Framework for systematic indicator selection to assess effects of land management on ecosystem services

Alexander P.E. van Oudenhoven\textsuperscript{a,*,1}, Katalin Petz\textsuperscript{a,1}, Rob Alkemade\textsuperscript{b}, Lars Hein\textsuperscript{a}, Rudolf S. de Groot\textsuperscript{a}

\textsuperscript{a} Environmental Systems Analysis Group, Wageningen University, PO Box 47, 6700 AA Wageningen, The Netherlands
\textsuperscript{b} Netherlands Environmental Assessment Agency (PBL), PO Box 303, 3720 AH Bilthoven, The Netherlands

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\section*{A B S T R A C T}

Land management is an important factor that affects ecosystem services provision. However, interactions between land management, ecological processes and ecosystem service provision are still not fully understood. Indicators can help to better understand these interactions and provide information for policy-makers to prioritise land management interventions. In this paper, we develop a framework for the systematic selection of indicators, to assess the link between land management and ecosystem services provision in a spatially explicit manner. Our framework distinguishes between ecosystem properties, ecosystem functions, and ecosystem services. We tested the framework in a case study in The Netherlands. For the case study, we identified 12 property indicators, 9 function indicators and 9 service indicators. The indicators were used to examine the effect of land management on food provision, air quality regulation and recreation opportunities. Land management was found to not only affect ecosystem properties, but also ecosystem functions and services directly. Several criteria were used to evaluate the usefulness of the selected indicators, including scalability, sensitivity to land management change, spatial explicitness, and portability. The results show that the proposed framework can be used to determine quantitative links between indicators, so that land management effects on ecosystem services provision can be modelled in a spatially explicit manner.

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1. Introduction

Ecosystems provide humans with numerous benefits, such as clean water, medicines, food, and opportunities for recreation. The Millennium Ecosystem Assessment (MA, 2005) highlighted the importance of these ecosystem services for sustaining human well-being. The Economics of Ecosystems and Biodiversity study (TEEB, 2010) provided insight in the economic significance of ecosystems. As a result, the ecosystem services concept has now gained importance at the policy level, illustrated by the establishment of the International science-policy Platform on Biodiversity and Ecosystem Services (IPBES), and the incorporation of ecosystem services in the 2020 targets set by the 10th Conference of Parties to the Convention on Biological Diversity (Larigauderie and Mooney, 2010; Mace et al., 2010).

Policy and environmental planning decisions largely influence how land is being managed (Fisher et al., 2008; Carpenter et al., 2009; von Haaren and Albert, 2011). On a regional scale, land management is one of the most important factors that influence the provision of ecosystem services (Ceschia et al., 2010; Fürst et al., 2010b; Otieno et al., 2011). Land management is defined by the presence of human activities, that affects land cover directly or indirectly (Kremen et al., 2007; Olson and Wäckers, 2007; Verburg et al., 2009). It comprises ecosystem exploitation, land use management, and also includes ecosystem management (Brussard et al., 1998; Bennett et al., 2009). Land management refers to human activities; land cover to the biotic and abiotic components of the landscape, e.g. natural vegetation, forest, cropland, water, and human structures (Verburg et al., 2009). Land use refers to the purpose of human activities which make use of natural resources, thereby impacting ecological processes and functioning (Veldkamp and Fresco, 1996). Land management includes but does not equal ecosystem management, because it refers to managing an area so that ecological services and biological resources are conserved, while sustaining human use (Brussard et al., 1998; MA, 2005). Examples of land management include irrigation schemes, tillage, pesticide use, nature protection and restoration. (Follett, 2001; Bennett et al., 2009; Blignaut et al., 2010; Carvalho-Ribeiro et al., 2010; Ngugi et al., 2011).

