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Juutinen, Artti

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Trade-offs between economic returns, biodiversity, and ecosystem services in the selection of energy peat production sites

Artti Juutinen^{a,b,*}, Miia Saarimaa^a, Paavo Ojanen^c, Sakari Sarkkola^d, Arto Haara^e, Jouni Karhu^a, Mika Nieminen^d, Kari Minkkinen^c, Timo Penttilä^d, Matti Laatikainen^f, Anne Tolvanen^a

^a Natural Resources Institute Finland, P.O. Box 413, FI-90014 University of Oulu, Finland

^b Department of Economics, P.O. Box 8000, FI-90014 University of Oulu, Finland

^c University of Helsinki, Department of Forest Sciences, P.O. Box 27, FI-00014 Helsinki, Finland

^d Natural Resources Institute Finland, Latokartanonkaari 9, FI-00790 Helsinki, Finland

^e Natural Resources Institute Finland, Yliopistokatu 6, FI-80100 Joensuu, Finland

^f Geological Survey of Finland, P.O. Box 96, FI-70211 Kuopio, Finland

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ABSTRACT

Economic development creates challenges for land-use planners in balancing between increasing the use of natural resources and safeguarding biodiversity and ecosystem services. We developed and utilized multi-objective numeric optimization models to analyze the trade-offs between biodiversity and ecosystem services (BES). The approach was used in the land-use planning process in northern Finland when selecting potential peat production sites as a part of the development of the regional master plan. We first quantified Net Present Value (NPV) of peat production, biodiversity, greenhouse gas (GHG) emissions, and water emissions of peatlands. Then we applied multi-objective optimization to examine the trade-offs between the variables as well as to determine a cost-efficient selection of potential peat production sites, that is, a selection which would simultaneously generate the greatest possible economic returns and environmental benefits. Our results showed that with a relatively small decrease in NPV, a substantial decrease in biodiversity loss and a reduction in water emissions compared to the benchmark level could be attained. However, a significant decrease in GHG emissions resulted in a substantial decrease in NPV. We conclude that it is possible to significantly improve land-use management by applying multi-objective optimization in land-use planning.

1. Introduction

Economic development creates challenges for land users and policy makers in balancing between increasing the use of natural resources and safeguarding biodiversity and ecosystem services (BES) (Millennium Ecosystem Assessment, 2005). This means that trade-offs are inevitable, and compromises are needed when multiple, often controversial, objectives are taken into account in land-use planning and decision making. Instead of concentrating on direct economic returns obtained from nature, the aim should be multi-functional landscape that simultaneously generates ecological, social, and economic benefits. Alternative strategies exist for supporting multi-functional land-uses including land-sparing, land-sharing and mixed strategies (Law et al., 2017). Since the effects of these strategies vary across heterogeneous landscapes, a thorough analysis of the impacts of alternative land-uses is needed to identify the cost-effective strategy for

land-use planning.

Trade-offs occur when one ecosystem service is enhanced at the expense of another. If trade-offs are not acknowledged and identified within a thorough analysis, no response policy may be particularly efficient in managing ecosystem services in a sustainable way (Inostroza et al., 2017). Considerable trade-offs occur particularly in the use of peatlands, which are widely utilized peat-forming wetland ecosystems throughout the world. Peatlands provide habitats for many species and they also provide a variety of ecosystem services such as peat and timber production, carbon sequestration, and recreational benefits (e.g., Zedler and Kercher, 2005). Due to intensive use of peatlands in Europe (Joosten and Clarke, 2002; Chapman et al., 2003), any further deprivation should be well justified.

The most intensive peatland use is energy peat production, practiced especially in countries rich in peatlands, such as Belarus, Estonia, Finland, Indonesia, Ireland, the Russian Federation, and Sweden.

* Corresponding author at: Natural Resources Institute Finland, P.O. Box 413, FI-90014 University of Oulu, Finland.

E-mail address: artti.juutinen@luke.fi (A. Juutinen).

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Finland constitutes 59% of the annual energy peat use in the EU (World Energy Council, 2013). In 2014, a total of 69,000 ha, around 0.8% of the total peatland area, was under peat production for energy, horticultural, and other uses in Finland (Finnish Statistical Yearbook of Forestry, 2014). Energy peat is mostly produced by large companies, such as Vapo (<https://www.vapo.com/en>). Despite plans to reduce the use of energy peat by 2025 (Ministry of Economic Affairs and Employment of Finland, 2013), replacing peat with woodchips or other renewable resources takes time. Thus, new energy peat production sites are still being established.

This study focuses on the tradeoffs between BES in the selection of potential energy peat production sites at a regional level. The study presents a real-world decision-making problem associated with the land-use planning, since it was integrated in updating a regional master plan in northern Finland (Council of Oulu Region, 2018). In Finland, regional councils are responsible for drawing up regional master plans, which set out a framework for all local land-use planning. The Finnish Government Program on the sustainable use of mires and peatlands (Ministry of Agriculture and Forestry, 2012) states that all actions that considerably change the function of peatlands, such as peat production, should be allocated to drained or otherwise degraded peatlands. Hence, in regional land-use planning process the suitability of areas for peat production needs to be considered to reconcile both peat production and conservation needs. This means careful evaluation of trade-offs. The study utilizes iterative stakeholder engagement to take into account the needs of the regional planner, as well as to enable a more informed dialogue (Rosenthal et al., 2014). In general, spatial planners can be seen as the key players in finding solutions to alleviate trade-offs caused by alternative land-use or management choices (Turkelboom et al., 2018).

Various methods have been developed and utilized for the evaluation of trade-offs between BES as shown in the reviews by Seppelt et al. (2013), Deng et al. (2016), and Ochoa and Urbina-Cardona (2017). Also recent special issue edited by Inostroza et al. (2017) provides a broad view on integrated approaches to evaluate trade-offs between BES (Grêt-Regamey et al., 2017; Shoyama et al., 2017; Sun et al., 2017) or between ecosystem services (Hermanns et al., 2017; Sherrouse et al., 2017; Trodahl et al., 2017).

In general GIS-based assessments (Maes et al., 2012) and multi-criteria methods (Haara et al., 2018) have been shown to effectively reveal trade-offs between multiple targets at varying temporal and spatial scales. Ecosystem services are spatial by nature (e.g., Potschin & Haines-Young, 2011; Schröter et al., 2015), their spatial mapping is important (Hauck et al., 2013), but methods to choose the best land-use solutions under given levels of ecosystem services are also needed. Scenario analysis is the most frequently used tool for assessing land-use options and characterizing possible future scenarios (Seppelt et al., 2013). The analysis provides information on the contribution of certain types of land-use to selected ecosystem services and monetary values. Optimization can be used to identify efficient land-use solutions under given constraints and social preferences or values (Nelson et al., 2008; Polasky et al., 2008; Armsworth et al., 2012; Kennedy et al., 2016; Pennington et al., 2017). Still, quantification of the non-linear relationship between ecosystem services and land-use remains a challenge for sustainable land-use (Deng et al., 2016). Non-linear relationships indicates that there may be many land-use options with small losses in satisfying immediate human needs but large gains in maintaining ecosystems (De Fries et al., 2004).

