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# The effect of forest owner decision-making, climatic change and societal demands on land-use change and ecosystem service provision in Sweden

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Abstract: The uncertain effects of climatic change and changing demands for ecosystem services on the distribution of forests and their levels of service provision require assessments of future land-use change, ecosystem service provision, and how ecosystem service demands may be met. We present CRAFTY-Sweden, an agent-based, land-use model that incorporates land owner behaviour and decision-making in modelling future ecosystem service provision in the Swedish forestry sector. Future changes were simulated under scenarios of socio-economic and climatic change between 2010 and 2100. The simulations indicate that the influence of climatic change (on land productivities) may be less important than that of socio-economic change or behavioural differences. Simulations further demonstrate that the variability in land owner and societal behaviour has a substantial role in determining the direction and impact of land-use change. The results indicate a sizeable increase in timber harvesting in coming decades, which together with a substantial decoupling between supply and demand for forest ecosystem services highlights the challenge of continuously meeting demands for ecosystem services over long periods of time. There is a clear need for model applications of this kind to better understand the variation in ecosystem service provision in the forestry sector, and other associated land-use changes.

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Dear Editor,

We would like to thank you very much for managing our manuscript, and the reviewers for the insightful, thorough and constructive comments. We believe that they have helped to improve our manuscript substantially. We hope that you too will find that the manuscript is now ready for its publication in 'Ecosystem Services'.

Correspondence for this manuscript should be addressed to the first author, Victor Blanco, to the e-mail address v.blanco@ed.ac.uk.

Thank you very much for your attention and assistance.

Yours faithfully,

Victor Blanco

## **Highlights**

- Variability in owner behaviour determine the direction and impact of land-use change
- Changing demands and climate lead to important changes in land-use and ES provision
- Accelerating timber harvesting and land-use change negatively impact forest services
- It is difficult to steadily meet demands for forest ES over time at large scales
- This requires mechanisms using national-scale information to regulate forestry processes

The effect of forest owner decision-making, climatic change and societal demands on land-use change and ecosystem service provision in Sweden

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Abstract

The uncertain effects of climatic change and changing demands for ecosystem services on the distribution of forests and their levels of service provision require assessments of future land-use change, ecosystem service provision, and how ecosystem service demands may be met. We present CRAFTY-Sweden, an agent-based, land-use model that incorporates land owner behaviour and decision-making in modelling future ecosystem service provision in the Swedish forestry sector. Future changes were simulated under scenarios of socio-economic and climatic change between 2010 and 2100. The simulations indicate that the influence of climatic change (on land productivities) may be less important than that of socio-economic change or behavioural differences. Simulations further demonstrate that the variability in land owner and societal behaviour has a substantial role in determining the direction and impact of land-use change. The results indicate a sizeable increase in timber harvesting in coming decades, which together with a substantial decoupling between supply and demand for forest ecosystem services highlights the challenge of continuously meeting demands for ecosystem services over long periods of time. There is a clear need for model applications of this kind to better understand the variation in ecosystem service provision in the forestry sector, and other associated land-use changes.

**Keywords:** agent-based modelling, behaviour, ecosystem services supply and demand, forestry sector, scenario analysis

## 1 Introduction

Land-use and land management change have important effects on the provision of ecosystem services (ES) (MEA 2005). Forests provide a particularly wide range of ES, including timber and non-timber products, air purification, carbon sequestration, biodiversity preservation and recreation, which make fundamental contributions to human societies and natural systems (De Groot et al. 2010; MEA 2005). Meanwhile, pressures on the world's forests are increasing. Clearance for agriculture and timber harvesting, preservation and planting for climate mitigation, and climate-driven changes in growing conditions are all likely to interact to transform future ES provision (Buonocore et al. 2012; Zanchi et al. 2012; Alexandratos and Bruinsma 2012; Schroter et al. 2005; Soja et al. 2007; Tilman et al. 2001). Hence, forest management strategies are being revised (e.g. Jonsson et al. 2015; Kjaer et al. 2014) and future land-use change assessed (e.g. Thompson et al. 2011) through the use of computer models in an attempt to support adaptation to changing conditions and to meet future demands for ES supply.

One of the difficulties in designing management strategies for future conditions is the need to anticipate demands for ES. Such demands are difficult to estimate (Hayha et al. 2015), and forest modelling generally focuses only on timber yields as a result (Brown et al. in press). Where a wider range of ES are considered, assessment is often based on maps of suitability (e.g. Hayha et al. 2015; Soheli et al. 2015) or vulnerability (e.g. Metzger et al. 2008; Tziliavakis et al. 2015), which need not consider ES demand. Mapping of ES supply is also performed through ES valuation (e.g. Costanza et al. 1997), which assumes demands non-explicitly. Even where ES demands are acknowledged, only services with a market value are included (e.g. Verkerk et al. 2014). As a result, no study has investigated the provision of non-marketable ES in relation to demand levels; a necessary step to identify likely and desirable changes that enable forests to satisfy societal needs for ES.

Another challenge faced by models of future ES provision is that land use and management change, which determine ES provision, ultimately depend on the decisions of land owners. In forestry, behavioural and cognitive factors such as owner objectives and attitudes are known to have strong influences on management choices (Andersson and Gong 2010; Ingemarson et al. 2006; Vulturius et al. in review). However, due to lack of data and the uncertainty associated with long time horizons in forest management they are seldom incorporated into models, and never at scales larger than individual landscapes (Blennow et al. 2014; Rammer and Seidl 2015; Brown et al. 2016). Nevertheless, in terms of potential responses to future change owners can effectively be distinguished by the definition of categories (Blanco et al. 2015; Karali et al. 2013). Such categorisations are particularly useful in agent-based modelling (ABM) of land-use change, allowing the decision-making of individual land managers to be simulated heterogeneously and across large geographical extents (Matthews et al. 2007; Valbuena et al. 2010). The adoption of such models to map the effects of human behaviour on ES is recent (Boone et al. 2011; Brown et al. 2014; Murray-Rust et al. 2011), but holds great promise to reflect the drivers and consequences of change in the forestry sector more accurately.

The need for improved modelling of the forest sector is clearly illustrated by countries such as Sweden, which have large forest areas that are economically and culturally important, and which are likely to be significantly affected by climatic change. Sweden has 69% forest cover (SLU 2015), of which approximately 50% is owned by individual owners (Swedish Forest Agency 2015) with diverse objectives. In 2011, forestry accounted for 2.2% of Swedish GDP. We therefore adopt Sweden as a case study for the development of a forest management ABM that accounts for land owner decision-making and is capable of appraising provision of a wide range of ES under projected future levels of demand. We apply this model at national scale under combined socio-economic and climatic

scenarios (Shared Socio-economic Pathways and Representative Concentration Pathways – SSPs-RCPs; O'Neill et al. 2014, van Vuuren et al. 2011, van Vuuren et al. 2014) from 2010 to 2100. The purpose of this exercise was to explore: a) future ES provision and how ES demands may be met, b) land-use change, and c) changes in land owner objectives, in the Swedish forestry sector.

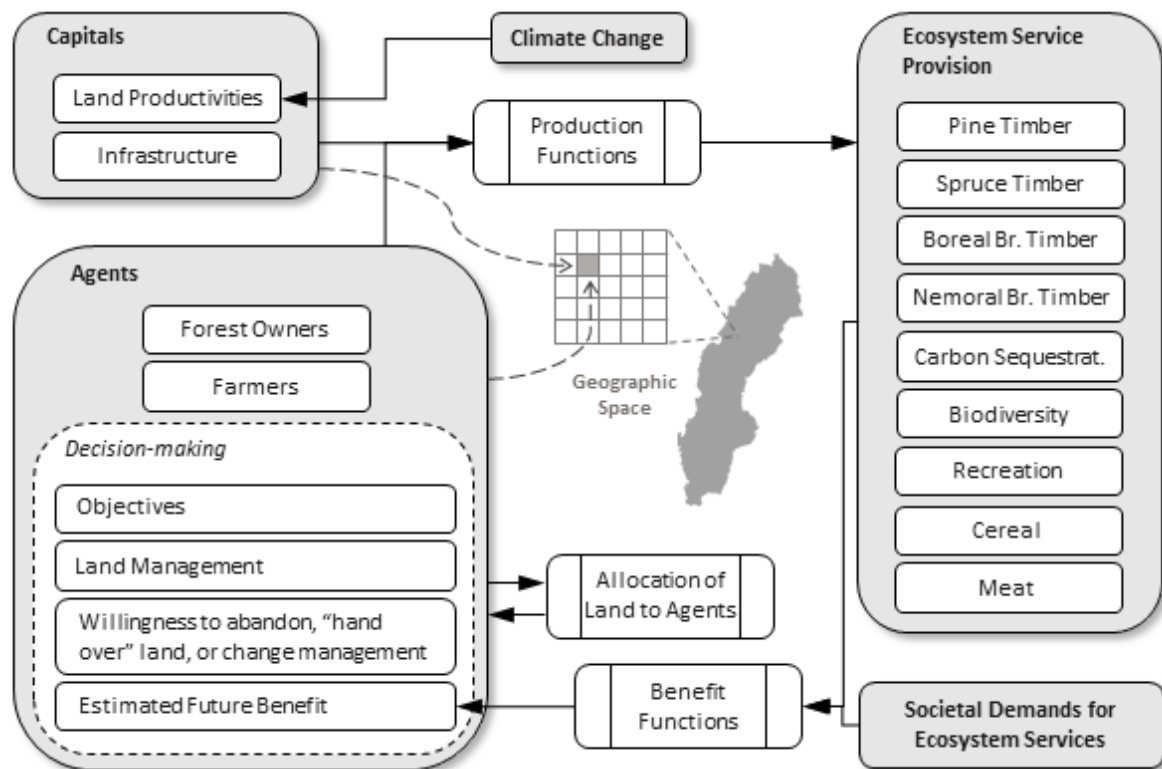
## 2 Methodology

To explore future ES provision and land-use change in Sweden, focusing on forestry, we developed the CRAFTY-Sweden model, based on the CRAFTY agent-based modelling framework (Murray-Rust et al., 2014) (see Appendix A for the model ODD protocol). CRAFTY allows the representation of large-scale land-use dynamics, based on demand and supply of ES (e.g. timber, food). Demand is given exogenously while supply depends on the productivities and behaviours of modelled agents, and the productivities of agents' locations (described by capitals representing the availability of resources such as infrastructure, human capital and crop suitability). Geographical space is represented as a grid of cells, each of which has defined levels of a range of capitals. Each cell may be managed by a single land-use agent, which uses the capital stock available within the cell to provide services according to its own production function. The competitiveness of a given level of service provision can be calculated on the basis of societal demands, overall supply levels and 'benefit' functions, which describe the monetary and non-monetary value to society of service production. Agents make decisions based on their current competitiveness and participate in an allocation procedure with potential new agents that may result in land-use change. We use agent functional types (Arneth et al., 2014; Rounsevell et al. 2012) (hereafter agent types) for the definition of agent production and behaviour. This approach helps to characterise agent typologies that define general characteristics of agents, from which individual agents can subsequently be drawn.

### 2.1 Model description

In CRAFTY-Sweden, agents include different types of forest owners and farmers. Farmers were defined to simulate the competition for land between forestry and agriculture. Forest owner decision-making involves four key components: 1) owner objectives and associated management practices, 2) the time of felling, 3) an estimation of the future benefits agents expect to obtain from their land-use, 4) and their willingness to abandon, change management or hand over land to a different owner considering their competitiveness. Farmers consider all but the second component. Using land productivities and infrastructure, modelled forest owners are able to produce timber from different tree species, carbon sequestration, biodiversity, and recreation, while modelled farmers choose to produce one or more services among cereal, meat and recreation (Fig. 1).

In the following, we describe the development of the land owner typology, and the owner production and decision-making mechanisms. We also explain how baseline capitals, land-use and land owner types were mapped throughout Sweden. Finally, we describe the approach to scenarios and the analysis of simulation results.



**Fig 1** Schematic representation of the structure of the CRAFTY-Sweden model showing flows (solid lines) and associations (dashed lines) between components

### 2.1.1 Land owner typology: design and validation

We developed a typology of forest and agricultural agents, focusing especially on the former. To define forest owner types we used as a basis the forest owner typology described by Blanco et al. (2015). Because this typology was based on studies performed at different scales and contexts to those found in Sweden, we performed a validation exercise of the typology using empirical information from 872 Swedish forest owners (Vulturius et al. in review). A cluster analysis showed that the five overarching management roles identified by the theoretical typology (productionist, multi-objective, recreationalist, conservationist and passive) were also clearly discernible in the empirical data. Supplementary materials on this validation can be found in Appendix B.1.

Within each overarching management role, different options for forest management are possible, including the use of different types of forest (defined by species composition). Forest types were assigned to each management role on the basis of existing forest stand compositions (Swedish Forest Agency 2015) and potential adaptation measures to climate change that consider species composition, number of thinnings and rotation lengths (Felton et al. 2016; Jonsson et al. 2015) on the basis of owner objectives (Blanco et al. 2015; Duncker et al. 2012a). Forest types assigned 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. The management and decision-making strategies of each owner type are described in sections 2.1.3, 2.1.4, and 2.1.5.



Given the current levels of agricultural production (Swedish Board of Agriculture 2009) and management intensities prevailing in Sweden (Institute of Environmental Studies 2015), farmers were separated by the main services provided (i.e. cereal or meat) in combination with their main objectives (i.e. commercial or non-commercial).

## 2.1.2 Capitals

The capitals that agents can use in service production are productivities for pine, spruce, boreal broadleaf, and nemoral broadleaf forests, grassland productivity (natural capital), and transportation infrastructure (infrastructure capital). Table 1 shows capital descriptions, their data sources, and the ES they contribute to producing (see Appendix B.2 for further detail on the calculations that led to final capitals).

**Table 1** Identities and data sources for modelled capitals, and the ecosystem services they contribute to producing

CAPITAL	DEFINITION	INPUT DATA (units; resolution)	ECOSYSTEM SERVICES	DATA SOURCE
Pine, Spruce, Boreal Broadleaf, and Nemoral Broadleaf Forest Productivities	Baseline productive potential for each forest type	Forest production potential per forest type ( $\text{m}^3 \text{sk ha}^{-1} \text{yr}^{-1}$ ; $1 \text{km}^2$ )	- Pine, spruce, boreal br. and nemoral br. timber - Carbon - Biodiversity	(Hägglund and Lundmark 1987) (Johansson et al. 2013) SLU
Grassland Productivity	Baseline productive potential for grassland and cropland	LPJ-GUESS simulated C3-grass NPP projection for 2010 driven by climate (radiation, temperature, precipitation) ( $\text{kg C m}^{-2} \text{yr}^{-1}$ ; $50 \times 50 \text{ km}$ )	- Meat - Cereal	Simulations done for this article (see section 2.2)
Transportation Infrastructure	Proximity to transportation networks and central markets	1. Road and rail networks 2. Waterway networks 3. Travel time to nearest town with over 50000 inhabitants ( $1 \text{km}^2$ )	- Pine, spruce, boreal br. and nemoral br. timber - Meat - Cereal - Recreation	1. UNECE 2. EEA 3. GEMU, JRC

SLU: SLU Forest Map, produced by Swedish University of Agricultural Sciences, accessed via

<ftp://salix.slu.se/download/skogskarta>

UNECE: United Nations Economic Commission for Europe, accessed via <http://www.unece.org/trans/areas-of-work/transport-statistics/statistics-and-data-online.html>

EEA: European Environment Agency, accessed via <http://www.eea.europa.eu/data-and-maps>

GEMU, JRC: Global Environment Monitoring Unit, managed by the Joint Research Centre, accessed via

<http://www.edenextdata.com/?q=content/jrc-accessibility-map-estimated-travel-time-nearest-city-population-50000>

## 2.1.3 Baseline land-use and land owner distribution

### Land-use map

To create a baseline land ownership map for 2010 we first devised a land-use map at  $1 \text{km}^2$  resolution that included pine, spruce, pine-spruce, pine-boreal broadleaf, spruce-boreal broadleaf, boreal broadleaf, and nemoral broadleaf productive forests, agriculture, protected areas, non-productive forests, semi-natural vegetation, wetlands, open spaces, 'other unmanaged' land,