The analysis of ecosystem services to support land management decisions faces a number of challenges. They include: (1) identifying comprehensive indicators to measure the capacity of
ecosystems to provide services; (2) dealing with the complex dynamics of the link between land management and ecosystem services provision; (3) quantifying and modelling the provision of ecosystem services by linking ecological processes with ecosystem services; and (4) accounting for the multiple spatial and temporal scales of ecological processes and ecosystem services provision (Turner and Daily, 2008; Carpenter et al., 2009; van Strien et al., 2009; Villa et al., 2009; De Groot et al., 2010b; Bastian et al., 2012).

Given these challenges, it is necessary to have a consistent and comprehensive framework for analysing ecosystem services (Ostrom, 2009; Posthumus et al., 2010). A framework provides structure to the research and enables better validation of its outcomes (Boockettler and Girardin, 2003; Niemi and McDonald, 2004). Furthermore, it is important to formulate a comprehensive set of indicators (Niemeijer and de Groot, 2008; Layke et al., in press) that enables the assessment of land management effects on ecosystem services provision, on different spatial scales (Carpenter et al., 2009; van Strien et al., 2009; De Groot et al., 2010b). With indicators, policy-makers and land managers can be provided with information, based upon which interventions can be identified, prioritised and executed (OECD, 2001; Layke, 2009). Finally, there is a need to test how ecosystem services frameworks can be used for the selection of indicators (Nelson et al., 2009).

The objective of our study was, therefore, to systematically select indicators which can be used to analyse the link between land management and the provision of ecosystem services at multiple scales. To achieve this objective we developed a consistent framework for indicator selection which builds on existing frameworks, in particular by TEEB (De Groot et al., 2010a) and Haines-Young and Potschin (2010).

We first describe our framework and how it can be used for indicator selection. Then we apply it to a case study to assess the effect of land management on ecosystem services provision. Characteristics of and interactions between indicators were studied, and all indicators were evaluated based on a selected set of criteria. The case study was done in a multifunctional rural landscape in the southern part of the Netherlands, where multiple ecosystem services are provided across different spatial scales.

2. Methods

2.1. Framework

Consistent and comprehensive frameworks that link human society and economy to biophysical entities, and include impacts of policy decisions, have been developed during the last decades. For the analysis of ecosystem services such a framework was developed in the context the Millennium Ecosystem Assessment (MA, 2003), which was itself based on a Driver, Pressure, State, Impact Response framework. We adapted the frameworks by TEEB (De Groot et al., 2010a) and Haines-Young and Potschin (2010) for indicator selection. These frameworks are among the most recent and comprehensive ecosystem services assessment frameworks. The TEEB framework explains the link between biodiversity, ecosystem services and human well-being (De Groot et al., 2010a) and builds on several recent studies (MA, 2003; Braat et al., 2008; Fisher et al., 2008, 2009). The TEEB-study calls for the development of indicators for the economic consequences of biodiversity and land use change (De Groot et al., 2010a; Reyers et al., 2010). The stepwise so-called “cascade-model” by Haines-Young and Potschin (2010) is useful for assessing the provision of ecosystem services in a structured way, linking ecosystem properties to functions and services. Although the importance of land management is acknowledged in (descriptions of) both frameworks, land management is not explicitly included. We therefore adapted the framework by including land management, which enables the selection of indicators for assessing the effects of land management and ecosystem services.

Fig. 1 shows the main elements of our framework: the driving forces, ecosystem, service provision, human well-being, and societal response. The scope of our study is indicated by the white boxes in Fig. 1: land management, ecosystem properties, function and service. Unless stated otherwise, definitions and relations provided are based on or adapted from the TEEB-study (De Groot et al., 2010a). In the framework we use the term “ecosystem”. We note, however, that the interactions which we describe below can refer to ecosystems at multiple spatial scales, e.g. at plot, landscape, regional or even national scale (Hein et al., 2006).

