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Simulation of a Swiss wood fuel and roundwood market: An explorative study in agent-based modeling

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ABSTRACT

This study discusses the potential of applying agent-based modeling (ABM) to wood markets. A corresponding model of the wood market of a Swiss canton, consisting of a coupled roundwood and wood fuel market, is presented. The model includes wood-producing agents, such as public foresters and private forest owners, roundwood-consuming agents, such as sawmills, different classes of wood fuel consumers, and in-between wood traders. Other important model elements include agent interaction and negotiation, execution and scheduling structures, and agent adaptation mechanisms. Two sets of scenarios demonstrate the model's power for scenario exploration. The first set of scenarios analyzes the effects of an excess and scarce supply of wood on both markets. The second set looks for the optimal number of roundwood agents in the market from the perspective of the various stakeholders involved. Taking a more in-depth view of important design decisions and their pros and cons, this study argues that ABM offers new opportunities for the explorative study of wood markets as a result of these markets' special characteristics.

1. Introduction

The analysis of wood markets is a difficult endeavor for several reasons. First, wood markets tend to be imperfect markets. Uncertainties exist regarding the long-term development of forest wood supply due to varying climate change scenarios and the possible occurrence of calamities. Second, the theoretically available amount of wood is limited by natural tree growth and long-term ecological concerns, leading to the prescription of the *annual allowable cut* (*AAC*). This measure can be relatively easily estimated, yet the actually available amount of wood on a market depends strongly on other factors. For example, technological advances, especially in the harvesting industry, have increased productivity in recent decades, leading to long-term changes in production costs. Political agendas and legal restrictions also can enforce increased or decreased wood production, beyond what is economically justifiable. Societal values might demand accessibility to forests for functions other than wood production. Suppliers and demanders alike are adaptable; they learn from past and anticipate future developments. Finally, individual psychological and behavioral factors apply. In many European and North American countries, non-industrial, private forest owners often pursue personal goals other than market participation or profit maximization (Beach et al., 2005; Bohlin and Roos, 2002; Conway et al., 2003), to the extent that some of them never even offer their wood on the market. Third, wood market analysis is difficult because of the tight intertwining of the roundwood and wood fuel markets, which results in hard-to-predict cyclic dependencies between them.

Therefore, when modeling wood markets, it is desirable to have a modeling technique that can accommodate the complexity of the situation. Agent-based modeling (ABM) — and more specifically, agent-based computational economics — is a technique that allows developing market models using a bottom-up approach that includes individual market participants' behavior. Whereas ABM shares some fundamental trade-offs with other modeling disciplines (i.e., model complexity versus traceability and understandability, degree of detail and richness of features versus desirable levels of aggregation and abstraction), it also offers some distinct promise. For example, ABM explicitly exposes the modeled relationship between the micro- and macro-levels of observed reality. It offers the possibility to observe emerging aggregate market behavior as a result of interactions of individualized agents. Therefore, it promises a means to investigate aggregated and averaged values, but it also can report individual data values at the micro-level. Similar to other simulation tools, ABM can tackle certain types of problems that are too hard to solve using classical analytical mathematical approaches (Maria, 1997). Simulation as a superclass of ABM also offers an alternative method to conduct otherwise infeasible experiments. One specific disadvantage of ABM is that it can aggravate the problem of limited computational power with regard to both processing speed and amassing data quantities.

Thus ABM has already been applied to a wide range of agricultural, land use, or ecological domains, though few authors have attempted

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to implement runnable agent-based models of wood markets. Troitzsch (2012) offers an introduction to the topic, and Gebetsroiter et al. (2006) describe a compound ABM consisting of two interlinked but otherwise independent agent-based submodels. One submodel simulates tree growth in a forest, with the trees modeled as competing agents, and the other simulates a market of suppliers and demanders of timber. Outside the field of wood market simulation but still related to forestry, several agent-based models have been developed to simulate forestry management decisions (Pérez and Dragićević, 2010; Purnomo and Guizol, 2006), explicate causal factors for deforestation in Mexico and the United States (Manson and Evans, 2007), and assess different demand-driven timber production strategies in Canada (Yáñez et al., 2009).

This study addresses the relative lack of applied knowledge in the field of agent-based wood market simulations by first expanding an agent-based model of a Swiss wood market and then exploring scenarios in which key supply and demand side parameters are varied. We followed the principles of the MAIA methodology (*m*odeling *a*gent systems based on *i*nstitutional *a*nalysis; Ghorbani et al., 2011) to create an agent-based model for the Swiss canton Aargau. It is based on precedent model versions, one first implemented by Olschewski et al. (2009), which was still relying on standard microeconomic assumptions, and a subsequent, more detailed version introduced by Kostadinov et al. (2012). We explored the model's capabilities by simulating two sets of economic scenarios and comparing them with a base scenario calibrated with default data from Aargau. In the first set of scenarios, we varied the supply side to simulate scarcity and excess supply situations. In the second set of scenarios, the demand side was varied through differing numbers of sawmills in the market. We used these sets of scenarios to conduct qualitative analyses of trading prices, traded amounts, and further measures.

In Section 2 we present the model and its constitutive elements (e.g., markets, agents, agent interactions), as well as its scheduling, execution, and negotiation processes. Section 3 demonstrates the model's application using explorative scenario analysis, including a base scenario and two sets of scenarios. In Section 4 we provide a critical review of the model's fundamental design issues, before we conclude in Section 5 with a short summary of ABM's strengths when applied to a Swiss wood market, as well as some limitations and suggestions for further research.

2. Model

The high degree of complexity and size of the model prevent us from giving a complete overview; we focus instead on core model elements. A complete model description, following the ODD protocol (*o*verview, *d*esign concepts, and *d*etails; Grimm et al., 2006, 2010) is available elsewhere.[1]

2.1. Model region and data

We chose the Swiss canton Aargau as the model region for several reasons. First, the data for this canton are relatively available. Second, Aargau takes a representative position among Swiss midland cantons in terms of its geographical location and conditions for wood production. Aargau is important for wood fuel production in Switzerland. Third, the number of agents to be modeled seemed manageable computationally and yet still sufficient to provide a high number of agent interactions. The model also could be transferred to and calibrated with data from other regions, whether other Swiss cantons or regions in countries with similar market structures, such as Germany or Austria.

Aargau has a size of 1404 km^2 and a population of approximately 620,000 people. The forest area in Aargau is approximately 49,000 ha (i.e. about one-third of the canton's area is forested). Public and semi-public organizations, such as municipalities and corporations, own 78% of the forests, whereas 22% are under private property. In the past years, an average of 435,000 m^3 wood was used yearly, including 60% as stem wood and 40% as wood fuel or industrial wood. For the model, we refer to stem wood as roundwood, and the term wood fuel also includes industrial wood (Kanton Aargau et al., 2010).

The simulation model focuses only on forest wood production and consumption, including wood fuel produced from industrial waste wood; it excludes other sources, such as post-consumer wood.

The following data sources were used for model calibration:

- The number, size, and location of wood fuel heating systems in Switzerland, as provided by Holzenergie Schweiz (Primas et al., 2011).
- The number of foresters and amount of forest managed, provided by the third Swiss National Forest Inventory (2010).
- Past oil price developments (US Energy Information Administration, 2011), to determine, among other factors, how attractive it is for new wood fuel consumers to install wood fuel heating systems and thus enter the market.
- Classification and typification of foresters, private forest owners, and certain wood fuel consumers, based on qualitative interviews conducted with market participants, scientific studies of non-industrial private forest owners (Beach et al., 2005; Schaffner, 2008), and the authors' own expert knowledge.

2.2. Model elements

The model consists of markets in which agents, representing real-world market participants, sell and buy wood. Agents are grouped into classes, according to their market roles. They also are assigned a certain type, which represents the market participant's behavioral or decision characteristics.

2.2.1. Markets

Forests are modeled rudimentary as homogeneous, renewable resources of a certain size, with a natural upper growth limit equal to the AAC. Tree growth is equally distributed over time. The model does not include seasonal influences, changing weather conditions, calamities, or natural preconditions for forestry. We model both the roundwood and the wood fuel market. On the roundwood market, only roundwood is traded, whereas on the wood fuel market, only wood fuel is traded. Both are assumed to be homogeneous goods. We omit differences in tree species, product segments, and product qualities. Fig. 1 provides an overview of these markets and their agents.

We model five markets purely exogenously: the timber products market, the pulp and paper market, the district heating market, the electricity market, and the oil and gas market. Although some agents depend on these highly aggregated markets in one way or another, no real agent interaction occurs, as is the case for the roundwood and wood fuel markets. In other words, these markets constitute the system's boundaries.

2.2.2. Agents and agent classes

Table 1 provides an overview of the agent classes. The presented agent characteristics are based on the data sources cited in the section "Model region and data". All agents have a fixed geographical location and a portfolio containing the agent's resources, which consist of forest (wood producers only), a stock of roundwood and/or wood fuel (wood consumers only), money (all agents), and possibly contracts. Agents act as suppliers, demanders, or intermediaries of roundwood and wood fuel. Not all agent classes are active in both markets. The columns "roundwood market" and "wood fuel market" in Table 1 show the roles of agents in a market.

