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RESEARCH

Assessing Landscape Functions with Broad-Scale Environmental Data: Insights Gained from a Prototype Development for Europe

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Abstract We examine the advantages and disadvantages of a methodological framework designed to analyze the poorly understood relationships between the ecosystem properties of large portions of land, and their capacities (stocks) to provide goods and services (flows). These capacities (stocks) are referred to as landscape functions. The core of our assessment is a set of expert- and literature-driven binary links, expressing whether specific land uses or other environmental properties have a supportive or neutral role for given landscape functions. The binary links were applied to the environmental properties of 581 administrative units of Europe with widely differing environmental conditions and this resulted in a spatially explicit landscape function assessment. To check under what circumstances the binary links are able to replace complex interrelations, we compared the landscape function maps with independently generated continent-wide assessments (maps of ecosystem services or environmental parameters/indicators). This rigorous testing revealed that for 9 out of 15 functions the straightforward binary links work satisfactorily and generate plausible geographical patterns. This conclusion holds primarily for production functions. The sensitivity of the nine landscape functions to changes in land use was assessed with four land use scenarios (IPCC SRES). It was found that most European regions maintain their capacity to provide the selected services under any of the four scenarios, although in some cases at other locations within the region. At the proposed continental scale, the selected input parameters are thus valid proxies which can be used to assess the mid-term potential of landscapes to provide goods and services.

Keywords Land use change · Ecosystem goods and services · Landscape functions · GIS model · Continental assessments · Mapping · Europe · Scenario analysis

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Introduction

Conceptual Framework and Definition of Landscape Functions

Ecosystems provide services to society, which include resources, such as food and fiber, regulation of environmental quality, and aesthetic qualities that are of great ecological, socio-cultural and economic value (Millennium Ecosystem Assessment, MA 2005). All these services need to be considered and valued to ensure the sustainable management of multi-functional landscapes that support the well-being of people. The classification of such services has been the focus of much discussion and several alternative classifications to the Millennium Ecosystem Assessment have been proposed (Boyd and Banzhaf 2006; Wallace 2007).

Despite the usefulness of the recent broad discussion about service classification systems, we feel that land managers require simple tools for assessing the capacity of entire regions to deliver ecosystem services. For the present study we therefore decided to adopt and refine the concept of *landscape functions*. Figure 1 adapts the cascade model initially suggested by Haines-Young and Potschin (2009) as a way of framing the concept of ecosystem services; the cascade model has been redrafted to emphasize the composite nature of the underlying capital stock represented by cultural landscapes. In line with the framework of ecosystem goods and services (see for example Heal and others 2005; MA 2005), we recognize policy and economy as drivers that have a significant impact on both the social-cultural and on the natural and cultivated capital stocks associated with cultural landscapes. These stocks manifest themselves in the form of landscape structures (e.g. mountains, woodlands, cities) and ecosystem processes and functions (e.g. Net primary productivity). "Goods and services" on the other hand represent the flows of benefits to society from these stocks. These flows (e.g. timber or food production) depend upon both the *capacity* of the landscape to supply these services and the *demand* from society for the benefits they provide. In this article we focus mainly on the capacity side, which we consider is dependent on: (1) the area available, that is the size of the asset stock; and (2) the quality of that stock, that is the integrity of the underlying socio-cultural systems on which flows of services depend.

In using the term landscape *'function'* we recognize that the word *function* is overlain by many different meanings (Jax 2005), which often confuse *means* with *ends*. Our notion of landscape function describes more the capacity of land for ecosystem service production, and should not be confused, for example, with the idea of 'land use function' (Helming and others 2008; Pérez-Soba and others 2008), which has been used elsewhere to describe the flows of social, economic and ecological benefits that land may generate.

State of the Art and Research Goals

In the last decade, the concept of ecosystem goods and services has become a widely adopted assessment framework, as a result of a number of publications including Daily (1997), Costanza and Farber (2002), MA (2005), Farber and others (2006); Bao and others (2007), and Turner and Daily (2008). Recently, several authors (e.g. Chan and others 2006; Troy and Wilson 2006; Lesta and others 2007; Naidoo and others 2008) advocate spatially explicit service or function assessments to facilitate the broad use of the service approach by decision makers. It is suggested that spatially explicit assessments would better enable them to balance region-specific goods and services or landscape functions against other issues in public debates on sustainable development.

As a result of the increasing availability of geo-referenced data (Bunce and others 2008), there are now a number of published *regional studies* linking landscape properties to goods and services (e.g. Bindraban and others 2000; Leibowitz and others 2000; Wu and others 2003; Peterseil and others 2004; Wrbka and others 2004; Fohrer and others 2005; de Groot 2006; Egoh and others 2008; Willemen and others 2008). We are however not aware of any studies that have successfully generated maps at the continental scale depicting the *potential* of landscapes to

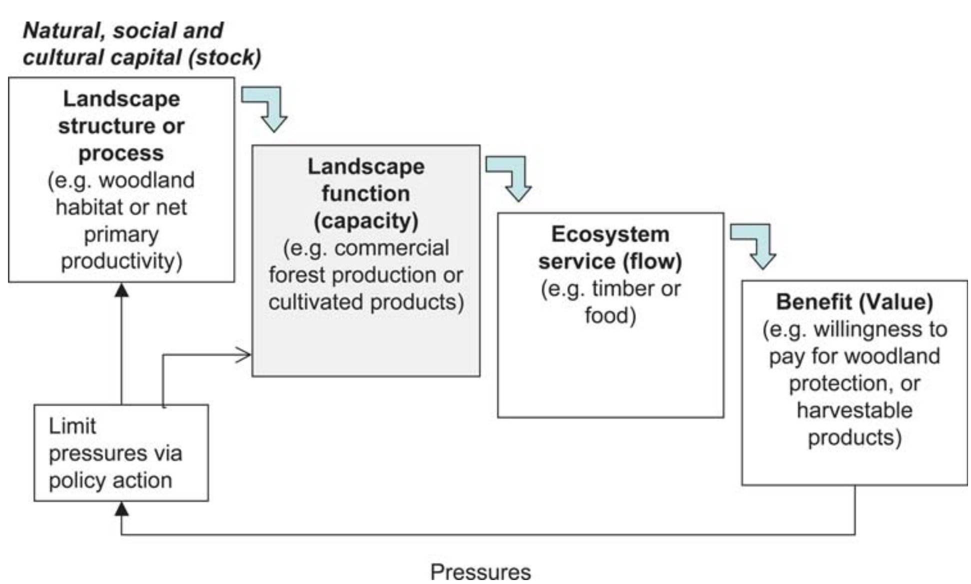

Fig. 1 Conceptual framework for analyzing landscape functions (redrawn and adapted from Haines-Young and Potschin 2009)

provide services. Recent studies of Metzger and others (2006, 2008) provide ecosystem *service* maps at the European scale for a few provisioning and regulating services. The study of Naidoo and others (2008) is an attempt to map ecosystem services at a global scale. Data availability forced these authors to restrict their analysis to only four ecosystem services.

Given current knowledge gaps, a concerted effort is needed by ecologists, GIS specialists, modelers and planners to explore the yet little known relationships between the ecosystem properties of a portion of land and its potential to provide goods and services. At the continental scale considered here, most of these interrelationships are either not known, or the level of detail of the input parameters does not meet the requirements for a proper up-scaling of non-linear behavior observed at the lower scale. This is the innovative aspect of the presented exploratory study, namely to check where and under what conditions complex interrelations can be neglected and still get a reasonably plausible output from the analysis. Thus the article *first* aims at developing a straightforward and consistent logic for linking land characteristics with functions. *Second,* these assessments are made spatially explicit to cover large geographical areas with widely differing environmental conditions. *Third,* quantitative and qualitative comparisons of the function maps with independently generated maps are performed to evaluate the links (look-up tables) and to check whether they perform in a plausible way using widely differing input values. Our approach has been designed to be:

- *Transparent and parsimonious:* the decision rules (see e.g. Gustavsson and others 2006; Metzger and others 2006) representing links between land characteristics and landscape functions fit the available knowledge at continental scales;
- *Expert-driven:* information from experts and from literature is implemented to supplement empirical knowledge;
- *Temporally and spatially explicit:* the method is applicable to multiple time steps and scenarios; and,
- *Theoretically consistent:* the proposed rules are consistent with the currently accepted ecosystem goods and service concept.

The Typology of Landscape Functions Used in the Present Study

Landscapes may host a number of different and often overlapping functions. Since there may be both synergistic and antagonistic relationships between functions, it is important to consider the sum of the functions in a given area—that is its multifunctionality—to make an overall assessment of the benefits that a landscape can provide to society (Helming and Wiggering 2003; Brandt and Vejre 2004).