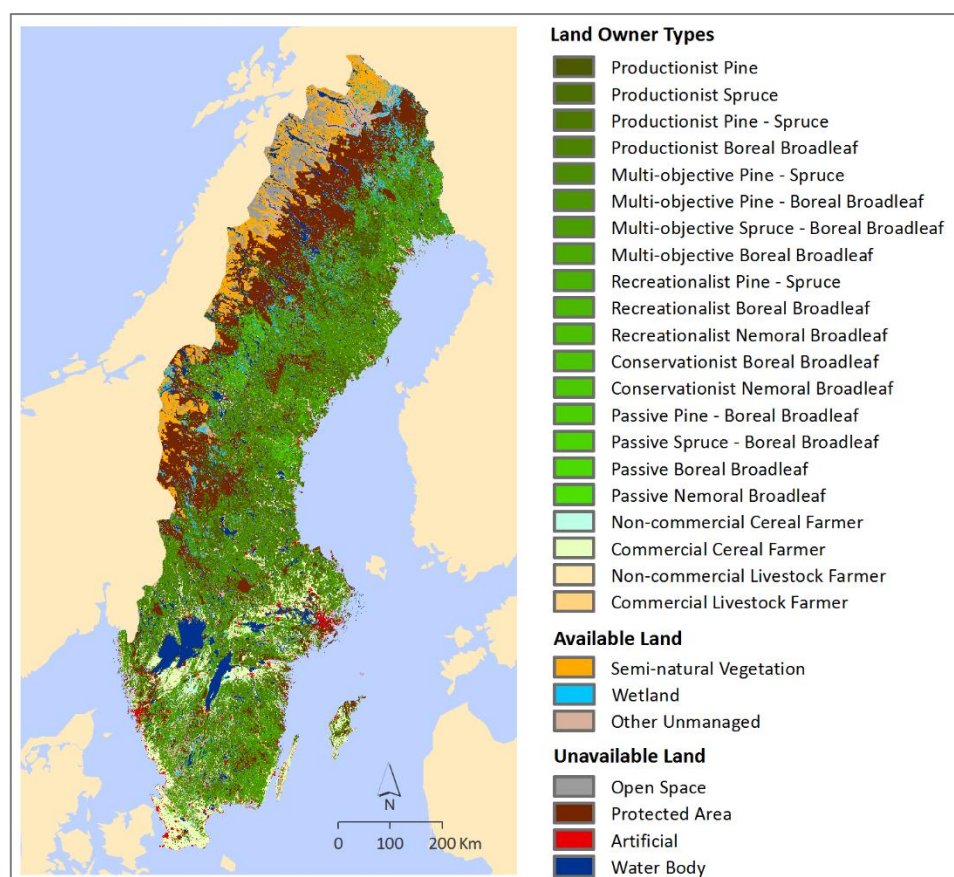
artificial, and water bodies. SLU Forest Map data (SLU 2010) on the proportion of different tree species per cell were used to identify forest cover and classify it according to the forest types assigned above, according to the proportion of forest within the cell, and the proportions of different species within that forest. CORINE land cover (EEA 2014) was used to identify all other land use/land cover classes. Nationally Designated Areas (EEA 2015) were then superimposed to define protected areas. Non-productive forests are also protected and unavailable for production (Swedish Forest Agency 2014). Thus, we identified them by:

1. Assigning to forested cells the value of the highest productivity found among all forest types within that cell; and
2. Given the proportion of non-productive forest per county (Swedish Forest Agency 2015), selecting for each county the equivalent number of cells with the lowest productivity values.

Mean forest age values from the SLU Forest Map were used to assign forest ages. While this dataset allows mapping of forest age throughout the country, it was found to overestimate the area covered by middle aged forest, planted during 1930-1970, and underestimate that of old forest and very young forest (see Fig B.2), when compared to age frequency distribution in the National Forest Inventory (Swedish Forest Agency 2015).

#### Agent locations

Forest owner types were allocated to productive forest types using data about: a) the area of productive forest land by county and ownership class for 2010 (Swedish Forest Agency 2015); and b) the proportion of owners in each county belonging to each group from the cluster analysis. Agricultural land and (some) semi-natural vegetation were assigned to commercial cereal, non-commercial cereal, commercial livestock, and non-commercial livestock farmer agents according to the land-use intensity in 2010 (Institute of Environmental Studies 2015). Remaining semi-natural vegetation, wetlands, and 'other unmanaged' land were left unallocated. Protected areas, non-productive forests, open spaces with little or no vegetation, artificial surfaces, and water bodies were not available for allocation during simulations. Fig. 2 shows the resulting map of Sweden, and Table 2 presents the share of land occupied by each owner type. Further detail on the creation of land-use and land owner type maps can be found in Appendix B.3.



**Fig 2** Map of land owner type distribution throughout Sweden in 2010. Available and unavailable land refer to land that can or cannot be managed by agents, respectively

**Table 2** Percentage of land area occupied by each owner type, per forest/ farmland type and management role, in Sweden in 2010. Percentages for forest owner types are given out of the total productive forest land, and out of total farmland for farmers

Forest Owner Type	Productionist	Multi-objective	Recreationalist	Conservationist	Passive	Total
Pine	8.34	-	-	-	-	8.34
Spruce	0.60	-	-	-	-	0.60
Pine-Spruce	30.00	22.50	13.78	-	-	66.28
Pine-Boreal Broadleaf	-	10.37	-	-	0.86	11.23
Spruce-Boreal Broadleaf	-	10.74	-	-	2.50	13.24
Boreal Broadleaf	<0.01	0.01	<0.01	<0.01	<0.01	0.02
Nemoral Broadleaf	-	-	0.17	0.08	0.03	0.28
Total	38.94	43.62	13.95	0.08	3.39	100
Farmland Owner Type	Commercial		Non-commercial		Total	
Cereal	86.86		5.02		91.88	
Livestock	3.94		4.17		8.11	
Total	90.80		9.19		100	

## 2.1.4 Land owner service production

The production of agricultural services was modelled on an annual basis. Forestry services are however dependent on forest age. Additionally, climatic change can affect service production by

acting on productivities. We therefore developed ways of modelling the time-dependent component of the different services in CRAFTY. The production of a service by an agent in a given year was based on the Cobb Douglas function, adapted to incorporate a time component (Eq. 1).

$$p_s = o_{s,a,t} \prod_c (c_i + \Delta c_{i,t})^{\lambda_{c,a}} \quad (1)$$

Production ( $p_s$ ) of a service  $s$  by an agent  $a$  within a cell at time  $t$  depends upon the initial (unit-less, i.e., [0-1]) levels of capitals ( $c$ ) within that cell plus annual climate-induced change in cell capitals ( $c_i + \Delta c_{i,t}$ ), weighted by the capital sensitivities of the agent type ( $\lambda_{c,a}$ ) and multiplied by the optimal production potential of that agent type ( $o_{s,a,t}$ ) (Table 3). The optimal service production  $o_{s,a,t}$  is the maximum production achievable in Sweden under ideal environmental conditions, and its levels are taken from an agent type-specific function (i.e. optimal production function) that describes the change in service production levels with forest age. Capital (i.e. land productivity and infrastructure) levels are used to adjust optimal production to production levels achievable at a particular site. Capital sensitivities adjust these site-specific production levels to what the agent type would be able to attain given its particular dependencies on capitals. To reflect individual variability, each agent's optimal production value and capital sensitivity levels were randomly drawn from uniform distributions around the agent type's mean values ( $[0.95\overline{o_{s,t}}, 1.05\overline{o_{s,t}}]$ ,  $[\overline{\lambda_c} - 0.1, \overline{\lambda_c} + 0.1]$ ). Timber supply (i.e. harvest) is recorded upon felling, while other forest services are supplied yearly. Production calculations for each service are described below.

### Timber

For timber production,  $o_{st}$  is given by a forest owner type-specific function that determines timber growth given the forest's age. The ProdMod model (Eko 1985) was used to generate timber growth curves for each owner type given their management preferences. Given passive owners' generalised lack of primary objectives for forestry, we assumed them to inherit forest, and therefore only enabled them to take over the forest and associated optimal production function of other owner types managing forests with the same tree species as them. Hence, optimal production functions were not calculated for passive owners. Table 3 shows parameter values used in ProdMod that differed for each owner type. See Appendix B.4.1 for further detail on optimal timber production function calculation.

**Table 3** Land owner type production, felling age and competitiveness (scenario-independent) parameters. Number of stems planted per ha for each forest type, site index, number of thinnings implemented, age at each thinning per forest type, and percentage removed per thinning are parameters given to ProdMod to calculate the (age-dependent) optimal timber production and (above ground) carbon sequestration functions. Additional information on ProdMod simulations and parameters can be found in Appendix B.4. These functions and remaining parameters in this table are CRAFTY-Sweden inputs. Yearly  $o_s$  illustrates yearly optimal farmer production. Productivity and infrastructure sensitivities ( $\lambda$ ) are given per service. Felling age means ( $\mu$ ) and standard deviations ( $\sigma$ ) represent number of years past minimum felling age (m.f.a.) of a forest, given as the m.f.a. range dependent on site quality.

Land Owner Type	Service Production							Felling Age		Competitiveness	
	No. Stems/ha	Site Index dm	No. Thinnings	Age at each Thinning	% Removed per Thinning	Yearly $o_s$ (tonne)	$\lambda$ Productiv.	$\lambda$ Infrastr.	m.f.a. Range	$\mu, \sigma$ Years past m.f.a.	Probability Giving-up
Productionist Pine	2500	280	3	24, 39, 54	25, 20, 20	-	0.8 <sup>a</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.2 <sup>a</sup> , 1 <sup>g</sup>	65-100	12, 10	0.05
Productionist Spruce	2600	360	3	23, 38, 53	25, 20, 20	-	0.8 <sup>b</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.2 <sup>b</sup> , 1 <sup>g</sup>	45-95	10, 8	0.05
Productionist Pine-Spruce	1250, 1300	280, 360	3	24/23, 39/38, 54/53	25, 20, 20	-	0.8 <sup>a,b</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.2 <sup>a,b</sup> , 1 <sup>g</sup>	45-95	10, 8	0.05
Productionist Boreal Br.	2200	320	3	15, 30, 45	25, 20, 20	-	0.8 <sup>c</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.2 <sup>c</sup> , 1 <sup>g</sup>	40-60	9, 7	0.05
Multi-objective Pine-Spruce	1150, 1250	280, 360	2	24/23, 39/38	30, 25	-	0.85 <sup>a,b</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.1 <sup>a,b</sup> , 0.8 <sup>g</sup>	45-95	15, 12	0.05
Multi-objective Pine-Boreal Br.	1840, 420	280, 320	2	24/20, 39/35	25/50, 20/25	-	0.85 <sup>a,c</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.1 <sup>a,c</sup> , 0.8 <sup>g</sup>	65-100	10, 8	0.05
Multi-objective Spruce-Boreal Br.	2000, 420	360, 320	2	23/20, 38/35	25/45, 20/25	-	0.85 <sup>b,c</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.1 <sup>b,c</sup> , 0.8 <sup>g</sup>	45-95	10, 8	0.05
Multi-objective Boreal Br.	2100	320	2	15, 30	30, 25	-	0.85 <sup>c</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.1 <sup>c</sup> , 0.8 <sup>g</sup>	40-60	15, 12	0.05
Recreationalist Pine-Spruce	1100, 1100	280, 360	3	24/23, 39/38, 54/53	25, 20, 20	-	0.9 <sup>a,b</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.3 <sup>a,b</sup> , 0.6 <sup>g</sup>	45-95	80, 14	0.05
Recreationalist Boreal Br.	2000	320	3	15, 30, 45	25, 20, 20	-	0.9 <sup>c</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.3 <sup>c</sup> , 0.6 <sup>g</sup>	40-60	100, 14	0.05
Recreationalist Nemoral Br.	1250, 1250	350, 300	3	25/22, 40/37, 55/52	25, 20, 20	-	0.9 <sup>d</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.3 <sup>d</sup> , 0.6 <sup>g</sup>	110-150	60, 14	0.05
Conservationist Boreal Br.	2100	320	1	15	35	-	0.9 <sup>c</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.3 <sup>c</sup> , 0.8 <sup>g</sup>	40-60	100, 14	0.05
Conservationist Nemoral Br.	1250, 1250	350, 300	1	25/22	35	-	0.9 <sup>d</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.3 <sup>d</sup> , 0.8 <sup>g</sup>	110-150	60, 14	0.05

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Passive Pine-Boreal Br.	-	-	-	-	-	-	0.9 <sup>a,c</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.1 <sup>a,c</sup> , 1 <sup>g</sup>	65-100	25, 17	0.05
Passive Spruce-Boreal Br.	-	-	-	-	-	-	0.9 <sup>b,c</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.1 <sup>b,c</sup> , 1 <sup>g</sup>	45-95	25, 17	0.05
Passive Boreal Br.	-	-	-	-	-	-	0.9 <sup>c</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.1 <sup>c</sup> , 1 <sup>g</sup>	40-60	15, 10	0.05
Passive Nemoral Br.	-	-	-	-	-	-	0.9 <sup>d</sup> , 1 <sup>e</sup> , 0.06 <sup>f</sup>	0.1 <sup>d</sup> , 1 <sup>g</sup>	110-150	10, 10	0.05
Commercial Cereal	-	-	-	-	-	201	0.8 <sup>h</sup>	0.5 <sup>h</sup>	-	-	0.2
Non-commercial Cereal	-	-	-	-	-	121	0.5 <sup>h</sup>	0.3 <sup>g,h</sup>	-	-	0.2
Commercial Livestock	-	-	-	-	-	324	0.6 <sup>i</sup>	0.5 <sup>i</sup>	-	-	0.2
Non-commercial Livestock	-	-	-	-	-	193	0.3 <sup>i</sup>	0.2 <sup>g,i</sup>	-	-	0.2

<sup>a</sup> Pine timber, <sup>b</sup> spruce timber, <sup>c</sup> boreal broadleaf timber, <sup>d</sup> nemoral broadleaf timber, <sup>e</sup> carbon sequestration, <sup>f</sup> biodiversity, <sup>g</sup> recreation, <sup>h</sup> cereal, <sup>i</sup> meat

## Carbon sequestration

Due to the difficulty of calculating soil carbon levels in interaction with forest productivities, only above-ground sequestered carbon (excluding the stump) was calculated. Optimal production functions of above ground carbon were also calculated using ProdMod outputs (Appendix B.4.2).

## Biodiversity

The calculation of optimal forest biodiversity production considered forest age (Duncker et al. 2012b; Koskela et al. 2007; Marchetti 2004), using the generation of coarse woody debris with age as a proxy (e.g. (Berg et al. 1994; Jonsell et al. 1998; Siitonen 2001), tree diversity (Gamfeldt et al. 2013; Marchetti 2004) and management practices undertaken by each owner type (e.g. woody debris removal), which have an influence on biodiversity (Blanco et al. 2015; Duncker et al. 2012a; Duncker et al. 2012b). We chose these forest attributes as indicators of biodiversity because of the availability of baseline data for them and the possibility of updating the data during model simulations. Finally, we considered the effect of forest productivity on biodiversity, specifically on coarse woody debris (Sturtevant et al. 1997), by assigning sensitivities to timber productivities. For further details of the calculation of optimal biodiversity production functions see Appendix B.4.3.

## Recreation

Recreational value in Scandinavia is largely determined by the age of a forest, but also by forest management practices, accessibility and, to a lesser extent, by the types of tree species present (i.e. conifer vs broadleaf, and monoculture vs mixed) (Edwards et al 2012). See Appendix B.4.4 for further detail on optimal recreation function calculation.

## Cereal and meat

Given baseline maps with available capitals and commercial cereal, non-commercial cereal, commercial livestock and non-commercial livestock agent locations (see section 2.1.6), their  $\alpha_s$  and  $\lambda_c$  were adjusted until total cereal and meat production equalled the total production in Sweden reported by the FAO (2015) for 2010. The production of non-commercial 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).

### **2.1.5 Forest Felling**

The forest in a cell is clear-felled when it reaches an age that depends on site quality (i.e. productivity) (Lagergren et al. 2012) and owner objectives. In Sweden, the stand age at felling is regulated by law for pine and spruce to guarantee that the production potential is utilised (Kunskap Direkt 2015), and for beech, birch and oak recommended rotation periods exist (Löf et al. 2009; Rytter et al. 2008). Hence, lowest minimum felling age was assigned to the highest productivity values, while highest minimum felling age corresponded to the lowest productivity values (Table 3; Appendix B.5). Also, each owner type was assigned a Gaussian distribution of the planned felling age (above minimum felling age) (Table 3). This distribution was defined as being within the recommended rotation periods for all owner types except for recreationalists, conservationists and passive owners managing broadleaf forests. As these latter groups are not primarily interested in

timber production (Blanco et al. 2015), they were assigned felling age distributions beyond the recommended rotation period. Felling age is determined at the time that an agent is allocated to a cell by randomly drawing a number (i.e. age) from within the agent type's distribution. Upon felling, timber is harvested and carbon sequestered in the standing timber is removed from the national pool.