Previous studies on the use of peatlands have mainly focused on peatland conservation and restoration (e.g., Evans et al., 2014; Glenk et al., 2014; Martín-Ortega et al., 2014; Albrecht and Ratamäki, 2016). A few approaches have also been used to locate suitable peat production sites in the practical planning process. For example, methods based on classification and exclusion of peatlands based on some pre-determined factors, such as proximity to nature conservation areas or settlements, and environmental and social impacts with respect to

watercourses have been applied (Onkila et al., 2012; Compton et al., 2013). Classification criteria can be exclusionary or advisory depending on the goals of decision makers and preferences of stakeholders. Additionally, inverse spatial conservation prioritization was developed for land-use zoning at the landscape scale to avoid negative ecological effects of peat production by identifying areas with the highest economic but lowest ecological value (Kareksela et al., 2013).

Glenk et al. (2014) propose a Cost-Benefit Analysis (CBA), including the valuation of ecosystem services, for targeting areas for peatland restoration. From an economic point of view, CBA is an ideal approach in the sense that it produces a socially optimum solution (i.e., the greatest welfare gains to society). CBA is also suitable for targeting areas for energy peat production. The valuation of non-market benefits provided by peatlands involves, however, many challenges, such as incomplete information on the impacts, and spatial and temporal differences in peatlands' responses to management (e.g., Martín-Ortega et al., 2014). Therefore, we quantify ecosystem service delivery but do not place monetary values on non-market benefits.

Our contribution to ecosystem service literature consists of a comprehensive quantitative approach which is directly incorporated into a practical decision-making process. We (i) integrate and elaborate existing economic and environmental data to quantify and value the economic returns and BES of peatlands, (ii) search for the cost-efficient selection of potential peat production sites which simultaneously generate the highest economic returns and BES possible, and (iii) examine trade-offs between economic returns and BES to assist land-use planning in the selection of potential peat production sites as a part of a regional planning process in northern Finland. Based on our discussions with the regional council we use four target variables in the analysis: NPV of peat production, biodiversity, GHG emissions, and environmental loading to watercourses. The variables are quantified by taking into account their long term development and utilizing available high-resolution environmental data in spatial format.

2. Methods and material

2.1. Study area

Our study area is the Vaala municipality in northern Finland (Fig. 1) covering an area of 1759 km², of which ca. 750 km² are classified as peatlands based on Multi-Source Forest Inventory (MS-NFI) data (Natural Resources Institute Finland, 2018; Mäkisara et al., 2016). The area represents a typical boreal landscape with a mosaic of mineral soil forests, peatlands, lakes, and farmlands. The Vaala municipality has a low population density (ca. 3000 inhabitants with 2.3 persons per km²) and it represents a typical northern Finnish rural area with a narrow economic structure and high unemployment rate (ca. 18%). A regional master plan, which guides the land-use allocation, was updated by the Council of Oulu Region for the Vaala municipality in 2018. Potential peat production sites had to be assigned as part of the plan, and since energy peat production is highly regulated in Finland, its potential economic, environmental, and social impacts had to be considered. Our results were incorporated into this planning process through continuous interaction with the Council of Oulu Region.

There was a quantitative target to assign approximately 2000 ha as potential peat production sites in the plan. Based on previous experience of the Council of Oulu Region the assigned area was about 2–3 times larger than would be the actual peat production area. This was because the private peat production enterprises would eventually not be able to utilize all potential sites due to their low economic profitability or because of the resistance by local people due to potential negative environmental impacts.

2.2. Decision criteria and land-use options

We pre-selected potential peat production sites using five exclusive

Fig. 1. Study area.

criteria that were defined by the Council of Oulu Region. The first two criteria were the average thickness of peat deposits (≥ 1.5 meters) and the size of the peatland site (≥ 10 ha), which aim to rule out sites with too low economic potential. These criteria were fulfilled by 103 peatland sites. The other three criteria were the distance to the nearest settlement (≥ 0.5 kilometers), the nearest nature protection area (≥ 0.5 kilometers), and the nearest groundwater discharge area reserved for drinking water supply (≥ 0.5 kilometers). The final data included 99 peatland sites.

NPV of peat production, biodiversity, GHG emissions, and environmental loading to watercourses were quantified for each potential peatland site. Under peat production, all peat soil is removed from a site, that is, the original habitat is permanently converted to another type of habitat. Therefore, the biodiversity value was calculated for the present state and that value was assumed to be lost in the case of peat production. The values for GHG emissions and environmental loading to watercourses were calculated as a difference between the two management options: the peat production option and the current land-

use option (i.e. business as usual), acknowledging that the current land-use also causes environmental impacts.

The current land-use was set according to the site data from the MS-NFI (Natural Resources Institute Finland, 2018) data and Corine Land Cover Classification (CLC2012, Finnish Environment Institute, 2018). In the current land-use option, forestry and agriculture were assumed to continue at those parts of the sites that were classified as forestry-drained or agricultural peatlands at the time of the study. Effects of forest growth and cuttings were predicted using the large-scale forest planning system MELA (Redsven et al., 2013) and growing stock and site data from MS-NFI (Natural Resources Institute Finland, 2018). Those parts of the sites that were classified as undrained peatlands were assumed to remain undrained in the simulation of the effects of the current land-use option.

Peat production and the associated impacts on GHG and watercourses occur over a long time period. Therefore, the values for these two environmental variables were assessed as cumulative values during the peat production period, usually 30–40 years. In the simulation of the peat production option, we made an assumption that all peat areas (undrained, forestry-drained, agriculture-drained) within the study sites would be brought into peat production.

Land-use planning requires detailed spatial information on the heterogeneity of the target areas. To this end, several sources of data were used to pre-select potential peat production sites, to assess their present status, and to quantify and value their biodiversity and ecosystem services (Table 1). For example, peatland mapping data were used to calculate NPV of peat production, whereas high-resolution MS-NFI data were used to identify the properties of sites in terms of their impacts on biodiversity, GHG emissions and environmental loading to watercourses.

2.3. NPV of peat production

NPV of peat production was calculated to measure the profitability of the potential peat production sites. For that purpose, all associated revenues and costs were assessed. The costs included the costs of establishing the production site (€9000 ha⁻¹), the costs of peat extraction (€8.08 MWh⁻¹), as well as those of haulage (€2.8 MWh⁻¹). The costs were estimated based on information provided by Vapo, the largest Finnish peat production company (personal communication). Peat production companies typically rent production sites from landowners, but land renting was not included in the costs of peat production. From the viewpoint of social planner, land rents are income transfers from peat production companies to landowners, thus having no effect on net benefits.

It takes several years to prepare a peatland site for peat production, that is, to harvest the tree stand and stumps, excavate drainage and main outflow ditches, construct roads, etc. We divided the costs of preparation equally for the first three years, after which peat production was assumed to start. Annual peat production was estimated to be 450 m³ ha⁻¹ yr⁻¹, which represents the past long-term average production in Finland (Vapo, personal communication; Flyktman, 2005). The production time for each site was calculated by dividing the total volume of peat by the annual peat production estimate.

The annual revenues were calculated by multiplying the annual peat production by the peat price. The peat price was €13.1 MWh⁻¹, which equals the average milled peat price for 2011–2015 (Statistics Finland, 2018; Table 1) adjusted by the producer price index. Finally, NPV was calculated with a 3% discount rate for all potential peat production sites. The NPV figures should be considered as rough estimates. In practice, NPV depends on several site-specific factors that we were not able to take into account.

