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Abstract

Adaptation is necessary to cope with or take advantage of the effects of climate change on socio-ecological systems. This is especially important in the forestry sector, which is sensitive to the ecological and economic impacts of climate change, and where the adaptive decisions of owners play out over long periods of time. Relatively little is known about how successful these decisions are likely to be in meeting demands for ecosystem services in an uncertain future.

We explore adaptation to global change in the forestry sector using CRAFTY-Sweden; an agent-based model that represents large-scale land-use dynamics, based on the demand and supply of ecosystem services. Future impacts and adaptation within the Swedish forestry sector were simulated for scenarios of socio-economic change (Shared Socio-economic Pathways) and climatic change (Representative Concentration Pathways, for three climate models), between 2010 and 2100.

Substantial differences were found in the competitiveness and coping ability of land owners implementing different management strategies through time. Generally, multi-objective management was found to provide the best basis for adaptation. Across large regions, however, a combination of management strategies was better at meeting ecosystem service demands. Results also show that adaptive capacity evolves through time in response to external (global) drivers and interactions between individual actors. This suggests that process-based models are more appropriate for the study of autonomous adaptation and future adaptive and coping capacities than models based on indicators, discrete time snapshots or exogenous proxies. Nevertheless, a combination of planned and autonomous adaptation by institutions and forest owners is likely to be more successful than either group acting alone.

Keywords: adaptive capacity, agent-based model, climate change, ecosystem services, land owner decision-making, scenario

1 Introduction

Adaptation is needed to offset or exploit the effects of climate change on socio-ecological systems. This is especially the case for forestry, a sector that is highly sensitive to the ecological and economic impacts of climate change (Hanewinkel et al., 2013; Keskitalo, 2011; Lindner et al., 2010), and where timespans of several decades exist between planting decisions and harvesting. Forestry also has great potential for climate change mitigation, through carbon sequestration and the use of wood biomass as a renewable energy source. However, competition for land with agriculture is likely to intensify as production potential changes and as food demands grow, further altering the distribution and composition of forests and the levels of ecosystem services that they provide (Alexandratos and Bruinsma, 2012; Buonocore et al., 2012; Tilman et al., 2001; Zanchi et al., 2012). However, despite the importance of managed forests and their sensitivity to global change, relatively little is known about how the sector can or will adapt to future change drivers.

The concept of 'adaptive capacity' has been used to evaluate the generic, sectoral and cross-sectoral potential for adaptation or adaptive actions (e.g. Acosta-Michlik et al., 2013; IPCC, 2012; Johnston and Hesseln, 2012; Lindner et al., 2010; Sharma and Patwardhan, 2008). The estimation of this capacity is commonly implemented through the use of indicators (e.g. income inequality, literacy rate, R&D expenditure, female activity rate), aggregated into adaptive capacity indices, which are, inevitably, specific to the (temporal) context in which they are defined (Acosta-Michlik et al., 2013; Metzger et al., 2006; Vincent, 2007). While the assessment of past and present adaptive capacity through such indices is generally accepted, no reliable method currently exists for their projection into the future, which requires consideration of complex system dynamics affecting indicator variables (Araya-Muñoz et al., 2016; Vincent, 2007). Furthermore, while some studies have considered present capacities in combination with impact projections to assess future vulnerability (Lung et al., 2013; Metzger et al., 2006; Preston et al., 2008), the (unquantified) uncertainty inherent within these approaches limits their utility (Lung et al., 2013).

A major constraint for indicator-based approaches to adaptation is the role of behavioural and cognitive factors (e.g. beliefs, values, experiences) in shaping adaptive decisions (Blennow, 2012; Niles et al., 2016; Thompson and Hansen, 2013; Vincent, 2007; Zehr, 2015). These factors are very difficult to incorporate in quantitative assessments of adaptive capacity because of their temporal dynamics and sensitivity to individual, socio-cultural and other, often subjectively understood, human conditions (Grothmann and Patt, 2005; Roncoli et al., 2009). Process-based models of socio-ecological systems have, however, the potential to better explore future adaptation processes because they

account not only for the system states, but also the dynamics that determine state changes (Brown et al., 2016a).

In land-based sectors, adaptive (or maladaptive) state changes involve changes in land cover and/or management strategies (i.e. land-use change), which are determined by the decisions of land managers. While these decisions are frequently modelled, at least in studies covering small geographical extents (e.g. Matthews et al. 2007; An 2012), work remains to be done in exploring a full range of behavioural processes, climate impacts and adaptive responses (Brown et al., 2017). In forestry, the *capacity* for adaptation to future environmental conditions under different management strategies has been evaluated (Le Goff et al., 2005; Seidl and Lexer, 2013; Valladares, 2008), but the behaviour and objectives that constitute the decision-making processes of forest owners about such management strategies (Andersson and Gong, 2010; Ingemarson et al., 2006; Vulturius et al., in review) have seldom been considered in such assessments. Instead, adaptation has generally been treated as a rational, economic process in which forest owners maximise profit on the basis of clear alternative strategies (e.g. Hannah et al., 2011; Morgan and Daigneault, 2015; Rose, 2014; Thompson and Hansen, 2013; Brown et al., 2017). Only Rammer and Seidl (2015) simulated adaptive management to climate change in forest landscapes by coupling human and environmental systems using agent-based models (ABM; i.e. models in which the individual behaviour of agents, such as land owners, is represented explicitly). To our knowledge, in no other cases have models been used to assess the suitability of particular forest management strategies for climate change adaptation given their socio-ecological, as well as economic, implications. Furthermore, despite the importance of regional and global drivers of forest change such as competition for land or societal demands for ecosystem services, climate change has only been assessed separately in models of adaptive forestry systems (e.g. Hannah et al., 2011; Morgan and Daigneault, 2015).

There is a clear need to improve understanding of forestry adaptation processes, the drivers and consequences of forest owner decisions, and the ability of different forest management strategies to meet societal requirements under future climatic and socio-economic conditions. Without these advances, management of the forestry sector by individual owners and organisations will be hindered by unexplored uncertainties and unexpected impacts. We propose a novel approach to adaptation assessment based on a land-use ABM. The model accounts for land owner behaviour, ecosystem service supply and demand, and the effects of climate change on land productivity. We apply this model to the Swedish forestry sector, including competition for land with agriculture. Simulations were undertaken for a range of socio-economic and climatic scenarios to evaluate the competitiveness of different forest management strategies and the ability of forest owners using them to cope with the scenarios as they develop through time. The model therefore illustrates potential courses and

consequences of autonomous adaptation (i.e. "adaptation in response to experienced climate and in response to experienced climate and its effects, without planning explicitly or consciously focused on addressing climate change" (IPCC, 2014), p. 1759) amongst forest owners, and highlights key behavioural processes that determine the adaptive capacity of the sector as a whole.