#### 2.1.6 Competition for land

Farmers can be taken over by other agents each year because they are assumed to manage on annual timescales. For forest owners however, we assume that they will not abandon or change the management approach on their land until the forest has reached maturity, in order to recover the initial investment. Hence, competition for forested land starts only once the minimum age of felling has been reached. At that point a 'potential' agent with a higher competitiveness score than the incumbent agent can take over its land, resulting in one of two outcomes:

1. If the potential agent is a forest owner type willing to plant the same forest type as 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 is however adjusted to meet the objectives of the new agent. As mentioned in section 2.1.3, passive owners follow this system exclusively and do not compete for unmanaged land.
2. If the potential agent is a farmer or a forester not meeting the above criteria, the standing forest is clear-felled and land is either converted to farmland or to newly-planted forest.

Forest owners plan what they will plant according to (non-climate sensitive) charts that show potential tree growth according to site conditions. Even though some owners may also consider climate change and risk spreading, this is currently not a generalizable trait of Swedish forest owner decision-making (Blennow et al. 2012). They generally use experience-based, practical knowledge, rather than abstract theoretical knowledge about possible future developments (Lidskog and Sjödin 2014). Hence, while farmers' service production is evaluated for the coming year, forest owners evaluate it for the (future) year of felling, based on present (rather than future) environmental and socio-economic conditions. To evaluate agent competitiveness for a given bundle of services we use the benefit ( $\beta$ ) function (Eq. 2):

$$\beta = \sum_s \frac{p_s/A_i}{d_s} b_s \frac{u_s}{d_s} \quad (2)$$

where the production level  $p_s$  is time-discounted by forest age at felling ( $A_i$ ) to reflect desire for shorter-term returns where possible. Time-discounted production is normalised by the current per-cell demand ( $d_s$ ) (i.e. demand divided by the total number of cells) to achieve levels that are comparable across agent types supplying services that are measured in different units. The per-cell unmet demand ( $u_s$ ), is also normalised by the demand to give a proportional unmet demand. Finally,  $b_s$  is a weighting factor representing the importance of the unmet demand of each service.  $A_i$  and  $b_s$  are parameterised to reflect observed time discounting and the assumed importance to society of meeting service demand levels, respectively.



If an existing agent's competitiveness is lower than its 'giving-up' threshold, it will abandon the cell. If a potential agent's competitiveness within a cell is greater than the existing agent's by a value larger than the existing agent's 'giving-in' threshold, then the potential agent takes over the cell. Giving-up and giving-in thresholds reflect minimum acceptable benefit and tolerance to competition respectively, and are drawn from agent type-specific Gaussian probability distributions to simulate individual differences (Murray-Rust et al. 2014). Also, because not all farmers and foresters are affected by market conditions to the same degree or at the same time, we implement giving-up probabilities for each agent type that apply to agents whose competitiveness falls below their giving-up threshold. Giving-up and giving-in mean values are scenario-dependent and are given in section 2.2, while standard deviations were set at 0.1 for all agents. Giving-up probabilities are given in Table 3.

## 2.2 Scenario analysis

Five future scenarios were defined by combining RCPs and SSPs. RCP4.5 (lower emission scenario) was combined with SSPs 1 ('Sustainability'), 3 ('Regional rivalry') and 4 ('Inequality'), and RCP 8.5 (higher emission scenario) with SSPs 3 and 5 ('Fossil-fuelled development'), so as to explore coherent combinations of emission and socio-economic futures (Carter et al. 2015). Each RCP was also simulated with three climate models. Each climate model-RCP combination consisted of a different set of climate-induced annual productivity changes. Table 4 presents scenario-specific parameters, and scenario narratives for the different SSPs used here can be found in Table B.3.

The ecosystem model LPJ-GUESS (Smith et al. 2001) was used to simulate forest dynamics during 2010-2100 using climate projections of 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). Annual climate-induced change was calculated for all productivities using LPJ-GUESS spatial projections of yearly timber volume growth for pine, spruce, boreal broadleaf and nemoral broadleaf forests, and yearly net primary productivity (NPP) change for grass until 2100 at 50x50 km resolution. Upon checking for non-linearities in volume growth and NPP change projections, linear models were considered to be adequate. Therefore, a regression coefficient was calculated for every cell by performing linear regression on projected growth values. These values were then downscaled to 1 km<sup>2</sup>. See Appendix B.6 for more details on calculations of climate impact on productivities.

Following land-use and European SSP storylines from Engstrom et al (2016) and Kok et al. (2015) respectively, SSPs differed in: a) future demands for ES, b) probability distributions for owner type giving-in and giving-up thresholds, c) the importance to 'society' of meeting demands for each service, and d) the possibility of farmland displacing forest land. Baseline demands for timber, cereal and meat were assumed to equal the observed production in 2010 (FAO 2015; Swedish Forest Agency 2015), while those for carbon sequestration, biodiversity and recreation were assumed to equal the simulated baseline supply. Future projections were calculated using the IIASA SSP data (IIASA 2015) on decadal rates of change of global forest land cover (for timber and carbon sequestration), and crop and livestock demands. Demands for biodiversity were projected following the SSP storylines with guidance from modelled global future changes in species abundance from UNEP (2007). Rates of change in recreational demands were assumed to be the same as those for biodiversity. Giving-in thresholds were set higher and giving-up thresholds lower for SSPs with

greater barriers to adaptation (i.e. SSPs 3 and 4). See Appendix B.7 for further details about the creation of service demand projections.

CRAFTY-Sweden simulations were run for Sweden for the 2010-2100 period at a 1km<sup>2</sup> 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. The model was then run under these static conditions (i.e. no change in climate or demands through time) for the period 2010-2100 to produce a reference scenario. To understand model behaviour, sensitivity analysis was performed by altering values of behavioural, benefit function components, demands and productivities individually (results are not reported here, but their implications are discussed in Section 4). To measure the effect of random model components 32 simulations were run under different random seeds, but otherwise identical parameterisations. Consequently, each climate model-RCP-SSP combination was run once (under one random seed).

**Table 4** Scenario matrix. Service demands are only shown for the years 2010, 2050 and 2100. Demands shown for 2010 under the Reference scenario also apply to all other scenarios

	Reference			SSP 1 - RCP 4.5		SSP 3 - RCP 4.5		SSP 3 - RCP 8.5		SSP 4 - RCP 4.5		SSP 5 - RCP 8.5	
Service Demands	2010	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
<i>Pine Timber</i> (mill. m <sup>3</sup> over bark)	35.29	35.29	35.29	37.98	40.22	32.85	31.14	33.00	31.77	36.71	36.24	34.97	35.30
<i>Spruce Timber</i> (mill. m <sup>3</sup> over bark)	44.45	44.45	44.45	47.84	50.66	41.37	49.22	41.56	40.01	46.23	45.65	44.04	44.46
<i>Boreal Br. Timber</i> (mill. m <sup>3</sup> over bark)	7.64	7.64	7.64	8.22	8.71	7.11	6.74	7.14	6.88	7.95	7.85	7.57	7.64
<i>Nemoral Br. Timber</i> (mill. m <sup>3</sup> over bark)	1.51	1.51	1.51	1.63	1.72	1.41	1.33	1.41	1.36	1.57	1.55	1.50	1.51
<i>Carbon Sequestration</i> (mill. tonne C)	592	592	592	637	675	551	522	554	533	616	608	587	592
<i>Biodiversity</i> (1000, unitless)	234	234	234	234	257	210	183	206	175	222	211	199	189
<i>Recreation</i> (1000, unitless)	345	345	345	345	380	311	270	304	258	328	312	293	279
<i>Cereal</i> (mill. tonne)	4.32	4.32	4.32	6.28	6.27	6.60	8.46	6.55	8.38	5.82	5.88	7.12	7.30
<i>Meat</i> (1000 tonne)	537	537	537	765	718	808	966	815	998	761	781	1226	1178
<b>Importance of meeting service demands</b>	<b><i>b<sub>s</sub></i></b>			<b><i>b<sub>s</sub></i></b>		<b><i>b<sub>s</sub></i></b>		<b><i>b<sub>s</sub></i></b>		<b><i>b<sub>s</sub></i></b>		<b><i>b<sub>s</sub></i></b>	
<i>Pine Timber</i>	1.1			1.1		1.1		1.1		1.09		1.1	
<i>Spruce Timber</i>	1.1			1.1		1.1		1.1		1.09		1.1	
<i>Boreal Br. Timber</i>	0.045			0.045		0.045		0.045		0.040		0.045	
<i>Nemoral Br. Timber</i>	0.010			0.010		0.010		0.010		0.007		0.01	
<i>Carbon Sequestration</i>	0.2			0.35		0.1		0.1		0.1		0.1	
<i>Biodiversity</i>	1.1			2.50		1.0		1.0		1.0		1.0	
<i>Recreation</i>	1.1			2.35		1.0		1.0		1.0		1.0	
<i>Cereal</i>	5.0			4.5		5.5		5.5		5.5		5.5	
<i>Meat</i>	4.5			4.0		4.8		4.8		4.5		5.0	

SSP Scenario Matrix (Continue)

	Reference		SSP 1 - RCP 4.5		SSP 3 - RCP 4.5		SSP 3 - RCP 8.5		SSP 4 - RCP 4.5		SSP 5 - RCP 8.5	
	Give Up	Give In	Give Up	Give In	Give Up	Give In	Give Up	Give In	Give Up	Give In	Give Up	Give In
<b>Agent Type Thresholds</b>												
<i>Productionist Pine</i>	0.30	0.10	0.30	0.10	0.28	0.12	0.28	0.12	0.28	0.12	0.30	0.10
<i>Productionist Spr</i>	0.30	0.10	0.30	0.10	0.28	0.12	0.28	0.12	0.28	0.12	0.30	0.10
<i>Productionist Pin-Spr</i>	0.30	0.10	0.30	0.10	0.28	0.12	0.28	0.12	0.28	0.12	0.30	0.10
<i>Productionist Bor.Br.</i>	0.26	0.10	0.26	0.10	0.24	0.12	0.24	0.12	0.24	0.12	0.26	0.10
<i>Multi-objective Pin-Spr</i>	0.29	0.10	0.29	0.10	0.27	0.12	0.27	0.12	0.27	0.12	0.29	0.10
<i>Multi-objective Pin-Bor.Br.</i>	0.25	0.10	0.25	0.10	0.23	0.12	0.23	0.12	0.23	0.12	0.25	0.10
<i>Multi-objective Spr-Bor.Br.</i>	0.25	0.10	0.25	0.10	0.23	0.12	0.23	0.12	0.23	0.12	0.25	0.10
<i>Multi-objective Bor.Br.</i>	0.25	0.10	0.25	0.10	0.23	0.12	0.23	0.12	0.23	0.12	0.25	0.10
<i>Recreationalist Pin-Spr</i>	0.24	0.30	0.24	0.30	0.22	0.32	0.22	0.32	0.22	0.32	0.24	0.30
<i>Recreationalist Bor.Br.</i>	0.20	0.30	0.20	0.30	0.18	0.32	0.18	0.32	0.18	0.32	0.20	0.30
<i>Recreationalist Nem.Br.</i>	0.20	0.30	0.20	0.30	0.18	0.32	0.18	0.32	0.18	0.32	0.20	0.30
<i>Conservationist Bor.Br.</i>	0.23	0.30	0.23	0.30	0.21	0.32	0.21	0.32	0.21	0.32	0.23	0.30
<i>Conservationist Nem.Br.</i>	0.23	0.30	0.23	0.30	0.21	0.32	0.21	0.32	0.21	0.32	0.23	0.30
<i>Passive Pin-Bor.Br.</i>	0.10	0.30	0.10	0.30	0.08	0.32	0.08	0.32	0.08	0.32	0.10	0.30
<i>Passive Spr-Bor.Br.</i>	0.10	0.30	0.10	0.30	0.08	0.32	0.08	0.32	0.08	0.32	0.10	0.30
<i>Passive Bor. Br.</i>	0.10	0.30	0.10	0.30	0.08	0.32	0.08	0.32	0.08	0.32	0.10	0.30
<i>Passive Nem. Br.</i>	0.10	0.30	0.10	0.30	0.08	0.32	0.08	0.32	0.08	0.32	0.10	0.30
<i>Commercial Cereal</i>	0.24	0.70	0.24	0.70	0.22	0.72	0.22	0.72	0.22	0.72	0.24	0.70
<i>Non-commercial Cereal</i>	0.00	0.90	0.00	0.90	0.00	0.92	0.00	0.92	0.00	0.92	0.00	0.90
<i>Commercial Livestock</i>	0.24	0.70	0.24	0.70	0.22	0.72	0.22	0.72	0.22	0.72	0.24	0.70
<i>Non-Commercial Livestock</i>	0.00	0.90	0.00	0.90	0.00	0.92	0.00	0.92	0.00	0.92	0.00	0.90
<b>Farm can take over forest</b>	NO		NO		YES		YES		NO		YES	

## 2.3 CRAFTY-Sweden outputs

Modelling outputs presented here are for land-use change and ES provision. Agent types were mapped for every year during 2010-2100, and are presented for each scenario grouped into land-use and management role categories through maps depicting hotspots of change, and figures showing nationally and regionally aggregated change. Hotspots were defined as 50x50 km (smaller next to country borders and on islands, down to 39km<sup>2</sup>) units of analysis where the category with the highest proportional increase (calculated as the mean increase from the three climate model runs for the scenario divided by the area of the analysis unit) experiences an increment above 10%. Following the larger administrative divisions used by the Swedish Forest Agency, regional changes were aggregated into the Swedish regions: Upper Norrland, Lower Norrland, Svealand and Götaland, and shown as percentage changes between 2010 and 2100 (i.e. area change relative to available area in the region) with error bars showing the variability in the change between maximum and minimum values generated among the three climate models. Finally, ranges of service provision defined by maximum and minimum values among climate models were plotted for each scenario.

## 3 Results

### 3.1 Ecosystem service provision

Timber provision grows steadily for all forest types except nemoral broadleaf during the first third of the simulation period across scenarios, as standing timber stocks are harvested (Fig. 3). Harvests fall thereafter and grow again during the last third of the century for the reference scenario, while for the SSP-RCP scenarios they remain largely unchanged during this period. Nemoral broadleaf timber provision, however, grows only modestly for all scenarios throughout the simulation period, while remaining far below demand levels. Carbon sequestration for the reference scenario mainly decreases during the first half of the century and increases during the second half. For all other scenarios it decreases throughout, though more slowly during the second half of the century.

Biodiversity and recreation provision generally increase for approximately the first 20 years, decrease until the middle of the century and increase thereafter. While scenarios with greater challenges to climate change mitigation (i.e. SSPs 3 and 5) tend to cluster together, others show higher supply levels and more differentiated trajectories. Biodiversity demands are met under four scenarios including the reference, while demand for recreation is only met under RCP3-SSP8.5.

Cereal provision grows and in some cases starts to stabilise in the second half of the simulation, although under no scenario does it reach demand. Meat supply does however meet demand throughout the simulation.

### 3.2 Land-use change

Overall, major land-use change was largely concentrated in the northernmost region (i.e. Upper Norrland), while the southernmost (i.e. Götaland) experienced the smallest changes (Fig. 4a). Changes in SSP3-RCP4.5, SSP3-RCP8.5 and SSP5-RCP8.5 are largely similar, although uncertainty in the magnitude of change is larger under RCP8.5 in the southern half of the country due to more divergent underlying climate change projections.

Nationally, we find an increase in agriculture and a decrease in unmanaged land, with the most extensive use of previously unmanaged land in the reference and SSP1-RCP4.5 scenarios. For other scenarios, extensive conversion of unmanaged land concentrates in Norrland. Agricultural expansion is generally larger under scenarios with higher mitigation challenges, and tends to concentrate throughout scenarios in the middle of the country (i.e. Lower Norrland and Svealand).

Monocultural conifer plantations tend to show minimal or no change. Pine-spruce forests generally expand extensively in the north and decrease in the south. Under the reference scenario however, they expand throughout the country. Mixed conifer-broadleaf forests expand in Upper Norrland and Svealand, but have only small increases in Lower Norrland. Trends in change for these forests differ in Götaland, where expansion happens under the reference scenario and SSP1-RCP4.5, but no change is observed under SSP4-RCP4.5, and loss occurs under all other scenarios. Boreal broadleaf forests have no observable change. Nemoral broadleaf forests undergo either no change or expansion, the latter being most prominent under SSP1-RCP4.5.