Drivers or driving forces are natural or human-induced factors which can influence the ecosystem, either directly (e.g. through climate change or environmental pollution) or indirectly (e.g. through changes in demography or economy) (MA, 2005). Although drivers such as climate change or environmental pollution also have an impact on the ecosystem, we focus in our assessment on the driving force ‘land management’. As described earlier, land management refers to the human activities that can affect ecosystem properties and function (Kremen et al., 2007; Bastian et al., 2012; Chen et al., 2011), as well as the ecosystem service that can be provided (O’Farrell et al., 2007; Edwards et al., 2011). Ecosystem properties are the set of ecological conditions, processes and structures that determine whether an ecosystem service can be provided. Examples include net primary productivity (NPP), vegetation cover, and soil moisture content (Johnson et al., 2002; Kienast et al., 2009). Ecosystem properties underpin ecosystem functions, which are the ecosystem’s capacity to provide the ecosystem service (De Groot et al., 2010a). An ecosystem function, or “potential” (Bastian et al., 2012), is the subset of ecosystem properties which indicates to what extent an ecosystem service can be provided. Examples of ecosystem functions include capturing of aerosols by vegetation (Nowak et al., 2006) and carbon sequestration (Diaz et al., 2009). The ecosystem service contributes to human well-being, for example cleaner air and reduced climate change. The benefit is the socio-cultural or economical welfare gain provided through the ecosystem service, such as health, employment and income. Finally, actors in society can attach a value to these benefits. Value is most commonly defined as the contribution of ecosystem services to goals, objectives or conditions that are specified by a user (Costanza, 2000; Farber et al., 2002). The value perception can cause changes in policy and decision making, for instance when certain services or resources are not available or too expensive. Alternatively, value perception can influence the ecosystem service value, for instance through increasing demand for a certain product. Policy and decision making form preconditions, constraints and incentives for land management and other drivers (Daily et al., 2009; Fisher et al., 2009).

2.2. Indicator selection and evaluation

To operationalise the framework for indicator selection, it is important to select indicators that provide accurate information on all main aspects of ecosystem services provision: land management, ecosystem properties, function, and service (Fig. 1). To be able to evaluate the usefulness of indicators for our purpose, we compiled a set of criteria. First, we assembled general criteria for indicators, based on information from ecological assessments. We found that the selection process of indicators should be flexible and consistent, and that indicators should be comprehensive and understandable to multiple types of end users. A flexible, yet consistent selection process implies that multiple frameworks can be used, depending on the scope and aim of the assessment (Niemeijer and de Groot, 2008). A test for comprehensiveness evaluates whether the whole set of indicators would provide
complete and consistent information, which relates to the specific research question (Niemi and McDonald, 2004). Considering that information should be communicated among scientists and other stakeholders, indicators should be clear and understandable in order to be useful to these multiple end users (Niemeyer and de Groot, 2008; UNEP-WCMC, 2011).

We also compiled criteria which were more appropriate for indicators for ecosystem services. We found that indicators need to be sensitive to (changes in) land management, temporally and spatially explicit, scalable, and quantifiable. These criteria apply both to individual indicators as well as sets of indicators and ensure that the indicators can be used for quantification and modelling purposes. Furthermore, indicators should provide information about causal relationships between land management and changes in ecosystem properties and function (Riley, 2000; De Groot et al., 2010b). Temporal and spatial explicitness refers to whether trends can be measured and mapped over time, and whether relations between indicators can be linked to specific locations, for instance through mapping and GIS analyses (NRC, 2000). An indicator is considered scalable if it could be aggregated or disaggregated to different scale levels, without losing the sense of the indicator (Hein et al., 2006). Quantifiable indicators ensure that information can be compared easily and objectively (Schomaker, 1997; Layke et al., in press).

Finally, we considered data availability, credibility, and portability as other criteria. Data availability is especially essential if information are compared among different studies (Layke et al., in press). Indicators should also provide credible information. This criterion tests whether indicators actually convey reliable information (Layke et al., in press). Portability refers to the question whether indicators are repeatable and reproducible in other studies, and across different regions (Riley, 2000).