2 Methodology

We used the CRAFTY-Sweden model (Blanco et al., 2017; ODD protocol in Appendix A) to explore adaptation to global change in the Swedish forestry sector. CRAFTY-Sweden is an applied extension of the CRAFTY ABM framework (Murray-Rust et al., 2014; code and documentation available via https://www.wiki.ed.ac.uk/display/CRAFTY/Home) that represents large-scale land-use dynamics based on the demand and supply of ecosystem services (Fig.1). The services represented here are timber (from several different tree species), carbon sequestration, biodiversity, recreation, cereal and meat production (from agriculture). Demands are defined exogenously while supply depends on land productivity (that varies through time and space), the behaviour of modelled agents, and the infrastructure present at a given location.

Agents include different types of forest owners and farmers characterised by their objectives and associated management practices (Blanco et al., 2017), with farmer agents included in order to simulate the competition for land between forestry and agriculture. Geographical space is represented as a grid of cells across the whole of Sweden at a resolution of 1km². Each cell has defined levels for a range of capitals representing the availability of infrastructure and land productivity (which depend upon socio-economic and climatic scenarios as defined below and, more fully, in Blanco et al. 2017). A cell is managed by a single agent, which uses the capital stock available within the cell to provide services according to a production function (see Section 2.2). The competitiveness of a given level of service provision can be calculated based on societal demands and overall supply levels through 'benefit' functions, which describe the monetary and non-monetary value to society of service production. The value of future service production is estimated on the basis of current environmental and market conditions. Agents use this value to decide whether to abandon their land, change management or relinquish land to a different owner. This results in changes in land management strategies, i.e. (autonomous) adaptation, and in land-use change if the type of forest or farm also changes.
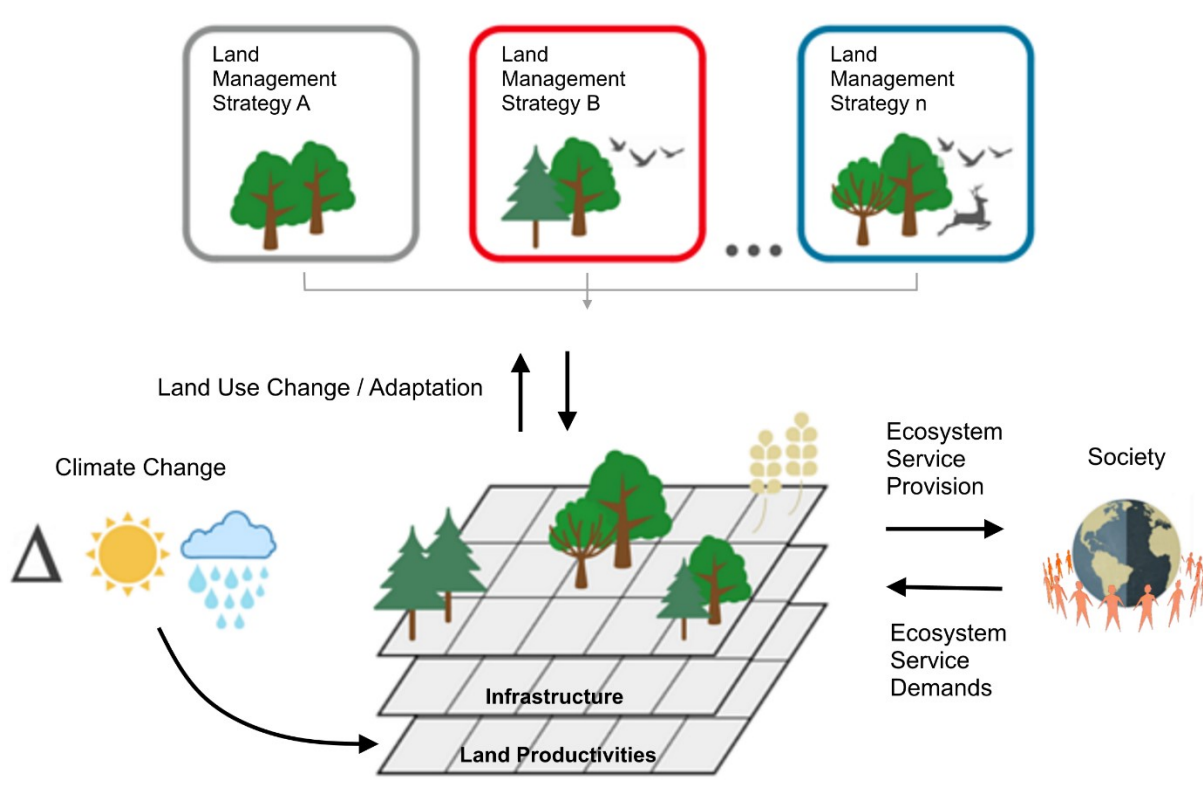
Fig. 1. Schematic representation of the drivers and their interactions in the CRAFTY-Sweden modelling approach. Driven by changes in environmental conditions (i.e., climate change) and societal demands for services, land managers adapt their management strategy, or the type of land use is changed.

In the following, we outline the land owner typology from which modelled agents are drawn, and the production and behavioural mechanisms. We then describe the approach to scenarios and the analysis of simulation results. For further detail regarding CRAFTY-Sweden see the ODD protocol (Appendix A) and Blanco et al. (2017).

2.1 Land owner typology

Forest owners are classified into five overarching management roles according to their objectives (productionist (economically-oriented); multi-objective (economic, environmental and social objectives); recreationalist (recreational objectives); conservationist; and passive (no clear objectives)) and associated management preferences. For further details on the characteristics of management roles see Blanco et al. (2015). Within each overarching management role, management preferences were based on forest type (defined by species composition), thinning programme and forest rotation period. Forest types were assigned to each management role on the basis of: a) existing forest stand compositions under different forms of management (Swedish Forest Agency, 2015), and b) adaptation measures to climate change known to be available to each management role that

consider species composition, number of thinnings and rotation lengths (Felton et al., 2016; Jonsson et al., 2015) (Blanco et al., 2015; Duncker et al., 2012a). Assigned forest types were pine (*Pinus sylvestris*), spruce (*Picea abies*), boreal broadleaf (*Betula pendula, B. pubescens, Alnus incana, A. glutinosa, Populus tremula*), nemoral broadleaf (*Fagus sylvatica, Quercus robur, Fraxinus excelsior, Ulmus glabra, Tilia cordata, Carpinus betula*), and combinations of these, resulting in 17 forest owner types (Table 1). The management and behavioural mechanisms of owner types are described in sections 2.2 and 2.3.

According to current levels of agricultural production (Swedish Board of Agriculture, 2009) and the prevalent management intensities in Sweden (Institute of Environmental Studies, 2015), farmer agents were classified according to the main services provided (cereal or meat production) in combination with their management role (commercial or non-commercial).

