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More is more? Forest management allocation at different spatial scales to mitigate conflicts between ecosystem services

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Abstract

Context. Multi-objective management can mitigate conflicts among land-use objectives. However, the effectiveness of a multi-objective solution depends on the spatial scale at which land-use is optimized. This is because the ecological variation within the planning region influences the potential for site-specific prioritization according to the different objectives.

Objectives. We optimized the allocation of forest management strategies to maximize the joint production of two conflicting objectives, timber production and carbon storage, at increasing spatial scales. We examined the impacts of the extent of the planning region on the severity of the conflict, the potential for its mitigation, and the strategies that were identified as optimal.

Methods. Using forecasted data from a forest simulator, we constructed Pareto frontiers optimizing the joint provision of the objectives in production forests in Finland. Optimization was conducted within increasing hierarchical spatial scales and outcomes were compared in terms of the severity of the conflict and the solution to mitigate it.

Results. The trade-offs between timber production and carbon storage appeared less severe and could be mitigated more effectively the larger the planning regions were, but the improvements became minor beyond the scale of ‘large forest holding’. The results thus indicate that this scale, approximately 100 stands or 200 ha, is large enough to effectively mitigate the conflict between timber production and carbon storage.

Conclusions. Management planning over relatively small forest areas (200 ha) can mitigate ecosystem service trade-offs effectively. Thus the effective use of multi-objective optimization tools may be feasible even in small-scale forestry.

Keywords: Carbon storage; timber production; land-sharing; land-sparing; landscape extent; multi-objective optimization; Finland

Introduction

The nature of the relationships among resource extraction, ecosystem services and biodiversity conservation is a central question in applied ecological research, landscape ecology, and sustainability science (Carpenter et al. 2009; Cimon-Morin et al. 2013; Abson et al. 2014). It is often of interest to promote all of these three objectives within the same land area, for example in agriculture (e.g. Swinton et al. 2007) or forestry (e.g. Edwards et al. 2014). However, they have been found to be commonly conflicting (Tallis et al. 2008; McShane et al. 2011), particularly resource extraction with the other two (MEA 2005; Burger 2009; Power 2010). Potential solutions to these conflicts include carefully designed management systems that are able to support multiple objectives in the same site (e.g. Miina et al. 2010), and the identification of optimal land-use allocation which prioritizes individual objectives in the sites that are the most favorable to them (e.g. Cordingley et al. 2016). These are sometimes termed ‘land-sharing’ and ‘land-sparing’ strategies, respectively (Maskell et al. 2013; Edwards et al. 2014). Both of them have the potential to lead to compromise outcomes, where the simultaneously achieved levels of multiple, conflicting objectives are maximized.

Several recent studies have explored the conflicts between resource extraction, ecosystem services and biodiversity in production forests, where timber harvesting and other forestry-related activities modify ecosystem structures and functions (Duncker et al. 2012; Schwenk et al. 2012; Gamfeldt et al. 2013; Mönkkönen et al. 2014; Zanchi et al. 2014; Triviño et al. 2015; Peura et al. 2016; Vauhkonen and Ruotsalainen 2017; Triviño et al. 2017). These studies have shown that management trade-offs between timber harvests, ecosystem services and biodiversity objectives are common but can be highly case and site dependent. As a consequence, some have suggested that a diversity of management approaches applied at a landscape level may be recommendable (Duncker et al. 2012;

Schwenk et al. 2012). Indeed, optimization studies (Mönkkönen et al. 2014; Triviño et al. 2015; Peura et al. 2016; Triviño et al. 2017) have shown that a combination of different management regimes across the landscape, ranging from intensive forestry to permanent set-aside, is required to most efficiently mitigate the trade-offs. In other words, a combination of 'land-sharing' and 'land-sparing' types of management may be required to achieve the best compromises to balance conflicting objectives. This is because forests are not of uniform quality with respect to different objectives or to the system's responses to management activities (Gamfeldt et al. 2013).

Conducting ecosystem service assessments, management planning or land-use prioritization always involves decisions about spatial scales, such as the size of the study area or planning region (landscape extent), the size of planning units (landscape resolution), and data resolution and coverage (e.g. Mills et al. 2010). Because ecosystem services and other management objectives are typically unevenly distributed (e.g. Egoh et al. 2008; Raudsepp-Hearne et al. 2010), these decisions may be highly consequential to the results of assessments and the management recommendations that are drawn from them. For example, Blumstein and Thompson (2015) found the spatial scale at which ecosystem service hotspots are identified (state, watershed, or town) to strongly affect their perceived abundance and distribution. Similarly, Anderson et al. (2009) and Raudsepp-Hearne and Peterson (2016) found the resolution of the analysis to influence the observed patterns in the supply of ecosystem services and the strength and direction of correlations between the services. In a conservation planning context, for example Rodrigues and Gaston (2002) showed that the definition and size of the planning region may significantly affect perceived species rarity and subsequent site prioritization.