Agents also maintain a "phone book" of other agents located nearby, which they use to find suitable trading partners during the negotiation

[1] This ODD protocol document is available at http://www.wsl.ch/fe/waldressourcen/produktionssysteme/publikationen.

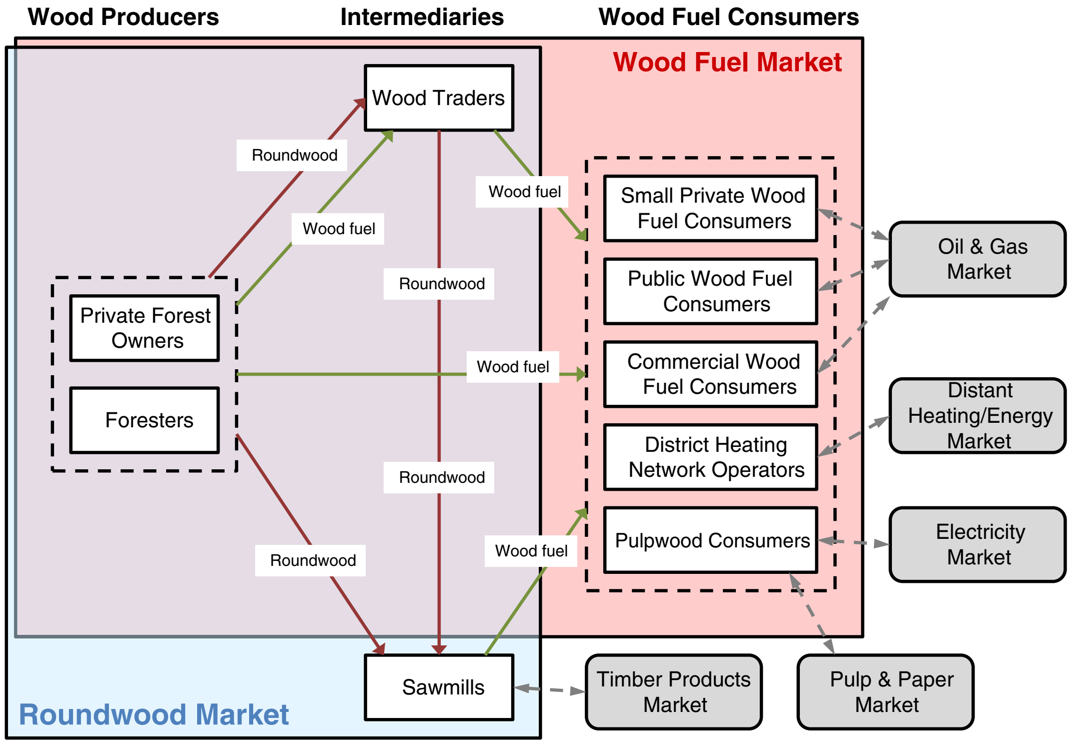

Fig. 1. Overview of modeled roundwood and wood fuel markets, agent classes (white boxes), and exogenous markets (gray boxes). Brown arrows indicate flows of roundwood, and green ones denote flows of wood fuel. Sellers of either roundwood or wood fuel are at the arrow's tail, and buyers are at its head. Dashed, gray arrows indicate agents' relationships with exogenous markets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

process. The larger an agent is, the more entries the phone book contains.

The column "Initial # of agents" in Table 1 lists the initial numbers of simulated agents. These numbers can vary significantly throughout the simulation, depending on market entry and exit of agents. Because of limited computational power, it was necessary to aggregate multiple real-world market participants per class into fewer scaled-down agents. However, it was not possible to use the same scaling factor for all agent

Table 1
Modeled agent classes and their characteristics. Numbers on wood consumption are given in m^3 per month (= m^3 p.m.; RW = roundwood, WF = wood fuel).

Agent class	Description	Roundwood market	Wood fuel market	Initial # of agents	Scaling factor	Production or consumption capacity	Default agent types
Forester	Usually full-time professionals managing forests on behalf of third-party owners (mainly municipalities).	Supplier	Supplier	73	1	Manage 80% of forest	50% profit, 50% friendship
Private forest owner	Own forests themselves. Average owned/managed patches are usually much smaller than the ones managed by foresters. In a base scenario, 50% of private forest owners have little interest in wood production and remain mostly inactive throughout the simulation.	Supplier	Supplier	285	50	Manage 20% of forest	50% profit, 50% friendship
Wood trader	Solely act as intermediaries, buying and selling roundwood and wood fuel on both markets. Do not produce or consume roundwood or wood fuel themselves.	Intermediary	Intermediary	43	1	Do not manage forest, do not consume wood	100% standard
Sawmill	Only class of roundwood consumers in the model, but they also act as suppliers of wood fuel on wood fuel market.	Consumer	Supplier	21	1	100% of RW consumption (16,300 m^3 p.m.)	100% standard
Small private wood fuel consumer	Single detached houses with a wood fuel heating system consuming small amounts of wood fuel.	–	Consumer	107	10	5% of WF consumption (1800 m^3 p.m.)	100% standard
Commercial wood fuel consumer	Private corporate entities running larger (corporate) buildings, up to small compounds with a wood fuel heating system installed.	–	Consumer	43	10	30% of WF consumption (11,700 m^3 p.m.)	100% standard
Public wood fuel consumer	Mostly municipalities or similar organizations running publicly owned buildings such as schools and fire departments. They enjoy preferential treatment by foresters.	–	Consumer	32	10	22% of WF consumption (8800 m^3 p.m.)	100% standard
District heating network operator	Commercial energy/heat producers. The produced heat is sold to houses attached to the same heating network.	–	Consumer	21	1	9% of WF consumption (3400 m^3 p.m.)	100% standard
Pulpwood consumer	Chemical and paper industry. They compete with other wood fuel consumers for the same good.	–	Consumer	2	1	34% of WF consumption (13,300 m^3 p.m.)	100% standard

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classes. Whereas certain agent classes correspond to several thousand real-world market participants, for other classes only one or two market participants exist. The corresponding scaling factors also appear in the table. For example, 43 commercial wood fuel-consuming agents with a scaling factor of 10 represent 430 real-world market participants. The effect of scaling on the simulation results is not clear. Several studies show how to technically parallelize the computation of agent-based models (Da-Jun et al., 2005; Lysenko and D'Souza, 2008), but no studies directly address the effects of scaling.

The column "production or consumption capacity" provides an overview of the market impact of an agent class in a base scenario. For example, foresters on average manage 80% of all forest available in the model, but private forest owners manage only 20%. How much roundwood and wood fuel they effectively produce cannot be directly deduced from the table, but it is an emergent result in the simulation. Roughly half the private forest owners[2] remain mostly inactive in a base scenario and do not produce roundwood or wood fuel at all. They only actively harvest and produce when wood prices cross an individually set threshold value. This threshold is set at 20%[3] above the initialized wood prices.

Sawmills are the only roundwood consumers in the simulation. Wood fuel production is a side effect of their roundwood processing activity. Thus, they also act as wood fuel sellers in the wood fuel market. Wood traders do not produce or consume wood themselves; they only trade it. They can buy wood from foresters and private forest owners at a reduced price (-5 CHF/m^3 wood)[4] because, according to the model design, they harvest the trees themselves. Pulpwood consumers are the largest wood fuel-consuming agents; combined, they consume roughly 34% of total wood fuel at the beginning of the simulation. Only two of them appear in the model. Small private wood fuel consumers represent the largest number of wood fuel consumers, but taken together, they only consume 5% of all wood fuel at the beginning of the simulation. The other classes of wood fuel consumers are somewhere in between.

Public wood fuel consumers enjoy preferential treatment by foresters. Foresters that receive multiple requests for wood fuel by several public and non-public wood fuel consumers always accept the public ones first, as long as they meet a minimal standard, even if the requests are otherwise inferior to those of non-public wood fuel consumers.

2.2.3. Demand behavior

Agents that demand wood are also producers. They produce either heat and "energy" or pulp and paper, in the case of wood fuel consumers, and timber products, in the case of roundwood consumers. Their goal is to keep their output per time unit constant. Every consumer agent has an individually set, unchanging, monthly need for wood. In each period, the agent uses up an amount of roundwood or wood fuel according to its need and then reevaluates its wood stock and tries to buy as much wood on the market as is required to refill its stock for the next period. If for any reason an agent does not succeed in buying the demanded quantity of wood during one period, its demand for wood in the next period will rise accordingly. If its attempts remain unsuccessful for more than a month, the agent will increase its willingness-to-pay price by 1%. If instead the agent can completely satisfy its demand for a month, its willingness-to-pay price decreases by 1% at the end of the month. Collectively, this leads to rising prices in a scarcity and falling prices in an excess supply situation. The 1% adaptation value is set at the start of the simulation and remains the same for all consumer agents, though it theoretically could be set per agent class, agent type, or individual agent. The higher it is, the faster price adaptations occur. This adaptation value is currently not empirically grounded; it represents a design decision. Should an agent fail to cover its need for a prolonged time or, in the case of sawmills or pulpwood consumers, run out of money, it will leave the market. The long-term, aggregated market demand therefore can decrease from market exit of consumer agents and increase from their market entry. If wood fuel prices are lower than oil prices, more new wood fuel consumers make a decision to install a wood fuel heating system and enter the market. In the short run, wood fuel demand is constant, because wood fuel is not substitutable. Roundwood consumers take into account combined criteria based on whether to enter the market or not. First, they consider the roundwood price development over the past two years. If it is falling, they tend to enter the market. Second, they consider the AAC utilization rate (see Section 3). The lower it is, the higher is the probability that new sawmills will enter the market.