2.4. Biodiversity value

The conservation of the biodiversity of peatlands is regulated in Finland. In addition to the conservation areas under the Nature

Conservation Act, sufficient attention must be paid to the general importance of all other natural peatland habitats for biodiversity and the preservation of landscape values.¹

The present biodiversity value of the potential peat production sites was assessed by applying the guidelines given by the Ministry of the Environment concerning the sustainable use of mires and peatlands in land-use planning (Ympäristöministeriö, 2015). It was estimated on the basis of six criteria that are expected to capture the most important determinants of biodiversity values of peatlands: habitat types (mire site types, water formations), mire complex types (Cajander, 1913) and geomorphological formations, presence of threatened plant and bird species, habitat connectivity, undrained peatland area coverage, and habitat suitability predictions for eight threatened plant species (for data, see Table 1). The biodiversity value, denoted hereafter as Biodiversity loss, of each peatland site was finally calculated as the weighted sum of the criteria-specific scores (for details of the calculations, see Supplement 1). The values varied from 0.85 to 3.05 with a mean of 1.39. Biodiversity loss should be interpreted as a relative index with higher values indicating more suitable sites for biodiversity conservation.

2.5. GHG emissions

GHG (CO₂, CH₄, N₂O) emissions of potential peat production sites were calculated as the difference between the total GHG emissions (Mg CO₂ equivalents, GWP100) for the peat production option and the current land-use option until the end of the peat production. First, annual GHG emissions and removals were estimated by multiplying the emission factors (Table 1, Table S21) by the size of the respective peatland site or the peat energy content. Second, annual emissions of each gas were summed for both land-use options to estimate the total emissions during the time period of peat production. Third, the total emissions of different gases were converted to CO₂ equivalents by multiplying them by their respective global warming potentials for a 100-year time interval (Myhre et al., 2013). For the peat production option, emissions from cutting of the tree stand prior to peat production, the burning of peat, as well as the soil emissions from the production area were included. For the current land-use option, soil emissions from undrained peatlands and peatlands drained for forestry and agriculture were included (for details of the calculations, see Supplement 2).

2.6. Environmental loading to watercourses

Water quality impacts caused by land-use activities were calculated for the total nitrogen (TN), total phosphorus (TP), and total organic carbon (TOC), which are among of the most important water quality parameters contributing to water eutrophication and brownification (Schindler, 1998; Williamson et al., 2015). For the peat production option, the exports induced by the preparation of the peat field for peat production and the following production phases were included. The net exports from undrained peatland sites were assumed to be zero.

The TN, TP, and TOC exports from agriculture were derived from the literature (Table S31), and the exports caused by peat production and forestry were calculated using the runoff and the so-called specific concentrations (Palviainen et al., 2015). For this, we first estimated the

¹ Environmental Impact Assessment (EIA) concerns peat production areas more than 150 hectares. In the EIA process, the impact of the project to environment is assessed at the preparation stage before any decisions are made and when the forthcoming solutions may still be influenced. The EIA process is a project planning tool, and its results must be taken into account when granting permits for projects. See” https://www.ymparisto.fi/fi-FI/Asiointi_luvat_ja_ymparistovaikutusten_arviointi/Ymparistovaikutusten_arviointi” for further information.

Table 1

Data used to pre-select and quantify and value the biodiversity and ecosystem services of potential peat production sites.

Data	Source
Size (ha), peat volume (m ³), and the energy content of peat (MWh) Land-use type (forestry/agriculture), resolution 20 m × 20 m	Geological Survey of Finland 2011*, 2016** Corine Land Cover Classification (CLC2012), Finnish Environment Institute (2018) , Härmä et al. (2013)
Stand volumes (m ³ ha ⁻¹) and carbon storage of tree biomass (kg ha ⁻¹)	Multi Source National Forest Inventory (MS-NFI) data, Natural Resources Institute Finland 2018 , Mäkisara et al., 2016
Spatial drainage stage data on peatlands, resolution 25 m × 25 m Topography, digital elevation model (DEM), resolution 10 m × 10 m Daily and monthly climate data, resolution 10 km × 10 km and 1 km × 1 km Occurrence records of threatened mire plant species (at least 100 m resolution) Occurrence of mire plants and birds (at least 100 m resolution)	Finnish Environment Institute National Land Survey of Finland Finnish Meteorological Institute, Pirinen et al. (2012) Finnish Environment Institute (Hertta), Rassi et al. (2010) Kainuu Centre for Economic Development, Transport and the Environment, Alanen and Aapala (2015)
Greenhouse gas emission factors (g gas m ⁻² year ⁻¹) for CO ₂ , CH ₄ , and N ₂ O (for details, see Table S21)	Alm et al. (2007) , Hyvönen et al. (2009) , IPCC (2006, 2014) , Minkkinen and Ojanen (2013) , Nykänen et al. (1996) , Ojanen et al. (2010, 2013) , Ojanen, Minkkinen and Penttilä (unpublished data) , Regina et al. (1996) , Salm et al. (2012) , Shurpali et al. (2008) , Sundh et al. (2000) , Väisänen et al. (2013)
Specific concentrations and specific exports of total nitrogen, total phosphorus, and total organic carbon, µg L ⁻¹ or kg ha ⁻¹ (for details, see Table S31)	Finér et al. (2010) , Huhta and Jaakkola (1993) , Joensuu et al. (2002) , Kortelainen et al. (2006) , Mattsson et al. (2003, 2015) , Myllys (2012) , Nieminen et al. (2010, 2017) , Nieminen (unpublished data) , Pöyry (2012)
Peat price, € MWh ⁻¹	Statistics Finland (2018)

* The peatland mapping data for "Pohjois-Pohjanmaan ja Länsi-Kainuun suo-ohjelma" -project, Spatial dataset (unpublished).

** The peatland mapping data for "Pohjois-Pohjanmaan 3. Vaihe-ohjelmakanta" -project, Spatial dataset, 1.12.2016 (unpublished).

annual runoffs for each potential peat production site by using the FEMMA hydrological process model ([Koivusalo et al., 2008](#)). Then, we determined the specific concentrations ([Palviainen et al., 2015](#)) for the peat production option and the current land-use option and calculated the TN, TP, and TOC exports as the product of the runoff and specific concentrations. These specific concentrations were determined empirically and illustrate how much each land-use option increases the concentrations above the natural background level. The specific concentrations were obtained either directly from the literature or were based on additional analysis of the data presented in previous studies ([Table 1](#), [Table S31](#)). To produce one variable for environmental loading to watercourses (named Water emissions hereafter), a specific common relative loading factor was calculated. It takes into consideration the specific impact of each element (TN, TP, and TOC) on water quality (for details of the simulations and calculations, see [Supplement 3](#)).

2.7. Models

We developed linear integer models to elaborate the social land-use planner's multi-objective peatland site selection problem. Consider a given geographical area with n different sites that are suitable for peat production according to the given preliminary criteria. We denote the status of sites by x_j ($j = 1, \dots, n$), which gets a value of 1 if the site j is assigned as a peat production site in the master plan and 0 otherwise. In selecting the sites the land-use planner takes explicitly into account the size of sites but not their connectivity. The size of site j is denoted by a_j . The overall target area for peat production is A . Let NPV_j be the NPV of peat production at site j , that is, the economic value varies between the sites. We denote the Biodiversity value of site j at the initial state before peat production is started by B_j . GHG and Water emissions of site j caused by converting the site to peat production are C_j and W_j , respectively.