Hotspots of land-use expansion in pine-spruce forest, mixed conifer-broadleaf forest, nemoral broadleaf forest, agriculture and unmanaged land are observable for the different scenarios (Fig. 5a). Western Norrland is a hotspot for pine-spruce forestry expansion across all scenarios. Pine-spruce forest hotspots occur also in the south under the reference scenario, and to a lesser extent under SSP4-RCP4.5, SSP3-RCP4.5, SSP3-RCP8.5 and SSP5-RCP8.5. Only one hotspot occurs of mixed conifer-broadleaf forest expansion in the south under SSP1-RCP4.5. This scenario also has several hotspots of nemoral broadleaf forests in Upper Norrland, Svealand and Götaland. Agricultural expansion hotspots are present in the southern regions under SSP1-RCP4.5, SSP3-RCP4.5 and SSP3-RCP8.5, while under SSP5-RCP8.5 they also occur towards the north. Finally, a hotspot of land abandonment exists consistently in south-eastern Götaland under all scenarios except the reference.

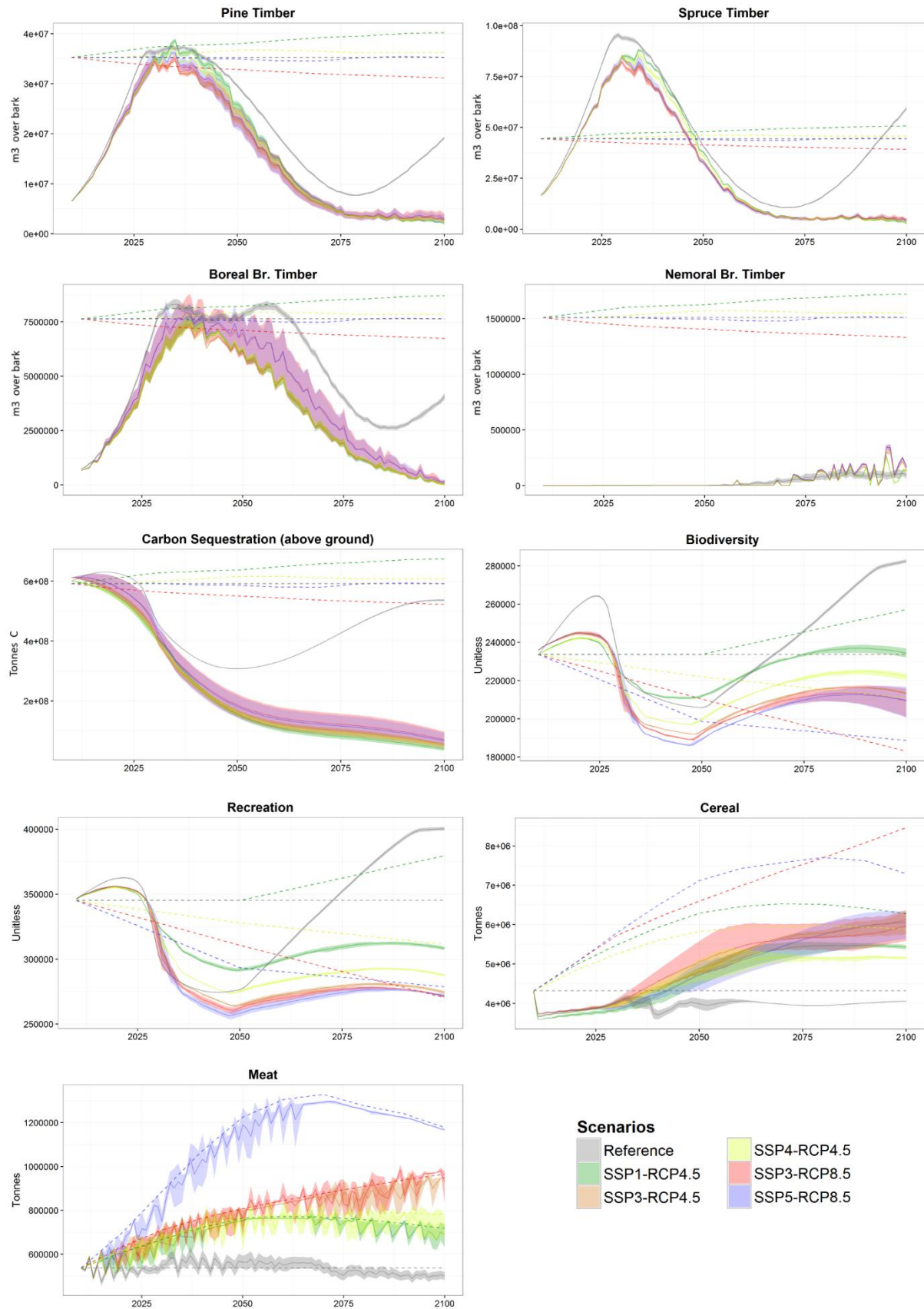
### 3.3 Changes in land owner management roles

Upper Norrland was the only region where no land owner management role had a discernible decrease across scenarios (Fig. 4b). In all other regions the percentage of productionists decreased, except in Götaland under the reference scenario. Productionist loss was strongest in Svealand and weakest in Götaland, reflecting a decrease in the proportion of productionists nationally under all scenarios except the reference. Multi-objective forest owners were most successful, substantially increasing in numbers except in the south under scenarios with greater challenges to climate change mitigation. This type experienced its largest increases in Upper Norrland.

Recreationalists decreased in the southern regions and increased in Upper Norrland, but their total numbers decreased under all scenarios except SSP1-RCP4.5 and the reference scenario. Conservationists experienced small or no changes in all regions and under all scenarios except for SSP1-RCP4.5, under which their numbers increased substantially, especially in Upper Norrland. The percentage of passive owners remained nearly unchanged under all SSP-RCP scenarios, but increased slightly under the reference scenario, mostly in Götaland.

Commercial farmers generally increased in numbers under all SSP-RCP scenarios, but decreased in southern regions under the reference scenario. Non-commercial farmers show very similar changes under all scenarios, increasing in the north, barely changing in the mid latitude regions, and decreasing in the south.

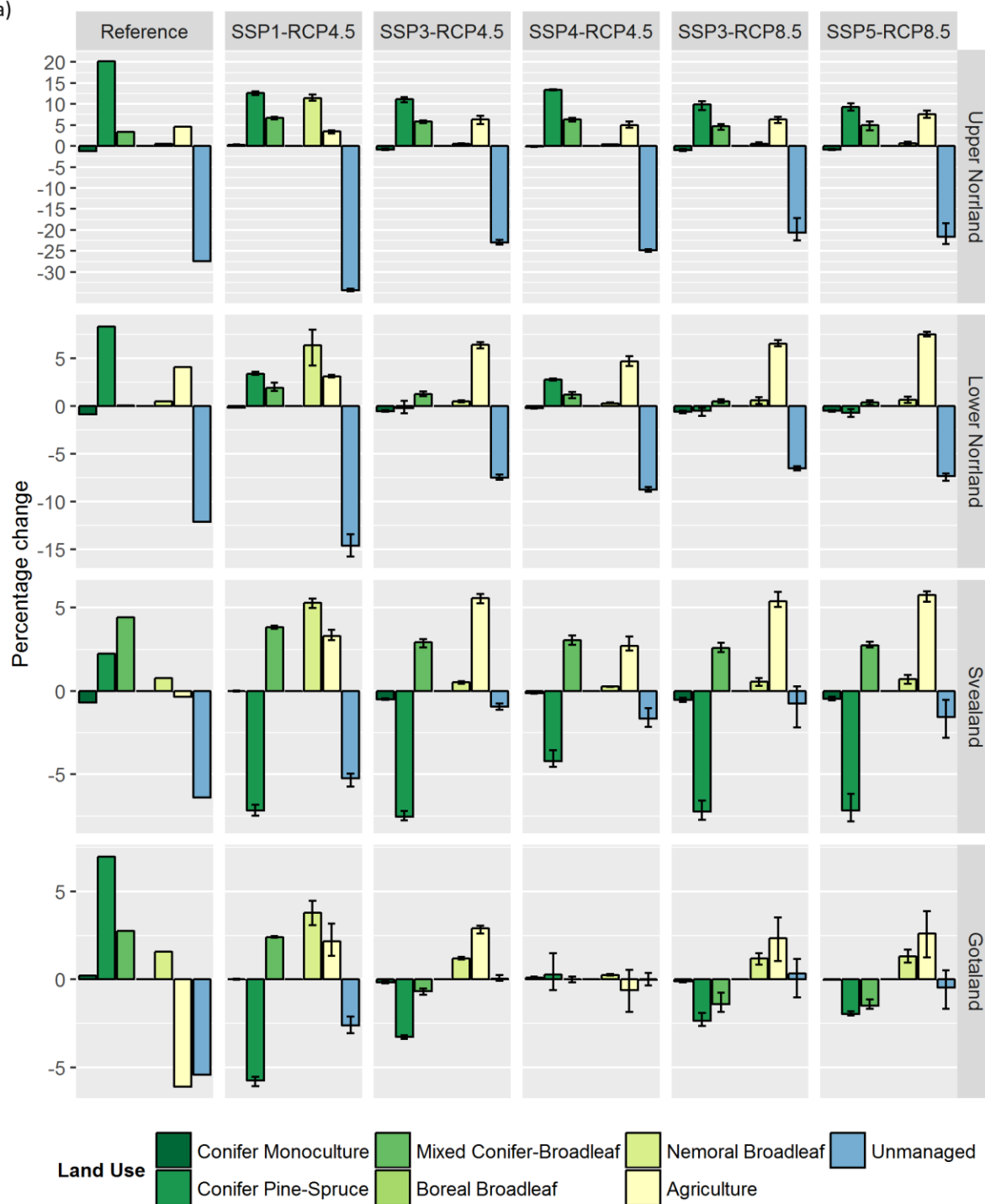
We observe hotspots of increase in productionist, multi-objective, passive, commercial farmer, and non-commercial farmer management roles among all scenarios (Fig. 5b). The reference scenario resulted in hotspots of productionists in Upper Norrland, multi-objective owners in all regions, and passive owners in Lower Norrland and Götaland. Under SSP1-RCP4.5 and SSP4-RCP4.5 multi-objective owner hotspots occurred in all regions although to a much lesser extent in the southern ones, where commercial farmer hotspots also occur under SSP1-RCP4.5. SSP3-RCP4.5 had incremental hotspots in multi-objective owners in southern regions, and commercial farmers in all regions. SSP3-RCP8.5 differs from SSP3-RCP4.5 in that it has a hotspot of multi-objective owners in the south, and it has no commercial farmer hotspots in Upper Norrland. Finally, SSP5-RCP8.5 has hotspots of multi-objective owners in all regions, primarily northern ones, commercial farmers throughout the country, and non-commercial farmers in Upper Norrland.

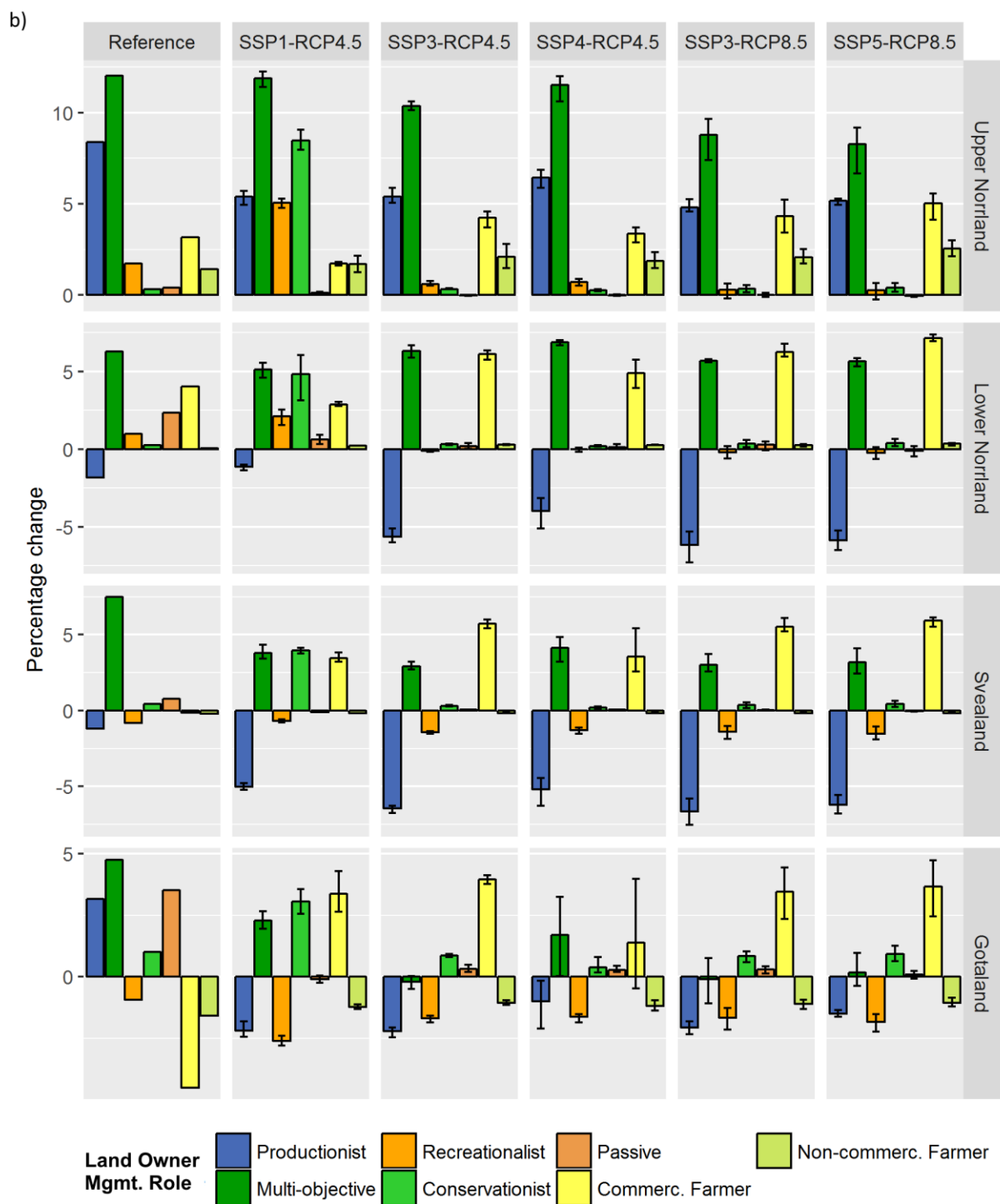


**Fig 3** Means (continuous lines) and ranges (semi-transparent areas) (defined by the three climate models) of ecosystem service provision, and service demands (dashed lines) through the study period, under the Reference and SSP-RCP



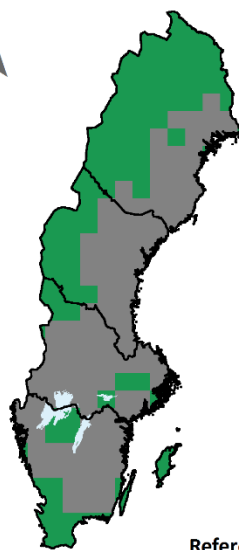
a)



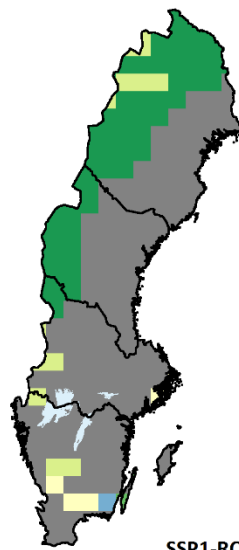


**Fig 4** Percentage change of a) land-use and b) land owner management role categories per scenario and region. Error bars show the ranges of change generated across the three climate models for each scenario

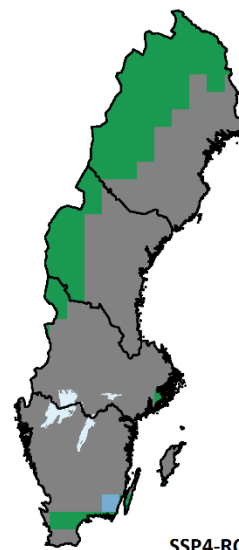
a)