2.2.4. Supply behavior

Production of roundwood, and therefore the roundwood supply in the short run, is mainly a demand-driven process. Wood producers may, but are not forced to, produce roundwood according to the demand they face. If they do not exploit the AAC at a given point in time, the corresponding wood quantity will still be at their disposal in later periods.

Production of wood fuel and therefore the wood fuel supply in the short run depends on roundwood production. A certain low quantity of wood fuel is produced constantly during maintenance work in the forests, and because wood producers try to cover fixed costs (e.g., employees' salaries) by maintaining a minimal constant workforce utilization. Yet the majority of wood fuel is produced either during roundwood production by wood producers or during the timber product manufacturing process by sawmills.

Wood producers observe the attractiveness of the roundwood market in relation to the wood fuel market. This attractiveness is measured as the relationship between the roundwood price and the wood fuel price. If this relationship is in favor of wood fuel, it is worth producing more wood fuel from wood segments otherwise still suitable as roundwood, and vice versa. The corresponding output ratio is called the wood fuel portion of the total tree mass (=WFM):

$$\mathrm{WFM} = \frac{\text{Wood fuel mass of harvested tree}}{\text{Total mass of harvested tree}}, \tag{1}$$

with bounds set to $0.2 \leq \mathrm{WFM} \leq 0.6$. Wood producers can never produce less than 20% of wood fuel per harvested tree, or more than 60%. As a consequence, consumers of both roundwood and wood fuel markets compete to a certain degree for the same good. Significant changes in one market's dynamics might influence the other market as well.

Wood producers can adapt to long-term changes of demand only to a limited extent. Within certain boundaries, they can decide to produce more roundwood at the cost of wood fuel, or vice versa, but they cannot significantly increase their output beyond the set AAC. This is because in the canton Aargau, as well as in Switzerland, upper limits to wood production are set by restrictions of space and territory and, thus, through set forest sizes, as well as for legal reasons that prescribe non-industrial forest management styles.

The aggregated long- and short-term market supplies for roundwood and wood fuel thus are emergent, discontinuous, interdependent functions with an upper limit. They are heavily dependent on the demand faced and other factors. Both supply and demand have a geographical dimension; suppliers and demanders tend to interact with the agents in their surroundings.

2.2.5. Decision-making process

Agents in a class can be categorized into different types according to their personal preference (or utility value) structure. Schaffner (2008) discusses a typification of private forest owners for the case of Germany, Austria, and Switzerland; Majumdar et al. (2008) do so for some southern states in the United States; and Boon et al. (2004) focus on Denmark. When facing the same decisions, agents of the same class and type apply the same value judgments in an equivalent

[2] Estimation, recommended by domain experts.
[3] Assumption, not based on empirical data.
[4] Estimation, recommended by domain experts.

situation. Therefore, a deterministic decision-making algorithm is required. Several authors quantify the decision-making processes of wood market participants. In two independent meta-studies, Amacher et al. (2003) and Beach et al. (2005) provide overviews of multiple econometric measures and their influences on non-industrial, private forest owners' management decisions. They agree, for example, that non-industrial private forest owner demographic characteristics, such as level of education, age, and professional occupation, influence their management decisions. Both Conway et al. (2003) and Størdal et al. (2007) use regression-based models to quantify non-industrial private forest owner behavior.

The current study adopts a different approach. An analytical hierarchy process (AHP; Saaty, 2008) is widely used in (sometimes automatable) supplier selection problems (Bruno et al., 2009). Similar to multi-criteria analysis, AHP is a standardized method for ranking different possible alternatives according to predefined, weighted selection criteria. One or multiple ranked alternatives then can be selected. Knoeri et al. (2011) apply AHP to operationalize agent behavior in an ABM. In our model, an agent's utility function and thus its decision-making process are also implemented as AHPs. Preferred deals get selected from a list of selling or buying opportunities. During the agent's AHP, a combination of three criteria is applied:

- *Profit criterion*: Sellers of roundwood and wood fuel want to maximize their monetary gains, whereas buyers want to minimize their expenditures. The profit criterion combines two measures equally: a price component and a quantity component. Low prices increase the price component value for buyers but decrease it for sellers. Furthermore, the ability to buy 100% of their needs through the same seller increases the quantity component value for buyers. For sellers, the quantity component value increases if they can sell all their wood at once to a single buyer.
- *Friendship value criterion*: Agents prefer selling to and buying from other agents with which they are friends. Friendship values are randomly assigned to pairs of suppliers and demanders during the simulation's start-up phase and remain unchanged throughout the simulation.
- *Geographical distance criterion*: This criterion represents two distinct but combinable utility values in the real world, namely, a preference to buy or sell from local forests, reflecting an inwardly felt connection with one's home place, and an agent's financially or ecologically based desires to minimize transport distances. Although in the model, agents do not pay transportation costs, they include the transportation distance as a criterion in their decision-making process.

Agents with the same AHP weights are assigned the same agent type. We use four default types for all agents in all classes: standard, profit-oriented, friendship-oriented, and distance-oriented types. Table 2 lists the weights used for each type.

The shares of each agent type per agent class in the base scenario appear in the column “Default agent types” in Table 1. Although we selected the criteria on the basis of qualitative interviews conducted with real-world market participants, the shares of each agent type listed in Table 1 and the weights applied to each criterion are not really empirically grounded.

Table 2
Weights assigned during AHP to different criteria by agent types.

Types	*Weight profit criterion*	*Weight friendship criterion*	*Weight distance criterion*
Standard	0.6	0.3	0.1
Profit-oriented	0.9	0.05	0.05
Friendship-oriented	0.05	0.9	0.05
Distance-oriented	0.05	0.05	0.9

Agents willing to pay high prices on the one hand and agents requesting larger quantities of wood on the other hand gain competitive advantages during the application of AHP. Because the friendship and distance criteria are statically set for the whole simulation, they can only distort competition, not intensify or weaken it.

2.3. Scheduling and execution

The main simulation process is split into sequentially executed sub-processes, as Fig. 2 shows. In MAIA terminology, they are *action situations*. Start and end are not real action situations; rather, they serve only to set up and tear down the simulation. The simulation is round based, and each round reflects a year's execution. Once a year, some agents can enter or leave the markets during the market entry and exit action situation. The roundwood market, the wood fuel market, and then the evaluation action situations are executed in sequence. This sequence gets repeated 12 times (= 12 months) per year. After a one-year cycle (one round) is completed, a new cycle starts.

Both market executions consist of two subsequent phases, repeated as pairs six times. In each phase, different agents act as sellers or buyers. Fig. 3 shows the implemented negotiation protocol and the involved agent classes for each phase in detail.

In each phase, buyers and sellers are activated in a random order. Both phases follow the same four main steps.

1. *Buyers make requests*. Buyers with demand for a certain good (roundwood or wood fuel) search for sellers in their phone books and send them a request with the demanded amount. They also add the price they are willing to pay to the request.
2. *Sellers make offers*. Each seller agent checks if it has received any requests. If it has, it orders the requests with AHP, applying the already mentioned criteria so that it answers the most advantageous request first. Then it checks whether it has enough of the resource requested and whether the buyer's willingness-to-pay price lies above its own reservation price. If both conditions are met, the seller sends an offer to the buyer; otherwise, it declines the request.
3. *Signing contracts*. All buyer agents check whether they have received any offers for their requests. If so, they order the incoming offers with AHP, so that they answer the most advantageous first. If their demand has not been satisfied, they sign additional offers (i.e., accept the offer and are willing to pay the price set in the contract). When their demands are satisfied completely and unsigned offers still remain, they decline them all.
4. *Fulfilling contracts*. At the end of a round, all contracts marked as “signed” are fulfilled. The fulfillment of the contract includes the exchange of the good specified in the contract and the transfer of money (i.e., the price specified in the contract).

Even after the execution of these four steps for both phases, some sellers still might want to sell goods, and some buyers might have unsatisfied needs. For this reason, the execution of the two phases is repeated six times, with a growing search radius on the buyers' side.

2.4. Model validation

To validate the model, we applied multiple techniques:

- The model's structure, execution algorithms, and simulation results were discussed in expert workshops.
- The model was based on and calibrated with empirical data, both quantitative and qualitative (as suggested by Boero and Squazzoni, 2005; Louie and Carley, 2008; or Schutte, 2010).
- A parameter sensitivity analysis was performed.
- A set of sample agents was tracked throughout the simulation.
- The integration of visual output into the simulation, or “visual debugging” (Grimm, 2002), was used to both display dynamically changing trading relations and chart important output parameters.