The above examples show that if management objectives are unevenly distributed, the extent of the planning region affects the identification of the best sites for different individual objectives as well as the sites where good ‘land-sharing’ outcomes are achievable. Finding a balance for conflicting objectives requires allocating management regimes to where they perform best, for instance sites which can provide high levels of multiple objectives should be managed according to the ‘land-sharing’ concept. Therefore, the extent of the planning region may influence exactly what can be achieved by optimizing management allocation, and how. With a larger planning region more options are available to efficiently assign each site to the most appropriate management regime for the problem at hand. This is indeed why land-use optimization is recommended to be done at large scales (e.g. ‘landscape scale’: Duncker et al. 2012; Schwenk et al. 2012; Mönkkönen et al. 2014; Triviño et al. 2015). Then again, the larger the planning region is, the more computationally demanding it is to solve the optimization problem (Martin 2001). Additionally, land management based on large-scale plans may be difficult to implement if there are no administrative systems in place at corresponding scales, for example if coordination of activities by several land-managers is required but there are no existing systems to support it. What is more, landscape-level management plans that are optimal for multiple objectives may result in an uneven distribution of costs and benefits among land owners which can hurt the plan’s acceptability (e.g. Kurttila et al. 2002; Jumppanen et al. 2003). To reconcile the benefits of planning at large spatial extents and the feasibility and implementation of more local land-use plans, it is useful to explore the consequences of how the planning region is defined and to identify the smallest scale at which conflicts among management objectives can be mitigated effectively.

In this paper, we test for the effect of the spatial scale at which management allocation is optimized on the achieved outcomes in production forests in Finland. We do this by constructing Pareto frontiers optimizing the joint provision of two objectives, timber production and carbon storage, with varying spatial scales within which optimal management allocation is identified. Pareto frontiers comprise a set of multi-objective solutions that cannot be improved in terms of any one objective without deteriorating in terms of at least one of the other objectives (Miettinen 1999). The use of Pareto frontiers in land-use planning can provide important information on land-use trade-offs and their possible solutions (Seppelt et al. 2013). The forest management alternatives included in our analyses encompass 19 management regimes. These regimes have different amounts of harvestable timber as well as carbon stored in the system depending on productivity of the site (Äijälä et al. 2014). Promoting tree growth and thus timber production is typically the main focus of management planning in production forests, while carbon-related functions are gaining increasing attention on policy agendas in order to mitigate climate change and to ensure the carbon neutrality of forest-based energy sources (e.g. Ministry of Agriculture and Forestry 2015). Previous work (Hynynen et al. 2005; Triviño et al. 2015; Pukkala 2016) has shown that there are conflicts between timber production and carbon storage in Finnish forests, but that the conflicts can be mitigated by landscape-level planning and prioritization. However, the definition of the required ‘landscape-level’ has remained imprecise and the effect of the spatial scale unknown.

We use hierarchical spatial scales to look for the most efficient scale of management planning: individual forest stand, small forest holding, large forest holding, watershed, and region. These scales reflect real administrative and/or natural boundaries, with increasing numbers of forest owners included within each scale. In Finland, the majority of production forests are privately owned and forest holdings are comparatively small with an average size of approximately 30 ha (Peltola 2014). Large-scale, landscape-level forest management planning may thus require the cooperation of several forest owners and potentially compensation systems that make the plan acceptable for all of them (Kurttila et al. 2001). We work with the assumption that due to both computational and real-world practicality it is desirable to minimize the spatial scale of management planning.

The main questions we aim to answer are: 1) Are there differences in levels of timber production and carbon storage that can be simultaneously achieved when management is optimized at different scales? 2) Are there differences in the distribution of different kinds of management regimes when management is optimized at different scales?

Methods

Forest data and forest growth simulations

The basic unit of forest management planning is a forest stand, i.e. a parcel of forest of relatively uniform structure and type. Our study areas, located in southern and central Finland, comprise a total of 28,886 forest stands, covering nearly 44,000 ha. The forests are of variable ages and mainly mesic heaths, herb rich heaths and sub-xeric heaths dominated by spruce (*Picea abies*), birch (*Betula pendula* and *Betula pubescens*) and pine (*Pinus sylvestris*) (Fig. 1). Stand-level forest inventory data from these areas, produced by the Finnish Forest Centre, were used as input data in the forest growth simulator SIMO (Rasinmäki et al. 2009). SIMO forecasts the development of a stand based on its initial condition and the forest management actions applied to it during the simulation period. We simulated the development of the stands for one hundred years into the future under 19 alternative management regimes. These included the management regime that is currently recommended in Finland (Äijälä et al. 2014), a total of 16 modified versions of the recommended regime, continuous cover forestry, and permanent set-aside. The currently recommended regime, henceforth termed business-as-usual, consists of commercial thinnings, a final felling timed to achieve the stand’s maximal growth, and regeneration of the stand by planting or seeding after final felling. In the SIMO simulations the timing of these operations is determined by decision rules regarding the site type, the height of the dominant tree species and the age of the stand. The modified versions of business-as-usual were implemented by adjusting these rules and included alterations of the timing of the final felling (postponing it by 5–30 years), conducting thinnings before and/or after final felling, refraining from thinnings completely, and adopting green tree retention for natural regeneration. These modifications are intended to reflect real-world variation in possible forest management choices and have corresponding policy incentives according to which forest owners are encouraged to modify management for multiple objectives (for further details, see Mönkkönen et al. 2014). Continuous cover forestry differs from business-as-usual in that it is based on regular, selective harvesting of large trees and no final felling (Pukkala et al. 2012). It has been suggested to have the potential to maintain forest biodiversity and ecosystem services better than conventional rotation forestry (Kuuluvainen et al. 2012). The set-aside option then again corresponds to protection of the forest, i.e. no management actions are taken and no timber is harvested. The simulation period of 100 years was divided into 20 five-year time steps, with the simulator producing predictions of stand development at each time step as output.