Table1. Possible combinations of overarching forest management roles (columns) and forest types (rows) found to be managed under such roles in Sweden. Each combination constitutes a management strategy

	Productionist	Multi-objective	Recreationalist	Conservationist	Passive
Pine					
Spruce					
Pine-Spruce					
Pine-Boreal Broadleaf					
Spruce-Boreal Broadleaf					
Boreal Broadleaf					
Nemoral Broadleaf					

2.2 Land owner service production

The production of agricultural services was modelled on an annual basis. Forestry services are however dependent on forest age and hence are less consistent through time (e.g. the changing provision of recreation, and the highly irregular provision of timber when a forest is thinned or felled). Additionally, climatic change can affect service supply by acting on productivities.

The production of a service within a cell was modelled as being dependent on the agent's productive ability, cell capitals, the annual climate-induced change in cell capitals, and the capital sensitivities of the agent type. To reflect individual variability, each agent's productive ability and capital sensitivity levels were randomly drawn from uniform distributions around the agent type's mean values (Arneth et al. 2014). The following section describes the main elements underpinning the calculation of the production of different ecosystem services.

Timber production is defined by a forest owner type-specific function that determines timber growth given a forest's age. The ProdMod model (Eko, 1985) was used to generate timber growth curves for each owner type given their management preferences (including different parameters relating to forest planting and thinning operations) (Table A.5). These curves were generated under ideal environmental conditions and values were subsequently varied to reflect capital levels. Production functions for above-ground carbon storage were also calculated using ProdMod. Biodiversity production was defined as a function of forest age (using the generation of coarse woody debris with age) (Blanco et al., 2015; Duncker et al., 2012b; Gamfeldt et al., 2013; Koskela et al., 2007; Marchetti, 2004), tree diversity and management practices undertaken by each owner type (e.g. woody debris removal). Production of recreation was also determined by forest age and management practices, but also depended on accessibility and the types of trees present (i.e. conifer vs broadleaf, and monoculture vs mixed) (Edwards et al., 2012). Full details of all production functions are given in Appendix A.

With the exception of timber, all services were modelled as being produced and supplied on an annual basis. Timber was supplied only when forests were clear-felled, at an age that depended on site productivity and owner objectives. These ages were set based on recommendations and legal regulations in Sweden designed to ensure that productive potential is utilised (Kunskap Direkt, 2015; Löf et al., 2009; Rytter et al., 2008), and varied according to owner objectives (e.g. conservationists would fell substantially later than productionists to maximise biodiversity). Felling age was determined whenever an agent was allocated to a cell by randomly drawing a value from an agent type-specific Gaussian distribution extending between the minimum and maximum permitted felling ages. Felling age-related parameters are given in Table A.5. Upon felling, timber is harvested and carbon stored in the standing timber is removed from the national pool, to avoid assumptions about the different lifetimes of the various products or uses to which timber is put.

The productive abilities and capital sensitivities of agricultural agents were adjusted so that baseline (mapped) agent type locations and capital values (Blanco et al., 2017) allowed production of cereal and meat equal to that reported in Sweden by the FAO (2015). The production of non-commercial agricultural agents was set at 0.6 times that of the commercial agents to reflect approximate differences in production potentials across equivalent classes in Van Asselen and Verburg (2013).

2.3 Competition for land

Competition for land occurs at every timestep, on a random subset (1%) of occupied and any available (unmanaged) cells (to represent a limited supply of land and search-ability of new owners). Farm land could be taken over by other agents each year because agricultural management is simulated on an annual timescale. For forest owners, however, we assumed no abandonment or change in management approach until the forest reaches maturity, so that forest agents can recover their initial investment. At this point, an alternative agent with higher competitiveness than the incumbent agent could take over the land, resulting in one of two outcomes:

1. If the new agent's forest type matches that already standing in the cell, it will inherit the production functions of the former owner, as the effect of changing management of a forest once maturity is reached is negligible. Age of felling was however adjusted to meet the service production objectives of the new agent. Because passive owners were assumed to acquire forests through inheritance, they followed this system exclusively and do not compete for unmanaged land.

2. If the new agent was a farmer or a forester not meeting the above criteria, the standing forest was clear-felled and the land was converted to farmland or to newly-planted forest.

Forest owners plan their planting and management according to (non-climate sensitive) data that indicate potential tree growth according to site conditions. In reality, some owners may consider climate change and risk spreading, but this has been shown not to be a generalisable trait of Swedish forest owner decision-making (Blennow et al., 2012). Hence, the expected service production levels of both farmers and foresters were evaluated under current conditions. Expected forest service production levels were evaluated for the (future) year of felling (current conditions still being factored into the assessment). Agent competitiveness was calculated on the basis of expected service production using a 'benefit function', which assigned a value to production on the basis of the societal demand level for each service. The value of expected forest service production was time-discounted by the time remaining until planned forest felling age to reflect preferences for shorter-term returns. Resultant values were normalised by current per-cell demand levels for each service to ensure equivalence between services measured in different units. The benefit function also contained a weighting factor representing the assumed importance to society of meeting demand levels for each service. For further details regarding benefit functions and parameter values used see Table B.1 and Blanco et al. (2017).

Following the calculation of agent competitiveness, unmanaged cells were assigned to the most competitive agent. Managed cells, however, were assigned according to the following procedure.

First, if the existing owner's competitiveness fell below its 'giving-up' threshold (the minimum value acceptable to that agent as a return on its management), the cell was abandoned. If an alternative owner's competitiveness was greater than the existing owner's by a value larger than the existing owner's 'giving-in' threshold (representing the returns the existing owner was willing to forego in order to persist with their management), then the cell was assigned to the alternative owner, subject to the time constraints described above. Giving-up and giving-in thresholds were drawn from agent type-specific Gaussian probability distributions to represent individual differences in dedication to land use (Murray-Rust et al., 2014). Differences in individual sensitivity to market conditions (e.g. due to savings or other resources) were also represented, by type-specific giving-up probabilities, defining the (0,1) probability of an agent abandoning their cell should their competitiveness fall below their giving-up threshold. Mean giving-in and giving-up thresholds, and giving-up probabilities, are shown in Table B.1.

2.4 Scenario analysis

Five future scenarios were defined by combining the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011) (i.e. potential radiative forcing pathways resulting from different greenhouse gas atmospheric concentrations) with the Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2014) (i.e. socio-economic scenarios integrated within a space of challenges to climate change adaptation and mitigation). RCP4.5 was combined with SSPs 1, 3 and 4, and RCP 8.5 with SSPs 3 and 5, in order to explore coherent combinations of emission and socio-economic futures (Carter et al., 2015). Each RCP was also simulated with three different climate models to capture some of the uncertainty across climate models. Each climate model-RCP combination consisted of a different set of climate-induced annual productivity changes.