The current literature (e.g. Costanza and others 1997; de Groot and others 2002; MA 2005; Hein and others 2006) suggests that a wide range of landscape functions and associated services can be identified belonging to four major groups, namely: (1) production functions—delivering provisioning services; (2) regulation functions—delivering regulating services; (3) habitat functions for maintaining ecological structures and processes—delivering supporting services such as, e.g., biodiversity-enhancing landscape structures; and (4) information functions—delivering cultural and amenity services.

Production functions represent the capacities of ecosystems to supply "natural" products to people. *Regulation functions* result from the capacity of landscapes to influence environmental quality, e.g. moderate climate, hydrological and bio-chemical cycles, earth surface processes, and a variety of biological processes. These functions have an inherent spatial dimension because locations where a service is generated and where its benefit is enjoyed may vary spatially (e.g. flood control). *Habitat functions* are those crucial for the maintenance of nature and biodiversity. *Information functions* relate to the benefits people obtain from landscapes through recreation, cognitive development, relaxation, and spiritual reflection. These benefits may involve visits, indirect enjoyment of an area (e.g. through nature movies), or gaining satisfaction from the knowledge that a landscape contains important biodiversity or cultural monuments.

As shown in Table 1 we defined 15 landscape functions. This intermediate number follows a suggestion of Kienast and others (2006) who found that the level of 15 functions matches the available scientific knowledge required to generate results at the continental scale best. Each function links to the underlying landscape properties/processes that generate them (Table 1).

Material and Methods

Expert Selection

The selection of experts followed the principle of the "theoretical sampling" (Glaser and Strauss 1967). This broadly accepted selection principle in social sciences maximizes variety, and not statistical representativeness (Patton 1990; Morse 1994; Hunziker and others 2008). Individuals/experts are chosen on the basis of widely differing views of a subject (in our case ecosystem service assessments). We selected five experts. Two of them were

Table 1 List of landscape functions used in the present study. For each function several required landscape properties or processes are listed together with examples of ecosystem goods and services. Adapted from Costanza and others (1997), de Groot (1992, 2006), de Groot and others (2002)

Landscape function	Required landscape properties/processes	Examples of goods and services associated with landscape function
I. Production functions → provisioning services		
Wildlife products	Conversion of solar energy into edible plants and animals	Food (e.g. game, fish)
	Genetic material in wild plants and animals	Raw materials (e.g. fiber, fuel wood)
	Variety in (bio)chemical substances in natural biota	Biochemicals
		Genetic resources
Cultivated products	Conversion of solar energy into cultivated products (depending on soil stability and fertility, irrigation, geology etc.)	Food and raw materials from cultivated land and aquaculture
		Bio-energy crops
Commercial forest products	Conversion of solar energy into forests	Timber, fiber
		Non-timber forest products
Transportation and housing	Ability of landscapes to provide shelter and safe transportation	Transportation by land and water
		Housing
Energy	Ability of the land to provide all types of energy production (hydro, wind, oil, coal)	Fossil fuels
		Hydro and wind power
II. Regulation functions → regulating services		
Climate regulation	Influence of land cover and biologically mediated processes (e.g. GHS-production) on climate	C-fixation
		Regulation of other GHG
Natural hazard reduction	Influence of ecosystem structure on dampening environmental disturbances	Storm protection (e.g. by coral reefs)
		Flood prevention (e.g. by wetlands and forests)
Water regulation	Role of land cover in regulating runoff and river discharge; retention and storage of fresh water (e.g. in aquifers)	Provision of water for consumptive use (e.g. drinking, irrigation and industrial use)
		Drainage and natural irrigation
Waste treatment and nutrient cycling	Role of ecosystems in bio-geochemical cycles (e.g. CO_2/O_2 balance, N and P balance, etc.)	UVb-protection by O_3 (preventing disease)
		Maintenance of (good) air quality
		Water purification
Erosion prevention	Role of vegetation, root matrix and soil biota in erosion control and soil retention	Maintenance of arable land through soil formation
		Prevention of damage from erosion/siltation
Biological control	Food chain dynamics	Pest and disease control
		Pollination
III. Habitat functions (maintaining ecological structures and processes) → supporting services		
Habitat function	Suitable living space and reproduction habitat for wild plants and animals	Maintenance of biological and genetic diversity (evolutionary processes)
		Habitat for migratory species (incl. nursery service)
IV. Information functions → cultural and amenity services		
Aesthetic information	Attractive landscape features	Enjoyment of scenery (e.g. scenic roads, housing)
		Non-recreational appreciation of landscape features
Recreation and tourism	Variety in landscapes with (potential) recreational uses	Travel to natural ecosystems for eco-tourism and (recreational) nature study
Cultural and artistic information	Variety in natural features with cultural and artistic value	Use of nature as motives in books, film, painting, folklore, national symbols, architecture, advertising
		Heritage value

natural scientists with backgrounds in assessing national and international biodiversity and natural resources. The others were a landscape ecologist, a social scientist and a scientist with expertise in assessing ecosystem goods and services.

Using Land Characteristics to Assess Landscape Functions

To provide a spatially explicit representation of landscape functions at the continental scale, we gathered independent input data from various sources that covered the entire territory of the European Union (EU-25 plus associated countries such as Norway and Switzerland). All data have been intersected with the administrative planning regions, the so-called NUTS-X regions (EEA, http://dataservice.eea.europe.eu/dataservice). NUTS-X regions are preferred over NUTS level 2 and 3 since they have a more uniform size across the European territory. Initially, data for over 50 land characteristics were assembled, and these were reduced to two subsets (see Tables 2, 3) that best characterize the target-functions. The reduction was based on conceptual considerations and correlation analysis. Parameters were kept only if: (1) both the expert panel (consisting of five experts) and the scientific literature considered them as important predictors of currently used goods and services; and, (2) the cross-correlation with other parameters (r^2) was below 0.3. Subset A (Table 2) consists of basic land characteristics (mostly nominal data) that best determine the target landscape functions. Subset B (Table 3) are land quality data (mostly interval data) used to refine the calculations of some target landscape functions. To assign a parameter to either subset A or B we checked whether it describes basic land characteristics in a nominal way (set A) or has a significant non-nominal quality component (set B). We acknowledge that the assignment was not always unambiguously possible (e.g. par. 3.16 or par. 2.1 through 2.3). Land use data represent about 40% of the input data. Since they are a snapshot of present conditions, it may be argued that they are not suitable as proxies for assessing the potential of an area to deliver services. Therefore we employed mid-term land use scenarios to check the sensitivity of the functions to expected land use change.

The final set of independent parameters describing basic land characteristics (subset A, Table 2) are made up of three major groups describing: geographic/locational information; topographical information; and, land properties/land use. Each independent parameter was overlaid with the map of the NUTS-X regions. For all parameters of subset A the percentage of land associated with the characteristics was calculated. The data containing information on geographical zones (1.1 through 1.3) and altitudinal range (2.1 and 2.2) were derived from Mücher and others (2003). Steepness (2.3) is used as a surrogate for the difficulty to cultivate the land and as a surrogate for wilderness. The land use parameters 3.3 through 3.13 are derived from the CORINE dataset (EEA 2002a) and have been calculated for present conditions as well as for year 2030 based on scenarios of the EURURALIS 2.0 study (Rienks 2008). Further parameters are the coastline (3.1) and the parameter "urban area > 50000 inhabitants" (3.2). The rather coarse CORINE land use data were complemented with information on "landscape and nature protection areas" (3.14 and 3.15) as well as "irrigated agricultural areas" (3.16). The data for parameters 3.14 through 3.16 are taken from various UN databases (GEO data portal, http://geodata.grid.unep.ch/).

The land quality data (Table 3) are used in a second step to refine some function assessments. An important quality parameter is the "Actual Net Primary Production (aNPP)". We distinguish between aNPP on arable (4.1) and on forested land (4.2). The metric aNPP was derived from remote-sensing data (MODIS product MOD17, 500 m pixel resolution, Zhao and others 2005). It is used to assess the current intensity of agricultural and forestry use. Note that aNPP measures the actual land-use intensity which can quite substantially deviate from the potential Net Primary Production (pNPP) through production losses or irrigation (Haberl and others 2007); aNPP is thus a mix of pixels with very high aNPP (literally the potential NPP) and pixels with very low aNPP. We decided to use aNPP and not pNPP since correct pNPP values would require one or more comprehensive regionally calibrated biogeochemical models (Haberl and others 2007; Maselli and others 2009) based on analyses outside the scope of this article. One could use existing global or continental estimates of pNPP (e.g. the 0.5 degree resolution data set of Haberl and others 2007) but only at the expense of a rather coarse resolution. Further quality data included Shannon's Land Use Diversity Index (4.3) calculated for the land use parameters 3.4 through 3.13 and a forest patch heterogeneity index (4.4). The latter is derived from the number and area of forest patches within a NUTS-X region and measures dominance and structural properties of forests (Table 4). Parameters 4.3 and 4.4 have been successfully linked to people's landscape preference (Orians 1986; Kaplan and Kaplan 1989; Appleton 1996; Hunziker and Kienast 1999; Lee and others 2008).

