparison of the harvested timber volume—as each forest owner acts in a similar way. Our model results in 2.756 mio m³ harvested timber in comparison with the ÖWI value of 2.867 mio m³ (ÖWI 2007–2009). This equals to a relative difference of 4.1% of total harvested timber. Thus, our (simple) harvesting model/module seems appropriate for the purpose.
To validate the market-oriented scenarios, we cannot compare absolute harvested timber values, due to a difference in the absolute timber quantities. Hence, we compare relative timber harvesting values from the simulation and ÖWI. In particular we compare the simulation results with the timeslots of ÖWI: 1994–1996, 2000–2002, and 2007–2009 (see Figure 10). The differences of the relative harvesting volumes for each forest owner type over the given ÖWI periods result in an average error of ±1.8%. A detailed evaluation is depicted in Figure 11. The biggest deviations are to be found in the category of small forest owners (ÖWI period 1994–1996) with a value −3.9% and in the forest companies category (ÖWI period 2000–2002) with a value of −4.1%. As the ÖWI—which is a sampling method—has an error of ±3.9% the differences between our agent-based simulation in this paper and the ÖWI seem tolerable.

The maximum deviation comes from small land owners (−3.9%) for the ÖWI period 1994–1996, small forest enterprises (−4.1%) for the ÖWI period 2000–2002, large forest enterprises (+3.6%) for the ÖWI period 2000–2002 and small forest enterprises (+2.4%) for the the ÖWI period 2007–2009.
This can be explained by the fact that in the test area—Province of Carinthia—the forested land is owned by the following forest owner categories (Austrian Research Center for Forests, 2016):

- Small forest owners (<200 ha): 73%
- Small forest enterprises (200–1,000 ha): 10.4%
- Large forest enterprises (>1,000 ha): 14.3%
- Austrian federal forests: 2.3%

Hence, it becomes obvious that the deviation of small land owners is partly to the large share of forested area in the test area. Besides there are a number of studies that deal with the situation and motivations of small private forest owners (e.g., Rizzo et al., 2019). Private owners have different objectives for and how to manage their forests (Kendra & Hull, 2005; Lidestav & Nordfjell, 2005; Majumdar, Teeter, & Butler, 2008). Butler and Leatherberry (2004) and Finley and Kittredge (2006)—among others—conclude that private forest owners are not interested in production and sale of timber. This can be justified by the owner’s main occupation and the relatively low income from timber sales. Additionally, the current forest owners live far away from the forest quite often (Canton & Pettenella, 2010; Schmithüsen & Hirsch, 2010). Sekot (2017) concludes that there is a category of “new forest owners,” that are characterized by their heterogeneity, various basic condition, needs and goals. These forest owners are no farmers and mostly have an urban background. Rizzo et al. (2019, p. 16) state that there exists a “strong link of small forest owners with their forests thanks to sentimental reasons and the use of firewood for family use and, secondly, of timber for self-consumption.”
8 | CONCLUSION AND DISCUSSION

The paper shows an approach to model and simulate the forest fuel market for the Province of Carinthia. The research work uses a spatial ABM for modeling and simulation purposes. Based on a rich set of spatial data on forests, forest owners, road network and heating plants in Carinthia we created the simulation environment and developed six simulation scenarios. In addition, we analyzed the forest fuel supply chain and extracted the stakeholders thereof. These stakeholders—that is, forest enterprises (having different sizes), heating plants and traders—were modeled as agents in the ABM approach in this paper—called SimFoMa. Each agent has a certain behavior and is capable of adapting the behavior according to the overall market situation (i.e., timber price levels). Concerning the harvest behavior of the forest enterprise agents, we had to make assumptions that are explained and justified in detail in the paper. The validation of the data shows that the results seem feasible and could reveal an overall future pattern/trend for the forest fuel supply chain.