2.3. Case study: indicator selection and evaluation for “Het Groene Woud”, The Netherlands

We applied the framework for the selection of indicators for nine ecosystem services in a rural area in the south of The Netherlands (Box 1 and Fig. 2). First, we focused on interactions between indicators for ecosystem properties, function and service. Secondly, we assessed the effect of land management on the provision of three ecosystem services. For both steps of the case study, we evaluated the indicators using the criteria as introduced in Section 2.2.

2.3.1. Indicator selection for ecosystem properties, function and service

We made an inventory of ecosystem services provided in Het Groene Woud, and of the indicators that describe these services or describe relevant properties. For this, we conducted expert interviews and consulted scientific literature, policy documents, reports from local projects and organisations, brochures, and websites. The typology of the TEEB study (De Groot et al., 2010a) was used to categorise the ecosystem services. The selected ecosystem service types are listed below, with the specific service for the study area between parentheses: food provision (milk production), air quality regulation (fine dust capture), climate regulation (carbon sequestration), regulation of water flows (water retention), biological control (protection from pest insects), opportunities for recreation and tourism (walking), lifecycle maintenance (refuge for migratory birds), aesthetic information (green residential areas), and information for cognitive development (research and education).

We selected indicators of ecosystem properties, function and service for each selected ecosystem service, and determined qualitative relations between them. Examples of these qualitative relations include if and how vegetation characteristics affect water retention and fine dust capture, or relations between carbon stored in vegetation and change in atmospheric CO2 concentration. If insufficient information was available on the provision of ecosystem services in the area, we consulted literature on similar services in other case study areas. Examples include air quality studies in other areas in The Netherlands (Wesseling et al., 2008) and in the UK, such as Glasgow (Beale et al., 2007) and east England (Beckett et al., 2000).
2.3.2. Linking indicators for land management and ecosystem service provision

To analyse the relation between land management and ecosystem service provision, we studied three services in detail: milk production, fine dust capture, and opportunities for recreation. For each service, we focused on the role of land management factors as well as relations (including feedbacks) between ecosystem properties, function and service. These relations were also determined qualitatively. There were several reasons for analysing three instead of all nine services. We considered it important to study an example of each of a provisioning, regulating and cultural service, to test whether the framework would enable the selection of an appropriate set of indicators for different ecosystem service categories. Moreover, the three services were identified as of key importance in the area (Blom-Zandstra et al., 2010; Het Groene Woud, 2011). In addition, fine dust capture by vegetation is an understudied ecosystem service (Nowak et al., 2006), yet considered highly relevant in The Netherlands (Velders et al., 2007; Wesseling et al., 2008; Hein, 2010).

After selecting indicators with management relevance, we studied how these could be linked to indicators for ecosystem properties, function and service. In addition, we looked at their spatial scales and also mapped the function indicators in order to spatially visualise the potential of the area for providing the service. We distinguished between landscape element, plot and landscape scale. We considered landscape elements such as individual trees, bushes, treelines or other physical structures of less than 1 km² that could be studied in isolation from the landscape (Grashof-Bokdam et al., 2009; Krewenka et al., in press); we assumed plot scale to correspond with patches of land cover (e.g. forest or grassland) with a size of 1–10 km²; and the entire study area (350 km²) was assumed to be representative of landscape scale.

3. Results

3.1. Indicators for provision of multiple ecosystem services

Relevant indicators for the provision of nine ecosystem services in Het Groene Woud were selected. These ecosystem services were: milk production, fine dust capture, carbon sequestration, water retention, protection from pest insects, refuge for migratory species, green residential areas, opportunities for walking, and research and education. We identified 12 key indicators for ecosystem properties, nine for functions, and also nine for service provision. An overview of these indicators is presented in Fig. 3.