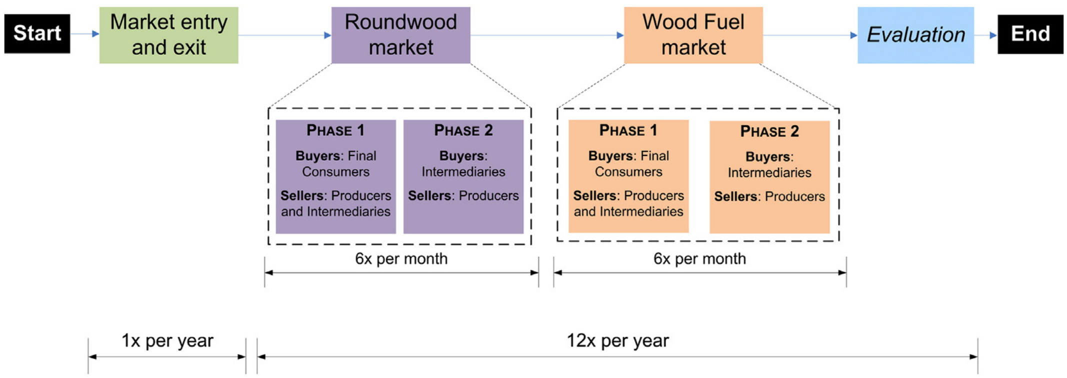

Fig. 2. Overview of the main simulation process with action situations.

- The model was documented using the standardized ODD protocol (Grimm et al., 2006, 2010).

A further modeling technique worth mentioning, which we did not apply, is ordinal pattern analysis (Thorngate and Edmonds, 2013). If data are available, they can be matched with simulation output using ordinal pattern analysis, which allows testing ordinal predictions gained from hypotheses against a set of observations. However, authors such as Oreskes et al. (1994) also claim that validation of open systems (e.g., our model), in a strict sense, is not possible at all.

3. Scenario simulation

Two sets of scenarios demonstrate the use of the proposed model for explorative inspection of different market situations. The simulation by no means attempts to predict the behavior of real markets; rather, we present the model's explanatory power by describing its complex behavior. In each scenario we vary only a single, initial parameter.

We introduce two simple measures that indicate the availability of wood fuel from the producers' and consumers' points of view. The AAC utilization rate (AUR) is:

$$AUR = \frac{\text{Amount of wood made available on the market}}{\text{Amount of wood available by the AAC}}. \tag{2}$$

The AUR shows the quantity of wood made available on the markets by wood producers with regard to the theoretically available quantity given by the AAC. A maximum value of 1 indicates that the AAC is exhausted to its full extent by the wood producers. All values less than 1 mean that a certain amount of wood remains unused in the forests. In the long run, the AUR cannot surpass 1, because otherwise, wood production would be non-sustainable. In the short run, the AUR can temporarily exceed 1, if unused AAC contingents from the past are used.

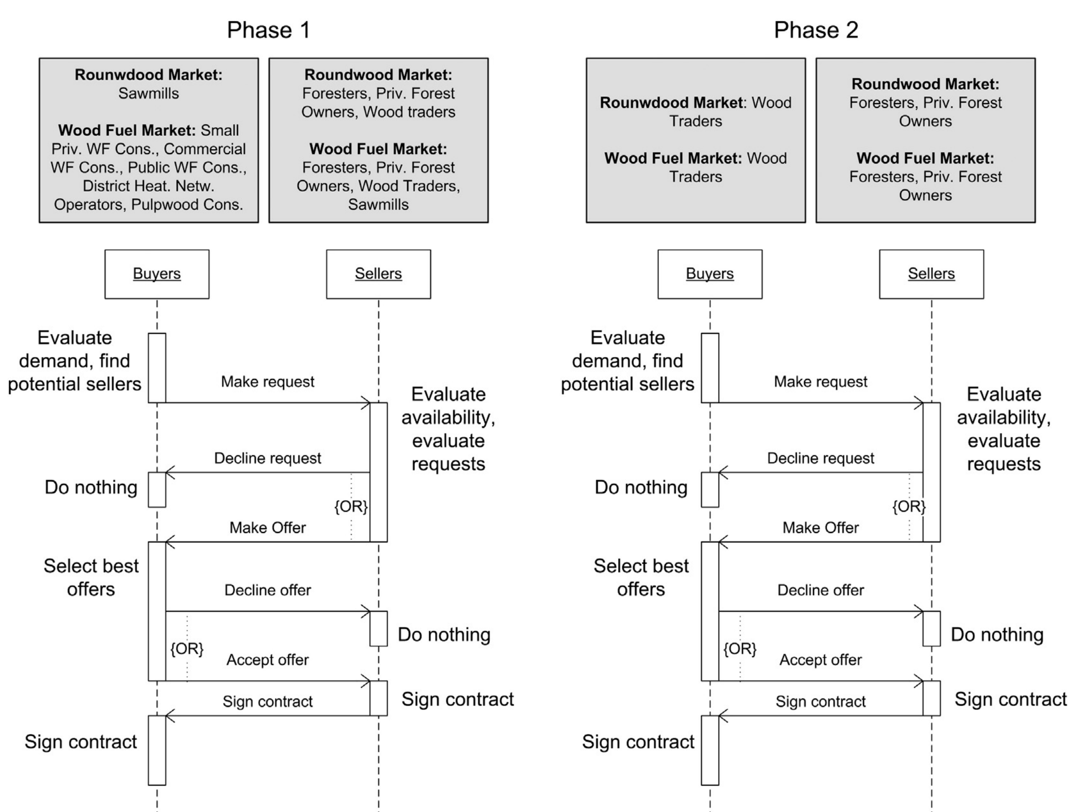

Fig. 3. Interaction diagrams of the two-phase buyer/seller negotiation protocol for both roundwood and wood fuel markets.

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Whereas the AUR is helpful to assess wood production, the availability of wood on the consumers' side can correspondingly be measured by the supply rate (SR):

$$SR = \frac{\text{Quantity of wood bought by consumers}}{\text{Quantity of wood needed by consumers}}. \quad (3)$$

The SR can be calculated as an average for whole classes of agents or for individual agents. A maximum value of 1 indicates that a certain agent class (or individual agent) can completely fulfill its demand for a good. All values less than 1 mean that at least some consumer agents are left unsatisfied. In general, this state is not a problem in the short run, because all consumers have a certain stock of the desired good to use, but in the long run, it may cause agents to exit the market.

Each of the following scenarios represents an average of 100 simulation runs with the exact same initial parameter setting but varied initial random seeds. After starting from their initial values, certain dynamically changing parameters such as prices require some time to arrive at a level that is specific to a single simulation run. In all scenarios, the simulation needs three to five years to overcome the initial calibration phase. Therefore, unless otherwise stated, we excluded the first five years from the computation of the sums, averages, and so forth.

The simulated absolute levels of prices or quantities traded depend heavily on the simulation's initial parameter choice. Data on how to set the parameters are not available, nor is there any such thing as an ultimately "correct" parameter choice. Therefore, of more interest than absolute numbers are their relationships and their relative development.

3.1. Base scenario ($S_{2.6}$)

In the base scenario ($S_{2.6}$), initial total supply equals initial total demand of both roundwood and wood fuel. The forest growth rate is a parameter set at the beginning of the simulation, which indicates the growth rate of trees in the forest per year. We measure it as the new amount of wood added to the (old) total amount of wood each year. In the base scenario, this parameter is set to 2.6%. The initial number of simulated agents per class is set as described in Table 1. While Fig. 4 shows a map of the chosen sample region during a single run at a certain point in time, Fig. 5 shows a Sankey diagram with the simulated aggregate average roundwood and wood fuel flows in m^3 between sellers and buyers in years 5–20.

Foresters produce and sell much more roundwood and wood fuel than private forest owners. Furthermore, wood consumers' aggregated monthly demand, as Table 1 shows, corresponds to the quantities bought. Note that for small wood fuel consumers, private forest owners as a source of wood fuel are more important than they are for big wood fuel consumers. Small private wood fuel consumers cover 39% of their needs through private forest owners and 42% through foresters. In contrast, pulpwood consumers obtain only 5% from private forest owners and 71% from foresters. For the rest of the wood fuel consumers, the ratios are roughly 10% and 72%. The reason is that large consumers in general, if the supplier is a small one, give poorer values to the quantity component of the profit criterion during the trading deal selection process using AHP.