We supposed that a land-use planner seeks to maximize NPV of peat production with the given constraints related to environmental impacts, that is, the planner selects the peat production sites cost-effectively. We first consider a model which does not include any area target for peat production. Formally, the model (Model 1) can be expressed as follows:

$$\max \sum_{j=1}^n NPV_j x_j \quad (1)$$

subject to constraints:

$$\sum_{j=1}^n B_j x_j \leq B \quad (2)$$

$$\sum_{j=1}^n C_j x_j \leq C \quad (3)$$

$$\sum_{j=1}^n W_j x_j \leq W \quad (4)$$

$$x_j \in \{0, 1\} \quad j = 1, \dots, n \quad (5)$$

$$\sum_{j=1}^n a_j x_j \leq A \quad (6)$$

where B , C , and W denote the target levels for Biodiversity loss, GHG emissions, and Water emissions, respectively. The objective function (1) sums NPVs of the selected sites. Constraint sets (2)–(4) ensure that Biodiversity loss and GHG and Water emissions impacts due to the selection of the peat production sites are smaller than or equal to the target levels. Constraint set (5) simply indicates that the choice variables must be binary, that is, each site is either assigned to peat production or not. Eq. (6) is the area constraint which ensures that the total area of the selected sites is smaller than or equal to the target area.

In what follows, we use the first model to reveal an efficiency frontier (also called a production possibility frontier) that illustrates two-dimensional trade-offs between NPV and the considered BES (Biodiversity loss, GHG emissions, and Water emissions) impacts. Therefore, we first solve the model using constraints (2)–(4) one by one with (1) and (5). The efficiency frontiers are revealed by solving the model multiple times with varying target levels of the considered BES variable. We repeat this procedure with the area constraint (6) to examine how the area restriction affects the two-dimensional trade-offs.

The second model (Model 2) is used to analyze multi-dimensional trade-offs between the economic returns and BES objectives. Model 2 includes (1) and (5) as well as the following restrictions:

$$\sum_{j=1}^n B_j x_j \leq k B^*, \quad k \leq 1 \quad (7)$$

$$\sum_{j=1}^n C_j x_j \leq z C^*, \quad z \leq 1 \quad (8)$$

$$\sum_{j=1}^J W_j x_j \leq y W^*, y \leq 1 \quad (9)$$

where k , z , and y are technical weight parameters that are varied to reveal the efficiency frontiers. The reference values for the three BES variables are denoted by B^* , W^* , and C^* for Biodiversity loss, Water emissions, and GHG emissions, respectively. In addition to the Eqs. (1), (5), (7)–(9), the second model includes two area constraints to ensure that the target for the peat production area is achieved. The two area constraints are used to allow some flexibility in the site selection, because in the regional master plan the area target is only approximate and clearly larger than the actual peat production area that private peat production enterprises will eventually be able to utilize. Formally, the area constraints are

$$\sum_{j=1}^J a_j x_j \leq A + 50 \quad (10)$$

$$\sum_{j=1}^J a_j x_j \geq A - 50 \quad (11)$$

Model 2 is first solved without (7), (8), and (9), and the obtained Pareto-optimal solution is used to calculate the reference values for the three BES variables denoted by B^* , C^* , and W^* . These reference values are then used as initial target levels for the BES variables in the multi-dimensional analysis. To ensure that the Pareto-optimal solutions are found, we applied the ϵ -constraint method (Miettinen, 1999).

3. Results

3.1. Characteristics of potential peat production sites

The BES (Biodiversity loss and GHG and Water emissions) and economic (NPV) characteristics of potential peat production sites varied considerably (Table 2). The coefficient of variation (CV) was highest for the Water emissions (CV = 1.3), followed by the NPV (CV = 1.1). NPV with a 3% discount rate was negative for twelve sites, indicating unprofitable peat production. The discount rate had a strong impact on the profitability of peat production, reflecting the fact that peat production occurs over a long time period. The production time was on average 37.3 years and varied from 18 to 62 years.

The characteristics of the potential peat production sites indicated strong variations, especially because GHG and Water emissions and NPV values were calculated on a per area basis, and the sites varied from 10 to 216 ha. The correlation between the size of the site and GHG emissions was strong ($r = 0.952$), whereas Biodiversity loss did not correlate significantly with the size of the site (Table 3). Correlations between peat production time and Water and GHG emissions were similar although weaker. Correlation coefficients between NPV of peat production and other variables were generally high, except for Biodiversity loss. Biodiversity loss showed high correlation ($r = 0.62$) only with Water emissions.

The values of Biodiversity loss and GHG and Water emissions are presented using a relative scale with respect to the NPV class based on the median NPV in Fig. 2. There were no sites that had lower Biodiversity loss than 27% of the maximum Biodiversity loss value. Otherwise, Biodiversity loss and GHG and Water emissions were relatively evenly distributed among the potential sites. The sites with low NPV

(NPV < median) seemed to involve lower GHG emissions than sites with high NPV (NPV $\geq$ median), as was also indicated by the correlation analysis (Table 3). Importantly, the potential peat production sites involved numerous different combinations of NPV of peat production, Biodiversity loss, GHG emissions, and Water emissions values. Therefore, the land-use planner is facing a challenging task to identify the set of sites that provides the targeted levels of these variables when selecting the potential peat production sites for master plan. Since all goals cannot be achieved simultaneously, compromises and sophisticated integrated assessment on trade-offs are needed.²

3.2. Two-dimensional trade-offs

As described in the Section 2.7 (Model 1), we first generated two-dimensional efficiency frontiers that illustrate trade-offs between the economic (NPV) and each BES (Biodiversity loss, GHG emissions, Water emissions) objective separately (Fig. 3). When the area constraint for the potential peat production sites was excluded, we found, as expected, that a decrease in Biodiversity loss, GHG or Water emissions (compared to the level obtained at the maximum NPV) reduced NPV of peat production (Fig. 3a–c). However, the nature of the trade-offs differed between each BES objective. Water emissions could first be reduced without any significant loss in NPV of peat production, but further reduction clearly decreased it (Fig. 3c). This pattern was even clearer for the Biodiversity loss frontier (Fig. 3a), but the GHG emissions frontier was close to a straight line (Fig. 3b).

In this study, there was a quantitative target to assign approximately 2000 ha as peat production area in the regional master plan. Accounting for this area restriction in the optimization had a considerable effect on the trade-offs (Fig. 3aa, bb, cc); the production possibility set decreased and the efficiency frontiers moved closer to the origin. Under restricted areal optimization, the steep slope of the Biodiversity loss and the Water emission efficiency frontiers clearly differed from that of the GHG emissions efficiency frontier. Therefore, the range of total NPV in which cost-effective solutions were found was quite narrow varying from €6.9–11.2 and €8.5–11.2 million for Water emissions and Biodiversity loss, respectively. For GHG emissions, the range was significantly wider, €2.3–11.2 million. Under the area restriction, the values of BES variables at maximum NPV (without BES objectives) were: Biodiversity loss = 34.6 units, GHG emissions = 11224 Gg CO₂ equivalents, and Water emissions = 672.6 units. Hence, the maximum potential for the reduction in Water emissions (571 units) was 84.9% from the Water emissions at maximum NPV. The percentage for reduction in GHG emissions was 44.9% and the potential maximum reduction in Biodiversity loss 51.2%. These results show that the possibilities for avoiding harmful environmental impacts due to

² Notably, we used different time periods in calculating NPVs, because the peat production time varied between the sites. The use of different time periods in calculation is, however, problematic. For example, two sites with identical NPVs, one accumulating NPV over 20 years and the other over 60 years are very unlikely to be considered equally valuable by the land-use planner. The problem could be avoided by including present value of net revenues from some after-use option in the calculation, but it is not known how the sites will be used after peat production. However, we calculated a sensitivity analysis, where all sites were used in forestry after peat production by including forest land value in the NPV calculation (Faustmann, 1849). Peatlands are rather low productive areas in terms of timber production, and therefore, we used 100 €/ha as a land value in the test (Anonymous, 2013). With this land value the rank of sites in terms of NPV remained almost the same as without land value. The result indicates that the use of different time periods was not a severe problem in this study. In addition, potential peat production sites were not selected using only NPV as a criterion in the multi-objective optimization. Therefore, even though the rank based on NPV was not clear for all sites this had no effect on the optimal selection of sites as there were differences in environmental variables between the sites.