#Fig. 1 approximately here#

Measurement of objectives

Two objectives were measured throughout the simulation period based on the forecasted stand properties: timber production and carbon storage. Timber harvests are the primary source of income to a forest owner from their land and as such typically the main focus of forest management. We used net present income as the measure of timber production. This was calculated by multiplying the recent average prices for different timber assortments (Peltola 2014) by the quantity of each assortment harvested during thinnings and/or final felling. We used a discount rate of 3% to discount income generated in the future. We used this rate as it has been traditionally used in forest economics (e.g. Gren et al. 2014; Asante and Armstrong 2016).

Carbon storage is a crucial ecosystem service contributing to climate change mitigation. Carbon stored in the forest was calculated as the sum of the estimated amounts of carbon fixed in living wood, dead wood and soil. Carbon contained in living and dead wood was estimated as 50% of the biomass. Carbon stored in soil was estimated using two models depending on the soil type: the Yasso07 models (Liski et al. 2005; Tuomi et al. 2009; Tuomi et al. 2011) were used for mineral soils and the carbon flux models of Ojanen et al. (2014) were used for peatland soils. Carbon storage was estimated for each time step of the simulation period and the average over the time steps was used in the optimization analysis.

Spatial scales

The 28,886 forest stands were grouped together at different spatial scales that correspond to administrative and/or natural boundaries: small forest holdings, large forest holdings, watersheds, and regional scale (Fig. 2, Table 1). These were hierarchical so that small holdings made up the large holdings, large holdings made up the watersheds, and the regional scale included all of the watersheds. The smallest scale groupings, small holdings, were created based on real forest property data. The large holdings were created by grouping together adjacent small holdings so that each large holding contained approximately 10 small holdings. The watershed scale was defined by the boundaries of third-level catchment areas as delineated by the Finnish Environment Institute (SYKE 2010). The average area and the average number of stands included in each of these levels are given in Table 1. We used these four hierarchical scales as planning regions, i.e. as boundaries within which management allocation was optimized in terms of the two objectives (timber production and carbon storage). The resolution was the same at every scale, i.e. the stand level.

#Fig. 2 approximately here#

#Table 1 approximately here#

Optimization analysis

If management objectives are conflicting, their maximal levels cannot be reached at the same time, i.e. by the same type of management. Multi-objective optimization tools can be used to find management plans that solve these types of conflicts as efficiently as possible (Miettinen 1999), for example maximize one objective given the constraint that another objective stays above a set target level. A Pareto optimal solution to a multi-objective optimization problem is one with an outcome that cannot be improved with respect to any of the objectives without causing losses in some of the other objectives. Pareto optimal solutions are a subset of all feasible solutions and make up a Pareto frontier, which for two objectives can be graphically presented as a production possibility curve. The steepness of the curve reflects the severity of the trade-off, because the steeper the curve the greater the loss in one objective caused by an increase in another objective.

For each group of stands, defined at the different spatial scales, we identified the set of Pareto optimal solutions that maximized the joint production of timber and carbon storage. We maximized the value of timber production under the constraint that carbon storage was above a set target level, and by adjusting this required level we were able to build the Pareto frontier. Each Pareto optimal solution comprised a selected management regime for each stand in the group, i.e. the optimal allocation of management regimes within the group. The stands were thus treated as individual planning units that contribute to the overall outcome across the group but do not interact with each other. At the largest scale (region), management allocation was optimized over all stands. At the smaller scales, management allocation was optimized within each group and the levels of the two objectives from each group were then summed together to produce the overall outcome. The optimization analyses were carried out using the IBM ILOG CPLEX optimizer, version 12.6.2 (https://www.ibm.com/developerworks/downloads/ws/ilogcplex/). In addition to the four stand groupings, we carried out the optimization for each stand individually by selecting the management regime among the 19 alternatives considered here that maximized the joint production of the two objectives in that stand. Similar to the sub-regional scales, the stand-scale values of the two objectives were summed together across stands and the total values were compared to the levels of the objectives that could be achieved when planning at the larger scales. We note that better solutions may be achievable by more detailed stand management optimization than what is allowed for by the 19 management alternatives, but the stand-scale results obtained here are meant to serve primarily as comparison with planning over larger forest areas.