The ecosystem model LPJ-GUESS (Smith et al., 2001) was used to simulate forest dynamics during 2010-2100 using climate projections from the Global Circulation Model - Regional Circulation Model ensembles (hereupon 'climate models') EC-Earth-RCA4, IPSL-RCA4 and NorESM-RCA4 for RCPs 4.5 and 8.5 from the EURO-CORDEX project (Jacob et al., 2014; Jones et al., 2011). Land productivity projections were calculated using LPJ-GUESS outputs. Following land-use and European SSP storylines from Engström et al. (in review) and Kok et al. (2015), SSPs differed in: a) future demands for ecosystem services, b) the importance to 'society' of meeting demands for each service, c) distributions of giving-in and giving-up thresholds, and d) the potential for farmland to displace forest land (Table 2 and Table B.1 for scenario-dependent parameter values).

CRAFTY-Sweden simulations were run for the 2010-2100 period at an annual temporal and 1km^2 spatial resolution. The model was calibrated to produce minimal short-term (decadal) changes in land management under constant levels of demand and productivities, so that the effects of long-term forest management and scenario conditions could be isolated (see Blanco et al. 2017). The model was then run under these static conditions for the period 2010-2100 to produce a reference scenario. In order to measure the effect of model stochasticity, 32 simulations of the reference scenario were run under different random seeds, but identical parameterisations. Finally, each climate model-RCP-SSP combination was run once (under one random seed).

Table 2. SSP scenario descriptions in relation to ecosystem service demands, importance to society of meeting service demand levels, and giving-up and giving-in thresholds (reflecting willingness to abandon land and tolerance to competition respectively). For parameter values see Appendix B.

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Reference	Demands for all services remain unchanged through time. Higher importance of meeting demands for pine and spruce timber than for boreal and nemoral broadleaf timber. Medium importance for all other services. More profit-oriented owner types, being more sensitive to benefit values, have higher giving-up thresholds and lower giving-in thresholds. Farmland cannot displace forestry.
SSP1 "Sustainability"	Demands for timber and carbon sequestration grow until the end of the century. Demands for biodiversity and recreation are stable until 2050 and grow thereafter. Cereal and meat demands grow until the middle of the century and slowly decrease afterwards. Farmland cannot displace forestry. Compared to the Reference, higher importance for carbon sequestration, biodiversity and recreation, and lower for cereal and meat. Similar giving-up and giving-in thresholds as under the Reference.
SSP3 "Regional Rivalry"	Demands for timber, carbon sequestration, biodiversity and recreation decrease, and cereal and meat demands grow, until the end of the century. Compared to the Reference, lower importance of meeting demands for carbon sequestration, biodiversity and recreation, and higher for cereal and meat. Lower giving-up and higher giving-in thresholds than under the Reference Farmland can displace forestry.
SSP4 "Inequality"	Demands for timber and carbon sequestration grow (less than under SSP1-RCP4.5) until 2050, and decline thereafter. Demands for biodiversity and recreation decrease throughout. Demands for cereal and meat grow until the middle of the century (less than under SSP1-RCP4.5 for cereal, but equally for meat) and stabilise thereafter. Compared to the Reference, lower importance of meeting demands for timber, carbon sequestration, biodiversity and recreation, and higher for cereal. Similar giving-up and giving-in thresholds as under SSP3-RCP4.5. Farmland cannot displace forestry.
SSP5 "Fossil-fuelled development"	Demands for timber, carbon sequestration, decline during the first half of the century and grow back to initial levels afterwards. Biodiversity and recreational demands decrease over the century, but at a higher rate during the first half. Demand for cereal grows substantially during the first half of the century and remains relatively stable thereafter. Meat demands more than doubles in the course of the first sixty years and slowly declines thereafter. Similar to SSP3-RCP4.5, but higher importance of meeting demands for meat. Similar giving-up and giving-in thresholds as under the Reference. Farmland can displace forestry.

2.5 CRAFTY-Sweden outputs

The model outputs presented here relate to forest owner competitiveness and *coping ability*, which together determine the course of autonomous adaptation. To evaluate competitiveness, agent types were mapped for every year during 2010-2100, and are presented as ranges of owner type numbers defined by maximum and minimum values among climate models plotted for each scenario. Coping ability is assessed using a coping index, which reflects whether a particular management strategy is at least as competitive under an uncertain future global change scenario (defined by the scenario space) as under present conditions (defined by the reference scenario). Coping index levels through time were calculated by assigning a yearly score to each management strategy depending on the number of scenario simulations (out of 15), which return a greater number of owners implementing that strategy than under the reference scenario. A point was scored for every simulation where numbers were larger than or equal to those under the reference, and a point was subtracted if they were smaller. The coping index was also assessed at the level of forest owner functional roles by aggregating index levels for management strategies belonging to each role, weighted by the maximum number of agents achieved under a simulation at each point in time.

3 Results

3.1 Competitiveness

In general, we see substantial changes throughout the simulations with distinct trajectories in the numbers of owners implementing the different management practices, despite uncertainty generated by the climate models (Fig. 2). All management strategies had different levels of competitiveness under different sets of objectives, given the same forest type. Multi-objective owners were always the most competitive managers for a particular forest type, while passive owners were always the least competitive. Other owners differed in relative competitiveness depending on their objectives and forest type. Owners managing forests containing pine or spruce showed an initial increase or no change in numbers until about 2025, followed by a decrease that lasted 10-25 years, and a subsequent increase that would either continue until the end of the simulation, level off, or lead to an eventual decrease. The decrease happening after 2025 was due to substantial forest felling, a legacy effect of a forest planting peak that occurred in Sweden approximately 70 years earlier (Blanco et al. 2017). Recreationalists and conservationists managing nemoral broadleaf forests showed somewhat similarly-shaped trajectories, while passive owners managing these forests differed, being stable in number until 2065-2080 and decreasing thereafter. There were very few owners managing boreal broadleaf forests, with 2010 numbers ranging from 1-19 depending on the owner type, and results