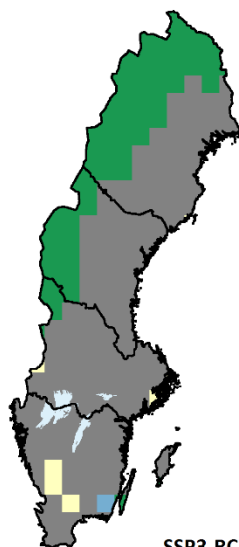
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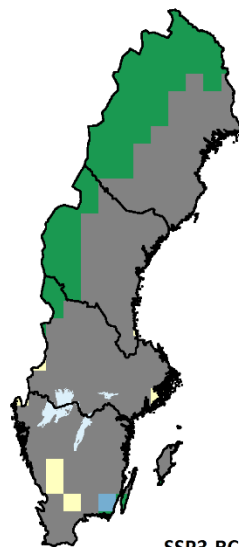
SSP1-RCP4.5



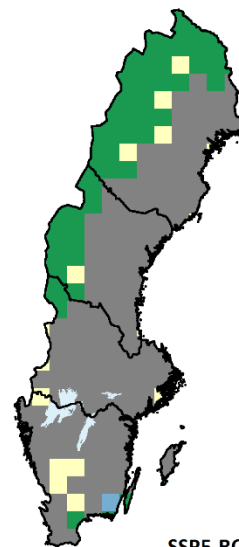
SSP4-RCP4.5



SSP3-RCP4.5



SSP3-RCP8.5



SSP5-RCP8.5

#### Land-use



Conifer Monoculture



Mixed Conifer-Broadleaf



Conifer Pine-Spruce



Boreal broadleaf



Nemoral Broadleaf



Agriculture

#### Other



Unmanaged



No Change

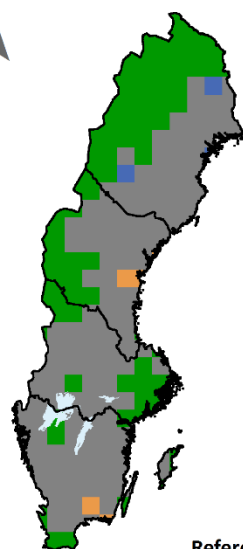


Lake

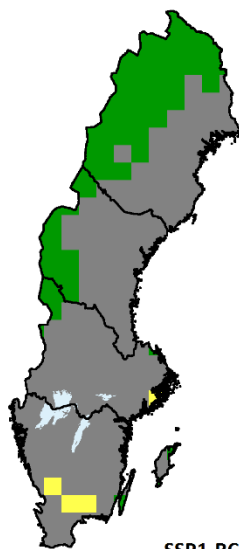


Regional Limit

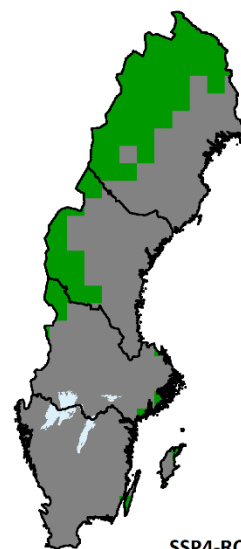
b)



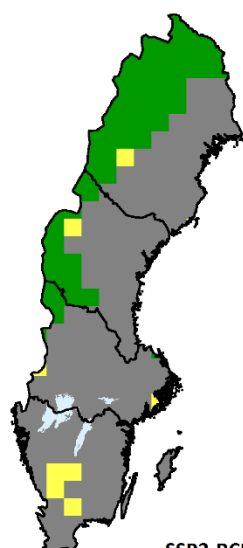
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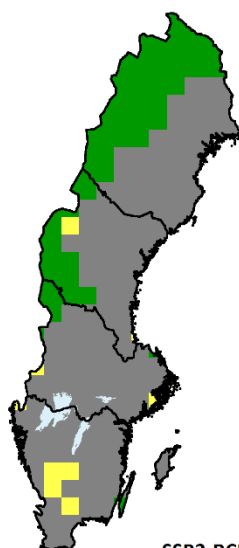
SSP1-RCP4.5



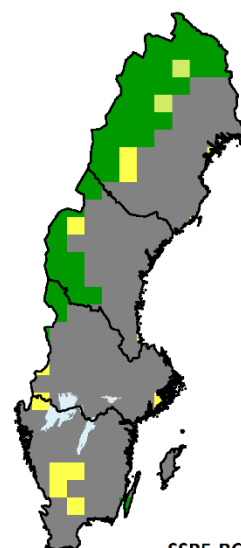
SSP4-RCP4.5



SSP3-RCP4.5

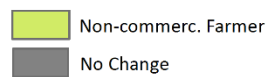
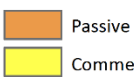


SSP3-RCP8.5

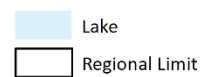


SSP5-RCP8.5

Prevailing land owner management role increase



Other



**Fig 5** Locations of hotspots of increase in a) land-use and b) land owner management role categories under all scenarios in Sweden

## 4 Discussion

### 4.1 Future changes in land use and ecosystem service provision

This work demonstrates the adoption of mechanisms to simulate forest owner decision-making in large scale land-use change and ES provision modelling, and uses these to assess possible changes in the Swedish forestry sector under different climate and socio-economic change scenarios. Findings suggest substantial scope for model applications of this kind, and also for great variation in ES provision in the Swedish forestry sector, and important land-use change throughout the country.

Some of the changes in ES provision that we simulate are not caused by scenario conditions or forest manager decision-making. In particular, the sinusoidal trajectory of pine, spruce and boreal broadleaf timber supply through time under the reference scenario is largely determined by the uneven distribution of forest ages within Sweden. This is a legacy of past land management decisions. Forestation in the country increased from the beginning of the 20<sup>th</sup> century until the 1960s, when highest rates of forest regeneration (i.e. including planting, seeding, and natural regeneration) per year were attained, after which rates began to decline (Swedish Forest Agency 2015). The model suggests that this will result in a peak in supply during the 2030s, approximately 70 years after the forest planting peak. In reality, the magnitude of this peak is likely to depend upon the extent to which felling can be coordinated to preserve supply and price levels, but the need to harvest within certain time periods does constrain the scope for such actions. As a result, decreases are likely in timber revenue and in the supply of other forest services, with reductions in the supply of biodiversity, recreation, and carbon sequestration being projected in our simulations. Therefore, it is clearly important that the impacts of a future acceleration in timber harvesting are considered and addressed.

More generally, the substantial decoupling between the simulated supply of, and demand for, forest services over the course of 90 years (in contrast to the results for agriculture) demonstrates the difficulty of continuously meeting societal demands for ES produced over long periods of time. The consistent supply of multiple forest services represents a complex optimisation problem that can only be solved, if at all, using national overviews and top-down (e.g. policy) mechanisms. An obvious example is the provision of biodiversity and recreation, which depends upon nationally designated areas and prohibitions on felling in non-productive forests (Swedish Forest Agency 2014), even in the most environmentally-friendly scenarios we modelled (i.e. SSP1-RCP4.5). Future analyses of service provision under such scenarios should therefore also consider services provided by protected natural systems, in order to evaluate how far they are able to absorb impacts of changes such as large-scale felling in productive forests. Another consideration is the extent to which food demand exerts pressure on forest management and ES provision, with our simulations suggesting shortfalls in cereal supply even under sub-optimal forest ES provision. A higher societal sensitivity to cereal supply levels would contribute to bringing supply closer to the demand, which would further compromise the provision of forest ES. Furthermore, the potential increase in agriculture in the north would entail a more widespread competition with forestry throughout the country. Our simulations suggest that this northward expansion would largely come at the expense of unmanaged land, comprising wetlands and semi-natural vegetation, which also supply ES such as water supply, nutrient retention, food, recreation, or biodiversity (Costanza et al. 1997). Hence, it is important to understand that meeting future demands for agricultural and forest services will likely entail trade-offs with ES supplied by other natural systems.

We also find that, under the SSP-RCP scenarios, carbon sequestration decreases as timber is increasingly felled throughout the first third of the century, but does not increase again as timber

1 felling decreases after that (in contrast to the reference scenario). Similarly, biodiversity and  
2 recreation decreases are never entirely reversed under the SSP-RCP scenarios, while they are under  
3 the reference scenario. The reason for this is that forest-to-forest land-use change is substantially  
4 more frequent under the SSP-RCP scenarios than for the reference, meaning that fewer forests  
5 reach their scheduled age of felling under the SSP-RCP scenarios. The lower mean national forest age  
6 reached under SSP-RCP scenarios also entailed smaller annual timber harvests nationally as younger  
7 forests were being felled, and this keeps carbon sequestration, biodiversity and recreation at lower  
8 levels. These findings confirm qualitative results from Roberge et al. (2016), who suggest that the  
9 provision of supporting and cultural ES, and economic outputs from timber would be negatively  
10 impacted by shorter rotations in Fennoscandian forests.  
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13 This phenomenon is explained by changes in demand levels and climate change, which together  
14 prompt forest managers to adapt their management activities more frequently and dramatically  
15 than they would otherwise do (with the size of this effect depending on the balance between the  
16 costs of early felling, timber prices and potential profits from alternative management  
17 strategies). This effect is consistent with the ongoing consideration of management alternatives (e.g.  
18 multi-species planting, or introduction of exotic species respectively) as adaptations to climate  
19 change (Felton et al. 2016; Kjaer et al. 2014). If forest owners do consider felling early when faced  
20 with a profitable alternative, the successful uptake of one or more innovations could trigger  
21 continued changes between forest types as simulated here, which could negatively affect the  
22 provision of services that increase with forest age. Further simulations including the uptake of  
23 innovations as a function of networks among forest owners (Satake et al. 2007) and relevant  
24 institutions would be particularly useful here.  
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29 Many of our findings were broadly consistent between SSP3-RCP4.5 ('Regional rivalry' and low  
30 emissions) and SSP3-RCP8.5 ('Regional rivalry' and high emissions), which seems to indicate that the  
31 influence of climatic change on land productivities (being the only parameter different between  
32 them) may be less important than that of socio-economic changes or behavioural differences.  
33 Additionally, the great resemblance between SSP3-RCP8.5 and SSP5-RCP8.5 ('Fossil-fuelled  
34 development' and high emissions) suggests that land owner and societal behavioural factors (e.g.  
35 sensitivity to profit levels on the part of landowners and sensitivity to supply levels on the part of  
36 society), despite substantially different service demand trajectories, are key in determining the  
37 course and impact of land use change. Furthermore, this holds true for the provision of timber and  
38 non-timber forest services.  
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43 Climate change, and especially service demand levels do, however, appear to influence the  
44 geographical distribution of land-use, as observed when comparing SSP3-RCP4.5, SSP3-RCP8.5, and  
45 SSP5-RCP8.5. We see an expansion in both commercial and non-commercial agriculture towards the  
46 north as a response to the higher demands for agricultural products and increasing suitability for  
47 agriculture in the north. Additionally, the distinctive expansion of nemoral broadleaf forests and  
48 conservationists across the country, and of recreationalists in the north under SSP1-RCP4.5, are  
49 consequences of the higher value and demand being placed by society on biodiversity and  
50 recreation.  
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## 56 **4.2 Model assumptions and limitations**

57 It can be difficult to identify causes and effects in simulations from complex system models because  
58 of the multiple interactions and feedbacks inherent within such models. However, we can identify  
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some relationships between model inputs and outputs from the sensitivity analysis and the exploration of simulation results, and sources of uncertainty among model assumptions. Giving-in and giving-up thresholds represent a range of personal characteristics that control an agent's responsiveness to demand levels. Here we assign random distributions to these thresholds, in the absence of empirical data with which they could be parameterised. Our, and previous (Brown et al. 2014; Brown et al. 2016; Murray-Rust et al. 2014), sensitivity analyses show that the effect of random model components on agent behavioural parameters has a lower impact on ES provision compared with components that differ between scenarios (demand and productivity changes, and mean behavioural values). Land owner giving-up probabilities help to regulate the rate of owner type and land-use change, with lower giving-up probabilities resulting in less abrupt yearly changes, especially for farmers/farmland. Greater randomness between agents means less 'rationality' in land use change. Further insight into how behavioural parameters affect simulation results, through extensive sensitivity analyses, are presented in Brown et al. (2014), Brown et al. (2016) and Murray-Rust et al. (2014).

The ES demand change scenarios were derived from the SSP-RCP scenarios, but it is important to acknowledge the difficulty in estimating such demands because of the substantial uncertainty inherent within these scenario assumptions. It is also important to be cautious with the results for owner type and land-use change in the north west of Sweden, dominated by the Scandes mountain range. In this area, the effect of topography on productivity changes arising from climate change is difficult to model since productivities were calculated from climate change data at a coarser spatial resolution (50x50 km). Therefore, the effect of climate change is highly uncertain in north-western Sweden. Furthermore, the model allocates forest in the mountainous region under all scenarios, including the reference, to cells where forest was previously not present. This is mainly due to the time lag between the moment when forests start being planted in response to unmet demands and the moment when demands are met. During this time period, while service supply from young forests is still low, forests continue to be planted, to the point that they occupy available areas that may be less productive. This may be unrealistic depending on the level of return that 'real world' land owners are willing to accept from forest activities.

Not allowing land ownership to change between forest owner types before stand maturation means that the effect of management on forest growth rates and their service provision throughout the life of the forest is fixed when the forest is planted. This would only be a limitation though if it were common for forest ownership and management to change during early forest development stages. Additionally, we did not account for voluntary set-asides for conservation, which make up at least 5% of the productive forest area (Swedish Environmental Protection Agency 2016). In addition, due to certification requirements, trees, tree groups and buffer zones are left on most felling sites, also reducing the harvested volume somewhat. Had voluntary set-asides and certification requirements been accounted for, yearly timber provision would have been lower and the outcomes of the modelled competition process slightly different. Conversely, as today, the majority of the planting material in Sweden comes from seed orchards, and these plants are expected to grow considerably faster (10-20%) compared to plants used in past decades, accounting for this effect would have led to higher standing volumes and timber supply. Consequently, the effect on timber provision of not including voluntary set-asides or certification requirements, and the effect of not including planting material from seed orchards have opposing effects at the aggregate level.

The trajectory of timber provision will, however, likely be less markedly sinusoidal than presented here. The forest age distribution used (from SLU Forest Map) was shown to overestimate the area covered by middle aged forest and underestimate that of old forest, even though more forest was

still planted around the 1960s. Consequently, while timber supply may still peak in the 2030s, harvesting is likely to be distributed more evenly through time than presented here. Simulation results presented in the Swedish national forest impact assessment show a relatively steady increase in timber provision throughout the century, mainly driven by increased productivity from climate change (Claesson et al. 2015). This higher regularity in supply resulted mainly from their inclusion of a more evenly distributed age distribution (from the National Forest Inventory). Ranges of levels of total timber provision were largely similar in their assessment and ours, even though we did not take the effect of tree breeding into account. CRAFTY-Sweden also considers some drivers that the national forest impact assessment did not (i.e. demands for ES and human behaviour), leading to different dynamics, especially towards the end of the century, as discussed below.

## 5 Conclusions

CRAFTY-Sweden brings us a step forward in the understanding and representation of large scale land-use change and its complexities under climate change. Our results show that variability in human behaviour has a substantial role in determining the effects of climatic forces and societal demands on ES provision and land-use change. Important changes in land-use and ecosystem service provision can be expected in Sweden as a result of changing demands and climate, especially towards the north of the country. Increasing food demands and increasingly favourable climatic conditions for agriculture would lead to agricultural expansion, if food imports are not increased. Such expansion would require trade-offs with currently unmanaged land, such as wetlands, which contribute important ES. Furthermore, accelerating timber harvesting throughout Sweden due to a nationally uneven age distribution, and increasing rates of forest land-use change between forest types may have negative consequences for forest ES provision. Finally, the challenge of steadily meeting societal demands for ES produced over long time periods and at large scales would require top-down mechanisms that use national-scale information to regulate forestry processes and, to the extent possible, their consequences.