In all scenarios of SimFoMa experiments the simulation was stopped after a certain number of cycles because of the fact that not enough forest fuel was available in Carinthia for all heating plants. That means that SimFoMa shows that during the next one to three decades the burning material for the existing heating plants may need to be imported from other countries or the style of supplying the existing plants have to be changed. That also means that building new heating plants in Carinthia makes only sense, if it will be accompanied by stimulation measures for the sustainable supply with regional burning material. Such measures can be the change in the timber harvesting behavior of farmers, in a way that they provide a more steady supply of forest biomass for heating purposes.

The methodology to georeference the forest enterprise types, tries to minimize bias. We randomly assign 20 ha hexagonal patches to forest enterprise types in each county—with respect to the share of the forest enterprise types in each county. This results in a spatial distribution that accurately represents reality on a macro scale. Nevertheless, there might be issues that are worth mentioning:

- On a micro scale, the representation might not be perfectly accurate.
- Clustering of small forest owners, due to the fact that we assign forest owner types to 20 ha patches of forest.

We know that this is just an approach to model the reality accordingly. Due to lack of real-world spatial data on forest owner types, we had to rely on the modeling approach that integrates several information layers.

The simulation results show that for both resource-oriented scenarios there is a positive, statistically significant correlation between transport distances and simulation year. This leads to the assumption that these scenarios utilize the available timber quite well, especially geographically around the biomass heating plants. Hence, the traders try to utilize the resources close to the heating plant immediately. Nevertheless, an maximum average transport distance of 41.5 and 47.6 km from forest to heating plants needs to be critically reviewed in terms of greenhouse gas emissions. The market-oriented scenarios show that the market situation (i.e., timber price and price expectations) may have an influence on the available timber. Especially, for the small forest owners the simulation results revealed that there is a correlation between price and produced timber quantity (significant), and that there is a correlation between the value of the difference of price...
and price expectation and the produced timber quantity. For the Province of Carinthia, where 73% of the forested area is owned by small forest owners, the motivation of the small forest owners is crucial to guarantee a steady timber production—which is discussed in Section 7.2 and in (e.g., Rizzo et al., 2019). The correlation proved to be statistically significant only for the positive market scenario, and is close to significant in the negative market scenario. These results may be because the negative market scenario has only eight successful simulation years.

Currently stochasticity beyond harvest time or harvest probability is not included. In future versions of the SimFoMa model one could include volatile forest management costs—as this could influence the decisions of forest owners as well. As this study is the result of a project with limited resources, we intentionally did not include this feature. In general, the functionality of having volatile forest management costs included in the ABM could be integrated. Therefore the forest management costs/ha need to be defined bound to a certain index (similar to the timber price). Higher costs would certainly be a driver to utilize the resources of the forest more intensively.

SimFoMa and future versions of the model can support such planning actions by extending its functionality and simulating further scenarios. Such extensions can be the consideration of foreign timber markets and offers as well as the demand of the paper and saw log industry. Further classes of agents can be introduced like forest owner cooperatives or new kinds of forest management activities.

A very important and highly topical extension would be the consideration of forest damages caused by natural hazards (e.g., wind, snow) or game animals. A transformation of the growing behavior of the trees caused by climate change could also be integrated in the SimFoMa functionality. The model could be also used for doing data science tasks like the prediction of the effects of new technologies for heating facilities or the prediction of people’s behavior as a reaction of new energy policies. The prescription for or the optimization of the supply of burning material for the heating plants and the minimization of the cost of the wood chips would be also interesting. Last but not least SimFoMa could be coupled with other simulation models of energy supply like water, wind and solar power, when the heating plants are also used for electricity production. The integration of models for the simulation of geothermal or hydrothermal or ambient thermal heat production or storage into a multimodal system could also be done during the next years.