For the approach presented in this article, socio-economic data *sensu-stricto* (e.g. GDP) enter the calculations indirectly via current and projected land use. The parameter "urban area >50000 inhabitants" (parameter 3.2) is neither a pure land use nor a socio-economic parameter but a simple spatially explicit surrogate for urban life. We kept it in the data set, primarily as a predictor for the information functions. The parameter is coded in a binary way, with presence being represented as 100%, and absence as 0%. A valid alternative to the parameter "urban area" would be the mean population density of the NUTS-X region. However, we preferred "urban area" over the population density since it creates a clearly distinguishable spatial representation of urban regions vs. rural areas.

Relating Land Characteristics to Landscape Functions

Different ways of linking the landscape functions with the independent parameters have been presented in the

Table 2 Final set of independent data describing the basic land characteristics of each NUTS-X region in a nominal way (subset A). As a rule, characteristics belonging to the same thematic layer (e.g. topographical parameters or land use) add to 100% representing the total area of the NUTS-X region, or in the case of parameter 3.1, the total perimeter of the NUTS-X region. Parameters relating to nature and landscape protection areas (parameters 3.14 and 3.15) add to a maximum of 87%, since NUTS-X regions are not designated for conservation purposes as a whole

Parameter number	Parameter description	Unit	Comments	Source	Approx. year of reference
Geographical zones					
1.1	All Europe except arctic and steppic	% land of NUTS-X region	1.1, 1.2, 1.3 add to 100%	LANMAP2[a]	Not relevant
1.2	Arctic	% land of NUTS-X region		LANMAP2[a]	Not relevant
1.3	Steppic	% land of NUTS-X region		LANMAP2[a]	Not relevant
Topographic parameters					
2.1	Up to 1500 m asl	% land of NUTS-X region	2.1 and 2.2 add to 100%	LANMAP2[a]	Not relevant
2.2	Higher than 1500 m asl	% land of NUTS-X region		LANMAP2[a]	Not relevant
2.3	Steep slopes	% land of NUTS-X region	Max. 100%	File Dominant Type of Problem Lands, FAO[e]	ca. 1990
Land properties/land use					
3.1	Coastline	% of NUTS-X perimeter	Max. 100%	LANMAP2[a]	Not relevant
3.2	Presence or absence of urban area with more than >50,000 inhabitants	Presence/absence	0% or 100%	EEA and ESPON[b]	ca. 2000
3.3	Artificial surface (Corine unit 1)	% land of NUTS-X region			
3.4	Arable land (Corine unit 2.1)	% land of NUTS-X region	3.3–3.13 add to 100%	CORINE[f] & Scenarios[c] for	1990–2000
3.5	Intertidal flats area (Corine unit 4.2.3)	% land of NUTS-X region			2030
3.6	Forested area (Corine unit 3.1)	% land of NUTS-X region			
3.7	Heterogeneous agric. areas (Corine unit 2.4)	% land of NUTS-X region			
3.8	Open space with little or no vegetation (Corine unit 3.3)	% land of NUTS-X region			
3.9	Pastures (Corine unit 2.3)	% land of NUTS-X region			
3.10	Permanent crops (Corine unit 2.2)	% land of NUTS-X region			
3.11	Shrub and herbaceous (Corine unit 3.2)	% land of NUTS-X region			
3.12	Water bodies (Corine unit 5)	% land of NUTS-X region			
3.13	Wetlands (Corine unit 4)	% land of NUTS-X region			
3.14	Nature protection area	% land of NUTS-X region	3.14 and 3.15 add to max. 87%	WDPA Consortium[d]	1970–2000
3.15	Landscape protection area	% land of NUTS-X region		WDPA Consortium[d]	1970–2000
3.16	Irrigated agricultural areas	% land of NUTS-X region	Max. 100%	File "europe_irrig_land" FAO and CESR[e]	1995

[a] Mücher and others 2003; [b] provided by EU-SENSOR (www.sensor-ip.org); [c] Based on Eururalis 2.0 scenarios, Verburg and others (2006); [d] World Database of Protected Areas ("WDPA") compiled by the WDPA Consortium, including UNEP-WCMC; [e] GEO data portal, http://geodata.grid.unep.ch/; [f] EEA (2002a)

Table 3 Final set of independent data describing land quality characteristics of each NUTS-X region (subset B). Parameters 4.1 and 4.2 are expressed in absolute values per NUTS-X region. Parameters 4.3 and 4.4 are indexed. The parameters of subset B (quality parameters) enter the calculation in a subsidiary second step and are used to refine the calculations of selected functions (i.e. production and information functions). For more details of the calculation process see paragraph "Relating land characteristics to landscape functions

Parameter number	Parameter description	Unit	Comments	Source	Approx. year of reference
4.1	Mean Actual Net Primary Production (aNPP) on forested land	kg C/m^2/year	Used to assess production functions	MODIS MOD17 product[a]	2001–2005
4.2	Mean Actual Net Primary Production (aNPP) on arable and grass land	kg C/m^2/year			
4.3	Shannon's Diversity Index of land use classes (par. 3.3–3.13, Table 2)	Index	Used to assess landscape heterogeneity of NUTS-X	CORINE	1990–2000
4.4	Forest patch heterogeneity Index	1–4 (see Table 4)	Used to assess forest structure of NUTS-X	CORINE	1990–2000

[a] Zhao and others (2005)

Table 4 Calculation of the forest patch heterogeneity index (par. 4.4)

Code	Landscape characteristics	Quantitative definition	
		Forested area in % of NUTS-X area	Number of forest patches (minimum size 1 km^2) per 10 × 10 km cells averaged over NUTS-X region
1	Slightly forested areas with a very variable number of forest patches, usually highly fragmented	<20	0–10
2	Landscapes with mixed land use, forest has some importance and is in medium to large patches	20–50	2–3
3	Forest dominated landscapes with large homogeneous forest patches and low fragmentation	>50	≤3
		20–50	≤2
4	Mixed to forest dominated landscapes with high fragmentation	≥20	>3

literature, e.g. process-based links (Krönert and others 2001; Haase and others 2007) or look-up tables expressing to what degree land characteristics hinder or support a particular landscape function. We are well aware that most interrelations are, however, not linear but characterized by trade-offs, thresholds, minimum requirements etc. (see for example Foley and others 2005; Kareiva and others 2007; Liu and others 2007; Turner and others 2007). Agricultural production, for instance, is often not linearly related to the amount of arable land due to variation in land use intensity, soil and climate constraints or other land quality parameters.

Given our aim to explore where and under what circumstances complex interrelations can be substituted by a simple methodology, we decided to use binary links (0/1 look-up tables), expressing whether a land characteristic has a supportive role (value 1) or a neutral role (value 0), for a given landscape function. Our link table shown in Table 5 was generated with the aid of the expert panel (5 experts) and the scientific literature. It took several iterations and rounds of discussion before the findings from the literature and the expert assessments were consistent and formed a credible framework describing how specific land characteristics are associated with each function. At the end of this process, it was not possible to separate expert and literature input. The experts assigned consistent values to roughly 40% of the landscape functions. For an additional 30% of the functions the links showed some but no significant deviation, and for the remaining 30% the expert ratings differed markedly. In the latter case the most frequent rating amongst the experts was used. However, because there is a lack of information on trade-offs and feedbacks between functions, the additive approach has its limits. In this article we have overcome these limitations by including a supplementary step in the calculation of a function using quality parameters. Note that the quality data (Parameters 4.1–4.4) were thus used to refine certain landscape function assessments, involving an estimate of the degree to which specific land properties enhance or detract from a given function along a quality gradient, such as net productivity (aNPP).