Table 2
Main characteristics of the potential peat production sites (99 sites).

	Total	Mean	Min	Max
Peat production area (ha)	7168	72.4	10	216
Biodiversity loss (index)	137.6	1.4	0.9	3.1
GHG emissions (Gg CO ₂ equivalents)	32710.5	330.4	26.5	1165.2
Water emissions (index)	1906.1	19.3	0.0	132.7
NPV (k€)	23117.8	233.5	−189.6	1152.6

Table 3
Correlation coefficients between selected variables (99 sites).

	NPV	Biodiversity loss	GHG emissions	Water emissions	Size of the site	Production time
NPV	1					
Biodiversity loss	0.159	1				
GHG emissions	***0.918	***0.286	1			
Water emissions	***0.567	***0.620	***0.679	1		
Size of the site	***0.799	***0.342	***0.952	***0.657	1	
Production time	***0.580	*0.169	***0.624	***0.452	***0.459	1

Note:

*** statistically significant at 1% level.

* statistically significant at 10% level

peat production under the area restriction differed considerably between the three BES variables.

3.3. Multi-dimensional trade-offs

When NPVs were maximized with the 2050 ha area constraint, the Pareto-optimal solution consisted of 24 peat production sites. This optimization solution was used as a benchmark for further examinations of multi-dimensional trade-offs. Technically, the trade-offs were revealed by systematically varying the weight parameters (Model 2: k , z , y) with 0.1 unit intervals until there were no more feasible solutions with the given weight parameter values. By using this procedure, 100 different Pareto-optimal solutions were identified. Multi-dimensional trade-offs between economic (NPV) and BES (Biodiversity loss, Water

emissions, GHG emissions) objectives in the selection of 1950–2050 ha for peat production are presented in Table 4 with the associated weight values of the solutions. For interpretation, note that a weight value of 0.9 for Biodiversity loss, for example, indicates that Biodiversity loss of a particular solution is at least 10% smaller than Biodiversity loss of the benchmark solution. The weights of water and GHG emissions are to be interpreted in the same way.

The first thing to notice is that the interval of feasible weight values differed between the BES variables (Table 4). The feasible weight value intervals for Biodiversity loss, Water and GHG emissions were 1.0–0.5, 1.0–0.2 and 1.0–0.6, respectively. Note also that the first solution in Table 4 describes the reference case in which NPV was maximized with weight values equal to 1 for all BES variables, that is, the BES objectives were set equal to the benchmark level.

Fig. 2. Biodiversity loss, GHG emissions, and Water emissions of potential peat production sites by NPV classes. Variable values are presented on a relative scale, in which 100 equals the maximum value of the respective variable among the 99 peatland sites.

Fig. 3. Efficiency frontiers showing two-dimensional trade-offs between economic (NPV) and environmental (Biodiversity loss, GHG emissions, Water emissions) targets in the selection of peat production sites. The values of environmental variables are shown as reduction from the level that was obtained at the maximum NPV. Left hand panels show the efficiency frontiers (blue lines) without the area restriction and the hectares assigned to the peat production (red lines). Right hand panels include the efficiency frontiers with the area restriction (1950–2050 ha) for peat production. Only potential production sites with a positive NPV are included (87 sites). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Pareto-optimal solutions for multi-objective selection of peat production sites.

Solution	Weight values			Variable values			
	Biodiversity loss	GHG emissions	Water emissions	NPV, mil. €	Biodiversity loss	GHG emissions	Water emissions
1	1	1	1	11.168	34.6	11,221	673
2	1	1	0.9	11.062	33.7	11,185	572
3	1	0.9	0.7	10.203	33.9	10,095	468
4	1	0.9	0.6	10.193	33.6	10,071	390
5	1	0.8	0.6	8.772	31.6	8973	360
6	1	0.8	0.5	8.745	34.5	8965	292
7	1	0.8	0.4	8.739	33.5	8976	264
8	1	0.8	0.3	8.613	33.8	8966	200
9	1	0.8	0.2	8.050	32.2	8928	134
10	1	0.7	0.5	6.617	33.9	7849	281
11	1	0.7	0.4	6.610	34.6	7849	214
12	1	0.7	0.3	6.586	34.6	7844	201
13	1	0.7	0.2	6.264	34.6	7849	134
14	1	0.6	0.4	3.800	34.6	6732	259
15	0.9	1	1	11.126	30.6	11,129	637
16	0.9	1	0.9	11.060	30.2	11,153	605
17	0.9	1	0.8	11.007	31.0	11,075	538
18	0.9	1	0.7	10.915	30.5	11,092	454
19	0.9	1	0.6	10.763	31.1	10,947	393
20	0.9	1	0.5	10.572	27.8	10,898	336
21	0.9	1	0.4	10.190	29.2	10,519	268
22	0.9	1	0.3	9.471	28.9	10,103	201
23	0.9	0.9	0.8	10.219	30.6	10,097	495
24	0.9	0.9	0.7	10.197	30.2	10,094	471
25	0.9	0.9	0.6	10.174	29.6	10,097	402
26	0.9	0.9	0.5	10.148	30.7	10,085	324
27	0.9	0.9	0.4	9.904	27.8	10,096	268
28	0.9	0.9	0.3	9.461	28.9	10,094	200
29	0.9	0.9	0.2	8.260	28.2	9086	134
30	0.9	0.8	0.6	8.750	30.5	8974	364
31	0.9	0.8	0.5	8.743	30.7	8972	331
32	0.9	0.8	0.4	8.706	30.7	8972	263
33	0.9	0.8	0.3	8.568	31.1	8961	199
34	0.9	0.7	0.5	6.535	31.0	7849	278
35	0.9	0.7	0.4	6.525	31.0	7843	257
36	0.9	0.7	0.3	6.456	31.0	7839	198
37	0.9	0.7	0.2	6.151	30.5	7849	134
38	0.9	0.6	0.5	3.353	31.1	6727	326
39	0.8	1	1	10.977	27.3	11,142	620
40	0.8	1	0.9	10.970	27.4	11,045	597
41	0.8	1	0.8	10.876	27.4	11,027	536
42	0.8	1	0.7	10.828	27.4	11,059	467
43	0.8	1	0.6	10.720	27.6	11,122	399
44	0.8	1	0.5	10.534	27.4	10,765	336
45	0.8	1	0.4	10.188	27.3	10,507	268
46	0.8	0.9	0.8	10.220	27.3	10,096	519
47	0.8	0.9	0.7	10.191	27.7	10,093	454
48	0.8	0.9	0.6	10.179	27.5	10,085	375
49	0.8	0.9	0.5	10.084	27.3	10,095	329
50	0.8	0.9	0.4	9.918	25.7	10,090	268
51	0.8	0.9	0.3	9.460	10,092	200	51
52	0.8	0.9	0.2	8.199	9140	134	52
53	0.8	0.8	0.6	8.663	8973	391	53
54	0.8	0.8	0.5	8.597	8964	330	54
55	0.8	0.8	0.4	8.586	8966	267	55
56	0.8	0.8	0.3	8.423	8972	189	56
57	0.8	0.8	0.2	8.043	8974	134	57
58	0.8	0.7	0.6	6.371	7852	382	58
59	0.8	0.7	0.5	6.295	7851	316	59
60	0.8	0.7	0.4	6.336	7845	213	60
61	0.8	0.7	0.3	6.148	7847	197	61
62	0.8	0.7	0.2	5.914	7825	131	62
63	0.7	1	1	10.761	11,156	623	63
64	0.7	1	0.9	10.745	11,188	567	64
65	0.7	1	0.8	10.690	11,131	493	65
66	0.7	1	0.7	10.630	11,139	457	66
67	0.7	1	0.6	10.544	10,924	371	67
68	0.7	1	0.5	10.317	10,943	333	68
69	0.7	1	0.4	9.852	10,382	267	69
70	0.7	0.9	0.8	10.065	10,082	481	70
71	0.7	0.9	0.7	10.019	10,078	465	71
72	0.7	0.9	0.6	9.942	10,098	401	72