## Acknowledgements

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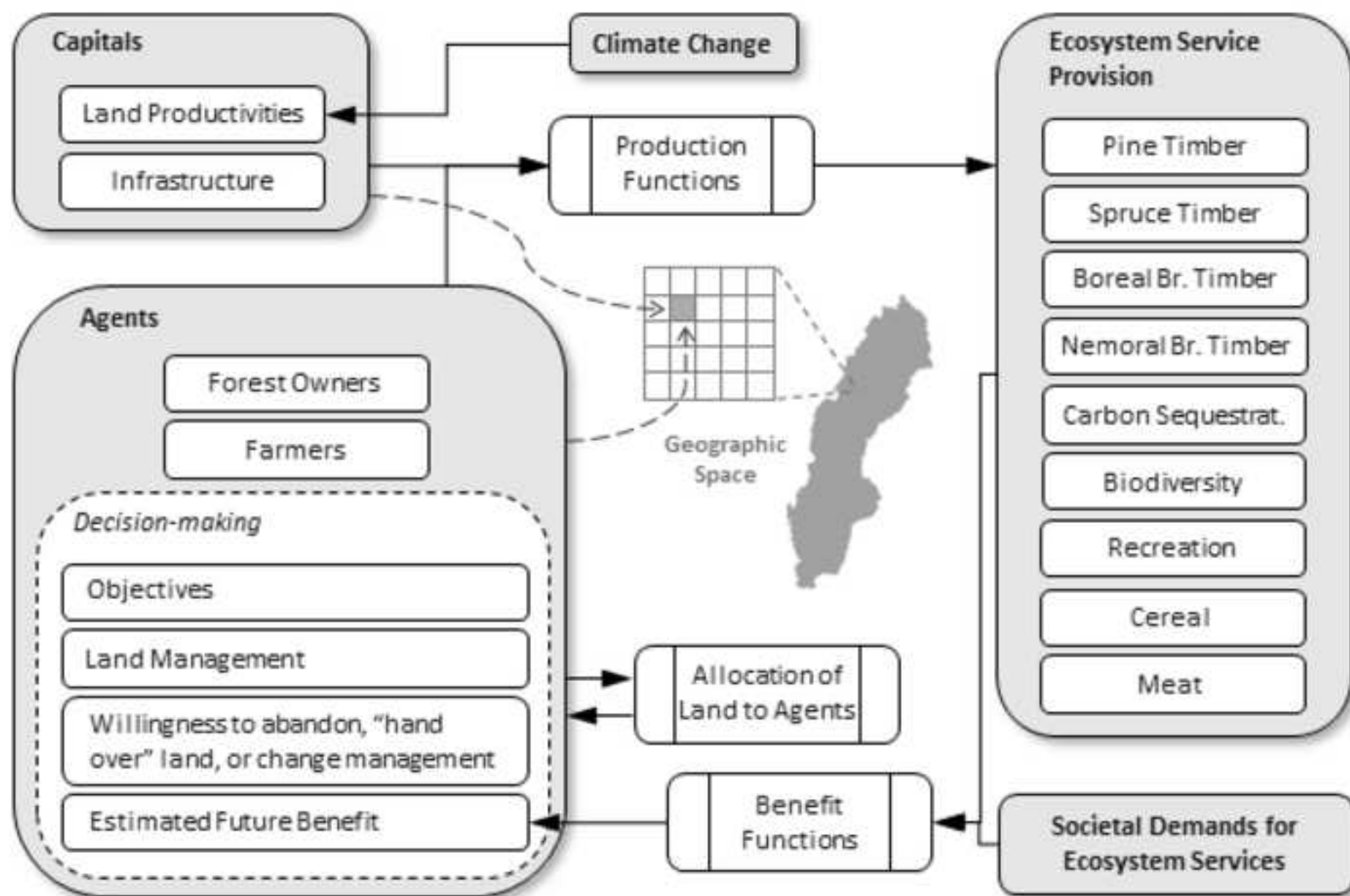
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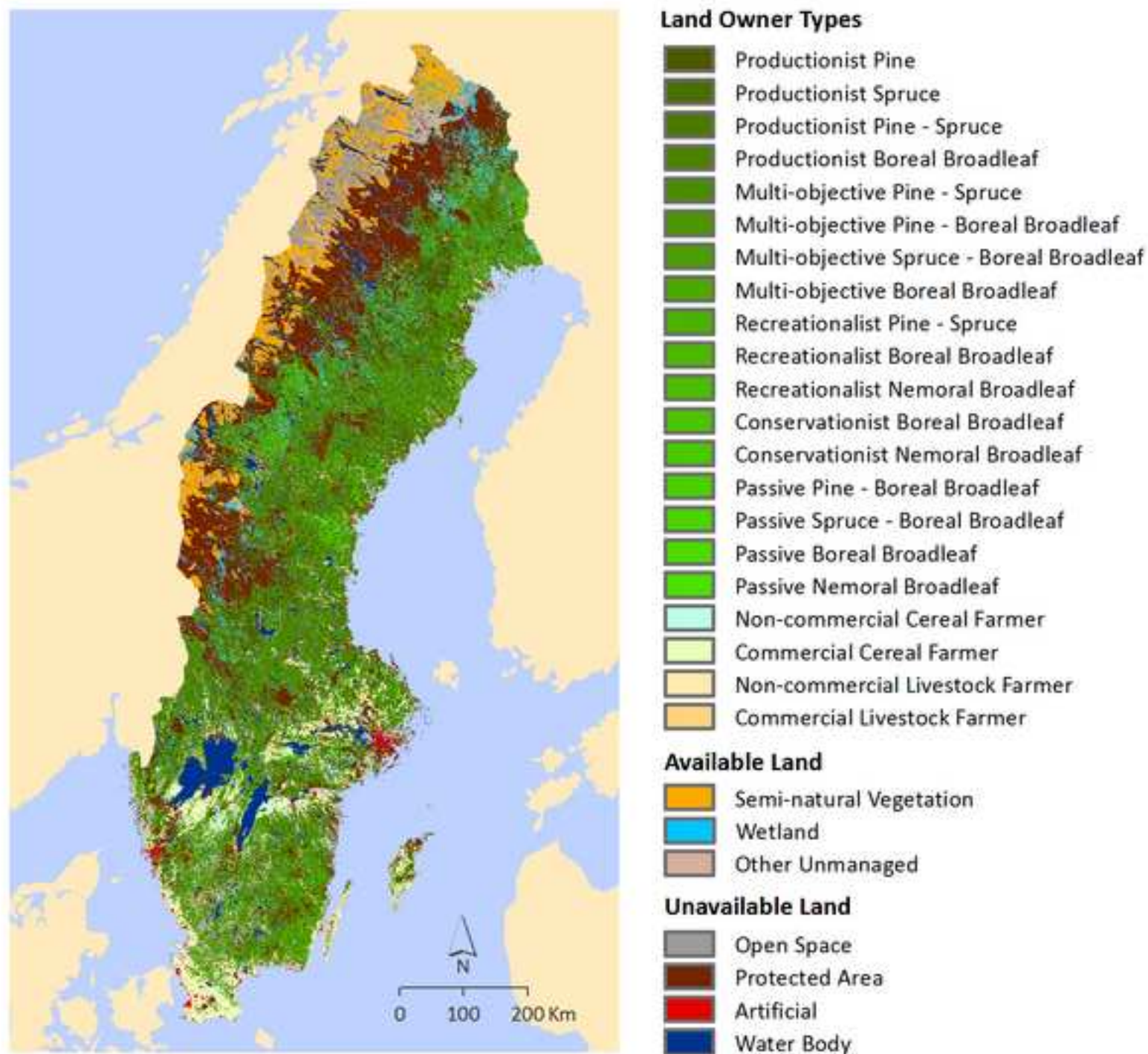
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Figure 1  
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**Figure 2**  
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**Figure 3**  
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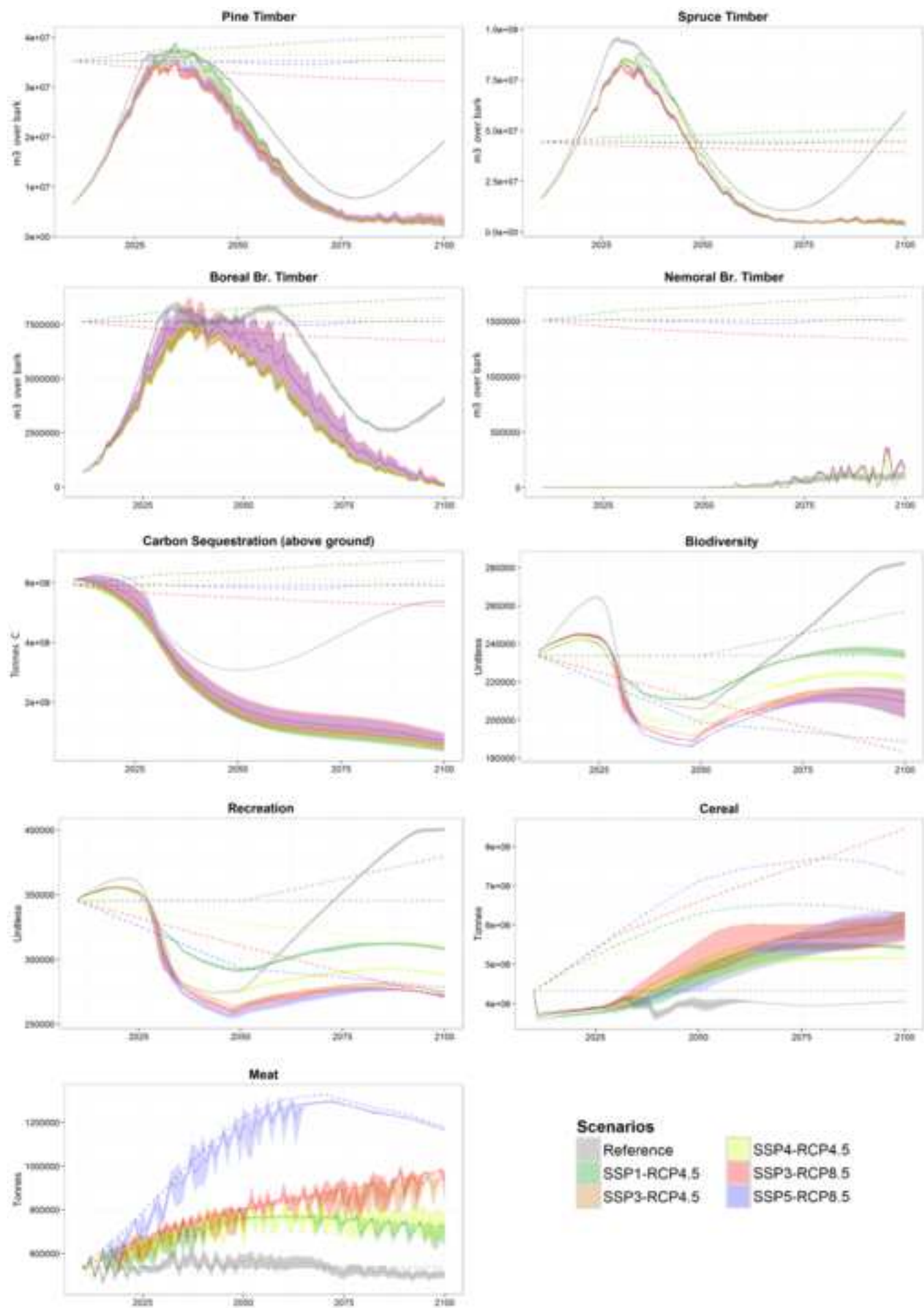




Figure 4a

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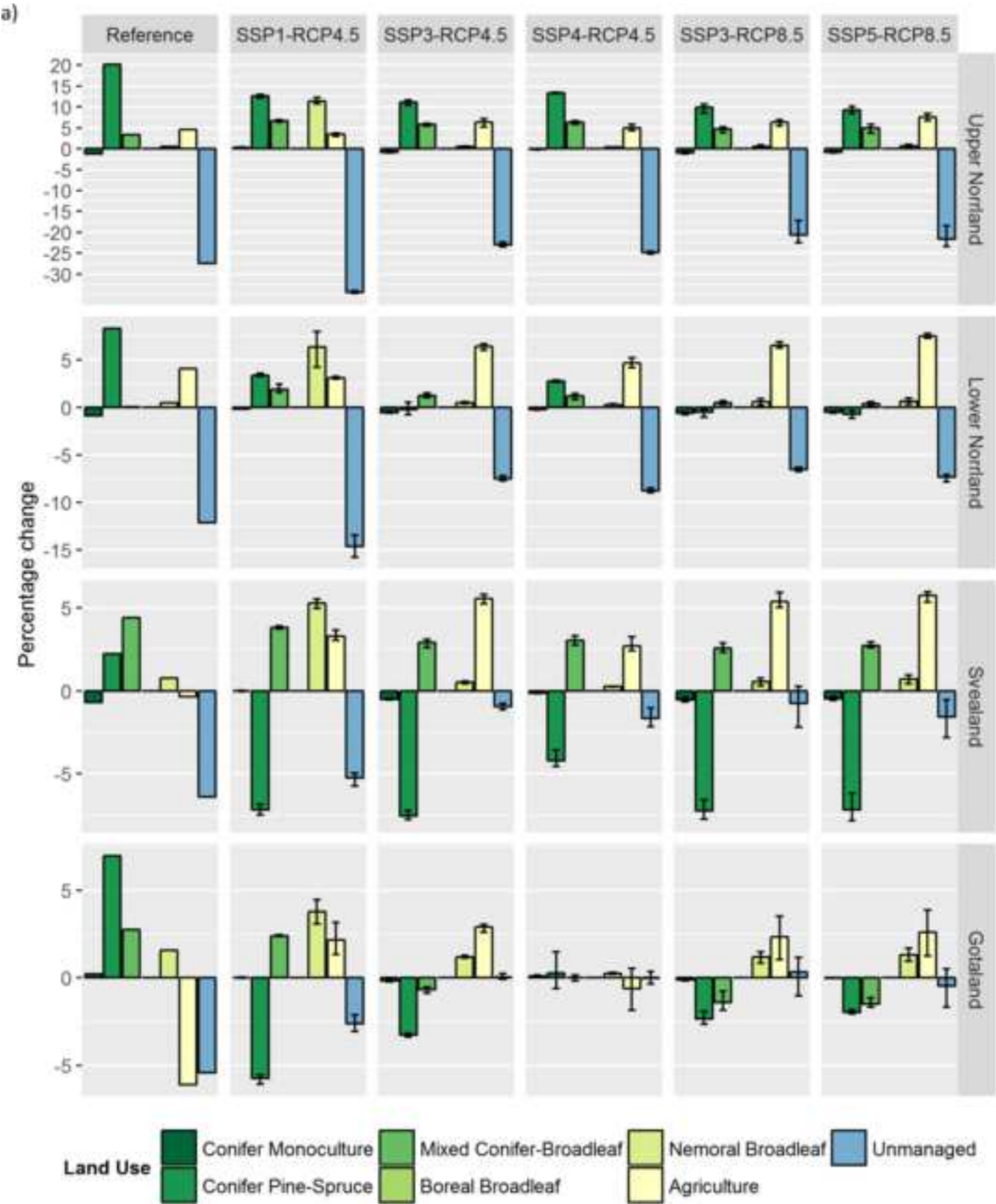
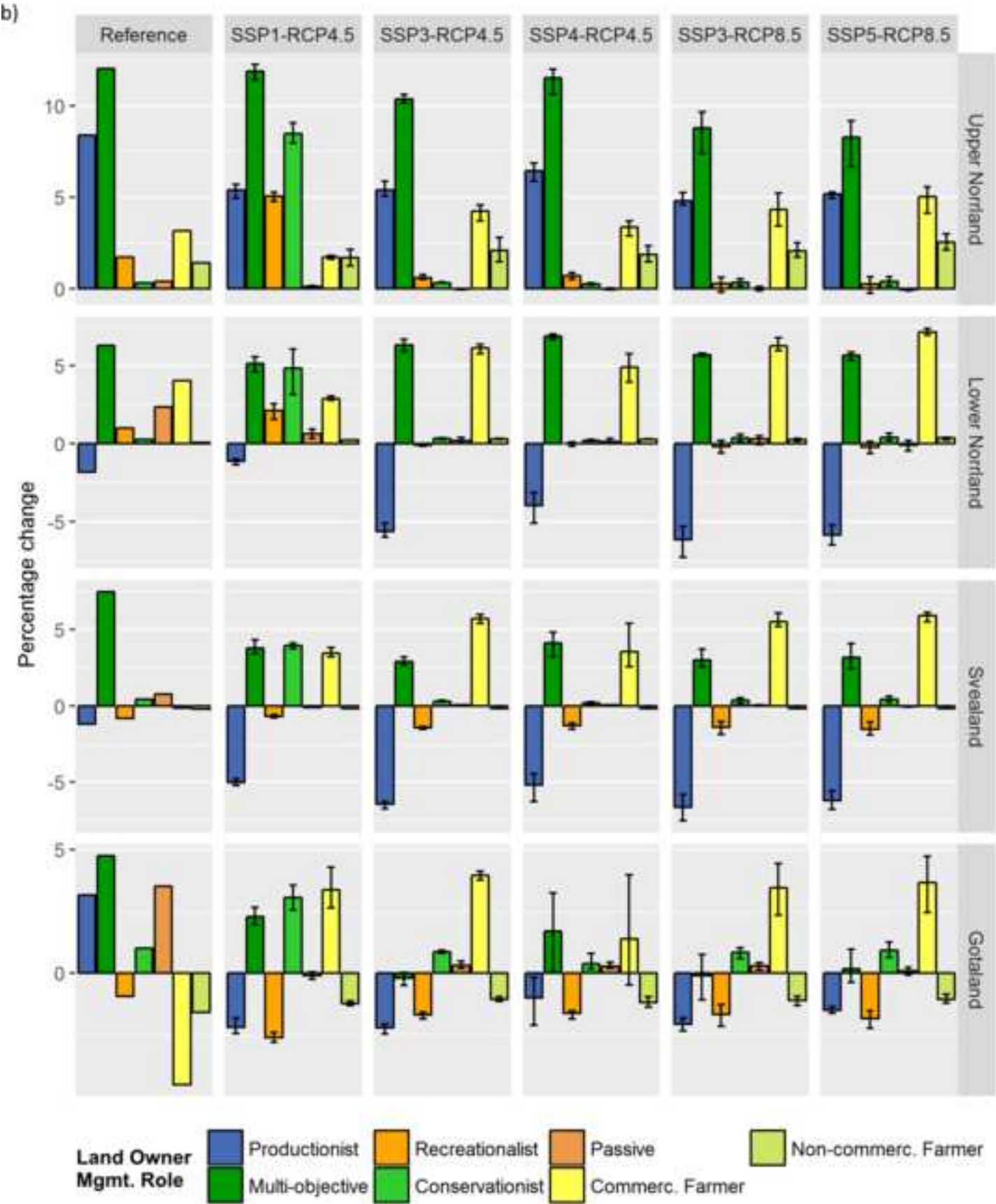
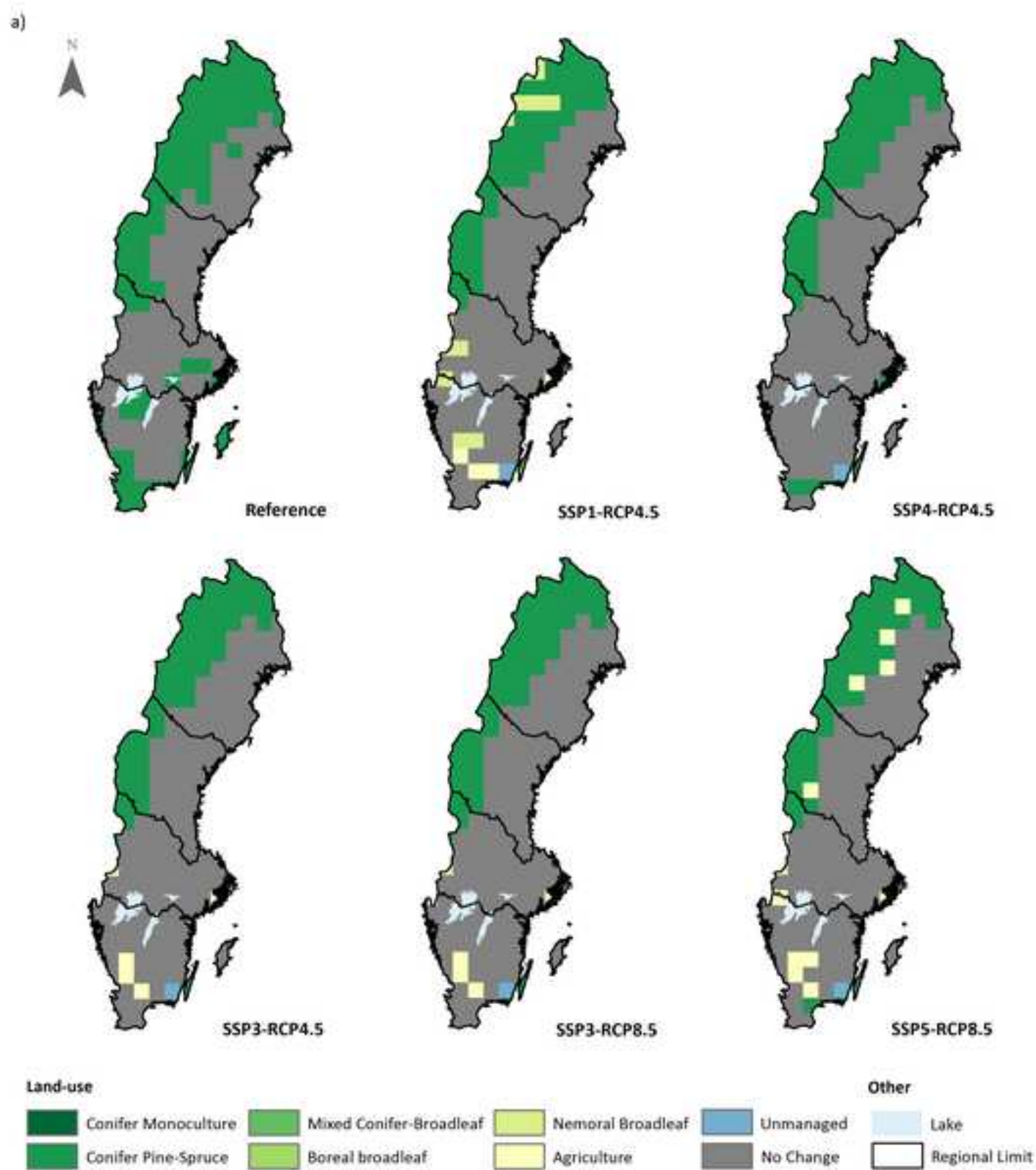