The trade-off between two objectives may be further characterized by three points on the production possibility curve that illustrate how compatible the objectives are: the two extreme ends of the curve and the ‘compromise’ point (Mazziotta et al. 2017). The compromise point is defined as the solution in the Pareto optimal set that minimizes the maximum loss in the objectives (Mazziotta et al. 2017). Roughly, this corresponds to the solution that is closest to an ideal solution where all objectives are maximized at the same time. In the general case for two objectives, the steeper the production possibility curve is, the farther the compromise solution is from the ideal solution. We identified the compromise solutions for timber production and carbon storage for the different spatial scales and used them to further examine the differences in the perceived severity of the trade-off and the optimal management allocations between the different scales (see below). We note that the compromise solutions identified here are optimal only in a mathematical sense, not in a ‘social’ sense. Selecting the ‘socially optimal’ solutions would require information on societal goals and weights assigned to different objectives.

As explained above, the compromise outcome is one point on the Pareto frontier and it is achieved by a set of management regimes, one for each stand. This set may consist of ‘land-sparing’ management regimes (either one of the objectives is maximized in a stand) and ‘land-sharing’ management regimes (both objectives reach moderate levels in the same stand). Within the compromise solutions for the different spatial scales, we recorded the proportions of ‘land-sparing’ and ‘land-sharing’ regimes. We identified these two types *post hoc* based on the regimes’ outcomes with respect to the two objectives, so that ‘land-sparing’ was defined as maximizing only one of the objectives and ‘land-sharing’ as both objectives being below their potential maximums. Additionally, we recorded the proportion of ‘win-win’ outcomes, defined as cases where both objectives were maximized by the same regime. We compared the total area of each of these options (land-sharing, land-sparing for timber, land-sparing for carbon, win-win) under the compromise solutions at different spatial scales.

Results

Joint production of timber and carbon storage at different spatial scales

The maximal value of timber production measured as net present income over the entire study area was 433 million euros, or 9,800 euros per ha, and the maximal carbon storage was 11.18 million tons, or 254 tons per ha. It was not possible to achieve both of these maximums at the same time, but the losses in carbon storage when timber production was maximized and vice versa were considerable: when timber production was maximized, carbon storage was 7.38 million tons (i.e. 66% of its potential maximum), and when carbon storage was maximized, the net present income for timber production was 21 million euros (i.e. 5% of its potential maximum). These two outcomes correspond to the extreme ends of the production possibility curve (Fig. 3). They are the same regardless of the spatial scale of the analysis, because the solution that is optimal in terms of only one objective consists of the best regime for that objective in each stand and so does not depend on the spatial scale within which management alternatives are allocated.

#Fig. 3 approximately here#

The smaller the spatial scale of management optimization, the steeper the resulting production possibility curve was (Fig. 3). The results obtained by selecting optimal management at the scale of individual stands stood clearly apart from results obtained by optimizing management over multiple stands (Fig. 3). Beyond this, the difference was the most notable between the ‘small holding’ scale and the three largest scales, while the differences among the three largest scales were very small. Differences in the outcomes that were achieved when management was optimized at the different spatial scales can be expressed as the difference in the value of one objective when the other objective is held at a set level. Excluding the stand-scale, this difference ranged up to 13%, depending on the objective, the required level of the constraint, and the scales compared. For example, when carbon was required to reach at least 95% of its maximal value and the optimization was conducted at the ‘small holding’ scale, timber production could reach 45.8% of its maximum, but when the optimization was conducted at the larger scales with the same carbon constraint, timber production could reach 51.0%, 51.8%, or 52.1% of its maximum at the ‘large holding’, watershed, and regional scale, respectively. In absolute terms, the difference of 6 percentage points between the ‘small holding’ and regional scale meant an increase of over 27 million euros.

Under the compromise solutions, i.e. where the losses in both objectives were simultaneously minimized, both objectives reached at least 76% of their maximal values at the stand scale and at least 82% of their maximal values at the larger scales (Table 2). When the scale of the management optimization was increased from the 'small holding' scale to larger scales, the simultaneously achievable values increased by an average of 1.1 percentage points. For the three largest scales, the compromise solutions were very similar and the values of the two objectives were within an average of 0.3 percentage points of each other.

#Table 2 approximately here#

Optimal management regimes

The two objectives differed substantially with respect to the forest management regimes that were optimal to them. Carbon storage was most often the highest under set-aside, while timber production was maximized by a combination of regimes, primarily continuous cover forestry, business-as-usual and business-as-usual without thinnings (Fig. 4). In the compromise solutions the distribution of management regimes was dominated by business-as-usual without thinnings, continuous cover forestry, set-aside, and to a lesser extent business-as-usual with extended rotation time (Fig. 4). When management was optimized at larger scales, more area was set-aside than at smaller scales (Fig. 4).

#Fig. 4 approximately here#

The share of 'land-sharing' management in the compromise solution decreased as the spatial scale of the management optimization was increased (Fig. 5). At most, when the scale was increased from the small holding scale to that of the entire region, the number of stands where a ‘land-sharing’ management was chosen decreased by 4%. This decrease was made up by an increase in the share of stands where only one of the objectives was prioritized. The share of ‘win-win’ outcomes, i.e. cases where the same kind of management maximized both objectives, was 2% and did not depend on the spatial scale of the analysis.