3.2. Example 1: Supply variation scenarios

In our first set of scenarios, we explore the effects of a varied supply on the market. How does a situation of scarce or excess supply affect the market? Scenario $S_{2.6}$ is the base scenario, with a forest growth rate of 2.6% (100% of 2.6%). Scenarios $S_{1.3}$ and $S_{1.95}$ are situations of scarcity, in which the forest growth rate reduces to 1.3% (50% of 2.6%) and 1.95% (75% of 2.6%), respectively. Scenario $S_{3.9}$ represents a situation of excess supply, with a forest growth rate of 3.9% (150% of 2.6%). We are not yet concerned about whether such diverse growth rates are realistic, but we attempt to illustrate clearly the effects of scarce and excess supply. In all scenarios, we adapt the AAC to the changed forest growth rate. We initially set all other model parameters to the

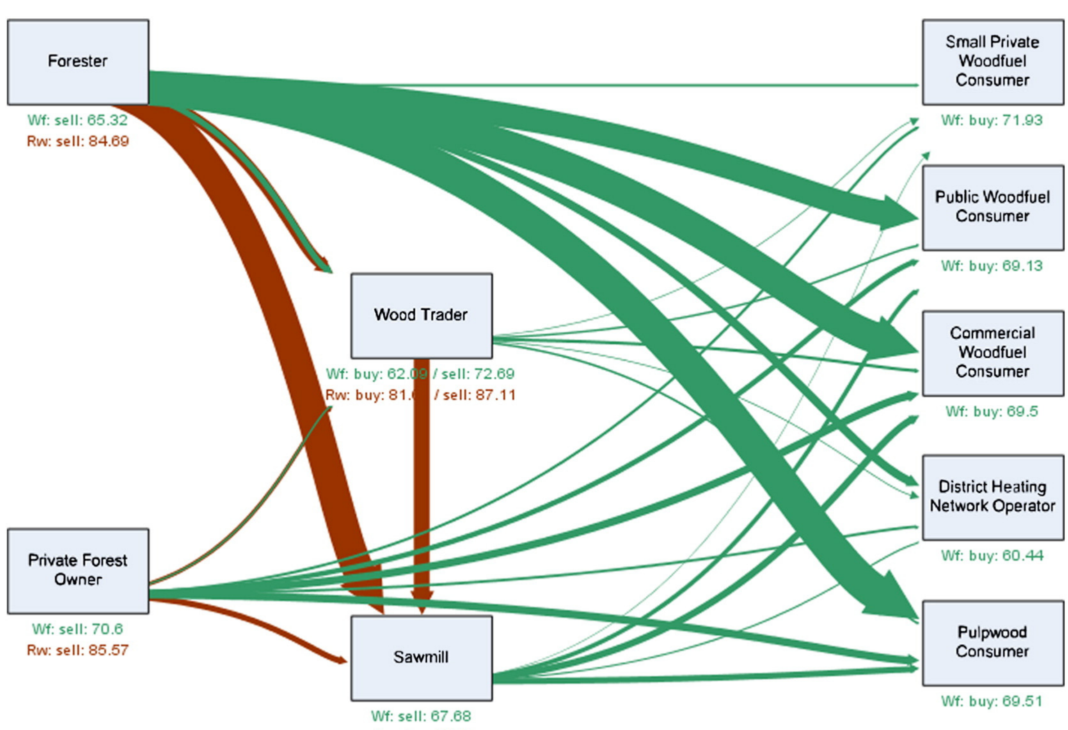

Fig. 4. Map of active trading relationships at a certain point in time during a single simulation run. Different shapes represent different agent classes. Arrows indicate executed trades with the seller at the arrow's beginning, with the buyer at its head. Roundwood trades appear in blue and wood fuel trades in red. One pulpwood consumer is clearly recognizable by its high number of active wood fuel trades over a larger distance. Also several sawmill agents are indicated by a large number of blue arrows pointing towards them.

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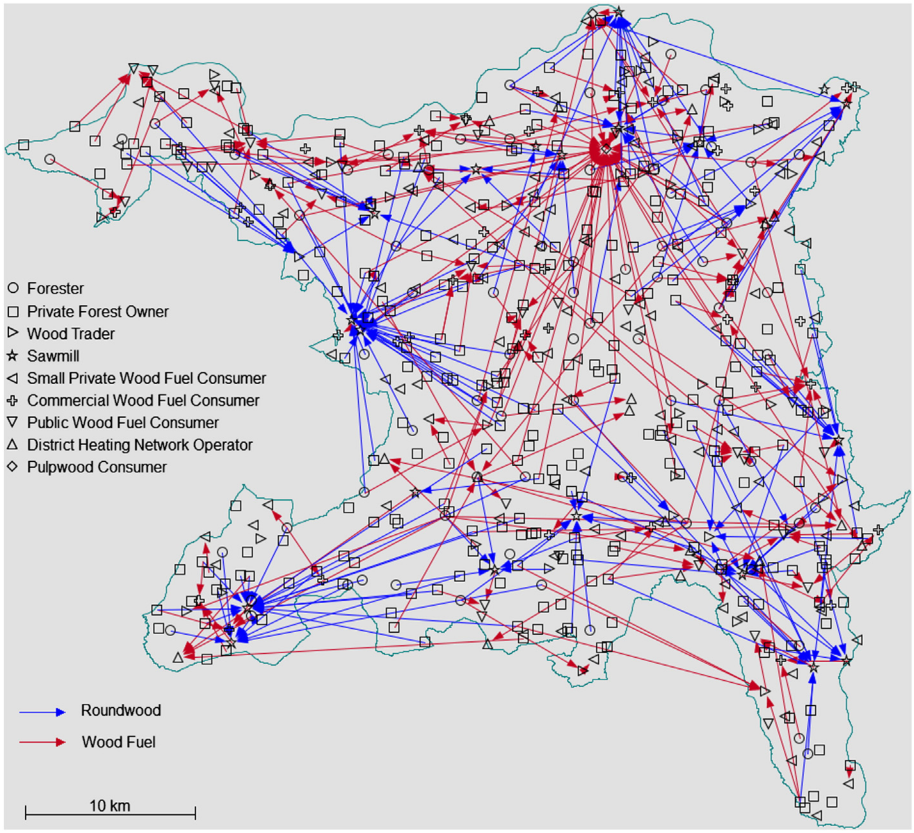

Fig. 5. Sankey diagram of the simulated aggregate average wood flows between suppliers and demanders in the base scenario ($S_{2.6}$). Brown arrows indicate roundwood flows, and green arrows indicate wood fuel flows. The thickness of an arrow is proportional to the average traded wood quantities between different classes of supplier and demander agents. The figure also shows the emerging average prices asked/paid by agent classes (all in CHF/m^3 wood). "Rw sell" is the price asked for roundwood by a class of supplier agents, and "Rw buy" is the price bid for roundwood by a class of consumer agents. Accordingly, "Wf sell" and "Wf buy" are the corresponding prices for wood fuel. Wood traders can buy wood at special conditions from foresters and private forest owners. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

exact same values for each scenario. Because, as mentioned previously, the short-term demand for wood is constant but the short-term supply is not, an excess or scarcity situation can occur in the short run.

Fig. 6 shows the development of the roundwood and wood fuel prices (in CHF/m^3; panels a and c) and the aggregated consumption (panels b and d) per month in the four scenarios. In general, consumption is the highest and prices are the lowest in scenario $S_{3.9}$, a situation of excess supply. Conversely, consumption is the lowest and prices are the highest (until year 12) in $S_{1.3}$, a situation of scarce supply. Scenario $S_{1.95}$ is somewhere in between $S_{1.3}$ and $S_{2.6}$.

In the years 11–14 in scenario $S_{1.3}$, the roundwood market crashes. The scarcity of roundwood is so extreme that many sawmills are forced to exit the market. The roundwood price crashes (panel c) as the demand for roundwood decreases significantly (panel d). Fig. 7 shows the development of demand for wood fuel as a stacked bar chart and the development of demand for roundwood as an overlaid single line for scenario $S_{1.3}$. In years 9–13, the demand for roundwood decreases. It reaches a minimum in years 13–15, from which it then recovers. Especially pulpwood consumers are sensitive to situations of under-supply (Fig. 7), because they are very few, but large agents. They are forced to exit the market in years 8–10.

Fig. 8 provides an overview of the WFM ratio (formula 1), the AUR (formula 2), and the SR (formula 3).

Wood fuel consumers can more or less collectively satisfy their demand in scenarios $S_{1.95}$ and $S_{3.9}$, but less so in $S_{2.6}$ and definitely not in $S_{1.3}$ (Fig. 8, panel f). In $S_{1.3}$, there is simply not enough wood on the market. The AUR (Fig. 8, panel h) is only low as an average figure because of the market breakdowns in years 11–14 (cf. Fig. 6). Otherwise, it would be the highest of the given scenarios.

In $S_{1.95}$, because of the higher forest growth rate, more wood can be produced, and because wood prices are also relatively high (Fig. 6, panels a and c), the AAC is fully exhausted (Fig. 8, panel h). At the same time, wood producers tend to produce less wood fuel in favor of roundwood (Fig. 8, panel g).

In $S_{2.6,}$ even more wood is offered on the market in absolute terms, and therefore the markets have become so attractive for wood fuel consumers that many new ones enter the market. At the same time, win margins become lower for wood producers, and some private forest owners are no longer motivated to produce wood. Thus, the AUR is slightly lower than in $S_{1.95}$ (Fig. 8, panel h). The combined effect is a slightly reduced SR in $S_{2.6}$ compared with $S_{1.95}$ and $S_{3.9}$ (Fig. 8, panel f).

In $S_{3.9}$, because of the excess supply, prices tend to be the lowest (Fig. 6, panel c), and market entry resulting in rising demand the fastest. Even more private forest owners stop producing wood in this case, and thus the AUR is lower than in $S_{2.6}$ (Fig. 8, panel h).