Indicators for ecosystem properties were grouped into five categories, of which three are described as “natural properties” (soil, water, flora and fauna) and two as indicating “human presence” (land cover and landscape structure, and infrastructure). Examples of these human presence indicators include the degree of naturalness (also a measure of urbanisation), noise level (mainly caused by traffic), and number and extent of milk farms. Function indicators were divided into four categories, in line with the ecosystem functions typology by De Groot et al. (2002) and as also used by Kienast et al. (2009). Function indicators refer to ecosystem’s capacity to provide a service, e.g. amount of water stored in vegetation, fine dust captured by vegetation, and the walking suitability of an area. Service performance indicators were grouped in accordance with the typology of the TEEB-study (De
Groot et al., 2010a). These indicators refer to the actual service provision or use from which people benefit. Examples include milk production, change in ground water level, change in atmospheric fine dust concentration, and the number of walkers in an area.

The number of ecosystem property indicators was highest. All functions depend on land cover and landscape structure, whereas vegetation characteristics influence all but the information and cultural functions. Indicators for ecosystem functions were found to depend on a large number of ecosystem properties and corresponding indicators. Indicators for regulating and habitat functions could be linked to many ecosystem property indicators: water stored in vegetation to most (eight), followed by carbon stored in vegetation (six), fine dust captured by vegetation (four), and natural predators abundance (four). We assigned one service indicator to each ecosystem function indicator. Therefore the number of service indicators corresponds with the number of function indicators.

3.2. Effects of land management on ecosystem properties, function and service: example for three ecosystem services

3.2.1. Food production: milk production

Management for milk production affects ecosystem properties, function and service provision (Fig. 4). Application of pesticides and...
nutrients, the first land management indicator in Fig. 4, influences several ecosystem properties. For instance, the net primary productivity (NPP) of grass can be enhanced by applying fertilizers (Jangid et al., 2008; Batáry et al., 2010). Veterinarian measures can influence the cows’ milk producing capacity through disease prevention and additional feeding. Mechanisation can affect the area of grassland and farm size that is required for milk production. Moreover, mechanisation can alter the grassland’s properties through mowing; the milk producing capacity of the cows through more efficient feeding; and the milk production through mechanised milking.

The number of milk cows (function indicator) is not only influenced by management, but also by ecosystem properties. The land cover type as well as the size and number of milk farms influence how many cows can graze on how much land. Milk production is influenced by the cows’ characteristics and NPP of grass influence, which in turn also determines the required grassland area. The milk production (service indicator) is directly related to the number of cows. However, milk production can also influence the ecosystem function and properties. For instance, if the (targeted) milk production is too high, the number of cows and the area of grassland would have to be altered. This would require either more nutrient application and mechanisation, an increase in the number of cows or area of grassland, or lowering of the milk production.

The service milk production is provided on grassland, which at the moment covers about 60% of the study area (Fig. 5). The highest numbers of cows (function indicator) are kept in the north-west, south and east, but these numbers are evenly distributed over the area. The actual service performance can be measured on plot (grassland) and landscape (entire area) scale, as its spatial pattern follows the allocation of the grassland across the landscape. Only a few parts of the area are at the moment not used for milk production. They include forest patches and urbanised areas.

3.2.2. Air quality regulation: fine dust capture

The key management action that influences the fine dust concentration involves selecting the location and planting (species choice) as well as maintaining forest plots and woody elements (Beckett et al., 2000; Oosterbaan et al., 2006; McDonald et al., 2007). Woody elements are forest patches and tree rows. For example, on a yearly basis coniferous tree species can capture twice as much fine dust as deciduous tree species (Oosterbaan et al., 2009). Vegetation characteristics such as leaf area and hairiness determine the deposition speed onto and therefore the capture of fine dust by vegetation (Beckett et al., 2000; Oosterbaan et al., 2009). Spatial planning is important because the distance between woody elements and fine dust emission sources (such as roads, intensive agriculture, and cities) determines the woody elements’ capacity to capture fine dust (function indicator) (Tonneijck and Swaagstra, 2006) (Fig. 6).

Intensive agriculture together with traffic are the main fine dust emission sources in the Groene Woud (Oosterbaan et al., 2009). Local emission directly influences the amount of fine dust that can be captured by vegetation (Nowak and Crane, 2000; Nowak et al., 2006), and naturally causes a change in atmospheric fine dust concentration (service indicator). On locations where concentrations are higher, e.g. “point sources” such as pork stables, vegetation can capture more fine dust than on other locations. The amount of fine dust captured by vegetation (function indicator) results in a change in atmospheric fine dust concentration (service).