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AUTHOR CONTRIBUTIONS
J. S. contributed the idea and the general methodology of the paper. The detailed methodology was developed collaboratively by F. B. and J. S., assisted by P. M. The manuscript and the revision was mainly written by J. S., with contributions from F. B. (experiment and results) and P. M. (conclusion and discussion). F. B.: Implemented the ABM approach and did all experiments and validation. Developed the figures and results. Contributed the sections: results and experiment. P. M.: Contributed to the discussion and review section and contributed to the validation and critically reviewed the manuscript.
ENDNOTES
1https://www.data.gv.at/katalog/dataset/d88a1246-9684-480b-a480-ff63286b35b7
2https://www.data.gv.at/katalog/dataset/66b52ac2-de69-44b3-a2f8-344acee36ebc
3https://www.data.gv.at/katalog/dataset/3febc838-791d-4dfe-975b-a4131a54e7c5

ORCID
Johannes Scholz http://orcid.org/0000-0002-3212-8864

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APPENDIX A: ADDITIONAL RESULTS OF THE BASE SCENARIO

| Simulation year | Maximum transport distance | Average transport distance |
|-----------------|----------------------------|----------------------------|
| 1               | 23.87                      | 11.92                      |
| 2               | 31.62                      | 16.36                      |
| 3               | 27.86                      | 14.02                      |
| 4               | 26.88                      | 13.46                      |
| 5               | 27.85                      | 14.10                      |
| 6               | 26.54                      | 13.13                      |
| 7               | 24.93                      | 12.38                      |
| 8               | 24.14                      | 12.10                      |
| 9               | 22.30                      | 11.14                      |
| 10              | 23.21                      | 11.92                      |
| 11              | 37.39                      | 20.24                      |
| 12              | 29.69                      | 15.47                      |
| 13              | 27.40                      | 14.26                      |
| 14              | 30.74                      | 16.11                      |
| 15              | 24.20                      | 12.00                      |
| 16              | 25.06                      | 12.65                      |
| 17              | 24.84                      | 12.64                      |
| 18              | 29.51                      | 15.35                      |
| 19              | 29.83                      | 15.47                      |
| 20              | 31.36                      | 16.30                      |
| 21              | 47.03                      | 23.35                      |
| 22              | 31.38                      | 16.52                      |
| 23              | 27.01                      | 14.29                      |
| 24              | 29.75                      | 15.53                      |
| 25              | 28.34                      | 14.48                      |
| 26              | 36.85                      | 17.50                      |
| 27              | 34.52                      | 16.53                      |
| 28              | 39.20                      | 17.85                      |
| 29              | 45.97                      | 22.86                      |
| Simulation year | Maximum transport distance | Average transport distance |
|-----------------|----------------------------|---------------------------|
| 30              | 48.23                      | 25.45                     |
| 31              | 43.15                      | 20.72                     |
| 32              | 48.82                      | 25.33                     |
| 33              | 53.11                      | 28.33                     |
| 34              | 67.39                      | 36.81                     |
| 35              | 52.76                      | 26.97                     |
| 36              | 61.40                      | 41.47                     |

**FIGURE A1** The wood stock amount in m³ for the base scenario is depicted in this figure. The colors indicate the wood stock, whereas yellow is below 100 m³, and dark green is a volume higher than 500 m³. Red cells indicate cells that are not harvestable cells, due to the harvest restrictions (age, or last forest operation has been carried out in the last 10 years). At Year 36 the non-harvestable cells dominate the map, which is depicted with red colorized cells.
FIGURE A2  The harvest patterns for each heating plant for three distinct time periods (Years 1–3, Years 18–21, Years 34–36) are depicted here. The maps show the harvested cells colored with the corresponding heating plant. Visually, you can see that the harvest patterns are concentrated around the heating plants at the beginning of the simulation. In later stages of the simulation, the harvested cells are spatially dispersed.
## APPENDIX B: ADDITIONAL RESULTS OF THE WEP SCENARIO