Table 5 Linking the basic land characteristics (subset A) with landscape functions using an expert rating and published scientific literature. Binary links (look-up tables) are used to express whether a land characteristic has a supportive (1) or an indifferent (0) role. Note that the parameters of subset B (quality parameters 4.1–4.4) enter the calculation in a second step and are used to refine the calculations of selected functions (i.e. production and information functions). For more details of the calculation process see paragraph "Relating land characteristics to landscape functions". "0" = indifferent role; "1" = supportive role

Land characteristics (lc) and parameter no.		Landscape functions (Lf)							
		Wildlife products	Cultivated products	Commercial forest products	Transportation and housing	Energy (biofuel and renewable energy)	Climate regulation	Natural hazards reduction	Water regulation
		Binary links (bl) between land characteristics and landscape functions							
All European landscape types except arctic and steppic	1.1	1	1	1	1	1	1	1	1
Arctic	1.2	1	0	0	0	0	1	0	1
Steppic	1.3	1	1	0	1	1	1	1	1
Up to 1500 m asl	2.1	1	1	1	1	1	1	1	1
Higher than 1500 m asl	2.2	1	0	0	0	1	1	1	1
Steep slopes	2.3	1	0	0	0	1	1	0	0
Coastline	3.1	1	1	0	1	1	0	1	1
Presence (100%) or absence (0%) of urban area with more than >50,000 inhabitants in NUTS-X region	3.2	0	0	0	1	0	0	0	0
Artificial surface (Corine unit 1)	3.3	0	0	0	1	0	0	0	0
Arable land (Corine unit 2.1)	3.4	0	1	0	0	1	0	0	0
Intertidal flats area (Corine unit 4.2.3)	3.5	1	0	0	0	0	1	1	0
Forested area (Corine unit 3.1)	3.6	1	1	1	0	1	1	1	1
Heterogeneous agric. areas (Corine unit 2.4)	3.7	1	1	0	0	1	0	0	1
Open space with little or no vegetation (Corine unit 3.3)	3.8	1	0	0	0	0	0	0	0
Pastures (Corine unit 2.3)	3.9	1	1	0	0	0	0	0	0
Permanent crops (Corine unit 2.2)	3.10	0	1	0	0	0	0	0	0
Shrub and herbaceous (Corine unit 3.2)	3.11	1	1	0	0	1	1	0	0
Water bodies (Corine unit 5)	3.12	1	0	0	1	0	0	1	1
Wetlands (Corine unit 4)	3.13	1	0	0	0	0	1	1	1
Nature protection area	3.14	1	0	0	0	0	1	1	1
Landscape protection area	3.15	1	1	1	0	0	1	1	1
Irrigated agricultural areas	3.16	0	1	0	0	0	0	0	0

Table 5 continued

Land characteristics (lc) and parameter no.		Landscape functions (Lf)						
		Waste treatment and nutrient cycling	Erosion prevention	Biological control	Habitat function	Aesthetic information	Recreation and tourism	Cultural and artistic information
		Binary links (bl) between land characteristics and landscape functions						
All European landscape types except arctic and steppic	1.1	1	1	1	1	1	1	1
Arctic	1.2	0	0	0	1	1	0	1
Steppic	1.3	1	1	1	1	1	1	1
Up to 1500 m asl	2.1	1	0	1	1	1	1	1
Higher than 1500 m asl	2.2	0	0	1	1	1	1	1
Steep slopes	2.3	0	0	0	1	0	1	1
Coastline	3.1	0	1	0	1	1	1	1
Presence (100%) or absence (0%) of urban area with more than >50,000 inhabitants in NUTS-X region	3.2	0	0	0	1	1	1	1
Artificial surface (Corine unit 1)	3.3	0	0	0	1	1	1	1
Arable land (Corine unit 2.1)	3.4	0	0	1	0	0	0	0
Intertidal flats area (Corine unit 4.2.3)	3.5	0	1	1	1	1	1	0
Forested area (Corine unit 3.1)	3.6	0	1	1	1	1	1	1
Heterogeneous agric. areas (Corine unit 2.4)	3.7	0	1	1	1	1	1	1
Open space with little or no vegetation (Corine unit 3.3)	3.8	0	0	0	1	1	1	0
Pastures (Corine unit 2.3)	3.9	0	0	0	1	1	1	1
Permanent crops (Corine unit 2.2)	3.10	0	0	1	0	1	1	0
Shrub and herbaceous (Corine unit 3.2)	3.11	0	0	1	1	1	1	1
Water bodies (Corine unit 5)	3.12	1	1	0	1	1	1	1
Wetlands (Corine unit 4)	3.13	1	1	1	1	1	1	1
Nature protection area	3.14	0	0	1	1	1	1	1
Landscape protection area	3.15	0	0	1	1	1	1	1
Irrigated agricultural areas	3.16	0	0	0	0	0	0	0

Calculating the Importance of a Landscape Function

The importance of a landscape function at a particular location (i.e. NUTS-X region) under given land characteristics is calculated as:

$$\mathrm{Ailf}_{(i,k)} = \sum_{1}^{n} \left(\mathrm{bl}_{(i,n)} * \mathrm{lcp}_{(n,k)}\right) \qquad (1)$$

where,

$\mathrm{Ailf}_{(i,k)}$	Additive relative importance of the *i*th landscape function in the *k*th NUTS-X region
$\mathrm{bl}_{(i,n)}$	Binary link (bl, see Table 5) between the *i*th landscape function and the *n*th land characteristic (lc, see Table 5)
$\mathrm{lcp}_{(n,\ k)}$	Percent value of the *n*th land characteristic in the *k*th NUTS-X region
i	index for landscape functions (total 15)
k	index for NUTS-X regions (total 581)
n	index for independent land characteristics (total 22)

"Ailf" is expressed as an additive percentage value of $\mathrm{lcp}_{(n,\ k)}$. "Ailf" achieves a maximum value of 787(%) in a hypothetical case, where all land characteristics ($\mathrm{lcp}_{(n,\ k)}$) in a NUTS-X region are assumed to be supportive. An example for a calculation is given in Table 6.

The calculations with relative values filter out any information about the absolute area of the NUTS-X region. This information *is* "re-introduced" when interpreting the values in the form of maps with equal area projection, as is done in this article.

Map Evaluation

Map evaluation was undertaken for two reasons: (1) to check the usability and practicability of the look-up tables to predict landscape functions across widely differing environmental conditions; and, (2) to identify those landscape functions for which our proposed framework yields qualitatively satisfactory results. Evaluation of the spatially explicit functional assessments was more difficult than expected due to limited availability of independent maps depicting landscape functions or ecosystem services. A few service assessments are available from Metzger and others (2006, 2008). Despite the fact that they represent services, they were found to be the only ones offering a meaningful comparison with our functions. All other maps are independently generated continent-wide maps of land resources/characteristics or their derivatives. These data sets (called subsequently "indicator maps") have not generally been developed for the purpose of assessing landscape functions, but are welcome precursors of landscape function assessments. Most of them are published by the European Environmental Agency (EEA). One-to-one comparison of these indicator maps with the landscape functions is technically possible but not always meaningful, because highly synthetic map content (i.e. the landscape function) is compared to a thematically narrow, single indicator. In these cases, a one-to-many comparison—i.e., landscape function vs. many indicators—is more appropriate. In addition, several indicator maps have a coarser spatial resolution than the function maps, and the original unclassified map information often could not be retrieved.

We decided to evaluate the landscape function maps with quantitative methods and—where not possible—with visual inspection. As stated by Pontius and others (2008) or Visser and de Nijs (2006), visual inspection often outperforms automated procedures and should therefore not be disregarded. However visual testing has to follow strict rules: in our research, function maps and independent maps were inspected region by region, and agreement was expressed on three qualitative levels (bad, fair or good). The quantitative comparison of the categorical maps was undertaken using the "proportion of agreement" and the "un-weighted Kappa" (Hagen-Zanker 2006 or Visser and de Nijs 2006). The boundaries of the map categories (classes) used throughout the study are quartiles.