There are large differences in capacity of land cover types to capture fine dust, and therefore deciding on the location and extent of land cover can have a large influence on fine dust concentration. Forests and woody elements have a higher capacity to capture fine dust than all other types of land cover. Moreover, adding or maintaining woody elements can further increase the area’s total capacity, as is shown in Fig. 7. Fine dust capture can be measured on the landscape element (e.g. treerows), plot (forest patch) and
Fig. 6. Framework with indicators for land management, ecosystem properties, function, and service, for the regulating service fine dust capture. Solid arrows indicate direct linkages between the boxes; the dashed line indicates feedback.

landscape scale (entire area). Fig. 7 shows the spatial pattern of woody elements and forest plots across the landscape in the Groene Woud area. It can be seen that all areas except those with urban infrastructure (white on the map) contribute to the capture of fine dust in the area.

3.2.3. Opportunities for recreation: walking

Managing the Groene Woud area, to improve walking opportunities, influences the area’s ecosystem properties and functions. Developing and maintaining nature reserves, parks and green areas influences the area’s degree of naturalness. It can also increase the length of walking tracks and the accessibility (Goossen and Langers, 2000). Protecting and maintaining historical landscape elements improves the historical distinctiveness of the area (Edwards et al., 2011; Het Groene Woud, 2011). Finally, improving the accessibility of rural landscapes and nature areas determines whether walkers can actually visit the areas (De Vries et al., 2007). Many walkers prefer to visit locations where parking space, route indication, walking routes and information boards are available (Goossen and Langers, 2000; De Vries et al., 2007) (Fig. 8).

The area’s suitability for walking (function indicator) can be improved by designating separate areas for walking. However, the suitability mainly depends on the area’s properties, such as land cover preference, accessibility, the length of walking tracks, the naturalness, the noise level and the presence of historic elements in the area (Goossen et al., 1997). Land cover types that are preferred by walkers are forest or heath land over arable land, grassland or urban areas (Goossen and Langers, 2000). The diversity of land cover is
also highly appreciated by walkers (van den Berg et al., 1998; De Vries et al., 2004).

The actual service performance can be measured by the number of walkers (service indicator), which is directly related to the walking suitability. Naturally, an area with higher suitability is more likely to attract larger numbers of walkers (Goossen and Langers, 2000; De Vries et al., 2004). At the same time, too many walkers can influence the function and properties, for instance through increased noise level and loss of naturalness (van den Berg et al., 1998). Forest and areas with high land cover diversity are preferred the most for walking (Fig. 9). This land cover preference (property indicators) can be measured on plot (e.g. forest patch) and landscape (entire region) scale. The map also indicates the distance from cities to potential walking areas. The majority of the area is either highly suitable or not suitable at all for walking.

4. Discussion

4.1. Methods: framework & indicator selection

In this paper we have presented a framework to analyse effects of land management on ecosystem services. The framework elements (driving forces, ecosystem, service provision, human well-being and societal response) basically follow the DPSIR approach (Driving forces, Pressure, State, Impact, Response), which was also used by Braat et al. (2008), Niemeijer and de Groot (2008), Layke (2009), and others. However, our framework enables the assessment of how land management can affect ecosystems (“State”), and their services and human well-being (“Impact”). These are two subjects of which the assessment faces most scientific challenges (ICSU et al., 2008; Carpenter et al., 2009).
To clarify the distinction between “state” and “impact”, Kienast et al. (2009) adapted the “cascade model” from Haines-Young and Potschin (2010) and defined the meaning of the terms “landscape function” and “ecosystem services”. The stepwise “cascade-model” was also referred to by Bastian et al. (2012) and De Groot et al. (2010a,b) but to our knowledge, the framework we present is a first actual application focused on the biophysical aspects and underlying management effects that matter for the provision of ecosystem services. Our framework enables this analysis in a structured and stepwise manner, avoiding the confusion between ecosystem properties, functions and services and thereby also avoiding double-counting (Bateman et al., 2011). This specification is essential to link ecosystem service assessments to valuation studies (Farber et al., 2006). Some remaining challenges are briefly described below.