**Table B1** The maximum transport distances from forest to heating plant of the 10 simulation runs (averaged over all heating plants), and the average transport distances over 10 simulation runs (averaged over all heating plants)

| Simulation year | Maximum transport distance | Average transport distance |
|-----------------|---------------------------|----------------------------|
| 1               | 28.30                     | 14.25                      |
| 2               | 30.97                     | 15.69                      |
| 3               | 27.43                     | 13.93                      |
| 4               | 27.07                     | 13.93                      |
| 5               | 26.40                     | 13.25                      |
| 6               | 27.48                     | 13.88                      |
| 7               | 25.25                     | 12.77                      |
| 8               | 21.99                     | 11.22                      |
| 9               | 22.09                     | 11.14                      |
| 10              | 20.78                     | 10.34                      |
| 11              | 29.27                     | 15.39                      |
| 12              | 28.52                     | 14.90                      |
| 13              | 26.65                     | 13.79                      |
| 14              | 27.75                     | 14.74                      |
| 15              | 27.88                     | 14.85                      |
| 16              | 25.36                     | 13.15                      |
| 17              | 24.44                     | 12.78                      |
| 18              | 26.06                     | 13.69                      |
| 19              | 29.13                     | 15.06                      |
| 20              | 30.19                     | 16.46                      |
| 21              | 29.06                     | 15.59                      |
| 22              | 31.47                     | 16.77                      |
| 23              | 32.75                     | 17.60                      |
| 24              | 36.58                     | 19.74                      |
| 25              | 33.60                     | 18.38                      |
| 26              | 34.99                     | 17.38                      |
| 27              | 39.14                     | 19.67                      |
| 28              | 43.04                     | 21.74                      |
| 29              | 51.32                     | 26.11                      |
| 30              | 52.65                     | 26.17                      |
| 31              | 59.89                     | 30.61                      |
| 32              | 81.07                     | 47.56                      |
| 33              | 51.39                     | 27.04                      |
**FIGURE B1** WEP scenario: Average transport distances of each heating plant for each simulation year/cycle. The black dash-dotted line represents the total wood stock in m$^3$ and the blue dash-dotted line represents the wood stock available for harvesting/thinning operations.
The wood stock amount in m³ for the WEP scenario is depicted in this figure. The colors indicate the wood stock, whereas yellow is below 100 m³, and dark green is a volume higher than 500 m³. Red cells indicate cells that are not harvestable cells, due to the harvest restrictions (age, or last forest operation has been carried out in the last 10 years). At Year 33 the non-harvestable cells dominate the map, which is depicted with red colorized cells.
The harvest patterns for each heating plant for three distinct time periods (Years 1–3, Years 18–21, Years 31–33) for the WEP scenario are depicted here. The maps show the harvested cells colored with the corresponding heating plant. Visually, you can see that the harvest patterns are concentrated around the heating plants at the beginning of the simulation. In later stages of the simulation, the harvested cells are spatially dispersed.
APPENDIX C: ADDITIONAL RESULTS OF THE POSITIVE MARKET SCENARIO

**TABLE C1** The maximum transport distances from forest to heating plant of the 10 simulation runs (averaged over all heating plants), and the average transport distances over 10 simulation runs (averaged over all heating plants)