tended to diverge with time (Fig. A.1). Generally, farmers increased during the first half of the century, followed by more divergence.
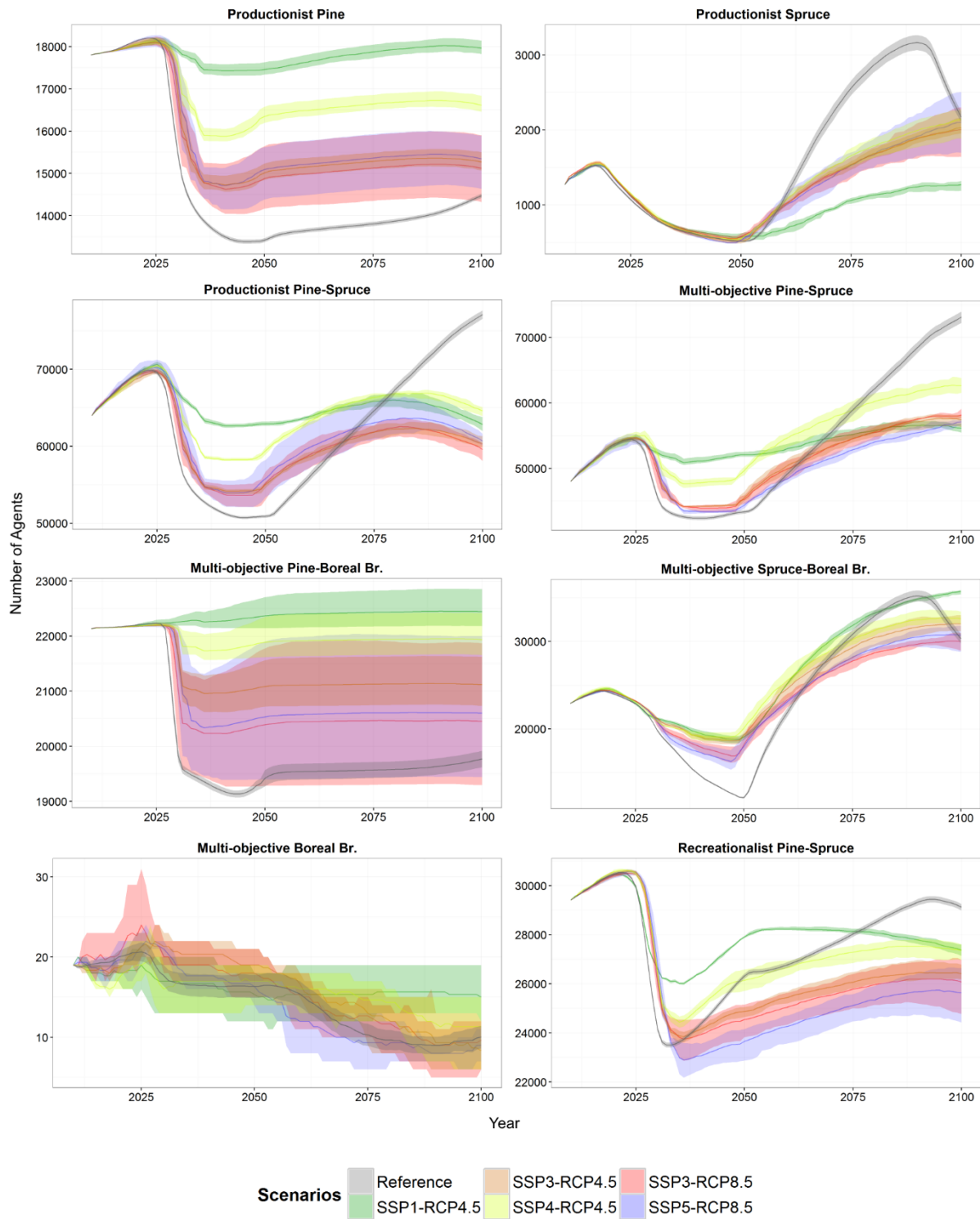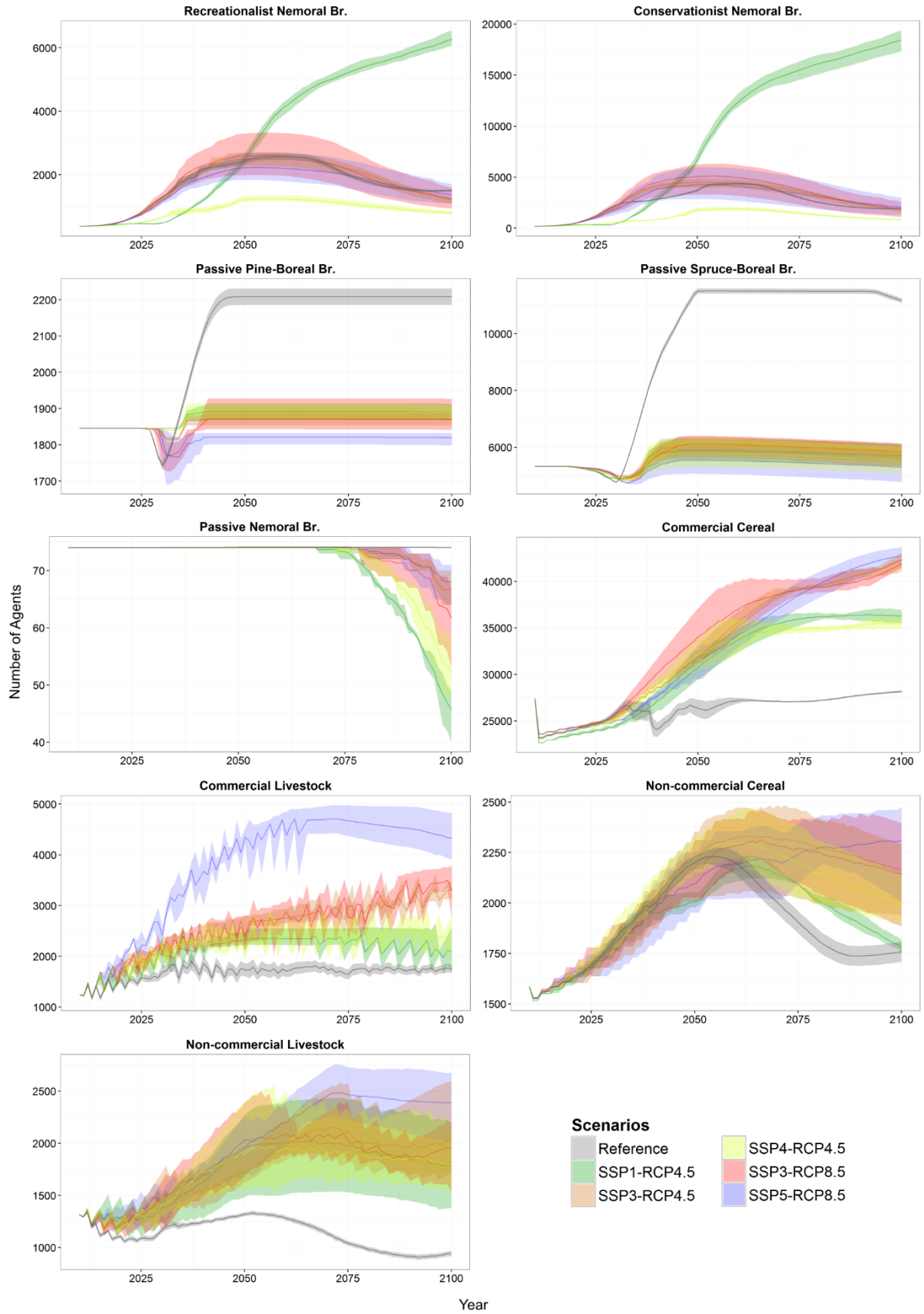
Fig. 2 Ranges in the number of agents for each management strategy through time, for the three climate models (shaded areas) and their means (solid lines) for the five SSP-RCP combinations, and the Reference scenario

(mean of 32 variations of random seed). Management strategies implemented by ten agents or less throughout the simulations are displayed in Fig. A.1.