#Fig. 5 approximately here#

Discussion

In this study, we examined how the mitigation of ecosystem service trade-offs by land-use optimization is affected by the scale of the planning regions in Finnish production forests. Our results show that by optimizing management allocation, trade-offs between timber production and carbon storage can be mitigated, and that this is done the more effectively the larger the planning regions are – but up to a certain point. Optimizing over several stands was substantially more effective than selecting optimal management for each individual stand separately. Apart from individual stands compared with multiple stands, the largest improvements could be achieved by increasing the scale of the planning regions from approximately 10 stands to approximately 100 stands. Beyond this scale the improvements were minor.

The trade-off between timber production and carbon storage indicated by our results is consistent with previous findings from production forests (Schwenk et al. 2012; Triviño et al. 2015): maximal levels of the two objectives cannot be reached at the same time, but if even small losses in one are permitted, the supply of the other can be improved considerably. The trade-off was severe particularly in terms of timber production, which reached only 5% of its potential maximum when carbon storage was maximized. When timber production was maximized, carbon storage could reach 66% of its maximal value. The low value of timber production when carbon storage was maximized is due to the fact that the set-aside regime provided the highest level of carbon storage in a majority of the stands. This has been shown also in previous work (Triviño et al. 2015). By definition, the set-aside regime does not produce any income from timber production because no timber is harvested. At best, both objectives could simultaneously reach 82-84% of their respective maximums. These compromise outcomes were achieved by a diverse combination of alternative management regimes that differed clearly from management targeting only either one of the two objectives.

Several studies have shown that interactions among ecosystem services can be dependent of the scale of observation (e.g. Anderson et al. 2009; Raudsepp-Hearne and Peterson 2016; Hou et al. 2017). Likewise, we found that the severity of the trade-off between timber production and carbon storage, as indicated by the steepness of the production possibility curves, was affected by the spatial scale of the planning region. The curve was further from origin, i.e. better joint production outcomes of the two objectives could be achieved, when the planning regions were larger. We hypothesize this improvement is due to an uneven distribution of the potential supply of the two objectives, i.e. variation among stands in features affecting them. However, the improvements were notable only between the smallest scale and the three larger scales, while the differences between the three largest scales were very small. If the effect of the planning region’s size stems from the amount of variation that is included within it, our results indicate that the variation in forest features that are relevant for the objectives considered here stops increasing beyond the scale of approximately 100 forest stands. Identifying the relevant features is beyond the scope of this study, but for example Triviño et al. (2015) suggested at least initial stand age and tree species distribution to affect forests’ potential for joint provision of timber and carbon services. Gamfeldt et al. (2013) found tree species richness to have a positive or positively humpshaped relationship with soil carbon storage and tree biomass production, with high proportions of birch and spruce in particular having a positive effect on both services.

We defined ‘land-sharing’ management of a stand as providing a less than maximal level of both of the objectives. This kind of management was more common as a part of the optimal solutions when the spatial scale of the optimization was smaller. In other words, the larger the planning regions were, the more stands were dedicated to the production of a single objective. This increased single-objective prioritization then enabled an improvement in the joint production of the two objectives over the entire study area. It is worth noting here that the concept of ‘land-sharing’ itself is scale-dependent (Ekroos et al 2016). While optimizing management allocation at larger scales led to less ‘land-sharing’ management applied at the stand level, it enabled a better ‘land-sharing’ outcome at the level of the entire study area because higher levels of both objectives were achieved at the same time.

In short, our results indicate that the scale of ‘large forest holding’, consisting of approximately 100 stands, may be large enough to mitigate the conflict between timber production and carbon storage as efficiently as possible. This means that the ‘correct’ or at least sufficient spatial scale for analyzing and solving the management trade-off between timber production and carbon storage may be much smaller than the scale of thousands of stands that has been used in previous work (Triviño et al. 2015). The spatial scales we compared ranged in area from 17 ha to over 43,000 ha, and the increases in the utility of the optimization exercise that were gained from increasing the scale beyond some hundreds of hectares were minimal. Assuming larger-scale analyses are more time and resource intensive to conduct, studies like the current work can inform how resources for planning can be used most efficiently. However, in the current study we considered only the two objectives, yet production forestry and stand management practices may affect the supply of a range of other ecosystem services (Pukkala 2016; Pohjanmies et al. 2017). Moreover, ecosystem service management that is actually carried out is a product of not only ecological but also social and institutional factors.

In particular, if a larger range of ecosystem services is considered, the issue of finding the ‘correct’ scale for ecosystem service management may be greatly complicated by the fact that services may be the products of ecosystem processes taking place at different scales (Kremen 2005). For example, in our case carbon storage may be measured per any land unit irrespective of scale, but some other ecosystem services may be provided by processes that are linked to fixed spatial scales or connectivity patterns (Mitchell et al. 2015; Kukkala and Moilanen 2016), such as processes regulating water quality and supply (Brauman et al. 2007), the movements of mobile organisms (Kremen et al. 2007), or the experience of aesthetic landscapes (Gobster et al. 2007). In our study system, this means that the condition of areas covering several stands or interactions among stands may affect the supply of some ecosystem services and may need to be considered to secure high levels of all of them. Finding the optimal land-use allocation would then involve spatial optimization, which makes the problem more challenging to formulate and solve.