Scenarios of Land Use Change

The sensitivity of the landscape function maps to changing land use was analyzed with the aid of land use change scenarios. To capture future uncertainties in global developments it is common practice to use contrasting narratives to develop scenarios. Out of the many scenarios available at the EU level, we employed four narratives and corresponding land use projections elaborated in the EURURALIS 2.0 project (Meijl and others 2006; Verburg and others 2006; Westhoek and others 2006; Verburg and others in press). The four contrasting narratives relate to different plausible developments defined by two axes similar to the IPCC Special Report on Emission Scenarios (Nakicenovic and others 2000) (Fig. 2). The vertical axis represents a global approach as opposed to a more regional one, whereas the horizontal axis represents market-orientation versus a higher level of governmental intervention. The narratives are quantified by assumptions on political developments, macro economic growth, demographic developments, technological assumptions, spatial policies and location preferences. A series of models have been used to link global level developments influencing land use to local level impacts (Verburg and others 2008). An extended version of the global economic model (GTAP) and an integrated assessment model (IMAGE) are used to calculate changes in demand for agricultural areas at the

Table 6 Example calculation of the additive relative importance (Ailf) for the landscape function "Cultivated products" in NUTS-X region ES616 (Jaén, Spain). Column 3 shows the relative amount of each land characteristic in % of the total area of this Spanish NUTS-X region. Column 4 is the binary link (bl) between each land characteristic and the landscape function "Cultivated products". Column 5 is the multiplication of columns 3 and 4. Note that Ailf is the sum of all rows in column 5. The shaded area depicts land characteristics whose percentages (column 3) are subject to change in the four land use scenarios A1, A2, B1, B2. The relative importance on the landscape function "Cultivated products" will change accordingly

1 Parameter number	2 Land characteristic…	3 …in % of NUTS-X region ES616 (Jaén, Spain) (lcp)	4 Binary link between the landscape function "Cultivated products" and the land characteristics (bl)	5 Relative importance of the landscape function "Cultivated products" in NUTS-X region ES616 (Jaén, Spain) for each land characteristic
1.1	All European landscape types except arctic and steppic	100	1	100
1.2	Arctic	0	0	0
1.3	Steppic	0	1	0
2.1	Up to 1500 m asl	98	1	98
2.2	Higher than 1500 m asl	2	0	0
2.3	Steep slopes	31	0	0
3.1	Coastline	0	1	0
3.2	Presence or absence of urban area with more than >50,000 inhabitants	0	0	0
3.3	Artificial surface (Corine unit 1)	0.8	0	0
3.4	Arable land (Corine unit 2.1)	22.9	1	22.9
3.5	Intertidal flats area (Corine unit 4.2.3)	0	0	0
3.6	Forested area (Corine unit 3.1)	7.6	1	7.6
3.7	Heterogeneous agric. areas (Corine unit 2.4)	7.8	1	7.8
3.8	Open space with little or no vegetation (Corine unit 3.3)	1.1	0	0
3.9	Pastures (Corine unit 2.3)	0	1	0
3.10	Permanent crops (Corine unit 2.2)	37.1	1	37.1
3.11	Shrub and herbaceous (Corine unit 3.2)	22.7	1	22.7
3.12	Water bodies (Corine unit 5)	0	0	0
3.13	Wetlands (Corine unit 4)	0	0	0
3.14	Nature protection area	13	0	0
3.15	Landscape protection area	14	1	14
3.16	Irrigated agricultural areas	22	1	22
4.1–4.4	Included at a later stage of the analysis			
			Ailf	332.1

country level while a spatially explicit land use change model (CLUE-s) was used to translate these demands to land use patterns.

The EURURALIS 2.0 land use projections at the 1 km^2 resolution were intersected with the NUTS-X regions, entered formula (1) and yielded landscape function loadings "Ailf"$_{\text{(scenario A1 through B2)}}$ for potential future states. Note that in the sensitivity analysis, the land use parameters (3.3 through 3.13) are the only ones that change. All other land characteristics are kept constant. Therefore the *differences* between "Ailf"$_{\text{(scenario A1 through B2)}}$ and "Ailf"$_{\text{(present)}}$ translate into area losses or gains of those land use types that excerpt a supporting role for a landscape function.

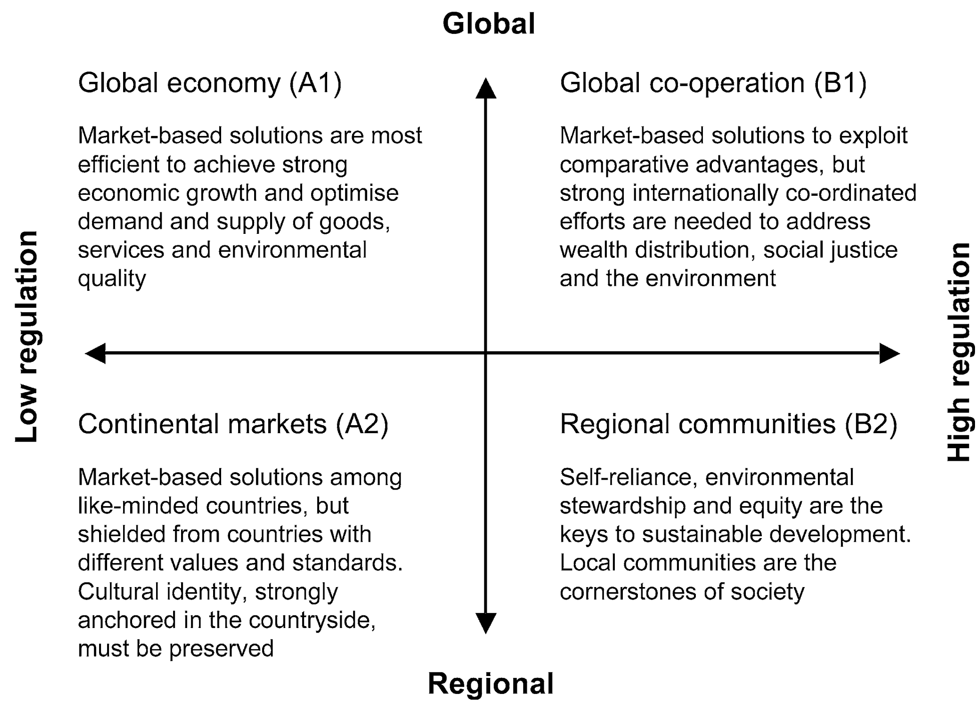

Fig. 2 The four scenarios used in the present analysis (adapted from Westhoek and others 2006)

Results

Current Spatial Distribution of Selected Landscape Functions

The use of formula (1) yielded spatially explicit loadings for 15 landscape functions in all NUTS-X regions under current environmental conditions. In this article only a few are presented (Figs. 3, 4, 5, 6) by way of evaluation. For all functions shown in the figures, we found fair to good spatial agreement with independent spatially explicit service assessments (see paragraph "Map evaluation"), and we conclude that the links between land characteristics and landscape functions are sufficiently well-supported by both expert knowledge and scientific literature. The map for "Cultivated products" (Fig. 3a) shows how important cultivated products are in each region and highlights the hotspots of agricultural and forestry production in Europe, with low priority areas in mountains and the Nordic regions. If this map is refined with aNPP (Fig. 3b), zones can be delineated where the importance (and need) to deliver cultivated products is well balanced with the actual production intensity. Similarly we are able to identify areas where aNPP would allow for intensive production, but the potential to generate cultivated products under current land use is below average. These are either wealthy, highly developed areas (Central Europe, Southern Sweden and Norway) or marginal areas experiencing population loss following land abandonment. Finally, areas may be delineated where aNPP is below average, but the potential to deliver cultivated products under current land use is high. Most of these areas are precipitation-sensitive drier areas in Eastern and South-Western Europe. A repeated, climate-induced reduction of aNPP as e.g. experienced in the record breaking summer 2003, where aNPP in Central, Eastern and South-Eastern Europe was considerably below the average, could pose a great risk to these areas. The rapid assessment used here provides a way of effectively highlighting such areas.

The map showing the potential for "Commercial forest products" (Fig. 4a) reproduces the well-known distribution of forest resources in Europe. Following our concept of landscape functions, no distinction is made between unexploited and exploited resources (flows). High mountain areas do not contribute to the loading of this function. This is particularly visible in the Alpine arc where forest resources have a minor commercial value but are economically important in terms of the protection they provide against natural hazards. The binary links are unable to make this distinction.

The function "Climate regulation" (Fig. 4b) shows high loadings in northern and southern latitudes, as well as for mountain areas. This function includes the potential for carbon sequestration in forest, shrub and wetland habitats, as well as the potential of a NUTS-X region to host migrating species (Hannah and others 2007). The latter is modeled using maps of existing nature and landscape conservation areas (parameters 3.14 & 3.15).

