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RESEARCH ARTICLE

The representation of landscapes in global scale assessments of environmental change

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Abstract Landscape ecology has provided valuable insights in the relations between spatial structure and the functioning of landscapes. However, in most global scale environmental assessments the representation of landscapes is reduced to the dominant land cover within a 0.5 degree pixel, disregarding the insights about the role of structure, pattern and composition for the functioning of the landscape. This paper discusses the contributions landscape ecology can make to global scale environmental assessments. It proposes new directions for representing landscape characteristics at broad spatial scales. A contribution of landscape ecologists to the representation of landscape characteristics in global scale assessments will foster improved information and assessments for the design of sustainable earth system governance strategies.

Keywords Landscape · Global · Spatial structure · Integrated assessment · Ecosystem services · Land use

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Introduction

Landscape ecologists have, since long, embraced the topic of scale dependency by studying interactions between levels of organization and the effects of variations in resolution and extent on the results of the analysis (Gardner 1998; Wu 2004). Scale has been identified as one of the important topics in ecology (Holling 1992) and upscaling of local understandings is key to many studies of environmental management (Thrush et al. 1997; Gibson et al. 2000). Although many landscape ecologists have met the challenge to scale ecological knowledge from the level of individual species to the level of the entire landscape (Liang and Schwartz 2009; Lafortezza et al. 2010), most studies in landscape ecology are confined to the landscape level or address regions with an extent below the national boundaries.

The strong connections between world regions through trade and climate change and the needs for global governance of environmental resources has provided an incentive for global scale assessments that address the current and future state of the earth system as a whole. These assessments have attracted attention from both the media and policy makers. Global scale assessments are mainly conducted by members of the integrated assessment community and feature large scale models of global ecosystem function (Alcamo et al. 1998; Sala et al. 2002; Wise et al. 2009; Pereira et al. 2010; Smith et al. 2010). As a result of the large spatial extent and computational complexity, a strong simplification of the representation of the earth surface and its landscapes is made in such models. Does this mean that the spatial structure and compositions of landscapes are not important for global scale assessments? This paper investigates to what extent concepts and knowledge from landscape ecology are important for environmental impact assessment and how this knowledge is used in global scale environmental models and assessments. Based on the findings a perspective will be provided on the possibilities to further integrate landscape ecology knowledge into large-scale assessments informing earth system governance.

Landscape ecology and environmental change

Landscapes are the result of spatial heterogeneity in the physical environment and the interactions of humans with the environment. More than 80 % of the land surface is directly affected by human activities while the remainder of the area is indirectly affected through human impacts on climate, water, air quality, changes in river discharge and flood frequencies (Foley et al. 2005; Ellis et al. 2010). This human influence has given rise to a wide variation of landscapes; their composition and spatial structure reflecting the variation in the natural environment and the specific interactions of human activities with that environment. Landscapes are heterogeneous over a range of different scales (Turner et al. 1989). There is variation in natural vegetation composition but also in terms of the mosaic of land cover and landscape elements. Human influence has, in some cases, resulted in a homogenization of landscape variation by replacing heterogeneous natural vegetation by a single crop type. In other cases, human influence has further enhanced natural variations by creating a complex mosaic of diverse human use. Landscape ecology has studied the interactions between structure, process and function in these heterogeneous landscapes (Turner 1989; Naveh 2001; Kienast et al. 2009). A wide range of studies have investigated the interactions between landscape structure and levels of species richness or biodiversity. Although no generic relations between landscape structure indices and species richness are found that hold across different contexts and scales, many studies have confirmed the importance of spatial structure as a determinant of species richness (Atauri and de Lucio 2001; Fahrig 2003; Di Giulio et al. 2009; Gimona et al. 2009). Others have investigated the role of spatial structure of landscapes in relation to resilience to disturbance (Peterson et al. 1998). The increasing importance of ecosystem services as an operational concept guiding environmental management has led to investigations into the role of landscape properties as determinant of ecosystem service provision (Daily et al. 2009; Nelson et al. 2009; Perrings et al. 2011). Recent studies have shown that the spatial diversity and structure of landscapes have a strong influence on the services delivered by the landscape (Willemen et al. 2008; Egoh et al. 2009; Crossman et al. 2010; van Berkel and Verburg 2012). Landscape structure is important for many regulating services such as water retention and purification, pollination and soil protection that support the provision of food, feed and fuel. Also for many cultural services including landscape aesthetics, tourism and the protection of cultural heritage ('sense of place') the spatial arrangement of landscape elements and the mosaic of land cover types plays an important role (Gobster et al. 2007). Often people appreciate small-scale landscapes that originate from long-term farming histories above wilderness areas given their variation, identity and heritage functions (Soliva et al. 2008; van Berkel et al. 2011). Abandonment of agriculture followed by re-wilding of such heterogeneous landscapes in mountain areas in Europe has given rise to various efforts to support the continuation of farming in these regions to preserve landscape quality (MacDonald et al. 2000; Tasser et al. 2007; Kuemmerle et al. 2008).