Most forest owner types increased in number under SSP1-RCP4.5, followed by SSP4-RCP4.5, while commercial farmers became less numerous under these scenarios. The results for SSP3-RCP4.5 and SSP3-RCP8.5 tend to cluster, as do the results for SSP5-RCP8.5, to a lesser extent. Productionist pine and multi-objective pine boreal broadleaf owners only maintained numbers under SSP1-RCP4.5, while productionist spruce owners increased in all scenarios except SSP1-RCP4.5. Productionist pine-spruce, however, only increased under the reference scenario. Multi-objective owners managing pine-spruce and spruce-boreal broadleaf forests always achieved higher numbers in 2100 than 2010 despite an initial decrease in numbers for most scenarios. Passive owners managing pine-boreal broadleaf and spruce boreal broadleaf rebounded from their initial decrease approximately 15 years earlier than multi-objective owners managing the same forest types. These passive owners eventually increased numbers towards the end of the century compared with 2010 under all scenarios (except SSP5-RCP8.5 for passive pine-boreal broadleaf), with maximum numbers under the reference scenario. Similarly, recreationalist pine-spruce owners recovered from an initial large decrease 15-20 years earlier than productionist and multi-objective owners of the same forest type, although never reaching their 2010 numbers. Recreationalist and conservationist nemoral broadleaf, in contrast, had higher numbers at the end of the century under all scenarios, especially SSP1-RCP4.5, while the opposite was true of passive nemoral broadleaf owners.

3.2 Ability to cope with global change

We find substantial variability in the coping ability of forest owners through time (Fig. 3). Generally, productionist and multi-objective owners have higher coping index values over longer time periods than other owner types. Nevertheless, both had lower levels of coping until approximately 2025, followed by relatively high levels until the 2060s and a decrease thereafter. During their final decline in coping ability, levels dropped slightly less for multi-objective owners than for productionists, and grew again slightly during the final decade. Coping levels of recreationalists and passive owners increased until approximately 2030, with coping ability then falling gradually for recreationalists and abruptly for passive owners. Finally, conservationist coping fell to relatively low levels during the first third of the simulation, before recovering thereafter.
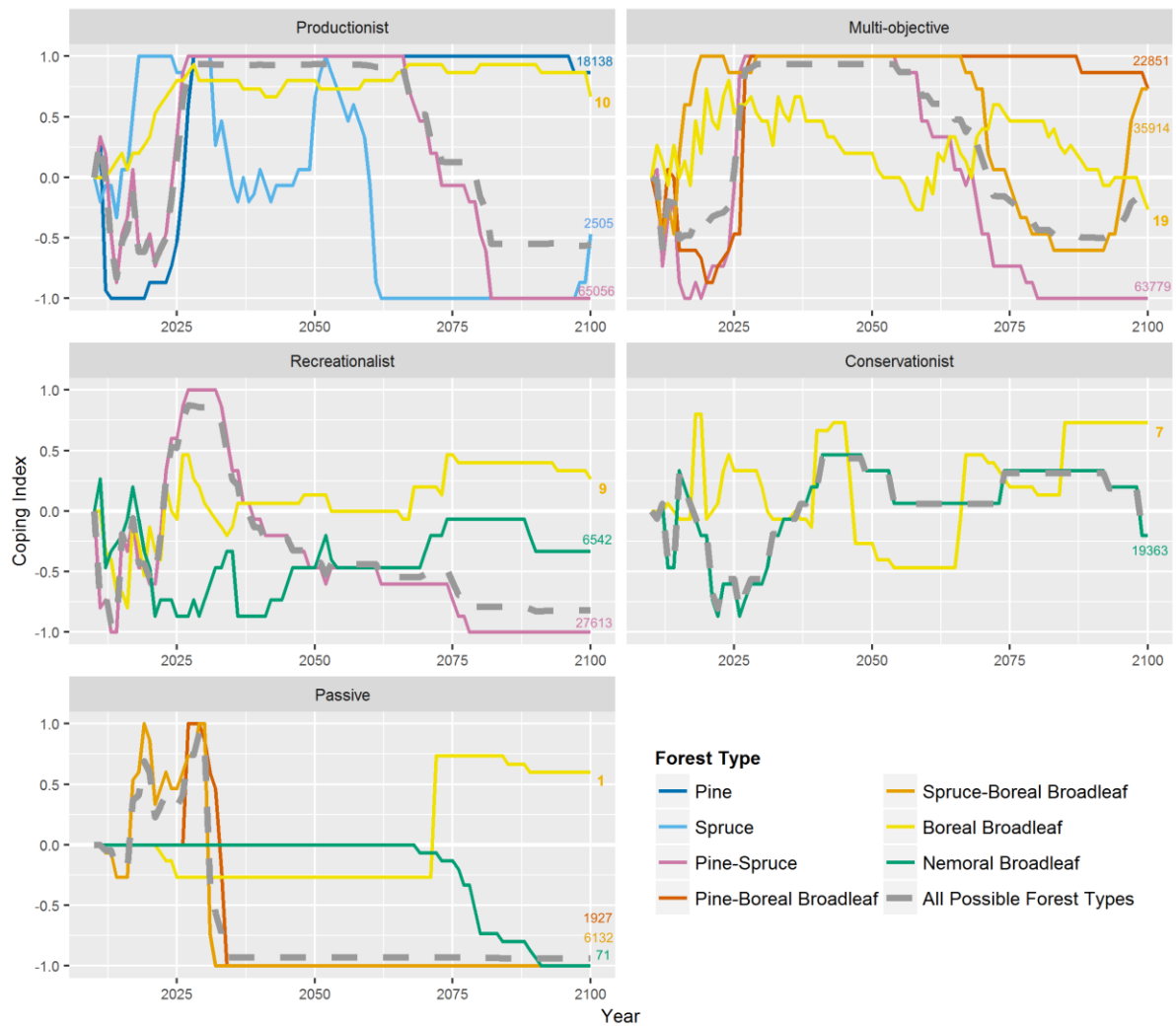
Fig. 3. Change in the forest owner type coping index through time. Each panel shows the coping levels of a forest owner functional role in managing different forest types (i.e. the coping ability of a forest owner under different management strategies) (solid lines), and the mean coping levels of each functional role weighted by the number of agents of that role managing each forest type each year (dashed lines). The number of agents implementing each management strategy in 2100 is shown to the right of each solid line. Results are calculated across all simulations, and so do not have associated ranges as in Figure 2.