Flexibility and comprehensiveness
Ecosystem assessment frameworks should be flexible enough to be modified in line with the aim of the assessment (De Bello et al., 2009; Czucz et al., 2011). Many studies have been carried out on impacts of land use on ecosystem services provision (Schröter et al., 2005; Fürst et al., 2010a; Barral and Oscar, 2012; Richert et al., in press) and on policy and land use planning in relation to ecosystem services (van Meijl et al. (2006), Fisher and Turner (2008), and Fürst et al. (2011)). Incorporating their findings into the framework would be an important next step to make it more comprehensive. Specifying more detailed relationships between policy and other drivers would also allow for a more complete ecosystem services assessment.

Quantification of indicators
Establishing causal relationships is an import factor, when seeking to improve more accurate quantitative relationships (Lin et al., 2009). Our framework can help to determine quantitative relationships between the various steps of service provisioning, e.g. how does ecosystem functioning depend on ecosystem properties, how do ecosystem functions provide ecosystem services, and how to measure the benefits derived from ecosystem services? Quantified relationships could also provide input for more reliable and accurate mapping, modelling, and valuing of ecosystem services (Syrbe and Walz, 2012; Burkhard et al., 2012).

Practical applicability
Indicators are important to understand how ecosystem services are provided, through both qualitative and quantitative links between the different steps. Initiatives like the Biodiversity Indicators Partnership (BIP) and the World Resources Institute (WRI) ecosystem services indicators database (Layke, 2009), as well as studies by Fisher et al. (2009) and others offer examples of frameworks for indicator selection and sets of ecosystem services indicators. However, practical guidelines to select multiple appropriate indicators, that can be used to both quantify and model ecosystem services provision, are still lacking (ICSU et al., 2008; UNEP-WCMC, 2011). A lack of robust procedures and guidelines for selecting indicators could decrease the validity of the information by the indicators (Dale and Beyeler, 2001).

The criteria we used to evaluate indicators for land management and ecosystem services provision can be seen as a first step towards a more streamlined indicator selection procedure for ecosystem services. Many criteria stemmed from ecology studies (Dale and Beyeler, 2001; Lin et al., 2009), but also recent studies that focused more strongly on ecosystem services provided us with useful criteria (e.g. UNEP-WCMC, 2011; Layke et al., in press). The twelve criteria could be divided into criteria that help evaluating the indicator selection process, the practical aspects of ecosystem service assessments, the indicators’ ability to convey information, and causal links between indicators.

4.2. Case study: applying the framework
In the first part of the case study, the complex relationships between ecosystem properties, functions and services were investigated. Each property indicator could be linked to several ecosystem functions which shows the fundamental role of ecosystem properties in the provision of multiple ecosystem services. The indicators provided a comprehensive overview of the biophysical state and structural characteristics of the study area.

Function indicators proved to be a subset or combination of ecosystem property indicators, as was earlier suggested by Kienast et al. (2009). Function indicators were more specific than property indicators and corresponded to only one specific service indicator. Although function indicators generally provide information about service potentials, they were rarely similar to service indicators. However, they often had corresponding units. Property and function indicators, also called state indicators, provide information on how much of a service an ecosystem can potentially provide in a sustainable manner (Layke, 2009; De Groot et al., 2010b). Service indicators, also called performance indicators, provide information on how much of the service is actually provided and/or used (Fisher and Turner, 2008; Layke, 2009; De Groot et al., 2010b). For ecosystem services assessments, be it quantitative, mapping or modelling studies, it would be commendable to select at least one state and one performance indicator per studied ecosystem service (UNEP-WCMC, 2011). It is also important to make the distinction between indicators for ecosystem function and for service.