Roundwood consumers, however, cannot satisfy their demand fully in any of the four scenarios (Fig. 8, panel f). Accordingly, we might expect roundwood consumers to leave the market and demand to drop in all three scenarios, which is not the case. Rather, it is caused by the assumptions of the sawmill agents' cost structure, in combination with a modeled guaranteed disposal of timber products on the (external) timber product market. On the one hand, in the model the relatively low fixed costs lead to a low pressure on high capacity utilizations. On the other hand, sawmills sell their products to the timber products market, which is modeled purely exogenously. Therefore, whatever amount of wood products they produce, they can always sell them on the timber products market. Whereas competitive forces are modeled regarding the productive input of roundwood consumers, no such forces exist in the model for productive output.

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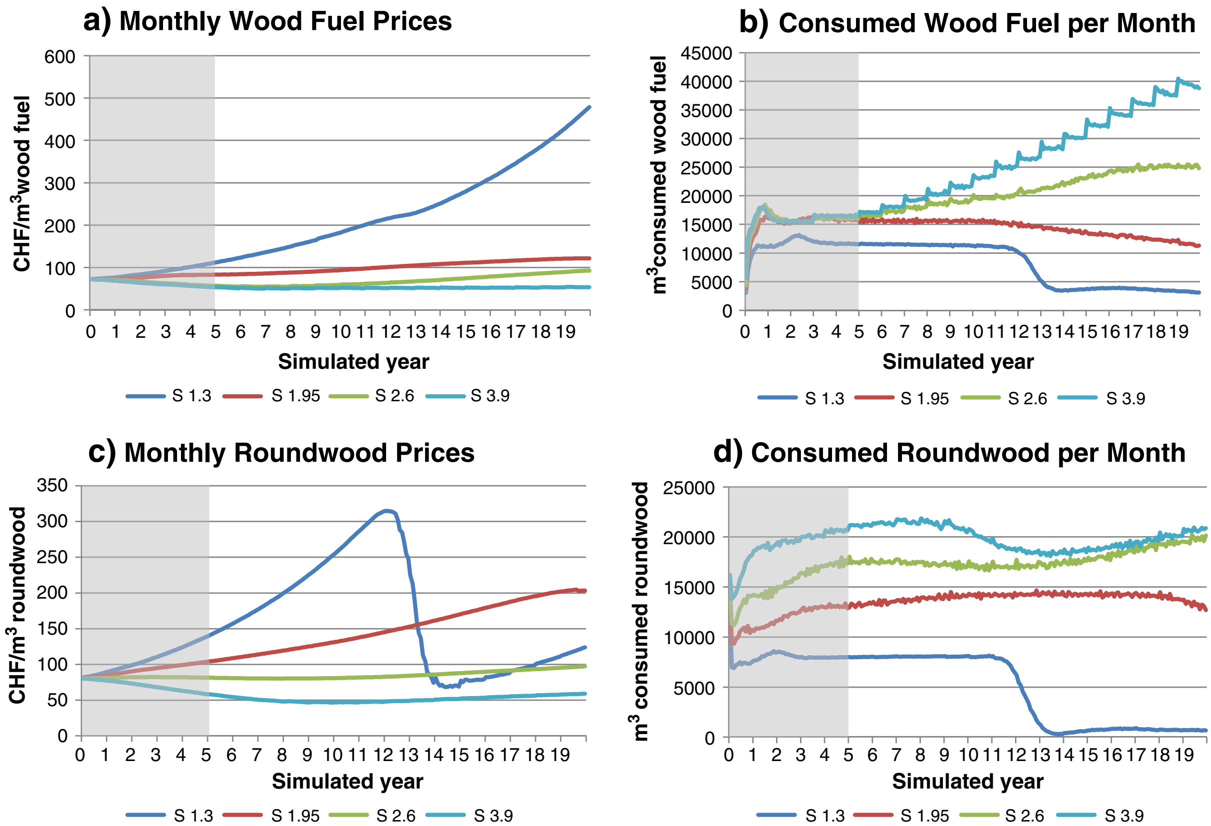

Fig. 6. Development of simulated wood fuel and roundwood prices and consumption in four scenarios. The first data points shown in the diagrams are the results after one month of simulation, so consumption levels in panels b and d might appear to vary initially, though for all scenarios at the simulation's beginning, they are set to the same initial values.

The effect of suboptimal roundwood supply for sawmills in Switzerland can indeed be observed in reality as Pajarola (2009), relying on Pauli et al. (2003), states. According to Pajarola (2009), reasons for suboptimal capacity utilization are related to high transport and harvesting costs.

3.3. Example 2: Demand variation scenarios

In a second set of scenarios, we explore the effects of varied demand on the market. This time, the initial number of roundwood consumers varies, starting with a simulation with 0 sawmill agents in scenario S_0, 5 in scenario S_5, 10 in S_{10}, and so on, up until 40 sawmill agents in scenario S_{40}. All other initial parameters are set as in the base scenario (which, if added, would be located between S_{20} and S_{25}). So we address the key question: What is the optimal number of roundwood consumers on the market from the perspective of:

i. roundwood consumers, desiring roundwood prices to be as low as possible;
ii. wood fuel consumers, desiring wood fuel prices to be as low as possible; and
iii. policy makers, needing to maximize a (sustainable) wood consumption level across the market?

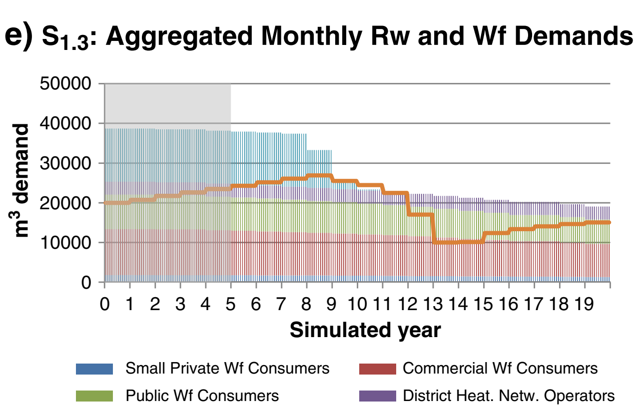

Fig. 7. Development of the aggregated monthly roundwood (orange line) and wood fuel (colored stacked bars) demands over time in scenario $S_{1.3}$.

In Fig. 9, panel a shows the average monthly roundwood prices, while panel b shows the SR of sawmills. From the perspective of roundwood consumers, being the only one (monopsony on the roundwood market) is desirable, because prices are the lowest (Fig. 9, panel f) and the SR is the highest (Fig. 9, panel b) as a result of the complete lack of competitors.

Fig. 10 shows the wood fuel consumers' perspective. If there are few roundwood consumers in the market (S_0–S_5 in Fig. 10, panel c), not enough wood fuel gets produced, resulting in high wood fuel prices above 100 CHF/m^3. Competition for the scarce good is fierce, although the WFM reaches a maximum value of 0.6 (S_0–S_5 in Fig. 10, panel e). To achieve the lowest wood fuel prices, an initial number of 10–15 roundwood consumers is required (S_{10}–S_{15} in Fig. 10, panel c). Fig. 10, panel d, depicts the SR: An SR slightly greater than 1 can occur in the short run but not in the long run. A minimum of five sawmill agents (S_5) is necessary to reach more or less satisfying levels for all wood fuel consumer classes.

Fig. 11 reflects a policy maker's perspective. If the goal is to maximize overall (sustainable) wood consumption on the market, between 25 and 30 sawmill agents are preferable, because at this level, the quantity of consumed wood is the highest (S_{25}–S_{30}, Fig. 11, panel f), and the AUR

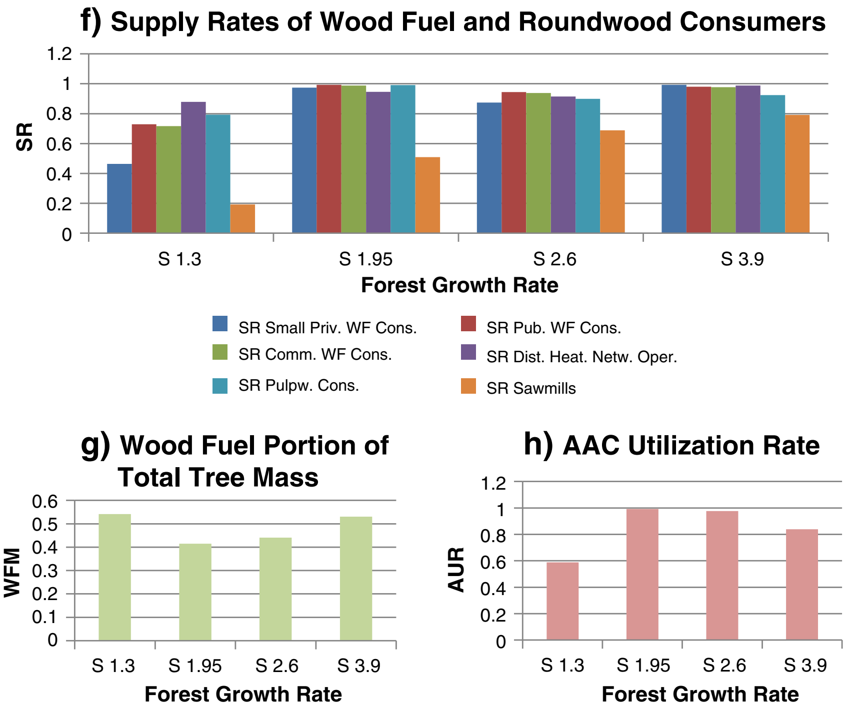

Fig. 8. f) SR for wood fuel consumers, g) WFM rate, and h) AUR in four scenarios: $S_{1.3}$, $S_{1.95}$, $S_{2.6}$ and $S_{3.9}$ (years 5–20).

levels are close to 1 (Fig. 11, panel h). A higher initial number of sawmills (S_{35}–S_{40}) forces more sawmill agents to exit the market because of unaffordable roundwood prices. For completeness, the consumption levels of wood fuel (Fig. 11, panel g) and roundwood (Fig. 11, panel h) are also given. On the one hand, to maximize the level of consumed wood fuel individually, between 10 and 20 sawmills are optimal (S_{10}–S_{20}, Fig. 11, panel g). On the other hand, to maximize the level of consumed roundwood individually, between 30 and 35 initial sawmill agents are optimal (S_{30}–S_{35}, Fig. 11, panel i).