These dynamics differed significantly across forest types. For instance, pine-spruce owners always experienced large decreases in coping levels from a peak in the 2020s, whatever their objectives. Pine, pine-boreal broadleaf, and boreal broadleaf forest owners were more robust, having medium-to-high levels of coping ability from the mid-2020s onwards, with the notable exception of passive owners of pine-boreal broadleaf forests. Nemoral forest owners had medium-to-low coping abilities throughout, with passive owners again faring the worst.

4 Discussion

The results demonstrate that competitiveness and coping ability are indicative of the suitability of strategies for climate and global change adaptation, and the capacity of forest owners to successfully implement those strategies under an uncertain future. The approach accounts for a range of ecosystem services provided through the implementation of different forms of forest and farmland management, and so goes beyond simple yield or economic-based assessments. It also allows an exploration of the potential future development in ecosystem service supply to assess the overall capacity of the forest sector to adapt to climate change.

The results suggest that substantial forest felling will occur in Sweden prior to 2050 as a consequence of concentrated planting in the past (Blanco et al., 2017). This felling contributes to a decline during this period in the numbers of owner types managing conifer or conifer-broadleaf forests. These rapid changes demonstrate the importance of large-scale felling events as windows of opportunity to incorporate new forest management strategies for adaptation to a changing global context. Hence, institutions such as national or regional governments, supra-national institutions or owner associations that administer top-down measures (e.g. information dissemination, awareness creation) can maximise their ability to trigger effective adaptation by targeting these periods. However, this requires advance planning as well as avoidance of new waves of planting that increase vulnerability in the supply of ecosystem services associated with uneven age distributions (Blanco et al., 2017; Rammer and Seidl, 2015).

After the initial felling period, higher rates of forest planting and competition for land occur. These rates are strongly dependent on assumptions about climatic and socio-economic change. During this later period, the majority of forest owner types were most competitive under the SSP1-RCP4.5 scenario largely due to the greater demands for forest services, the higher importance attached to meeting these demands, and lower demands for food. For similar reasons, commercial cereal and commercial livestock farmers were much more competitive under SSP3-RCP4.5, SSP3-RCP8.5 and SSP5-RCP8.5. The similarity between the agent types in SSP3-RCP4.5 and SSP3-RCP8.5 indicate a relatively low impact of climate change on forest owner competitiveness compared to that of behavioural attributes or societal demands. This is largely consistent with previous research suggesting that future socio-economic conditions are more important than climate change for land-based sectors (Brown et al., 2015; Brown et al., 2016b; Harrison et al., 2015; Harrison et al., 2016). Nevertheless, in many cases, uncertainty ranges for the number of agents were substantially larger for RCP8.5 than for RCP4.5, which arises from the larger differences in productivity between climate models in RCP8.5 than in RCP4.5.

Boreal broadleaf forest owner numbers remained very low throughout all simulations, suggesting that planting boreal broadleaf forests alone (i.e. not in combination with other forest types) is not a good way of adapting to future global change in Sweden. However, the low numbers of such forests in all scenarios means that few other conclusions can be drawn regarding owners of these forests. In contrast, recreationalists and conservationists managing nemoral broadleaf forests experienced substantial growth in numbers in spite of starting at relatively low initial numbers (371 and 180 respectively). Their substantial increase was mainly caused by the gap between supply and demand for nemoral broadleaf timber being relatively large throughout the simulations (Blanco et al., 2017). Furthermore, the high importance attributed to meeting demands for carbon storage, biodiversity and recreation in SSP1-RCP4.5 relative to other scenarios made these owner types considerably more competitive in SSP1-RCP4.5. Taken together, these results demonstrate the importance of changes in the demand and supply levels of forest ecosystem services in determining future land use change; a system component that is rarely considered in the current generation of forest sector models.

Most owner types whose forests underwent major felling during the first half of the century experienced lower rates of felling in SSP1-RCP4.5, followed by SSP4-RCP4.5, despite demands for timber being larger in these scenarios. This is mainly explained by higher demands for carbon storage, biodiversity and recreation, which are supplied at higher levels in older forests, under these scenarios, and by the relatively high importance given to meeting demands for these services compared to demands for timber. Large scale felling events concentrated within a short time period can determine the competitiveness of owner types such as productionist pine or multi-objective pine-boreal broadleaf under different scenarios. Others (for example pine-spruce forest owners in SSP1-RCP4.5), can have a higher competitiveness during the felling period, but become less competitive when the competition process is more intense, indicating the context-dependency of competitiveness.

The large variability in coping ability of most forest management strategies throughout the simulations was also caused by contextual factors such as the magnitude of past large-scale felling events, the magnitude of unmet demand for forest services, or the intensity of competition. Once again, these results indicate that both coping ability and competitiveness are dependent on past events as well as the current environmental and socio-economic situation. This suggests that the suitability of management strategies for autonomous adaptation is not an inherent, static characteristic of the system, but is dependent on the change in socio-environmental interactions through time. Therefore, the application of models capable of representing these interactions, as demonstrated here, illuminates important system-level emergent behaviours that might otherwise be hidden.

The success of different management strategies is also dependent on spatial characteristics (e.g. land productivity, infrastructure), as illustrated by regional differences (across Sweden) in changes in management strategies throughout the simulations (see Blanco et al., 2017). Although the impact of climate change on productivity did not substantially affect the competitiveness of management strategies in this study, it is likely that climatic change would determine the appropriateness of strategies in other areas of the world (e.g. Gauthier et al. 2014; Hannah et al. 2011; Pardos et al. 2015; Temperli et al. 2012). Thus, we can conclude that the suitability of strategies for autonomous adaptation is a dynamic characteristic of the system that is dependent on spatio-temporal contexts. Consequently, the implementation of adaptive management throughout stand rotation periods (i.e. monitoring and adjusting silvicultural operations such as thinning) (Pukkala and Kellomaki, 2012), may contribute to the successful adaptation of forests to future global change.

Moreover, the dynamic nature of the suitability of management strategies for autonomous adaptation indicates the need to re-evaluate the approaches currently used to study the adaptive/ coping capacity of individuals and their management strategies in socio-ecological systems. This is especially so in sectors such as forestry, where the decisions of owners and the implementation of strategies are time-decoupled from the provision of ecosystem services. Again, process-based models may therefore be a more appropriate method of studying autonomous adaptation and future adaptive/ coping capacity than models that project these capacities using static indicators based on discrete time snapshots.