The function "Recreation and tourism" (Fig. 5) is broadly defined and "Ailf" is driven by many land

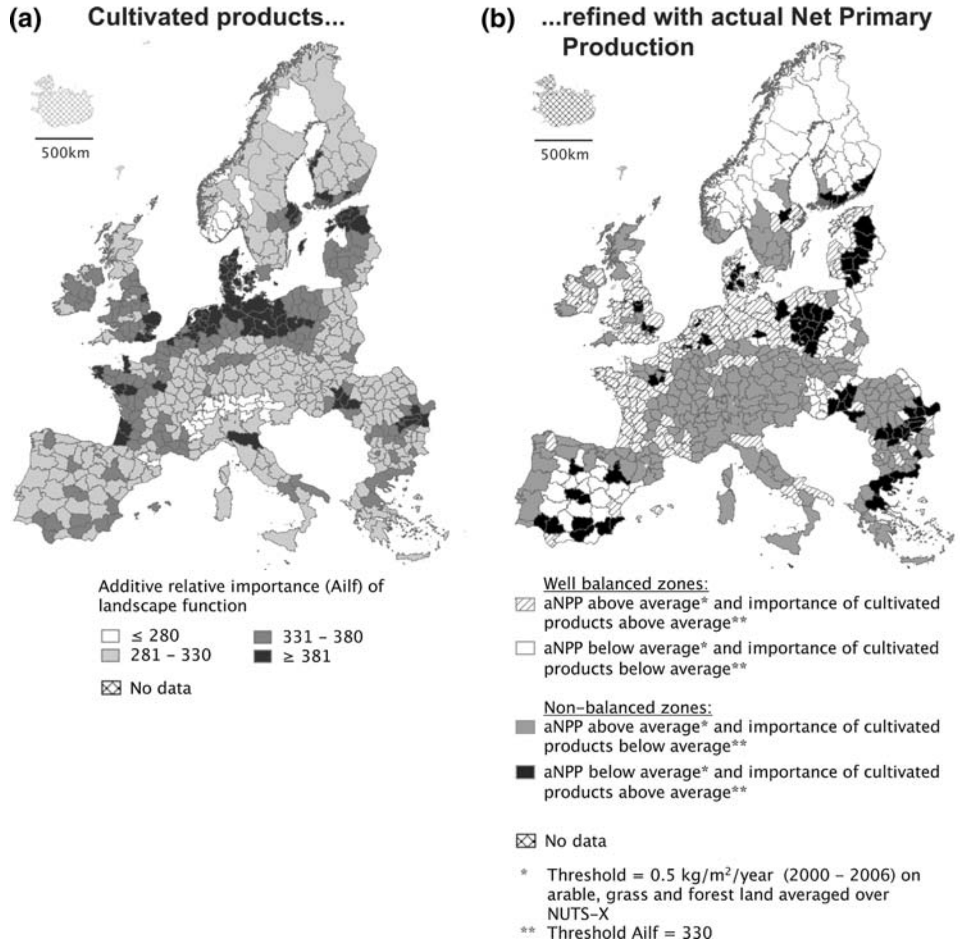

Fig. 3 **a** Additive relative importance (Ailf) of landscape function "Cultivated products" for present landscape characteristics (year of reference depends on individual country but is approx. 2000). The higher "Ailf", the more important is the landscape function. For more details on the calculation see formula (1) in text. **b** Refinement of landscape function "Cultivated products" with the quality parameter "Actual Net Primary Production" (aNPP). Well-balanced zones are those, where aNPP and the potential for cultivated products are both either below or above average. Non-balanced zones are those where aNPP and the potential for cultivated products are contrasting

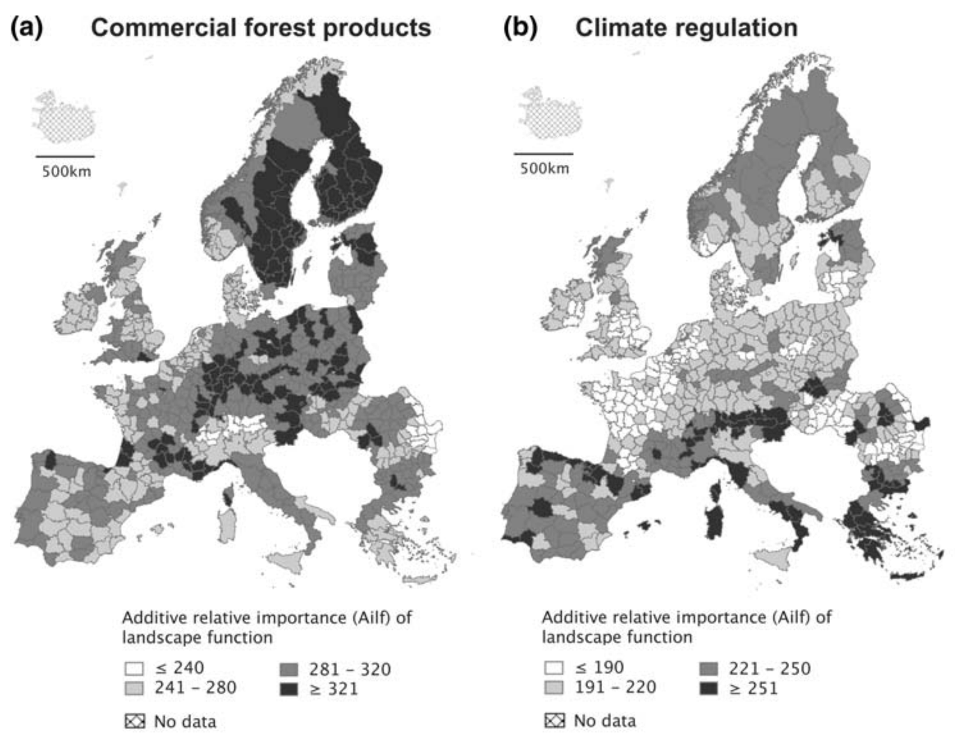

Fig. 4 Additive relative importance (Ailf) for landscape functions **a** "Commercial forest products" and **b** "Climate regulation" for present landscape characteristics (year of reference depends on individual country but is approx. 2000). The higher "Ailf", the more important is the landscape function. For more details on the calculation see formula (1) in text

Fig. 5 Additive relative importance (Ailf) for the landscape function "Recreation and tourism" for present landscape characteristics (year of reference depends on individual country but is approx. 2000). The higher "Ailf", the more important is the landscape function. For more details of the calculation see formula (1) in text

characteristics (Table 5). The resulting potential for tourism and recreation shows a good match with the major European summer and winter destinations, such as the Mediterranean and mountain areas in general. As we know from major perception and recreation studies, and other theoretical work (Hunziker 1995; Hunziker and Kienast 1999; Kianicka and others 2006; Hunziker and others 2007, 2008) people prefer highly diverse, structured landscapes over monotonous areas. To locate areas where specific landscape preferences may be satisfied, we refined the function "Recreation/tourism" with the landscape quality parameters "landuse diversity" and "forest heterogeneity" (par. 4.3 and 4.4). Figure 6 exemplifies the procedure for three perception profiles: (1) preference for landscapes with diverse land use (Fig. 6a); (2) preference for landscapes in only slightly forested, usually highly fragmented areas (Fig. 6b); and, (3) preference for landscapes in partially forested areas with medium to high fragmentation. Depending on the various profiles, different recreation/tourism hot-spots may be identified.

Map Evaluation

A total of 20 independent maps have been used to check the output of the look-up tables to model landscape functions across widely differing environmental conditions. Tables 7 and 8 report the results of the quantitative and the visual comparisons. Six functions were evaluated quantitatively using proportional agreement and un-weighted Kappa (Table 7). Three out of these six functions were evaluated with both quantitative and visual methods (marked with asterisks in Tables 7 and 8). In the quantitative comparison (Table 7) "Cultivated products" and "Commercial forest products" showed fair agreement with the corresponding ecosystem service maps of Metzger and others (2006, 2008). Major deviations between the landscape function "Cultivated products" and the ecosystem service indicator "Farmer livelihood" are observed in the Mediterranean where Metzger and others (2006, 2008) suggests a higher potential for land cultivation than our analysis. The landscape function "Commercial forest products" and the ecosystem service indicator "wood supply" diverge considerably in the Scandinavian countries. Here the different assumptions between function and service assessment become evident. Metzger's services emphasize yearly yield (harvested timber over time) whereas our functions emphasize the potential of an area to deliver wood products. The landscape function "Climate regulation", which involves not only C-storage but also vulnerability of ecosystems to climate change, shows no significant agreement with the indicator map "C-storage". No statistically significant agreement was found for the "Habitat function" when compared with the indicator map "Number of species". Fair agreement was observed for the function "Recreation and tourism" when compared with tourist accommodation and bed-places.

Seven functions were checked with visual methods (Table 8), and for 5 functions no evaluation was possible due to lacking independent indicator maps This lacuna is most obvious for the functions "Waste treatment", "Erosion prevention" and "Biological control" as well as for the information functions.