| Simulation year | Maximum transport distance | Average transport distance |
|-----------------|----------------------------|---------------------------|
| 1               | 17.99345784                | 8.100853044               |
| 2               | 27.26352952                | 14.13340113               |
| 3               | 38.71688981                | 20.05721386               |
| 4               | 30.40020552                | 15.02688873               |
| 5               | 32.95736309                | 16.56437612               |
| 6               | 35.20072382                | 17.12938083               |
| 7               | 56.5450802                 | 31.60360402               |
| 8               | 46.91727852                | 24.35956945               |
| 9               | 47.10325064                | 24.21655349               |
| 10              | 31.15177013                | 15.69015688               |
| 11              | 38.57037053                | 19.37065948               |
| 12              | 33.2571437                 | 16.62169314               |
| 13              | 24.6341495                 | 11.36499778               |
| 14              | 30.40016687                | 14.66267119               |
| 15              | 48.53036914                | 26.3437243                |
| 16              | 49.04903984                | 25.73814543               |
| 17              | 26.67062115                | 12.6774792                |
| 18              | 26.81637744                | 12.38420277               |
| 19              | 27.17321615                | 13.0296158                |
| 20              | 28.99592083                | 14.3859885                |
| 21              | 45.20633117                | 23.30854479               |
FIGURE C1 The wood stock amount in m³ for the positive market scenario is depicted in this figure. The colors indicate the wood stock, whereas yellow is below 100 m³, and dark green is a volume higher than 500 m³. Red cells indicate cells that are not harvestable cells, due to the harvest restrictions (age, or last forest operation has been carried out in the last 10 years). At Year 33 the non-harvestable cells dominate the map, which is depicted with red colorized cells.
FIGURE C2  The harvest patterns for each heating plant for three distinct time periods (Years 1–3, Years 10–12, Years 19–21) for the positive market scenario are depicted here. The maps show the harvested cells colored with the corresponding heating plant. Visually, you can see that the harvest patterns are concentrated around the heating plants at the beginning of the simulation. In later stages of the simulation, the harvested cells are spatially dispersed.
APPENDIX D: ADDITIONAL RESULTS OF THE NEGATIVE MARKET SCENARIO

**TABLE D1** The maximum transport distances from forest to heating plant of the 10 simulation runs (averaged over all heating plants), and the average transport distances over 10 simulation runs (averaged over all heating plants)

| Simulation year | Maximum transport distance | Average transport distance |
|-----------------|----------------------------|---------------------------|
| 1               | 17.19                      | 7.97                      |
| 2               | 26.53                      | 13.69                     |
| 3               | 30.78                      | 15.23                     |
| 4               | 33.33                      | 16.61                     |
| 5               | 38.65                      | 19.87                     |
| 6               | 44.61                      | 24.09                     |
| 7               | 43.97                      | 22.47                     |
| 8               | 53.99                      | 28.41                     |
FIGURE D1  The wood stock amount in m³ for the negative market scenario is depicted in this figure. The colors indicate the wood stock, whereas yellow is below 100 m³, and dark green is a volume higher than 500 m³. Red cells indicate cells that are not harvestable cells, due to the harvest restrictions (age, or last forest operation has been carried out in the last 10 years). At Year 33 the non-harvestable cells dominate the map, which is depicted with red colorized cells.
The harvest patterns for each heating plant for three distinct time periods (Years 1–3, Years 10–12, Years 19–21) for the negative market scenario are depicted here. The maps show the harvested cells colored with the corresponding heating plant. Visually, you can see that the harvest patterns are concentrated around the heating plants at the beginning of the simulation. In later stages of the simulation, the harvested cells are spatially dispersed.
APPENDIX E: ADDITIONAL RESULTS OF THE STABLE MARKET SCENARIO

**TABLE E1**  The maximum transport distances from forest to heating plant of the 10 simulation runs (averaged over all heating plants), and the average transport distances over 10 simulation runs (averaged over all heating plants)