Applying the framework to three dissimilar services (i.e. food provision, air quality regulation and recreation) illustrated that the linkages, including feedbacks, differ strongly per ecosystem service. Indicators for land management related to land cover, nature protection, application of pesticides and mechanisation, among others. Interestingly enough, they also included indicators that go beyond “traditional” ecosystem management (Grumbine, 1994). Results showed that land management can affect ecosystem services directly (food provision and air quality regulation) or indirectly through ecosystem properties and functions (air quality regulation and recreation). This underlines the importance of management (input) and the relatively smaller contribution of nature’s capacity in the case of food production. Moreover, management aimed at a certain function or service could have feedbacks on the properties that are fundamental for the provision of other services as well. Applying the framework and mapping the function or property indicators enabled us to see at which spatial scale services were provided and, additionally, at which spatial scale land management could affect the provision of these services. The consideration of multiple scales is important not only because service provision can occur at several scales, but also because the level of service provisioning and decision making might differ (Hein et al., 2006; Daily et al., 2009; Seppelt et al., 2012). The selected indicators could be linked to landscape element, plot, and landscape scale. Results showed that property indicators and some function indicators could be linked to all three scales, whereas some function and all service indicators could only be linked to plot and landscape scale.

Our criteria can be used as guidelines to select and evaluate indicators. The evaluation of the indicators can be seen in Table 1. Although we did not test the indicators for usefulness to multiple end-users, quantification and modelling, and portability, we conclude that the selection procedure was sufficiently flexible and allowed for the selection of a consistent set of comprehensive
indicators. Although some indicators (e.g. refuge for migratory species) were difficult to link to land management, the large majority was sensitive to changes in land management. All function indicators were or could be made temporally and spatially explicit, and many could be linked to one or more of the three spatial scales. The amount of available literature and other information implies that most indicators are credible, i.e. provide reliable information. In general, indicators for ecosystem properties were found to be most difficult to fully comprehend and utilise, because fewer criteria were met. Especially habitat and cultural functions met only a few criteria. It can be expected that such indicators, will be difficult to utilise in ecosystem service assessments and mapping and modelling exercises.

Perhaps an important criterion to further develop would be one that focuses on evaluating whether an indicator would be suitable as a property, function or service indicator. This would facilitate the selection of more universally accepted indicators. The set of indicators presented here, as well as the maps, could provide local decision-makers with useful information when developing regional management plans. Although the case study yielded indicators that could be relevant for other ecosystem services assessments, we point out that the indicators we found were specific to the area’s policy needs, socio-economic situation and spatial configuration.

5. Conclusion

This paper describes a framework to select indicators to assess effects of land management on the provision of ecosystem services. The framework was tested in the Groene Woud area, a multifunctional landscape in the Netherlands. Our framework explicitly relates land management to ecosystem properties, functions and services. For the nine studied ecosystem services, we identified twelve key ecosystem property, nine function and nine service indicators. Indicators for ecosystem properties that could be linked to each function were land use, land cover and landscape structure. Indicators for regulating and habitat functions could be linked to most ecosystem property indicators. Furthermore, land management was found to affect ecosystem properties and functions, as was the case for three key ecosystem services in the study area: milk production, fine dust capture, and recreation). In the case of food provision and air quality regulation, ecosystem services were also found to be affected directly by land management.

We conclude that the framework enables the flexible selection of indicators to analyse land management effects on ecosystem services at multiple scales. The criteria we used to evaluate the selected indicators can be seen as a step towards practical guidelines for indicator selection. We recommend that future ecosystem service assessments follow an equally structured methodology, and select at least one state and performance indicator per ecosystem service. The framework we presented in this paper is useful to better understand and quantify the interactions between land management, ecological processes and the provision of ecosystem services. Therefore, the framework can be used to determine quantitative links between indicators, so that land management effects on ecosystem services provision can be modelled in a spatially explicit manner.

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