The ‘correct’ scale of ecosystem service management is further related to how the spatial scale of service provision matches with institutional and administrative scales (Hein et al. 2006; Schwerdtner Máñez et al. 2014). Mismatch among the scales at which ecosystem services are produced, at which their benefits accrue, and at which relevant management decisions are made may hinder their effective and equitable management. Even if the ecologically correct spatial scale of ecosystem service management is identified, it may be difficult to operate at it. For example, in forest stands timber production and carbon storage both depend on tree growth and are thus generated at the same spatial scale. However, they differ with respect to the institutional scales at which their benefits are realized: the benefits of timber production accrue at the forest ownership scale, while the benefits of carbon storage are global. They also differ with respect to the administrative scales where desired outcomes are defined: forest management for timber production, albeit influenced by regulations, is decided by the forest owner, while goals related to carbon storage and climate change mitigation are set at higher administrative scales. In a review of ecosystem service studies, Howe et al. (2014) concluded that when stakeholders are acting at different scales and have conflicting private and public interests in ecosystem services, trade-offs between the services are especially likely to occur. It should be noted, however, that also private forest owners may attach diverse, non-economic values and goals to their forests and seek to manage them accordingly.

Because of challenges concerning the practicality of optimizing land-use and implementing the resulting management plans, it may be beneficial to identify the smallest scales where such endeavors are maximally useful. Our results show that there are clear benefits to considering an area beyond a single stand or a few stands in forest management planning, but they also indicate that moderately small spatial scales, corresponding in area to a few typical Finnish forest holdings, are enough to provide the best possible compromise outcomes for timber production and carbon storage in Finnish production forests. They thus suggest that cooperation of only a few forest owners is required. This is tentatively encouraging for the practicality of real-world implementation of multi-objective optimization tools in landscape-level forest management planning. A more substantial obstacle may be lack of incentives for forest owners to target high levels of public non-timber benefits from their forests. For carbon storage, possibilities include payments to forest owners for carbon services or regulation of forest management practices to restrict carbon losses (e.g. Pohjola and Valsta 2007; Cao et al. 2010).

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Table 1. Total number of groups of stands used as planning regions, average number of stands in a group, and average area of a group as defined at the different spatial scales.

Scale	Total number of groups	Mean number of stands	Mean area (ha)
Stand	28886	1	1.5
Small holding	2537	11	17.3
Large holding	228	127	192.9
Watershed	16	1805	2748.1
Region	1	28886	43970.2

Table 2. The compromise solutions in terms of the two objectives in absolute values and relative to their maximal values.

Scale	Timber production (million €)	Carbon storage (million tons)	Percent of maximal timber production (%)	Percent of maximal carbon storage (%)
Stand	331.46	8.70	76.59	77.33
Small holding	363.44	9.20	83.97	82.32
Large holding	362.17	9.39	83.68	84.00
Watershed	364.55	9.39	84.23	84.00
Region	365.99	9.39	84.56	84.00

Figure captions

Fig. 1. The distribution of the site types (x axis) and current development stages (bar fill) of the forest stands included in the study areas. Site types are presented according to the Finnish forest classification system (Hotanen et al. 2008). The development stage ‘Young’ refers to a stand with an average diameter at breast height of 8–16 cm, and ‘Mature’ to a stand with an average diameter at breast height greater than 16 cm but that is not yet ready for final harvest. The development stage ‘Ready for harvest’ is defined according to current Finnish recommendations for the timing of final felling (Äijälä et al. 2014).

Fig. 2. Examples of the sub-regional scales analyzed. A) An example of a watershed. The large forest holdings contained within the watershed are drawn on the map with black outlines. The dark grey area marks the large holding shown in (B). B) An example of a large forest holding with small forest holdings drawn with black outlines and the small holding shown in (C) highlighted in dark grey. C) An example of a small forest holding with individual forest stands drawn with black outlines.

Fig. 3. Production possibility curves showing the simultaneously achievable levels of timber production and carbon storage over the entire study area when optimal management allocation was determined at different spatial scales.

Fig. 4. The distributions of management regimes that maximize the two objectives (‘Carbon’ and ‘Timber’) or provide the compromise outcome (‘Compr. Small hold.’ for compromise solution at the small holding scale and ‘Compr. Region’ for compromise solution at the regional scale). For visual clarity, the 16 modified versions of business-as-usual (see Methods) have been grouped into 4 categories based on their defining features (extended

rotation time, green tree retention, thinnings before final felling, or no thinnings). The abbreviations in the legend refer to: BAU - business-as-usual; BAU ext - business-as-usual with extended rotation time; BAU w GTR - business-as-usual with green tree retention; BAU w thin - business-as-usual with thinning before final felling; BAU wo thin - business-as-usual without thinnings; CCF - continuous cover forestry; and SA - set-aside.

Fig. 5. The distributions of management regimes in the compromise solution characterized as prioritizing a single objective ('Carbon' or 'Timber'), producing a land-sharing outcome ('Sharing') or producing a win-win outcome where both objectives are simultaneously maximized ('Win-win') when optimal management allocation is determined at different spatial scales. The compromise solution refers to a solution where the losses in both objectives are minimized.