As an overall result, 9 out of 15 functions pass our tests with fair to good agreement, i.e. the evaluation yields the same or very similar geographic patterns of hot-spot areas to those identified in other independent studies. The remaining functions appeared to be of lower quality; this has primarily been caused by inadequate knowledge of how landscape characteristics contribute to a given function, or insufficient thematic or spatial resolution of the input data. A major barrier for an adequate assessment of

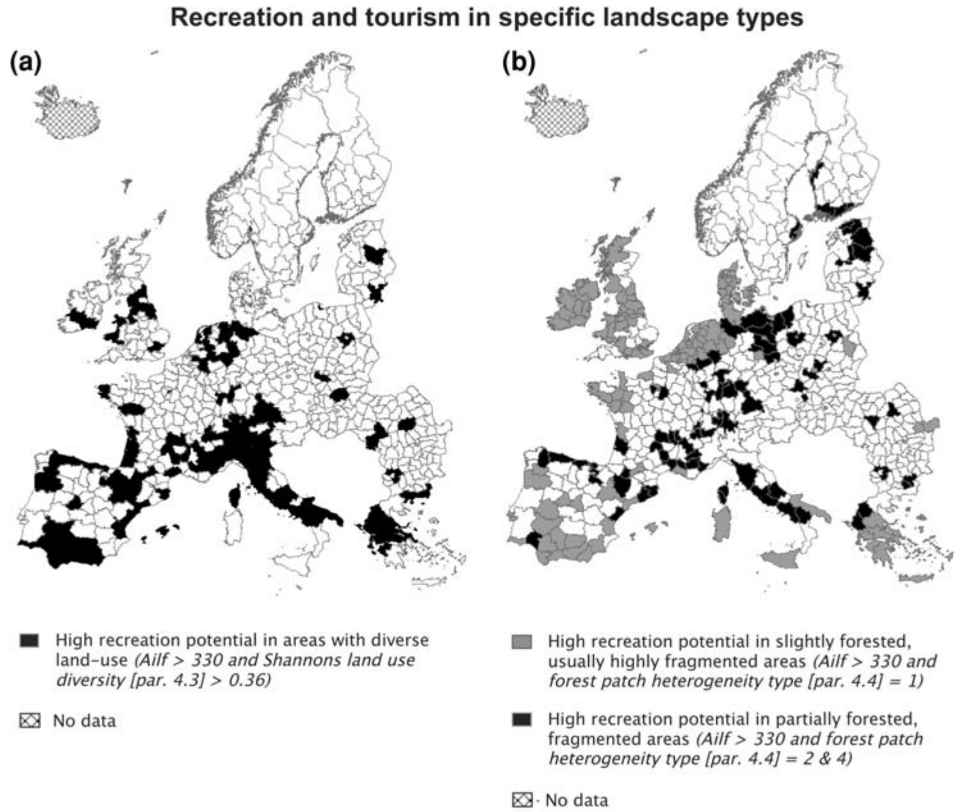

Fig. 6 Areas with high recreation and tourism potential in specific landscape types **a** in areas with diverse land use; **b** in slightly forested, highly fragmented areas and in partially forested, fragmented areas

all functions is, however, the coarse spatial resolution of the input data.

Sensitivity Analysis

The landscape functions have been subjected to a sensitivity analysis with the four EURURALIS scenarios A1 through B2, to check whether significant spatial shifts of landscape-function loadings might take place as a result of changing land use. Note that the sensitivity analysis refers only to the 9 functions modeled with medium to high quality, which results in a bias towards production functions, and neglects changes in land use quality, e.g. land intensification. Figure 7 provides the results for the A1 scenario. For 72% of the EU25 territory all presently modeled landscape functions are still supported in 2030, i.e. the relative change of supporting land use types is less than 10% of the NUTS-X area. For 20% of the EU-25 territory, one or two out of 9 functions show higher support with changing land use (Fig. 7). Across 8% of the EU-25 territory more than two functions show significant changes. For the vast majority of these regions the number of positively influenced functions outweighs the number of negatively influenced functions.

The four scenarios (A1 through B2) show slightly different impacts on the landscape functions. In the B1 and B2 narratives, the number of stable regions increases to 80% (72% in A1) with almost no negative impacts (i.e. no decreasing “Ailf”). The outcome for the A2 scenario is very similar to the A1 scenario in spite of very different land use change trajectories (Verburg and others in press).

Discussion

We present a transparent methodology for analyzing the relationships between ecosystem properties and landscape functions. The approach is embedded in the paradigm of “ecosystem goods and services” and is currently one of the few assessments of landscape functions at the continental scale (Verburg and others 2009). Our target audience are land managers who might use the approach in an operational context, such as for stakeholder workshops or policy evaluations. To ensure a successful application we mention several critical points of our endeavor which should be considered before applying the approach.

(1) *Landscape dynamics and functions:* The assumption that land use data are reasonable proxies for estimating landscape functions, can be questioned, given their temporal dynamics. Our analysis showed that at the coarse spatial level of NUTS-X regions (median area

Table 7 Quantitative map evaluation with independent spatial data

Landscape function	Independent map	Method of quantitative comparison		Overall quality of agreement
		Proportion of agreement incl. 95% error margins	Un-weighted Kappa	
Cultivated products	Map of ecosystem service "farmer livelihood" [source: Metzger and others (2006, 2008)]	0.4583 (chance agreement: 0.25) Upper 95% 0.5133 Lower 95% 0.4044 (4 class comparison; class boundaries = quartiles)	0.2778 (fair agreement) Upper 95% 0.3488 Lower 95% 0.2068 (4 class comparison; class boundaries = quartiles)	Fair
Commercial forest products	Map of ecosystem service "wood supply" [source: Metzger and others (2006, 2008)]	0.4162 (chance agreement: 0.25) Upper 95% 0.4712; Lower 95% 0.3631 (4 class comparison; class boundaries = quartiles)	0.2216 (fair agreement) Upper 95% 0.2921; Lower 95% 0.1511 (4 class comparison; class boundaries = quartiles)	Fair
Energy (Biofuel and renewable energy)[a]	Solar Potential (source: www.energie-atlas.ch; www.geni.org)	0.6986 (chance agreement: 0.6453) Upper 95% 0.741; Lower 95% 0.653 (2 class comparison; class boundary = 75% percentile)	0.1504 (slight agreement) Upper 95% 0.2715; Lower 95% 0.0293 (2 class comparison; class boundary = 75% percentile)	Slight
Climate regulation[a]	Map "C-storage in Biomass and Soil" [source: Metzger and others (2006, 2008)]	Below chance agreement	Below chance agreement	Below chance agreement since landscape function "Climate regulation" is broadly defined and includes vulnerability of ecosystems as well as C-storage
Habitat function[a]	Map "number of species (bird, plant, trees, reptiles)" (Metzger and others 2008)	Below chance agreement	Below chance agreement	Below chance agreement
Recreation and tourism	Map of indicator "tourist accomodation, bedplaces" (source: http://epp.eurostat.ec.europa.eu)	0.6957 (chance agreement: 0.612) Upper 95% 0.737; Lower 95% 0.651 (2 class comparison; class boundary = 75% percentile)	0.2155 (fair agreement) Upper 95% 0.3239; Lower 95% 0.1071 (2 class comparison; class boundary = 75% percentile)	Fair

[a] Also visually inspected (see Table 8)

Table 8 Visual map evaluation with independent spatial data

Landscape function	Independent map	Overall quality of agreement	Comment
Wildlife products	(a) Map "Areas with relatively little influence from urbanisation, transport or intensive agriculture" [source: Report EEA (1998)] (b) Map "Ratio of forest and semi-natural areas to agriculture and urban areas" [source: Report EEA (1999)]	Fair agreement with maps (a) and (b), north-eastern Europe does not match well	Definition of function very coarse
Transportation and housing	Map "Pressures by urban areas and transport network" [source: Report EEA (1999)]	Fair agreement	Thematic and spatial resolution of database low
Energy (biofuel and renewable energy)[a]	Map "Suitability for residue extraction according to environmental criteria" [source: Report EEA (2006)]	Fair to good agreement	
	Maps (a) "Bioenergy" (b) Hydropower (c) Ocean Energy Potential (d) Wind potential (sources a through d: www.energie-atlas.ch; www.geni.org)	Fair agreement with composite of maps (a) through (d)	
Climate regulation[a]	(a) Map "Vulnerability of forest production across Europe to climate change" [source: Report EEA (2005a)] (b) Map of "Expected changes in plant species distribution in Europe due to climate change" [source: Report EEA (2005a)]	Fair to good agreement	
Natural hazards reduction	Map "Occurrence of major natural disasters (1998–2002)" [source: Report EEA (2003)]	Bad agreement	Thematic and spatial resolution of database insufficient; definition of function too coarse
Water regulation	(a) Map "Average annual runoff in Europe" [source: Rees and others (1997)] (b) Map "Water stress in European river basins around 2000" [source: Report EEA (2005b)] (c) various maps from Lehner and others (2006)	Fair agreement with maps (a) through (c)	
Habitat function[a]	(a) Map "Special Protection Areas under the EU Birds Directive in the Atlantic Biogeographical Region and the Mediterranean Biogeographical Region" [source: Report EEA (2002b)]	Fair agreement	

[a] Also quantitatively inspected (see Table 7)

7000 km^2), land use data are acceptable proxies for a mid-term assessment (20–30 years), if a sensitivity analysis with scenario-generated data is undertaken. At the moment we do not see any valid alternative that could replace the land use data. Dynamic, climate-driven model projections of actual or potential NPP are presently not available and spatially explicit paleo-proxies for assessing potentially natural land conditions are by far too coarse and biased.