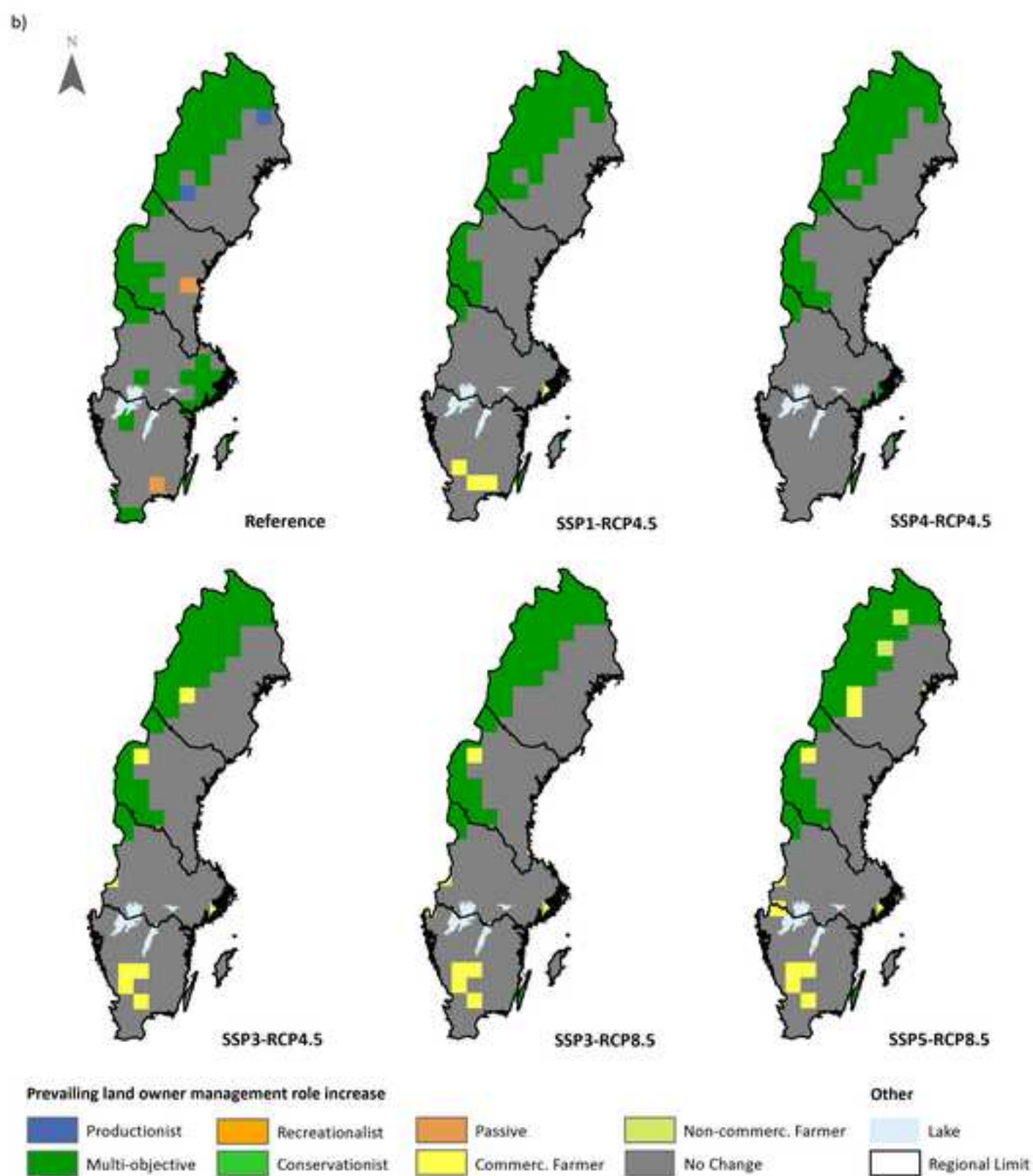
Figure 4b  
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**Figure 5a**  
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**Figure 5b**  
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## REVIEWERS' COMMENTS

### General reply to editor and reviewers:

Dear editor and reviewers,

We would in the first place like to thank you for your insightful, thorough and constructive comments. We believe that they have helped to improve our manuscript substantially. We hope that you too will find that the manuscript is now ready for its publication in 'Ecosystem Services'. Below you may find our response (in black) to all comments and suggestions made by the reviewers (in blue).

### Response to reviewers:

**Reviewer #1:** the manuscript 'the effect of forest owner decision-making, climatic change and societal demands on land-use change and ecosystem service provision in Sweden' reports of a first attempt to apply agent based modelling of forest owners at national scale. The amount of work performed by the authors is impressive, however, there are a couple of points on which I find the manuscript in its current form unfit for publication.

In general the manuscript hinges on two ideas;

1. the introduction of a new methodology to the field of ecosystem services, land-use change and forestry and the implementation thereof.
2. the future development of the Swedish forest derived ecosystem services.

Although the authors herald their efforts for the first, the specific implementation that is introduced here (Crafty-Sweden) is poorly analysed on its own. Especially in the results and discussion section the results of the model are not placed in the context of the model assumptions (only in the context of the broader scenario lines). With the lack of a proper uncertainty analysis (beyond the inclusion of three climate realisations per scenario) this omission undermines the credibility of the second aim of the paper; the application of the model for a projection of future developments.

As such, I would recommend major revisions to the manuscript before publication. However this manuscript is very promising and shows that a lot of work has been done. I am very impressed with the full ODD and extensive appendix B (which is almost a full paper on itself)

We appreciate the positive comments and accept the reviewer's points about the presentation of the model. We have made extensive changes to address these points, providing additional detail, references and discussion, and hope these improve the interpretability of the model, particularly with respect to underlying assumptions.

Some specific remarks:

1. the introduction lacks a clear direction. I cannot find the focus and there is a lack of connection between the introduction and the rest of the manuscript.

We have substantially re-written the introduction to account for these points.

2. the technical details of the model are unclearly explained in the core text. More specifically, the idea of capitals and their production, the moment of their production are hard to follow. I also do not understand the frequent use of the word optimal in relation to capital production, I do not see the optimisation. From the text I get the impression that the services carbon sequestration and recreation are produced only at harvest time. The time integration of the different services in the decision making is unclear.

We have now made a number of changes to clarify these sections. The optimal service production is the maximum production achievable in Sweden under ideal environmental conditions, and its levels are taken from an agent type-specific function (i.e. optimal production function) that describes the change in service production levels with forest age. Capital (i.e. land productivity and infrastructure) levels are used to adjust optimal production to production levels achievable at a particular site. Capital sensitivities adjust these site-specific production levels to what the agent type would be able to attain given its particular dependencies on capitals. An explanation about optimal service production and how it relates to actual service production has now also been introduced in the 2<sup>nd</sup> paragraph in section 2.1.4.

(Sentence 4) Carbon sequestration and recreation, just like biodiversity, are produced yearly. Timber, however, is supplied only when the forest is felled. For clarification, we have now added a sentence to the 2<sup>nd</sup> paragraph in section 2.1.4: “Timber supply (i.e. harvest) is recorded upon felling, while other forest services are supplied yearly”. When the forest is felled, the carbon stored (above ground) is removed from the national account (this is stated in the last sentence of section 2.1.5, on forest felling).

3. I personally find the numbered scenarios difficult to grasp. There is little explanation on the rationale behind the scenarios and their assumptions. This makes it difficult to follow the discussion.

Relevant scenario narratives for the SSPs used here are now included in Appendix B in the form of a table (Table B.3), which is now mentioned in the first paragraph in section 2.2.

4. There is no systematic analysis of the effect of model assumptions on the model performance (e.g., the assumption to exclude land tenure before stand maturation, and the effect of the assumption that all agent-type parameters should be randomly distributed)

5. there is no analysis of the results in terms of the specific input, only an interpretation of the consequences of the results

While the effects of model inputs are discussed for some parameters (e.g. climate change, ES demands, behavioural parameters) throughout the Discussion, we agree with the reviewer (regarding points 4 and 5) that the effects of model assumptions and inputs should be explained further. We therefore now discuss the effect of model assumptions and specific inputs on the model performance in the section 4.2, including the effects of: giving-in and giving-up thresholds, giving-up probabilities, random behavioural components, demand

changes over time, spatial resolution of productivity changes, time lags in the system, stands not being felled before maturation, not including voluntary set-asides, certification requirements or planting material from seed orchards, and forest age frequency distribution. Furthermore, we also refer now the reader to other papers that have used CRAFTY and present sensitivity analyses that are relevant to interpreting the results presented here.

**Reviewer #2:** The paper is interesting and well-written. Incorporating land owner behavior in modelling of ecosystem service provision on large scales is a timely research field which has not been very well explored so far, and is of large importance given the high share of private ownership in many countries. I also appreciate the attempt to combine several important impact factors - land owner decision making, climatic change and societal demand - in one model, as all of these factors can be expected to have large impacts on ecosystem service provision, as well as the attempt to relate ecosystem service supply to its demand.

However, I have major concerns on the modelling of forest growth and yield, which I think should be addressed before potential publication:

The model you used for calculating timber growth (ProdMod) is a stand model. If I understand correctly, you used only one stand type (latitude of 57°, altitude of 100m, with an understory of herbs and grasses) to calculate timber growth for all forest types across Sweden. Given the large range in stand types and productivity in Sweden, I wonder how you came to choose just this stand type, and how this influences your results. Forest growth is site-specific, and I do not see how you can cover the large variety and shifting growing conditions present in Sweden with just one stand type (even if you seem to assume a small number of different site indices).

ProdMod was used only to establish growth curves for the different forest types and management practices under optimal conditions. To reflect optimal conditions for Sweden, we chose a location and conditions (understory of herbs and grasses) that would result in optimal yields. Forest owner type-specific growth curves obtained in ProdMod are then used in Crafty-Sweden. Through the Cobb-Douglas function, the effect of site environmental conditions is considered through capitals representing forest productivity, which reflects the site index (i.e. the site-specific productivity level weights the maximum production achievable in Sweden per unit of area under ideal environmental conditions, resulting in generally lower production levels that reflect site conditions). In this function, the age-dependent optimal production level ( $o_{st}$ ) is taken from a growth curve generated in ProdMod. Therefore, for a specific location, the growth curve calculated in ProdMod for a particular owner type only remains unchanged under maximum levels of productivity (and infrastructure). Otherwise, for productivity values  $<1$ , which may occur towards the north of the country for instance, yearly growth is smaller than it would be under perfect conditions.

For clarity, we have now introduced in the 2<sup>nd</sup> paragraph in section 2.1.4 a detailed explanation of what we refer to as optimal service production and how it is used.

You mention site index on P 9 Table 2. But I do not find an explanation where the data on the site index comes from and how you define it.