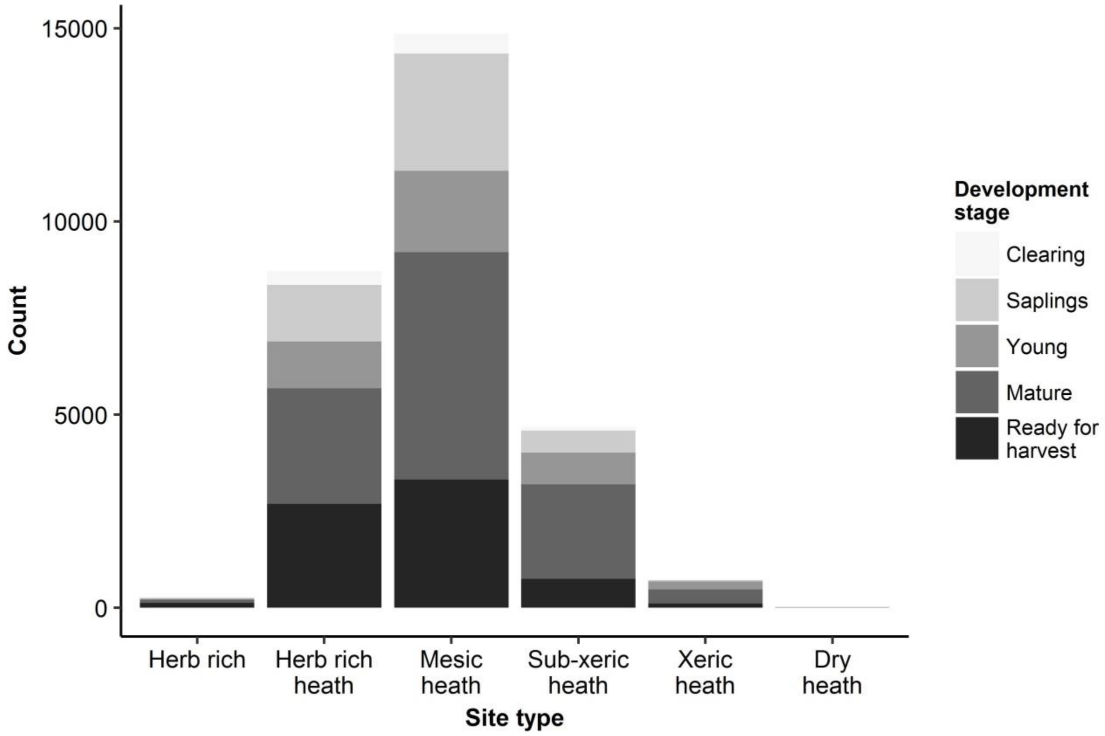
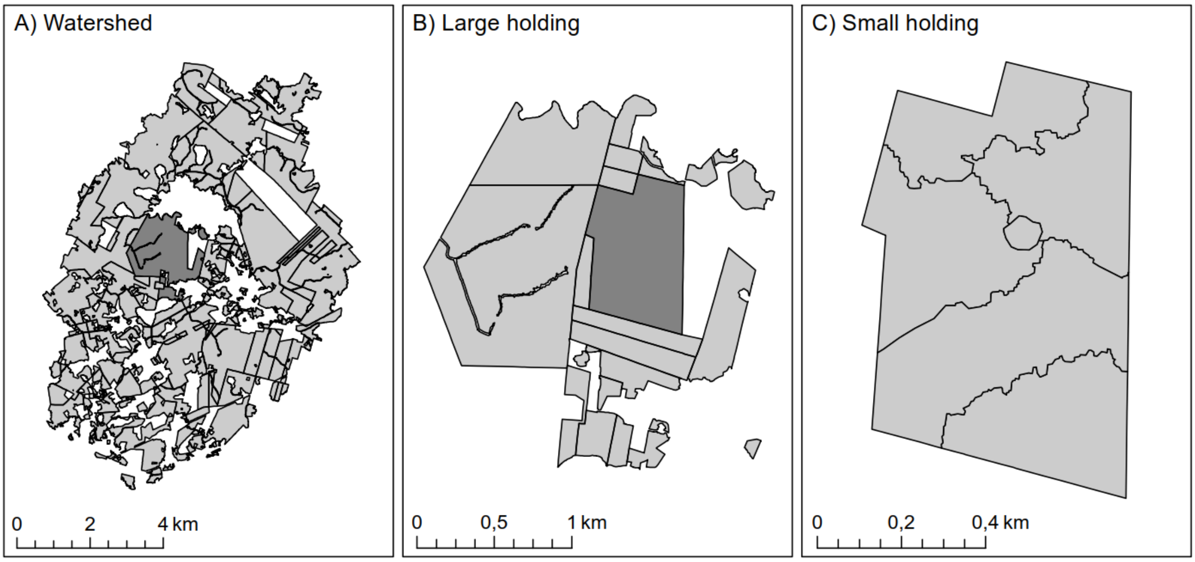

Count
15000
10000
5000
0
Herb rich
Herb rich heath
Mesic heath
Sub-xeric heath
Xeric heath
Dry heath
Site type
Development stage
Clearing
Saplings
Young
Mature
Ready for harvest

Fig. 1.