(2) *Linking landscape functions and land characteristics:* A major purpose of the study was to check whether the coarse and sometimes intuitive binary links between land characteristics and landscape functions (Table 5) can reproduce complex processes adequately. We found this true for roughly 60% of the functions. It could be argued that more process-oriented models would do a better job. Indeed some papers (e.g. Smith and others 2002; Naidoo and

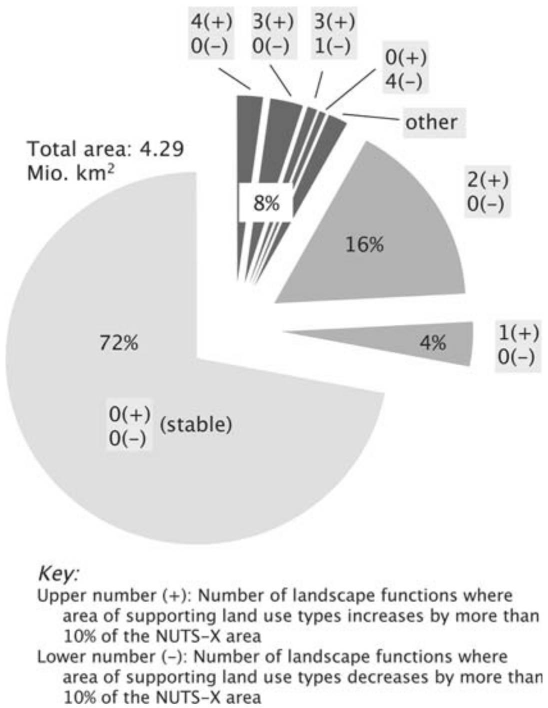

Fig. 7 Sensitivity analysis showing the potential impact of projected land use (EURURALIS A1 scenario, year 2030) on 9 landscape functions across the 25 EU member states (without Norway and Switzerland and other regions which do not have sufficient data, e.g. Vatican, Liechtenstein etc.). The pie chart shows the percentage of EU territory where the number of supported landscape functions is stable (*light grey*) or unstable (*darker grey tones*). Unstable areas are subdivided into different classes representing the number of functions that are either gained or lost. A total of nine functions identified with medium to high quality (Tables 7, 8) have been considered in the pie chart, i.e. "Wildlife products", "Cultivated products", "Commercial forest products", "Transportation & housing", "Energy (biofuel & renewable energy)", "Climate regulation" "Water regulation", "Habitat function", and "Recreation & tourism"

Ricketts 2006; Troy and Wilson 2006; Naidoo and others 2008) show that sophisticated, complex response functions are able to capture the link between ecosystem services and land characteristics quite adequately. The authors cited above, however, acknowledge, that their approaches are either not feasible at the continental scale or not adequate for services with very limited process knowledge. Indeed most continental studies known to us yield no more than a few maps for provisioning or regulating services.

(3) *Validating the continent-wide approach:* As mentioned here and in the scientific literature (Beck and others 1997; Mayo and Spanos 2004), the quantitative evaluation of landscape function estimates with independent data is difficult at the continental scale. The combined evaluation procedure (Kappa, qualitative visual inspection) used here meant, that a large number of independent maps could be compared. Only a few of them are, however, continental service assessments. Most are so-called indicator maps, representing only a small thematic proportion of a landscape function. Hence our solution to compare each landscape function map with as many service and indicator maps as possible is essentially a comparison of different modeling approaches (Haidvogel and others 2000), rather than a strict model validation based on independently gathered field data. We recommend improving our evaluation by more sophisticated procedures as more independent function maps become available. This could involve techniques such as fuzzy-based Kappa (Visser and de Nijs 2006) or budgeting spatially explicit components of shared information (Pontius and others 2008).

(4) *Quality data:* The quality data used to refine some function assessments in a second step are not complete. We could, for example, imagine using additional quality data such as e.g. willingness-to-pay information or land prices.

(5) *Sensitivity analyses:* The sensitivity analysis showed that at the selected spatial resolution (NUTS-X), land use is a valid proxy to assess the mid-term potential of landscapes to deliver goods and services. This finding applies to 9 landscape functions, the selection of which is biased towards production functions, and is subject to the following boundary conditions:

(a) To employ land use scenarios with a relatively low sensitivity. The ones used in the present article are considerably less sensitive compared to similar approaches across Europe (Busch 2006);

(b) To assume only area changes and no changes in landscape quality (e.g. aNPP) that might occur as result of climate change or altered management policies, e.g. by improved husbandry practices, changes in soil fertility or agricultural intensification;

(c) To use rather high thresholds (10% area change), above which an area change in supporting land use types is assumed to substantially diminish or increase the function; and,

(d) To assume a linear relationship between the additive relative importance (Ailf) of a function in a NUTS-X region and its benefit for society. This assumption is, however, debatable. Threshold behaviour has been reported in the ecological literature (e.g. With and Crist 1995; Betts and others 2007), and so the possibility of non-linear change or regime shifts should be considered.

Conclusions

We have described the insights gained from an exploratory study which aimed at assessing the capacity of larger portions of land to provide goods and services. The rigid testing of the proposed framework shows that for 9 out of 15 functions the construction of simple binary links was able to generate medium to high quality geographical patterns. This conclusion holds for “Wildlife products”, “Cultivated products”, “Commercial forest products”, “Transportation & housing”, “Energy (biofuel & renewable energy)”, “Climate regulation” “Water regulation”, “Habitat function”, and “Recreation & tourism”. These functions can be modeled over a time frame of 20 to 30 years (or longer if suitable land use scenarios are available). The assessments are primarily based on area measurements and only marginally on measures of quality (aNPP, forest structure, land use diversity). The number of successfully mapped functions is high compared to other recent studies (e.g. Naidoo and others 2008) but we acknowledge that the approach needs further refinement with more detailed spatial data, especially relating to land quality and socio-economic characteristics, e.g. land prices for various land uses to assess competing services, or people’s values in relation to competing ecosystem services. The latter would be extremely helpful for improving the information functions, as for example have been described in a recent paper by Raymond and others (2009).

Bearing in mind our target audience of land managers who require simple assessment tools, we summarize crucial practical points for a successful application of our modeling framework:

- Use a medium number of landscape functions (10–15) at a clearly defined level of thematic detail;
- Use medium-sized spatial units (in our case NUTS-X regions) for analysis; small enough to preserve specific environmental properties in the input data, large enough to account for spatial heterogeneity. For Europe a size of 5000–10,000 km^2 is advisable;
- Complement land use data at a resolution of 0.1–1 km^2 with more static environmental parameters and quality data (e.g. aNPP, landscape-structural data to capture heterogeneity within the spatial units, or participation and other socio-cultural data);
- Make sure that land use scenarios exist for at least 20–30 years; otherwise land use data should not be employed. No valid function assessment can be made for periods that are beyond the time frame of the scenario analysis; and,
- Assemble a medium number of experts from widely differing fields. Our experience is that too low a number (<3) involves the risk of bias, a too high a number (>10), on the other hand, does not seem to provide new insights into the assessment problem.

Advantages of the approach for stakeholder workshops include: the intuitive methodology; the simple calculation of the additive relative importance (Ailf) of a landscape function; and, the representation of the functions in a spatially explicit way. Maps are good communication tools that can be used to foster a dialogue between experts and stakeholders. Maps can also be easily evaluated using existing knowledge. However, because there is a lack of information on trade-offs and feedbacks between functions, the additive approach has its limits. In this article we have overcome these limitations by including a supplementary step in the calculation of a function using quality parameters. Finally, a feature of our approach is that it can be used to generate broad-scale multi-functionality assessments (Potschin and Haines-Young 2006) by adding function loadings for all or selected landscape service themes. The resulting cumulative function loadings can be seen as a surrogate for multi-functionality (Lorenz and others 2001; Brandt and Vejre 2004; Gimona and van der Horst 2007).

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