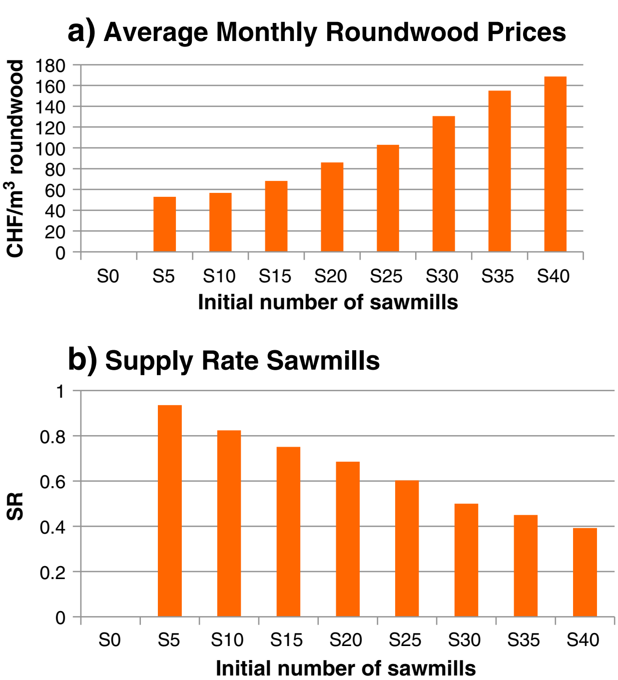

Fig. 9. Average monthly roundwood prices and SR for sawmill agents in nine scenarios: S_0–S_{40} (years 5–20).

The conclusion to be drawn here is that no single optimal initial number of sawmill agents can satisfy the interests of all stakeholders. A higher initial number of sawmill agents leads to higher levels of roundwood consumption (Fig. 11, panel f) and competition among roundwood consumers, which in turn prompts higher prices (Fig. 9, panel a) and lower roundwood SR (Fig. 9, panel b). A minimal initial number of sawmill agents is required to achieve a satisfying level of wood fuel production and affordable wood fuel prices (Fig. 10, panel c). Yet the two optima do not necessarily coincide with the one that leads to maximal total wood consumption (Fig. 11, panel f).

4. Discussion

4.1. Interpretation of the scenarios

The supply variation scenarios confirm some basic economic assumptions about markets, such as that a scarce supply leads to higher prices and lower consumption, whereas excess supply has the opposite effects. More advanced analyses, such as aggregation by agent class or even agent type, are possible too. For example, as Fig. 7 shows, the class of pulpwood consumers is especially vulnerable in a situation of extreme scarcity, more so than other classes of wood fuel consumers. One reason is that their win margins are especially low, compared with those of other wood fuel consumers, due to strong competitive forces. In addition, the markets' behavior can be nonlinear or even discontinuous, as in the observed breakdown in $S_{1.3}$. Multiple overlapping effects and the existence of threshold values can cause output parameters to behave in hard-to-predict ways. For example, though the average demand is highest in $S_{3.9}$ (Fig. 6, panels b and d), the AUR is not necessarily (Fig. 8, panel h). As explained previously, this result is mainly due to the presence of inactive private forest owners with activity threshold values.

The demand variation scenarios demonstrate how the model enables more complex analyses as well. Different stakeholder groups can have competing interests, and often no single optimum situation exists for a given problem. Wood fuel consumers might be interested in a market structure with a large number of sawmills, because it increases wood fuel availability. Yet it also increases competition among roundwood

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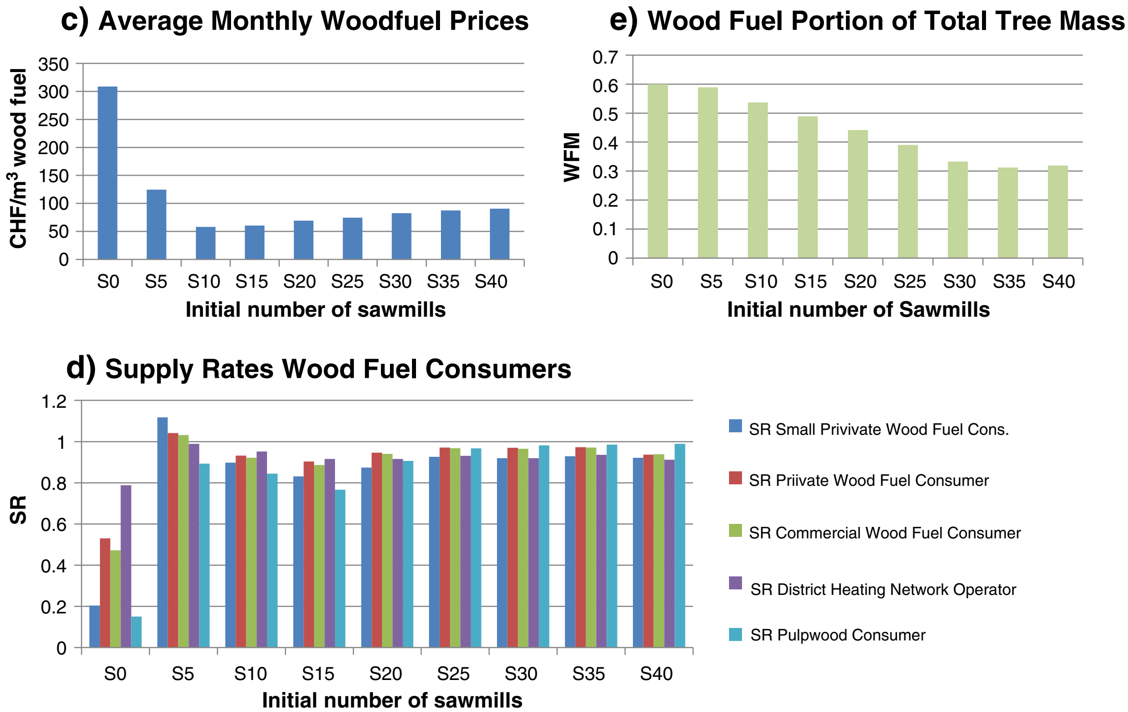

Fig. 10. c) Average monthly wood fuel prices, d) SR of wood fuel consumers, and e) WFM in nine scenarios (years 5–20).

consumers and therefore might be contrary to their interests. In such a situation of coupled markets the interdependencies can become quite complex and therefore difficult to manage from a policy maker's point of view. A consolidation of roundwood producers can be observed as a long-term trend in Aargau and Switzerland, there are nowadays fewer but bigger roundwood producers in business than during the mid 1990s (Bundesamt für Statistik, 2012a, 2012b). Additionally, in the same time the interest in using wood fuel as an alternative energy source has increased. It would require a more in-depth investigation to come to a conclusion on what the effect of these combined developments is on the markets under different oil price developments.

Not shown in the scenario analysis are micro-level analyses (individual agent behavior), though these are theoretically possible, assuming the produced amount of data can still be handled. An example with scenarios focusing more on agent behavior is available in Kostadinov et al. (2012).