The management strategies of multi-objective owners were found to be more suitable for adaptation than those of owners with different objectives managing similar forest types. While managing forests for multiple objectives often implies both synergies and trade-offs between the ecosystem services provided (Blanco et al., 2015; Gamfeldt et al., 2013; Holm, 2015), the success of multi-objective owners reflected a higher capacity to provide, under the simulated scenarios, more benefits through the provision of multiple services than owners with less diverse objectives. This finding is consistent with that of Brown et al. (2016b), which identifies the ability of multifunctional management to provide different services and limit trade-offs as very important in shaping land-use change across sectors. This supports the adoption of multiple objective or multifunctional forestry, which has been integrated into national forest management planning in many countries over the last decades (e.g. Carvalho-Ribeiro et al., 2010; Rico and Gonzalez, 2015; Swedish Forest Agency, 2014; Zhang et al., 2000). It is still necessary however to better understand the extent to which multiple services can in reality be produced together, and multifunctional management needs to be better incorporated in models of the forestry sector (e.g. by incorporating more comprehensive sets of ecosystem services). Owners with a narrower set of objectives were, however, also somewhat successful at using particular

management strategies (e.g. productionist spruce), and can be particularly successful in specific locations and scenarios. Therefore, while multi-objective management strategies may be a good solution to meet present and future forest service demands, it does not represent a panacea for all future conditions and is unlikely to prove superior to the maintenance of heterogeneity in ownership and management objectives across larger scales (Rammer and Seidl, 2015). Hence, a combination of strategies that can support multifunctionality at different scales is advisable.

We found that while some management strategies may become more competitive in the future (e.g. multi-objective spruce-boreal broadleaf), and especially so for particular scenarios (e.g. SSP1-RCP4.5), others may become less competitive, such as productionist pine in SSP3-RCP8.5. Nevertheless, some strategies that are less competitive now may become more competitive under future conditions, as illustrated by productionist pine or multi-objective pine-boreal broadleaf. This suggests that, while competitiveness and coping ability are both determinants of the suitability of a management strategy for autonomous adaptation, they are independent of one another and provide complementary insight into the adaptation process. This suggests the need to evaluate these concepts separately in studies of coping and adaptation, which is not yet identifiable in the adaptation literature.

The objectives of forest owners made a difference to both the competitiveness and coping ability of forest types. It is, therefore, important to not only consider the suitability of tree species or species compositions in adapting to climatic or socio-economic change, but also how well management practices associated with particular objectives perform under future changes. Species choice and composition is not an adaptation solution on its own. Hence, policy makers and forest advisors need to understand that societal demands for ecosystem services will be most successfully met when forest types are managed in ways that align with owner objectives.

Many of these conclusions are, of course, conditional upon model design. Model assumptions, limitations and uncertainties are presented and discussed in detail in Blanco *et al.* (2017) (Section 4.2), and include parameter settings, scenario representations and process omissions, all of which have some impacts on model outputs. Those most relevant here include an absence of modelled climate change effects on biodiversity, voluntary set-asides and, especially, agent abilities to interact freely or to learn. These latter behaviours are very relevant to climate adaptation and can influence, for example, willingness to adapt, the extent and rate of uptake of successful (or unsuccessful) adaptations, and attempts to adapt through aggregate, rather than individual, strategies (Niles et al., 2016; Thompson and Hansen, 2013; Zehr, 2015). Additionally, besides age constraints on when forests could be substituted or management strategies changed, we assumed free conversion from one management strategy to another (e.g. productionist to conservationist), competitiveness

allowing. Such a conceptualisation may be correct if the change in strategy is associated with a change in ownership. However, in terms of actually realising adaptation by individual or collective owners, there may be barriers to transitioning to different strategies due to knowledge, values, attitudes and objectives (Boon et al., 2010; Kilgore et al., 2008; Kline et al., 2000). In this case, the change from a strategy based on a particular set of objectives to one based on different objectives is likely to be more gradual than simulated here, and in many cases may not happen at all due to the reluctance to alter objectives. Conversely, learning and interaction between agents might hasten changes that are clearly advantageous. In either case, changes between strategies with more similar sets of objectives (e.g. productionist to multi-objective) are more likely than changes to more distinct strategies (e.g. productionist to conservationist). Governmental organisations have therefore an important role in promoting successful adaptation strategies and facilitating, as far as possible, transitions between strategies with very different objectives when appropriate.

Even where successful individual-level adaptation is achieved, successful sectoral-level adaptation does not necessarily follow. Our results indicate that under enhanced competition and high rates of forest land-use change (leading to shorter rotation periods), the Swedish forestry sector may not be able to meet demands for ecosystem services (see also Blanco et al., 2017). This indicates that even if potentially successful strategies are available and implemented as adaptations, contextual conditions may affect their impact on the forestry sector as a whole and the extent to which societal demands for forest services are met. Hence, planned adaptation through policies and incentives is likely to be essential in addition to autonomous adaptation by individual owners, if future ecosystem service demands are to be met. Our findings suggest that process-based models that account for temporal dynamics in competitiveness and coping ability, ecosystem service provision and forest owner decision-making have a crucial role to play in supporting such adaptation measures.

5 Conclusions

Adaptation is not a static, inherent characteristic of a system, but evolves in response to changing contexts that include both the external global change drivers and, importantly, the internal dynamics of actor interactions. Process-based models, capable of simulating the heterogeneity of real-world actors, socio-environmental interactions and change, are therefore a valuable tool in studying adaptation processes, including future coping and adaptive capacity. Competitiveness and coping ability were shown to be independent determinants of the suitability of management strategies for

adaptation, each providing different, but complementary types of information about the adaptation process. Furthermore, assessment of the extent to which a diverse range of ecosystem services can be provided by mono- or multi-functional management is critical in understanding the potential of future adaptation strategies.

The objectives of forest owners determine the success of particular species and species combinations in adapting to global change. Among the management strategies simulated, those aiming to balance provision of multiple ecosystem services may be better at adapting to global change, at least in regions with bio-physical and socio-economic conditions similar to those of Sweden. Across large regions, a combination of management strategies is nevertheless advisable to meet forest service demands by taking advantage of location-specific context and changes, and to present heterogeneity of adaptive actions in the face of uncertain global change. Many findings (e.g. the competitiveness of management strategies) were more uncertain under high-end climate change scenarios, suggesting that more extreme futures will be more difficult to adapt to. Large-scale felling events represent windows of opportunity to incorporate new forest management strategies for sectoral adaptation in a changing global context. In general, while management strategies exist that are suitable to successfully cope with future global change, their implementation does not guarantee that the forestry sector at the larger scale will be able to adapt successfully. Forestry in the future will likely be unable to meet societal demands for forest services on the basis of autonomous adaptation alone. Therefore, top-down mechanisms such as monitoring, providing information about potentially more successful strategies, and promoting proactive decision-making are likely to be necessary to help individuals and the sector as a whole to meet ecosystem service supply goals.

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