(continued on next page)

Table 4 (continued)

Solution	Weight values			Variable values			
	Biodiversity loss	GHG emissions	Water emissions	NPV, mil. €	Biodiversity loss	GHG emissions	Water emissions
73	0.7	0.9	0.5	9.911	10,082	299	73
74	0.7	0.9	0.4	9.782	10,092	261	74
75	0.7	0.9	0.3	9.157	9928	202	75
76	0.7	0.8	0.6	8.406	8968	379	76
77	0.7	0.8	0.5	8.321	8959	330	77
78	0.7	0.8	0.4	8.205	8977	265	78
79	0.7	0.8	0.3	8.196	8970	192	79
80	0.7	0.8	0.2	7.456	8813	132	80
81	0.7	0.7	0.4	5.776	7830	221	81
82	0.7	0.7	0.3	5.703	7825	199	82
83	0.6	1	0.8	10.387	11,136	506	83
84	0.6	1	0.7	10.298	10,916	466	84
85	0.6	1	0.6	10.230	11,040	401	85
86	0.6	1	0.5	9.875	10,694	333	86
87	0.6	0.9	0.7	9.635	10,075	426	87
88	0.6	0.9	0.6	9.627	10,091	398	88
89	0.6	0.9	0.5	9.522	10,075	328	89
90	0.6	0.9	0.4	9.187	9994	266	90
91	0.6	0.9	0.3	8.328	9564	200	91
92	0.6	0.8	0.7	7.803	8968	407	92
93	0.6	0.8	0.6	7.801	8950	381	93
94	0.6	0.8	0.5	7.738	8949	336	94
95	0.6	0.8	0.4	7.714	8977	269	95
96	0.6	0.8	0.3	7.486	8948	199	96
97	0.5	1	0.7	9.064	10,217	457	97
98	0.5	1	0.6	8.852	10,196	397	98
99	0.5	0.9	0.7	8.983	10,063	469	99
100	0.5	0.9	0.5	8.742	10,068	334	100

It is noteworthy that the reduction in Biodiversity loss did not cause reduction in GHG or Water emissions. For example, when Biodiversity loss was 10% lower than in the benchmark and GHG emissions were not restricted (GHG weight value = 1), Water emissions varied according to its own weight value (see solutions 15–22 in Table 4). Water emissions would have reduced more strongly if the reduction in Biodiversity loss had caused the reduction in Water emissions. This outcome indicates that the Biodiversity loss objective lacked synergy with the GHG and Water emissions objectives.

Including restrictions in GHG emissions clearly reduced NPV of peat production compared with the benchmark level. Notably, restriction in GHG emissions also resulted in reduction in Water emissions, in particular at the higher target levels of emissions reductions. For example, solution 7 with 20% lower GHG emissions compared with the benchmark level enabled 40% reduction in Water emissions, thus the solutions with 0–30% Water emissions reductions were not Pareto-optimal.

Despite that the Biodiversity loss objective did not influence the GHG and Water emissions objectives, reduction in Water emissions reduced Biodiversity loss. For example, in the case when Water emissions were at least 20% lower than in the benchmark and there were no restrictions in GHG emissions, it was possible to reduce Biodiversity loss by 10% at the same time (see solutions 17–22 in Table 4). Additionally, when the Water emissions reduction target was set to 80% it was possible to obtain reductions in Biodiversity loss and GHG emissions in some solutions (e.g., solutions 29 and 57).

To further investigate the features of the Pareto-optimal solutions, an additional analysis was conducted in which the average characteristics of the selected and non-selected potential production sites were calculated. Only solutions 1–50 are presented in this paper (Table 5). In general, the average NPV of peat production was clearly higher and the average Biodiversity loss and Water emissions values were lower for the selected sites than for the non-selected sites, the outcome depending strongly on the weight values. GHG emissions were lower for the selected sites only with the GHG weight value of ≤ 0.7 . When the BES objectives had a weight value close to 1.0, the difference in the NPV per

hectare value was higher and the difference in the BES variables was lower between the selected and the non-selected sites. The opposite pattern was observed when the weight values were lower. In particular, the solutions 14 and 38 in which GHG weight was 0.6 indicated lower average NPV per hectare for the selected than non-selected sites. A decrease in Biodiversity loss resulted in the selection of larger sites (e.g., the number of selected sites lower in solutions 15–38 than 1–4). In addition, putting greater emphasis on BES objectives decreased to some extent the average peat production time of the selected sites.

4. Discussion

Land-use planning involves trade-offs between BES and economic returns that are difficult to assess in an explicit and systematic way. In this study, we developed and utilized multi-objective numeric optimization models to analyze the trade-offs associated with the selection of potential peat production sites as part of the development of a regional master plan in northern Finland. The examined BES variables, which were identified to be relevant for the local authority, were Biodiversity loss, GHG emissions, Water emissions. In addition, to address provisioning services we examined economic returns measured by NPV of peat production.

The novelty of our study is made up of a number of factors that are rarely dealt with in the literature. First, the cost-effectiveness analysis by applying multi-objective optimization has been widely applied to solve complex land-use and land-management problems involving multiple ecosystem services and their trade-offs (e.g., Nelson et al., 2008; Polasky et al., 2008; Triviño et al., 2015; Kennedy et al., 2016; Pennington et al., 2017), but as far as we know, it has not been used for peatland use planning. Second, we considered a real-life land-use planning problem and conducted the research interactively with the regional land-use planner. The outcome of our work is realized in the ratified land-use master plan (Council of Oulu Region, 2018). Several authors have addressed that despite recent advantages in ecosystem service research the implementation of ecosystem service concept at the

Table 5

The average characteristics of selected and non-selected sites in the Pareto-optimal solutions.