| Simulation year | Maximum transport distance | Average transport distance |
|-----------------|----------------------------|---------------------------|
| 1               | 17.14                      | 7.92                      |
| 2               | 28.42                      | 14.32                     |
| 3               | 38.10                      | 19.56                     |
| 4               | 37.16                      | 19.18                     |
| 5               | 37.18                      | 18.92                     |
| 6               | 30.78                      | 14.41                     |
| 7               | 29.39                      | 13.58                     |
| 8               | 30.63                      | 14.27                     |
| 9               | 30.99                      | 15.10                     |
| 10              | 37.44                      | 19.98                     |
| 11              | 49.34                      | 25.77                     |
| 12              | 45.43                      | 23.50                     |
| 13              | 37.16                      | 18.88                     |
| 14              | 25.48                      | 12.19                     |
| 15              | 28.23                      | 13.11                     |
| 16              | 30.29                      | 14.58                     |
| 17              | 31.53                      | 15.05                     |
| 18              | 33.31                      | 16.24                     |
| 19              | 30.26                      | 14.84                     |
| 20              | 31.15                      | 15.38                     |
**FIGURE E1** Stable market scenario: average transport distances of each heating plant for each simulation year/cycle. The black dash-dotted line represents the total wood stock in m³ and the blue dash-dotted line represents the wood stock available for harvesting/thinning operations.
FIGURE E2  The wood stock amount in m$^3$ for the stable market scenario is depicted in this figure. The colors indicate the wood stock, whereas yellow is below 100 m$^3$, and dark green is a volume higher than 500 m$^3$. Red cells indicate cells that are not harvestable cells, due to the harvest restrictions (age, or last forest operation has been carried out in the last 10 years). At Year 33 the non-harvestable cells dominate the map, which is depicted with red colorized cells.
FIGURE E3  The harvest patterns for each heating plant for three distinct time periods (Years 1–3, Years 10–12, Years 19–21) for the stable market scenario are depicted here. The maps show the harvested cells colored with the corresponding heating plant. Visually, you can see that the harvest patterns are concentrated around the heating plants at the beginning of the simulation. In later stages of the simulation, the harvested cells are spatially dispersed.
## APPENDIX F: ADDITIONAL RESULTS OF THE VOLATILE MARKET SCENARIO

**TABLE F1** The maximum transport distances from forest to heating plant of the 10 simulation runs (averaged over all heating plants), and the average transport distances over 10 simulation runs (averaged over all heating plants)

| Simulation year | Maximum transport distance | Average transport distance |
|-----------------|----------------------------|----------------------------|
| 1               | 17.30                      | 8.07                       |
| 2               | 26.26                      | 13.92                      |
| 3               | 39.61                      | 20.68                      |
| 4               | 31.72                      | 15.71                      |
| 5               | 42.65                      | 22.37                      |
| 6               | 62.20                      | 35.80                      |
| 7               | 25.68                      | 11.87                      |
| 8               | 38.50                      | 19.54                      |
| 9               | 28.59                      | 13.47                      |
| 10              | 40.71                      | 20.87                      |
| 11              | 28.54                      | 13.80                      |
| 12              | 68.77                      | 41.26                      |
| 13              | 42.94                      | 22.62                      |
| 14              | 40.77                      | 22.26                      |
| 15              | 39.56                      | 20.29                      |
| 16              | 37.95                      | 19.31                      |
| 17              | 32.00                      | 15.37                      |
| 18              | 40.65                      | 21.65                      |
| 19              | 31.00                      | 14.39                      |
| 20              | 43.60                      | 22.21                      |
FIGURE F1  Volatile market scenario: average transport distances of each heating plant for each simulation year/cycle. The black dash-dotted line represents the total wood stock in m³ and the blue dash-dotted line represents the wood stock available for harvesting/thinning operations.
FIGURE F2  The wood stock amount in m³ for the volatile market scenario is depicted in this figure. The colors indicate the wood stock, whereas yellow is below 100 m³, and dark green is a volume higher than 500 m³. Red cells indicate cells that are not harvestable cells, due to the harvest restrictions (age, or last forest operation has been carried out in the last 10 years). At Year 33 the non-harvestable cells dominate the map, which is depicted with red colorized cells.
FIGURE F3  The harvest patterns for each heating plant for three distinct time periods (Years 1–3, Years 10–12, Years 19–21) for the volatile market scenario are depicted here. The maps show the harvested cells colored with the corresponding heating plant. Visually, you can see that the harvest patterns are concentrated around the heating plants at the beginning of the simulation. In later stages of the simulation, the harvested cells are spatially dispersed.