A) Watershed
B) Large holding
C) Small holding
0
2
4 km
0
0,5
1 km
0
0,2
0,4 km

495 **Fig. 2.**

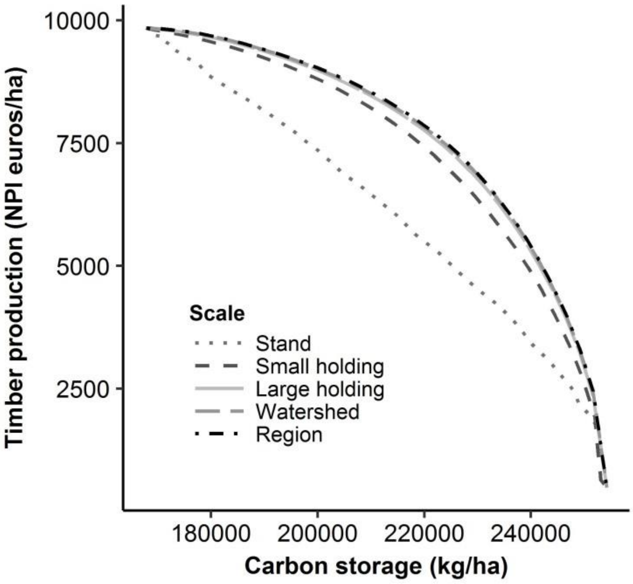

10000
7500
5000
2500
Timber production (NPI euros/ha)
180000
200000
220000
240000
Carbon storage (kg/ha)
Scale
Stand
Small holding
Large holding
Watershed
Region

Fig. 3.

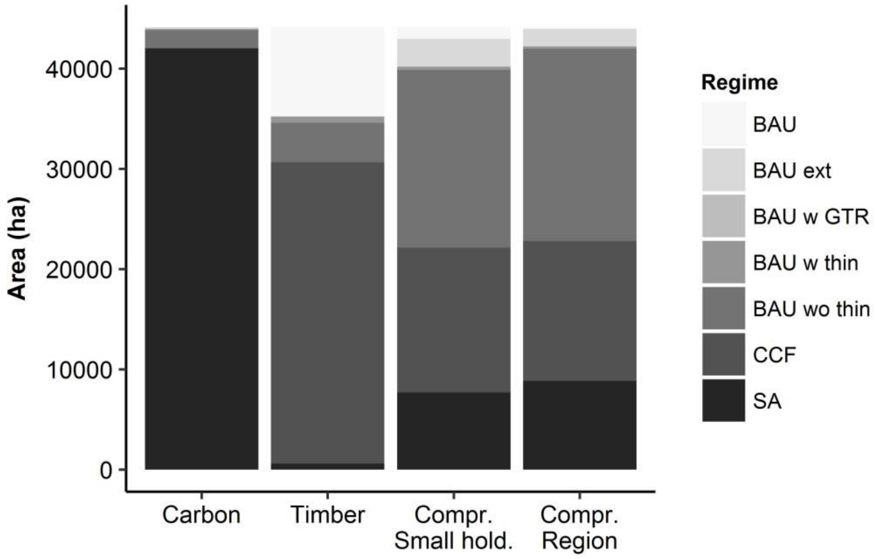

40000
30000
20000
10000
0
Area (ha)
Carbon
Timber
Compr.
Small hold.
Compr.
Region
Regime
BAU
BAU ext
BAU w GTR
BAU w thin
BAU wo thin
CCF
SA

Fig. 4.

500

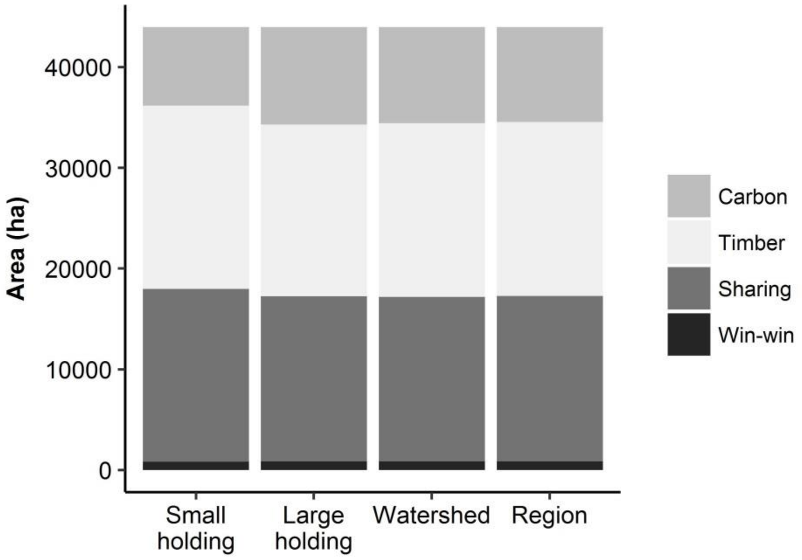

Area (ha)
40000
30000
20000
10000
0
Small holding
Large holding
Watershed
Region
Carbon
Timber
Sharing
Win-win

Fig. 5.

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