Weight values				Selected sites				Non-selected sites									
S	B	G	W	N	Size	Time	NPV	B	G	W	N	Size	Time	NPV	B	G	W
1	1	1	1	24	85.4	44.1	5448	1.69	547	32.8	75	68.2	39.1	2335	2.01	420	24.1
2	1	1	0.9	24	85.2	44.1	5412	1.65	547	28.0	75	68.3	39.2	2353	2.03	420	26.0
3	1	0.9	0.7	27	72.6	40.4	5208	1.73	515	23.9	72	72.3	40.6	2479	1.99	434	27.6
4	1	0.9	0.6	26	75.5	40.2	5190	1.71	513	19.9	73	71.3	40.7	2484	2.00	435	29.1
5	1	0.8	0.6	26	75.2	35.4	4487	1.62	459	18.4	73	71.4	42.5	2752	2.03	456	29.7
6	1	0.8	0.5	28	69.6	35.4	4485	1.77	460	15.0	71	73.5	42.5	2754	1.98	455	30.9
7	1	0.8	0.4	28	69.8	35.4	4475	1.72	460	13.5	71	73.5	42.5	2757	2.00	455	31.5
8	1	0.8	0.3	29	67.2	35.4	4417	1.73	460	10.3	70	74.5	42.5	2780	1.99	455	32.7
9	1	0.8	0.2	27	72.3	36.9	4126	1.65	458	6.9	72	72.5	41.9	2888	2.02	456	34.0
10	1	0.7	0.5	28	69.6	31.3	3394	1.74	403	14.4	71	73.5	44.0	3162	1.99	477	31.1
11	1	0.7	0.4	28	69.6	31.2	3390	1.77	403	11.0	71	73.5	44.1	3164	1.97	477	32.4
12	1	0.7	0.3	29	67.2	31.2	3377	1.77	402	10.3	70	74.5	44.1	3168	1.97	477	32.7
13	1	0.7	0.2	29	67.2	32.0	3212	1.77	403	6.9	70	74.5	43.8	3230	1.97	477	34.0
14	1	0.6	0.4	28	69.7	28.0	1948	1.77	345	13.3	71	73.5	45.3	3703	1.97	498	31.6
15	0.9	1	1	22	93.1	43.6	5430	1.49	543	31.1	77	66.5	39.4	2343	2.09	422	24.8
16	0.9	1	0.9	23	89.1	43.7	5395	1.47	544	29.5	76	67.3	39.3	2356	2.10	421	25.4
17	0.9	1	0.8	23	88.6	43.5	5401	1.52	543	26.4	76	67.5	39.4	2361	2.08	422	26.7
18	0.9	1	0.7	24	85.4	43.6	5325	1.49	541	22.1	75	68.2	39.3	2384	2.09	423	28.4
19	0.9	1	0.6	26	78.8	43.2	5250	1.52	534	19.2	73	70.1	39.5	2414	2.08	425	29.6
20	0.9	1	0.5	23	89.0	43.5	5165	1.36	532	16.4	76	67.4	39.4	2450	2.14	426	30.7
21	0.9	1	0.4	25	81.8	41.7	4983	1.43	514	13.1	74	69.2	40.1	2523	2.12	433	32.0
22	0.9	1	0.3	24	85.4	39.9	4620	1.41	493	9.8	75	68.2	40.8	2666	2.12	442	33.3
23	0.9	0.9	0.8	24	81.3	40.4	5235	1.57	517	25.4	75	69.5	40.6	2473	2.05	434	27.1
24	0.9	0.9	0.7	25	79.4	40.0	5137	1.52	509	23.7	74	70.0	40.8	2493	2.07	437	27.7
25	0.9	0.9	0.6	24	82.6	40.1	5133	1.49	509	20.3	75	69.1	40.7	2496	2.08	436	29.0
26	0.9	0.9	0.5	26	76.2	39.6	5120	1.55	509	16.3	73	71.0	40.9	2501	2.06	437	30.5
27	0.9	0.9	0.4	24	82.4	40.7	5010	1.41	511	13.6	75	69.2	40.5	2546	2.11	436	31.6
28	0.9	0.9	0.3	24	85.4	39.8	4615	1.41	492	9.7	75	68.2	40.9	2668	2.12	442	33.3
29	0.9	0.9	0.2	24	81.3	37.9	4236	1.45	466	6.9	75	69.6	41.6	2847	2.10	453	34.0
30	0.9	0.8	0.6	25	78.0	35.6	4485	1.56	460	18.6	74	70.5	42.4	2754	2.05	455	29.6
31	0.9	0.8	0.5	25	78.1	35.5	4479	1.57	460	17.0	74	70.5	42.5	2756	2.05	455	30.2
32	0.9	0.8	0.4	26	75.0	35.5	4465	1.57	460	13.5	73	71.5	42.4	2762	2.05	455	31.5
33	0.9	0.8	0.3	27	72.4	35.3	4381	1.59	458	10.2	72	72.4	42.5	2791	2.04	456	32.8
34	0.9	0.7	0.5	25	78.1	31.5	3346	1.59	402	14.2	74	70.5	44.0	3180	2.04	477	31.2
35	0.9	0.7	0.4	25	78.0	31.3	3344	1.59	402	13.2	74	70.5	44.0	3181	2.04	477	31.6
36	0.9	0.7	0.3	26	75.0	31.3	3309	1.59	402	10.2	73	71.5	44.0	3194	2.04	477	32.7
37	0.9	0.7	0.2	26	75.1	32.1	3149	1.56	402	6.9	73	71.4	43.7	3254	2.05	477	34.0
38	0.9	0.6	0.5	24	81.3	29.2	1719	1.59	345	16.7	75	69.6	44.8	3788	2.04	498	30.3
39	0.8	1	1	21	97.6	43.7	5355	1.33	544	30.2	78	65.6	39.3	2372	2.16	422	25.1
40	0.8	1	0.9	21	97.5	43.7	5357	1.34	539	29.2	78	65.6	39.3	2373	2.15	423	25.6
41	0.8	1	0.8	22	93.1	43.3	5308	1.34	538	26.1	77	66.5	39.5	2391	2.15	424	26.8
42	0.8	1	0.7	22	93.2	43.8	5282	1.34	539	22.8	77	66.5	39.3	2401	2.15	423	28.1
43	0.8	1	0.6	23	89.1	44.4	5229	1.35	543	19.5	76	67.3	39.0	2422	2.15	422	29.4
44	0.8	1	0.5	23	88.9	42.5	5154	1.34	527	16.4	76	67.4	39.8	2456	2.15	429	30.7
45	0.8	1	0.4	23	88.4	41.8	5009	1.34	517	13.2	76	67.6	40.1	2518	2.15	433	31.9
46	0.8	0.9	0.8	21	92.9	41.0	5238	1.40	517	26.6	78	66.9	40.4	2472	2.11	434	26.6
47	0.8	0.9	0.7	23	84.9	40.8	5218	1.42	517	23.3	76	68.6	40.5	2479	2.11	434	27.8
48	0.8	0.9	0.6	22	88.6	40.5	5220	1.41	517	19.2	77	67.8	40.6	2480	2.11	434	29.4
49	0.8	0.9	0.5	23	86.0	39.9	5095	1.38	510	16.6	76	68.3	40.8	2512	2.12	436	30.4
50	0.8	0.9	0.4	22	89.2	41.1	5055	1.31	514	13.6	77	67.6	40.4	2535	2.15	435	31.5

Notes: S = Solution id; B = Biodiversity; G = GHG emissions; W = Water emissions; N = Number of sites; Size = Average size of sites (ha); Time = Average production time of sites (years); NPV = Average NPV/ha of sites; Average Biodiversity (B)/ha * 100, GHG emissions (G)/ha * 100, and Water emissions (W)/ha * 100. The averages are weighted by the size of the site.

regional and local levels of planning remains poor and the bridge between research and decision making is yet to be built (e.g., Rall et al., 2015; Tammi et al., 2017). Finally, the study presents an ideal example of how available environmental spatial data can be used in a comprehensive manner to generate long-term model predictions that effectively track the dynamics of trade-offs between BES and capture their spatial variability (Schröter et al., 2015).