We now provide an explanation of the origin and definition of the site index in the first paragraph of Appendix B.4.1, and refer to it in Table 2 in the manuscript

Site index is defined as the dominant stand height at 100 years of forest age. Site index values for pine and spruce forests come from Swedish Forest Agency statistical data on “Productive forest land area by county/region and site index for pine forest and spruce forest” for the period 2008-2012. Site index values for boreal and nemoral broadleaf forests were obtained by applying a function (from Hägglund B, Lundmark J-E (1987) *Handledning i bonitering med Skogshögsskolans boniteringssystem Del 2 diagram och tabeller*. Skogsstyrelsen, Jönköping, 70 pages) to go from site index for spruce to site index for beech. The site index for beech was assumed to be valid for both nemoral and boreal broadleaf forests.

Shouldn't it be dm instead of cm?

Yes, that is correct, thank you. We have now changed it to dm.

Site index varies much more throughout the country than Table 2 suggests. In the northern part of Sweden, you have a lot of forest with a site index considerably below 28 m (even below 20 m), which you do not seem to cover at all. Hence forests grow much slower in the north, on average 3 m<sup>3</sup>/ha/yr in northern Sweden, compared to around 11 m<sup>3</sup>/ha/yr in southern Sweden. Having a correct distribution of site index is crucial for realistic growth and yield results. So I think your timber yield production assumptions are very uncertain, which in turn affects your results carbon sequestration, forest biodiversity and recreation, as all these depend on forest age class distribution to a large degree, which is in turn dependent on harvest patterns. Uncertainties in growth and yield projection also influence the agent-based modelling part. As realistic growth and yield projections are essential for modelling the influence of the factors you attempt to assess - forest owner decision making, climatic change and societal demands - I think this part deserves much more attention. Please explain how you deal with site conditions in more detail, and take up related potential methodological uncertainties in your discussion section.

To improve model transparency and limit uncertainties from growth and yield projections, we have also included in Appendix B.2 a table that presents normalised mean, maximum and minimum baseline productivity levels for all forest types and grassland, and for the four Swedish regions for which results of land-use change and change in functional roles are presented (see Table B.2). This new table in Appendix B.2 shows that productivity values vary over an appropriate range that takes into consideration variations in site index.

We now explain in more detail in the 2<sup>nd</sup> paragraph in section 2.1.4 how site conditions are dealt with: “Capital (i.e. land productivity and infrastructure) levels are used to adjust optimal production to production levels achievable given site conditions”. The calculation of productivity levels for the different forest types throughout Sweden is explained in section B.2 in Appendix B, and we now provide further clarification about how we deal with site conditions in the same section.

There are models more suitable for national level forest growth and yield projections (e.g. Heureka RegWise, <http://www.slu.se/en/Collaborative-Centres-and-Projects/forest-sustainability-analysis/heureka/heureka-systemet/en-heureka/> ). You should also compare your results with the latest national forest impact assessment (<http://www.skogsstyrelsen.se/Myndigheten/Skog-och->



miljo/Tillstandet-i-skogen/Tillstandet-i-skogen/), which presents national timber balance scenarios, also including climate change impacts, using the Heureka RegWise model.

While we were aware of the existence of Heureka RegWise, we decided for ProdMod because it suited our purpose (i.e. to calculate levels of maximum production achievable in Sweden per unit of area by different owner types under ideal environmental conditions) and because Heureka RegWise was unnecessarily complex for what we needed to do.

We now compare our results in the 4<sup>th</sup> paragraph in the Discussion with those presented in the latest national forest impact assessment in terms of model drivers and resulting dynamics in timber provision.

I also wonder if you took the effect of tree breeding into account. The majority of the planting material in Sweden comes from seed orchards, and these plants are expected to grow considerably faster (10-20%) compared to plants used during past decades, leading to higher standing volumes.

No, we did not account for this effect. Given the potentially substantial impact of this, we discuss implications in the 4<sup>th</sup> paragraph in the Discussion.

In your results, timber harvest fluctuates dramatically over time (Fig 3 on page 20), and harvest volume in the beginning of the simulation is way below current harvest levels in Sweden (less than 30 mill m3 compared to around 90 mill m3). This is a striking difference, and I would like to see a more thorough discussion of this. Your timber harvest projections differ considerably from the aforementioned national projections, which I think should be addressed. A part of the explanation may lie in your choice of input data: the SLU forest map tends to underestimate the age (and volume) of old forests, and overestimates the age of young forests to some extent. I think it would be advisable to compare your initial age class structure with data from the National Forest Inventory. You will probably find that you overestimate the share of middle aged forest, which could help explaining the sinusoidal shape of your timber volume curves. But I think the main problem constitutes your choice of growth and yield modelling.

The reviewer is right to say that the dramatic fluctuations may be a result of the choice of input data, and we very much appreciate him/her pointing this out. In fact, the age distribution that we used is the result of both the raw SLU Forest Map data and the method used to spatially aggregate the raw data (by averaging stand age values for 20x20m pixels) to 1 km<sup>2</sup> cells. A 1 km<sup>2</sup> cell can represent approximately 10-100 stands in southern Sweden and about 5-50 stands in northern Sweden, with potentially different stand ages. Therefore, after aggregation, the cell represents an average age and the information of distribution of ages between stands in the cell is lost. This is a difficult challenge to overcome when working with high resolution data. An alternative could have been to draw just one random SLU Forest Map pixel within each 1 km<sup>2</sup> cell and use it as representative for the whole cell. Still, a choice needed to be made between having 1 km<sup>2</sup> cells with age values that were most representative for each single cell or a group of cells that best represented the total variation across Sweden. We chose to have the best possible representation at the cell level, which is why simulation results are more representative of the mean ages than of the original age distribution.

We now acknowledge this caveat in our methodology, section 2.1.3, and expand with an explanation and a figure (Fig B.2) in Appendix B.3, where we compare the aggregated SLU Forest Map and National Forest Inventory data to show the differences in forest age distributions. We bring up this point again in section 4.2 in the manuscript.

I also have a few minor comments:

P6 L17-18: I assume that voluntary set-asides are not included in the protected areas, however, they make up at least 5% of the productive forest area. In addition, due to certification requirements, trees, tree groups and buffer zones are left on most felling sites, reducing the harvest volume somewhat.

We agree with the reviewer that, had these been accounted for, timber harvests would have been lower. We now acknowledge this in the 2<sup>nd</sup> paragraph of the Discussion.

P6 L36: Did you account for property size distribution here? According to the cluster analysis (B1) (but compare also Eggers, J., Lämås, T., Lind, T., Öhman, K., 2014. Factors Influencing the Choice of Management Strategy among Small-Scale Private Forest Owners in Sweden. *Forests* 5, 1695-1716. doi:10.3390/f5071695), owners of large estates are more likely to be production-oriented, so the share of forest area controlled by production-oriented owners is likely to be larger than the share of production-oriented owners (among all other owners) might suggest.

Yes, we did account for property size distribution in allocating forest owner types to cells with productive forest. As mentioned in section 2.1.3 under “Agent locations”, the area of productive forest land for each county and for each ownership class were considered in the allocation. We have now edited the sentence where this is mentioned to make it clearer.

P7 Fig 2: The greens in the map are hardly distinguishable. Maybe you could use a broader classification in the map, and present details (share of land area per land owner type) in a table.

The purpose of the map is to illustrate the baseline map of agent type distribution throughout Sweden including all categories of forest and agricultural agents, rather than to show exact locations of agent types. Nevertheless, we see high added value in the reviewers’ suggestion to present details of share of land area per land owner type in a table. Therefore, a table with share of land area per land owner types for forest owners and farmers has now been included (see Table 2).

P11 L23-29: The demand for outdoor recreation is highest close to where people live. The majority of the Swedish population lives in urban areas, which makes urban and peri-urban forests very important for recreation. However, these forests make up only a small share of all forests in Sweden (around 15% according to Olsson, O., 2014. *Out of the Wild - Studies on the forest as a recreational resource for urban residents* (PhD Thesis). Umeå University, Umeå, Sweden). Thus, it would in theory be possible to provide forests with high recreational value for the majority of the population even if the average recreation index is lowered. While I acknowledge that it is difficult or impossible to include such spatial patterns in your simulations, it could be worth mentioning somewhere in the discussion.

Technically, we do include peri-urban forests, as they fall beyond the limits of the urban areas (identified as “artificial” surfaces in our land use classification, as it is in the source CORINE data). We also represent the higher recreational value of forests closer to urban areas by the inclusion of the infrastructure capital, as higher levels of recreation can be provided closer to towns/cities and transportation networks. Olsson (2014) states that peri-urban make approximately 15% of Swedish forests. According to him, urban forests, which we indeed did

not simulate, only make 0.29% of the total Swedish forest cover. Therefore, like Olsson, O., we find that the contribution of peri-urban forests towards the provision of recreation for urban residents is of greater relevance than that of urban forests. Nevertheless, we thank the reviewer for raising this point, as we now use this information to strengthen our justification for using the infrastructure capital, given in Appendix B.2.

P12 L32-33: Forest owners often plant spruce even though pine would be more productive due to high browsing pressure from moose and roe deer. There is a trend for increased spruce regeneration especially in Southern Sweden. (see e.g. Lidskog, R., Sjödin, D., 2014. Why do forest owners fail to heed warnings? Conflicting risk evaluations made by the Swedish forest agency and forest owners. *Scandinavian Journal of Forest Research* 29, 275-282. doi:10.1080/02827581.2014.910268)

Our model does not take into consideration preferences for particular species in particular regions in defining owner behaviour, despite there being evidence for such behaviours (e.g. choosing spruce in Southern Sweden in spite of better risk-mitigation options being available). Instead, land owners in the model use heuristics that can differ between owner types depending on owner objectives and management preferences. So these heuristics are particular to the owner (type), but not to the location. Nevertheless, we do find the suggested article very useful to briefly expand on and support how forest owners plan what to plant in our model. We now mention in the fourth paragraph in section 2.1.6 that: forest owners “generally use experience-based, practical knowledge, rather than abstract theoretical knowledge about possible future developments (Lidskog and Sjödin 2014).”

P13-14 Scenario analysis

Was the reference scenario run without climate change impacts?

That is correct. We have now specified in the last paragraph of section 2.2 what we mean by running the reference scenario under static conditions: “no change in climate or demands through time”.

P14 L3: You mention a sensitivity analysis in the methods section, but I fail to see their results reported in the results section?

We don't present results on sensitivity analysis but we do now discuss their implications for our findings, together with the impacts of our assumptions, in section 4.2 in the Discussion. As extensive sensitivity analysis of CRAFTY model parameters have been done in the past and presented in other papers (written by several of the authors involved in this manuscript), we now also refer the reader to them for further detail on these. These papers are largely theoretical and experimental, so they show substantial exploration and control over model parameters in order to understand how model inputs affect output results.

P 20, Fig 3:

Timber: m3sk is a unit used in Sweden. I think the international equivalent would be m3 overbark. (This also concerns Table 3 on page 15.) Further, having the y scale in the same format (e.g. million m3) would simplify interpretation by the reader.

Carbon sequestration: is that tonnes C per year?

The reviewer is right regarding both timber volume and carbon sequestration measurement units. We have now made sure that timber volume is reported in m<sup>3</sup> over bark throughout the

manuscript and appendices, including Table 3 and Fig 3. Carbon sequestration is now reported in tonnes of C in all documents too.

P 23, Figure 5:

Your scenarios seem to project a major expansion of forests in the mountainous region in the western part of northern Sweden. I guess this means that the tree lines moves upwards considerably (due to warmer climate?), however it seems to do so even in the reference scenario (without climate change?). Can you offer any explanation?

As can be observed in pages 21 and 23, Figures 4a and 5a, under most scenarios there is an expansion in conifer pine-spruce forests in the northern regions, which is, to a large degree, concentrated along the north-western Swedish mountains. It is important to remember that the hotspot maps show areas where expansion in a particular land-use is >10%. This means that at least 10% of the area in the maps corresponding to conifer pine-spruce forests was converted from a different land-use to that forest use. As we can see in Figure 4a, the expansion of this forest type in the northern regions is in fact larger under the reference scenario than under the SSP-RCP scenarios. This suggests that the increase in conifer pine-spruce in that area is actually largely caused by non-climatic factors, like the area being somewhat suitable for growing such type of forest by particular owner types (e.g. multi-objective owners), or competition for land between owner types. But the primary reason why the model allocates forest in the mountainous region under all scenarios (including the reference) to cells where forest was previously not present is the time lag between the moment when forests start being planted in response to unmet demands and the moment when demands are met. Therefore, during this time period forests continue to be planted, potentially beyond what may be optimal to meet future demands, to the point that they occupy available areas that may be less productive. Climate change and changes in demands, however, have a somewhat negative effect on the expansion of this type of forest in the northern regions (in favour of other forest types or farmland), and seemingly also in the mountain area.

We have now also included a short explanation for this expansion in section 4.2 (Model assumptions and limitations).

Also, how do you determine forest site index for previously unmanaged land (which seems to be the land type that is afforested)? Up there, forests have very low productivity, but you don't seem to have any site index with such low site index in your data.

As explained above, site indices presented in Table 3 were only used to derive optimal production functions, and do not represent baseline site index levels occurring across the country. Site indices across Sweden are represented by forest productivities. These productivities were normalised to [0-1] values, and regions with lowest productivity levels would feature productivity=0. Therefore, in least productive areas forests would not grow or would do so very slowly.

Is topography accounted for in your modelling of areas that can undergo afforestation?

CRAFTY-Sweden does not explicitly consider topography among its parameters. Production depends on site productivities, infrastructure, management practices, and owner behaviour. Topography was not (directly) considered either in the calculation of forest productivities, for which data on tree species, mean forest height and age, and total wood volume were used

(see Appendix B.2). Nevertheless, these productivities reflect the productive potential for each forest type (based on empirical height, age and volume data) throughout Sweden. Tree height, age and volume and the ratios between these variables are the result of environmental conditions (e.g. topography). Therefore, the productivities we used do reflect the effect of environmental variables like topography, precipitation or temperature.

The effect of topography on productivity changes from climate change, however, is not represented accurately, as these productivity changes were calculated at a coarser spatial resolution (50x50 km). The uncertainty of calculating productivity changes at this resolution are now discussed in the 2<sup>nd</sup> paragraph in section 4.2 in the Discussion.

P25 L14: Forest area changed only slightly since the beginning of the 20th century. However, growing stock in the forest increased steadily, 100 years ago the forests were rather degraded. Is this what you mean?

We mean that more trees were regenerated in the middle of the century than they were at the beginning or towards the end of the century, as shown in section 2.1.3 and in Fig B.2. We have now rewritten the relevant sentence (in the 2<sup>nd</sup> paragraph of the Discussion) to express this more clearly. The modified part of the sentence is underlined here:

“Forestation in the country increased from the beginning of the 20<sup>th</sup> century until the 1960s, when highest rates of forest regeneration (i.e. including planting, seeding, and natural regeneration) per year were attained, after which rates began to decline”.

P25 L15: Do you mean planted or regenerated (i.e. including planting, seeding, and natural regeneration)? All these different measures have been (and are being) used, so a drop in area planted per year does not necessarily mean that less forest is regenerated. There was a felling peak around 1970 (oil crisis). But this regards felling volume, not necessarily area. Actually, I do not find any information on regeneration areas under the reference you provided, only felling volumes. As standing volume has doubled during the last 100 years, it is not straightforward to make any conclusion on regeneration area based on felling volumes.

The reviewer is right to point out that we should have written ‘regenerated’ instead of ‘planted’. We now use the word regenerated, as shown in the answer to the comment directly above this one. The reference we provide shows information on “Productive forest land area by age class within county/regions exclusive protected productive forest land, 1993-“. This is dataset 3.04 under the subject area Forest and Forest Land. Having the data on area by age class, one can find out the area regenerated in each year period by subtracting the age to the year 2010 (for the data reporting period 2008-2010).

#### Editor's comments

This manuscript is certainly interesting to be published in ECOSER, as it presents a novel method to assess LU change and ES provision by applying agent based modelling of forest owners at national scale. However, the two reviewers coincide that it need a major revision before it is ready for publication. Both reviewers have major concerns regarding the modelling assumptions of forest growth and timber yield within the specific context of Sweden, which seem to be very uncertain, and affect results on carbon sequestration, forest biodiversity and recreation and also influence the agent-based modelling part. As realistic growth and yield projections are essential for modelling the influence of the factors assessed in the manuscript - forest owner decision making, climatic change

and societal demands - this part still needs substantial attention. Reviewer 2 is an excellent expert in Swedish forestry and provides helpful suggestions for the authors on how to improve their modelling exercise.

We agree that the reviewers' comments were very helpful indeed and hope that our changes and explanations satisfy their concerns.