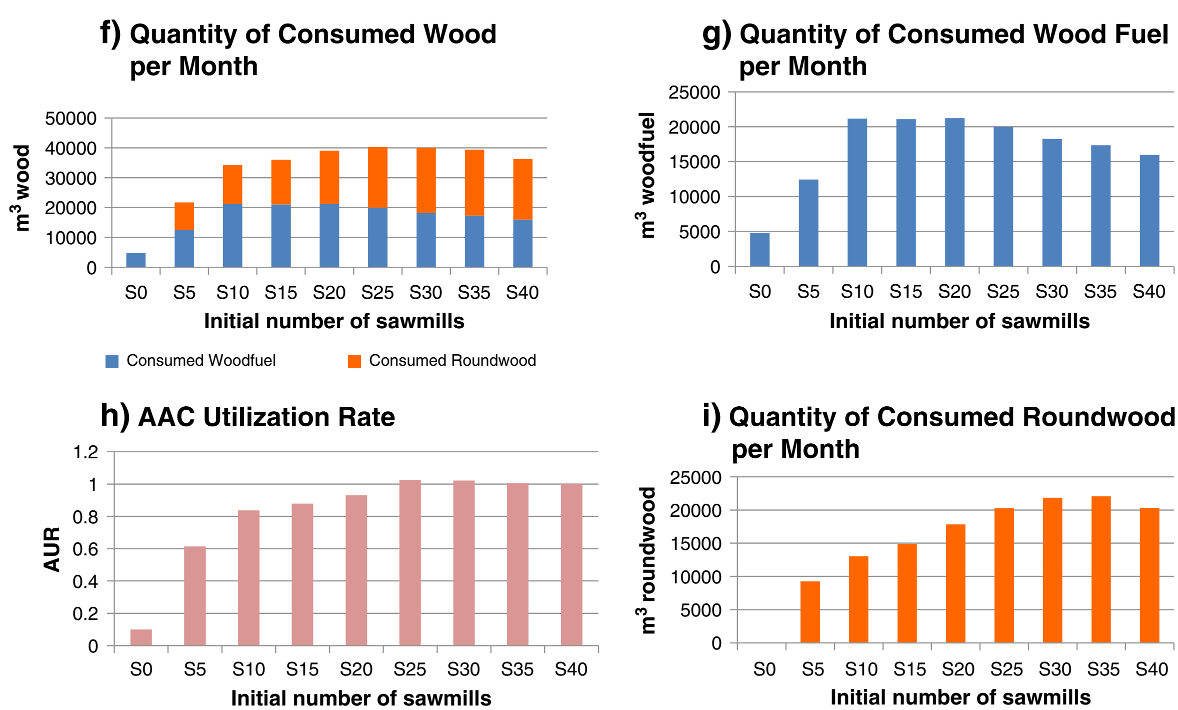

Fig. 11. Summed and individual consumed wood fuel and roundwood quantities per month and AUR in nine scenarios (years 5–20).

4.2. Model boundaries

There are different applicable criteria regarding how to set a market's scope or model boundaries; the choice should match the model's purpose. For the reasons we described in Section 2, we chose to focus on the Swiss canton Aargau, which had several consequences. Whereas in Switzerland, the geographical horizon of most small to mid-sized wood fuel consumers does not exceed a few kilometers, big consumers (e.g., pulpwood consumers) buy wood fuel on international markets. For big wood fuel consumers, being located inside Aargau's boarders might constitute an artificial geographical boundary, whereas for smaller consumers, it usually does not.

On the roundwood markets, the relevant geographical scope depends more on the product segment. Low quality, mass segment roundwood is mostly traded inside the canton's or country's borders, yet it is not uncommon for high quality products to be shipped internationally. However, Pajarola (2009), relying on Pauli et al. (2003), points out that in Switzerland, wood is mostly harvested in municipalities and then sold to local sawmills. Again, setting the model's scope equal to canton Aargau's boarders might not result in a fully appropriate geographical size for all cases, but it should be sufficient for the majority.

One of our basic intentions was to reach a better understanding of the market participants' behavior and interactions. This goal affected our choice of canton Aargau, because this model scope still enabled us to conduct qualitative interviews with market participants close to us. We plan to increase the model boundaries and include several cantons, and if possible the whole of Switzerland, once we resolve some performance issues.

4.3. Traded goods

The selection of goods being traded must take into account the model's purpose. In our case, a differentiation of roundwood and wood fuel was sufficient. For other purposes, it might be necessary to distinguish varying product qualities or between hard and soft wood. The needs of consumers applying wood fuel to energetic use also might diverge to some extent from consumers from the pulp and chemical industries. Furthermore, because harvesting hard and soft wood usually results in significantly different roundwood-to-wood fuel ratios (WFM), we calibrated the model with regard to canton Aargau's relative shares of hard and soft wood. Both roundwood and wood fuel traded in our model therefore represent "averaged products."

4.4. Agent classes and types

In accordance with the roundwood and wood fuel markets, we required at least one consumer agent class for each market. We prioritized modeling the wood fuel consumers, so there are more wood fuel consumer classes than roundwood consumer classes. For the agent typification, statistical classification algorithms might be used, but these required data were not available, so we relied on qualitative interviews instead.

4.5. Agent behavior

A key finding was the importance of the qualitative interviews conducted with market participants and especially non-industrial wood producers. The resulting data supported many of the findings of studies presented by Beach et al. (2005), Bohlin and Roos (2002), and Conway et al. (2003). Similar alignment might not arise for markets in which industrial wood production is predominant.

It is difficult to judge whether AHP is an adequate tool to describe market actors' decision behavior. We assume that for decisions made rationally and consciously, AHP might be adequate, whereas decisions based mainly on gut feelings might be more random in nature and thus not be adequately represented by AHP. There exists no single, agreed-on, best practice in the ABM community regarding how to implement human decision behavior algorithmically. Alternative, complementary approaches include the physis, emotion, cognition, and social status (PECS) model (Urban and Schmidt, 2001) or the belief, desire, intention (BDI) software model (Georgeff et al., 1998). This is one of the issues we would like to address in further studies more in depth.

4.6. Negotiation protocol

We faced difficulties with regard to how to model a geographically distributed interaction and negotiation protocol, where agents are located in space (or, more abstractly, on a plane), rather than meeting with all other agents in a virtual marketplace (a point). A geographically distributed negotiation protocol is closely related to agents' social network. We solved this issue by introducing the phone books (see "Agents and agent classes" section) and extending each agent's search radius incrementally when it remained dissatisfied with the outcome of a negotiation phase. Another difficulty was that wood traders act as both buyers and sellers of roundwood and wood fuel, and our suggested protocol needed to map these dual roles.

Defining the agent interaction protocol is perhaps the most important modeling step of ABM. Different negotiation protocols might lead to different simulation outcomes, but replacing one protocol with another for testing purposes is usually impossible, without having to rewrite substantial parts of the simulation code. In many financial market models, auction protocols serve to model interactions between agents; Pellizzari and Dal Forno (2007) compare the effect of different auction protocols to the simulation outcome of a clearly defined financial market. Auctions come close to the observed interaction between market participants in most financial or securities markets. Furthermore, in Switzerland, very high quality roundwood is often sold through on-site auctions, but medium to low quality roundwood and wood fuel is not. The suggested negotiation protocol thus represents the observed interaction between market participants better than an auction. Whereas for technical multi-agent systems, prior studies suggest a variety of negotiation protocols, the same cannot be said for ABM of human social systems.

5. Conclusions

We have presented an agent-based model of a Swiss wood market. With ABM, we can combine several important peculiarities of Swiss wood markets in a single, coherent modeling approach:

- *Agent decision behavior and interaction*: Other than price, factors such as friendship and mutual trust, as well as market participants' personality types, play a major role in the business relations between wood producers and consumers. Modeling individualized decision behavior and relations is one of ABM's core strengths. We added a friendship criterion in the agent decision process and assigned a corresponding friendship value to the agents' social networks. Agent types were modeled with varying weights applied to criteria in the AHP.
- *Market interdependencies and feedback loops*: Although wood production focuses on roundwood as its main product, wood fuel is a valuable side product. Markets for both goods are linked through temporal, spatial, and economic feedback loops, so a simulation approach such as System Dynamics or ABM is appropriate. We combined the sequential execution of the two markets, such that wood producer agents adjusted their relative output of both goods (WFM) and adapted market entry/exit thresholds. As a result, we could observe feedback loops in the sample scenarios.
- *Wood production constraints*: Wood production in Switzerland can adapt to significant increases in demand only to a limited extent, even in the long run. An upper bound for harvesting set by the AAC, limitations in space and territory, technological advances, ecological concerns, and a political agenda must all be considered when analyzing the long-term availability of wood. Our model covered some but not all of these aspects.

- *Spatial distribution of wood production and consumption*: A spatial distribution of production and consumption is explicitly, though simply, modeled; we have presented a corresponding negotiation protocol.

However, these points also turned out to be the most difficult ones to solve.

First, the definition of the model boundaries was challenging. In a first attempt, we chose the geographical boundaries of the canton of Aargau as the model boundaries. Yet not all wood produced inside Aargau is also processed in its geographical boundaries. Large sawmills in adjacent cantons buy wood from suppliers in Aargau. We hope to address this issue in further work by both increasing the model size and more fundamentally rethinking the criteria for defining such boundaries.

Second, with regard to geographical and territorial limitations, more realistic model assumptions might result if we could improve on the model's internal geographical representation, especially on transport routes.

Third, as we have argued, we offer no recommended best practices regarding how to model the decision-making processes of market participants and their interaction or negotiation algorithmically. A further, perhaps even more important problem is that empirical data on market participants often are not available and must be gathered. We plan to collect more empirical data about market participants' decision behavior, their individual preference structures and utility functions, and the operational cost structures both on the supplier and consumer side. To do so, we will use companion modeling (Bousquet et al., 2005), laboratory experiments and role-playing games. Overall, considering these options for further research, we remain convinced that ABM is worthy of further pursuit.

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