Our results show that despite trade-offs between economic returns and BES there are ways to improve environmental performance through careful planning of land-use without imposing large costs. For example, reduction in Water emissions by 20% with a concurrent decrease in Biodiversity loss by 20% relative to the benchmark levels reduced NPV of peat production by only 2.6%. These results are similar to previous studies in which relatively high environmental benefits were achieved

with a low reduction in economic returns. For example, Pennington et al. (2017) showed that reorganizing land-use and land management reduced the baseline phosphorus loads due to agricultural runoff by 20% and sediment loads by 18% without any reduction in the annual net returns from agriculture.

On the other hand, our results also show that considerable reductions in Biodiversity loss and Water emissions increased costs significantly. For example, 30% reduction in Biodiversity loss concurrently with 70% reduction in Water emissions (and 30% reduction in GHG emissions) reduced NPV of peat production by 49% from the benchmark level. This was also found by Triviño et al. (2015) who examined joint timber production and carbon storage: the first increments in carbon storage or sequestration from an optimal timber production level were inexpensive, but further efforts in carbon sequestration

increased the costs considerably. Typically, the more ambitious are the objectives of biodiversity conservation and those of regulating and cultural services, the more the net returns from provisioning services are reduced, and vice-versa (Nelson et al., 2009; Gascoigne et al., 2011; Pennington et al., 2017). In our case, restricting the total area of peat production to 2000 ha further reduced the possibility of avoiding negative BES impacts, as no less than 2000 ha could be allocated to peat production no matter how detrimental the BES impacts. Thus, there was a limit to what could be accomplished with the given area restriction and without significant reductions in the net returns from peat production. Hence, the land-use planner should note that when selecting valuable BES sites for peat production in the master plan, the profitability of peat production is reduced significantly and many of the selected sites will eventually not be used for peat production.

Unlike Biodiversity loss and Water emissions, reduction in GHG emissions decreased NPV linearly, without any threshold. In addition, the possibility to avoid harmful environmental impacts of peat production was significantly lower for GHG emissions than Biodiversity or Water emissions. GHG emissions are unavoidable when peat is burned. GHG emissions are governed by the volume of peat, which typically increases with the size of production site. These features cause challenges in reducing GHG emissions when peat production and burning is allowed.

Earlier life-cycle analyses on peat production in boreal peatlands (Kirkinen et al., 2007; Väisänen et al., 2013) have shown that GHG emissions can be reduced efficiently by site allocation. When the emissions from the current land-use are high, such as peatlands drained for agriculture, allocating peat production to those sites could have potential for emission reductions. However, only a few percent of peatlands are under agriculture in Finland (Päivänen and Hännel, 2012). This was also observed in this study: only 10 of the 99 studied sites had greater agricultural peatland coverage than 10%. In forestry-drained peatlands, such as the majority of the sites in our study, high levels of GHG emissions are exceptional (Ojanen et al., 2013). Hence, allocation of peat production to high-emissions sites may, after all, have very limited use in reducing GHG emissions.

From the above discussion a question arises, whether it is reasonable to use GHG emissions as an environmental criterion in the allocation of potential energy peat production sites. GHG emissions reduction as an objective in land-use planning will undermine the profitability of potential peat production. Hence, when peat production is allowed as a land-use option in the first place, it may not be cost-efficient to restrict the associated GHG emissions through land-use planning. A better option may be to use the prevailing policy instruments, such as national energy taxes and the EU Emission Trading System, to control fuel prices and let the energy market determine the demand for alternative fuels. In our case, there was a given area requirement, 2000 ha, for land-use planning, but the demand for peat will eventually determine the area taken into production.

Water quality is an important local environmental issue related to many land-use and land-management decisions (e.g., Polasky et al., 2011; Kennedy et al., 2016; Pennington et al., 2017). Water quality has also been observed to be a significant factor in explaining variations in people's preferences for alternative uses of peatlands (Tolvanen et al., 2013). Our results showed that there are two ways to cost-efficiently reduce Water emissions through land-use planning. First, reduction can be obtained by allocating potential peat production sites to agricultural peatlands with typically high water emissions. Owing to the small area of agricultural peatlands, this is again not an efficient means of decreasing emissions on a large-scale. The second option would be to allocate peat production to those peatland forests where Water emissions are high. However, this is also not a very straightforward means to decrease emissions, since, whereas phosphorus exports are generally higher from low-productivity peatlands (Nieminen, 2003; Kaila et al., 2014), carbon and nitrogen exports are highest from fertile peatland sites (Nieminen, 2004; Kaila et al., 2015). Due to high variation in the

effects of forest management on water quality, comparison of Water emissions between peat production and forest management is very site specific (see Supplement 3 for details).

Reduction in Biodiversity loss had little impact on GHG and Water emissions. The reason may lie in the site characteristics of potential peat production sites. An important criterion for site selection was a thick peat layer, which is generally associated with sites of low vegetation diversity (Laine et al., 1995). The number of threatened species, one of the criteria producing the Biodiversity loss value, was also low at these sites. The overall low biodiversity indicates that there was little potential to decrease Biodiversity loss through the selection of peat production sites, as was also revealed in the Pareto-optimal solutions.

Another reason for low synergy between Biodiversity loss and GHG and Water emissions may be that, unlike GHG and Water emissions, Biodiversity loss was not directly linked to the size of the site or peat production time. There was an indirect linkage, however, as our variables producing Biodiversity loss value, such as number of mire complex types, habitat types and geomorphological formations, are likely linked to the size of the site. The fact that the area size had minor effect in our study is again probably because our peatland sites were relatively homogeneous and naturally species-poor ecosystems. Nevertheless, although Biodiversity loss was calculated in a policy relevant manner using similar criteria as used nationally and in former regional master planning, it is clear that some of the effect of area size on biodiversity was lost. A subject of further research is therefore how the size of site affects its biodiversity value.

Unlike Biodiversity loss, GHG and Water emissions were calculated on per size of the site and peat production time basis, which apparently explains their strong synergy. Previous studies have applied varying practices regarding the effect of size of sites on ecosystem service provision. In Nelson et al. (2009), biodiversity value (the potential for habitats to support a suite of vertebrate animals) was dependent on the area of suitable habitats, and many other ecosystem services were also linked to the area.

Multi-objective optimization provides a systematic approach to explicitly examine trade-offs between BES and economic returns for land-use planning. However, quantification of ecosystem services for the multi-objective optimization and for methods assessing trade-offs in ecosystem services involves many uncertainties (Cavander-Bares et al., 2015). Further research to test and validate model predictions that are utilized in the optimization is needed to reduce these uncertainties. For example, impacts of peat quality on GHG and Water emissions, the differences in environmental loading between sites and geographical regions, and the impacts of climate change on BES need further research. In addition, there are challenges to estimate economic returns because production costs are private information and are not directly measurable by researchers (Armstrong et al., 2012).

Despite the uncertainties involved in multi-objective optimization, our analyses showed that it produces useful estimates of the economic and environmental outcomes of alternative land-uses, thereby providing meaningful information to decision makers. In the selection of potential peat production sites, the local land-use planner may avoid significant negative environmental impacts, but must take into account that all objectives may not be achieved simultaneously. Hence, prioritizing the objectives is necessary, and for that purpose the method can be developed further. An interesting avenue for future research could be to incorporate benefit-relevant indicators (Olander et al., 2017) or social values (Glenk et al., 2014; Pennington et al., 2017) into the optimization framework to achieve a deeper understanding of both the ecological supply and the social demand for the BES.

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Appendix A. Supplementary data

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