The relation between the spatial structure of the landscape and the ecological processes that determine the functioning of the landscape plays an important role in environmental change. Changes in human preferences and demand, moderated through global markets and the development of technology, lead to changes in human interactions with the environment. Consequently, this leads to changes in landscape composition in terms of land cover, management but also in terms of its spatial structure. While land cover changes as deforestation can have drastic impacts on landscape function, also more subtle modifications of management and spatial structure (such as removal of landscape elements) can have large implications for the functioning of the landscape and the services it provides to human well-being. Intensification of farming practices leads to impacts on water quality and biodiversity (Herzog et al. 2006; Vermaat et al. 2008; Kleijn et al. 2009). Removal of hedgerows and other landscape elements related to historic farming systems does not change the overall land cover of a region but has strong impacts on green infrastructure, biodiversity and landscape aesthetics (Burel and Baudry 1995; Baudry et al. 2000; Dramstad et al. 2001; Herzog et al. 2006). Changes in forest management not only impact biodiversity but also carbon stocks and recreational values (Robinson et al. 2009; Lindner et al. 2010; Edwards et al. 2011).

Increasing demands for commodities with growing population numbers have generally led to increasing pressure on ecosystems and a specialization of the service supply of many landscapes. Intensification and expansion of agricultural area increase the provision of food, feed or fuel but have negative tradeoffs, mainly on regulating and cultural services. In experiencing the negative feedbacks of ecosystem modification, measures to adapt or mitigate the negative consequences of environmental change processes can be found in the modification of the architecture of landscapes (Vos et al. 2008; Lawler 2009). For example, adaptation to increased irregularities in river discharge takes place through increasing the retention capacity of upstream catchments and/or the designation of flooding areas downstream (Vos et al. 2010; Nedkov and Burkhard 2011). Ecological restoration often focuses on re-establishing connections in the landscape such as ecological corridors to avoid isolation and create resilience against shifts in climate conditions by allowing migration of species (Heller and Zavaleta 2009; Jongman et al. 2011). Designing appropriate conservation networks may help avoiding negative feedbacks of climate change on Amazon vegetation (Nobre et al. 2009; Walker et al. 2009). These examples indicate that while global environmental change emerges from local changes in landscapes also many options to mitigate and adapt to global changes are found in modifying the composition, spatial structure and management of these landscapes.

Representation of landscapes in global environmental assessments

In recent years a number of intensive, large-scale, efforts have been made to assess the state and future of the Earth's environment focused on different aspects of the environmental system. While the IPCC assessment mainly focuses on the climate implications of changing human-environment interactions (Smith et al. 2009), the Global Environmental Outlook (UNEP 2007) and the Millennium Ecosystems Assessment (MEA 2005) took a more overarching perspective. The Global Biodiversity Outlook (Pereira et al. 2010) focused on the provision of scenarios that address the threats to global biodiversity while the 'The Economics of Ecosystem Services and Biodiversity (TEEB)' (ten Brink 2011) focused on scenarios of changes in the monetary value of ecosystems to human well-being. Next to these large international assessments, which mostly involve a whole range of different assessment models, numerous studies have been conducted that apply individual global-scale integrated assessment models to study global environmental change (e.g. the OECD's Environmental Outlook 2008, 2012), or specific impacts, including climate policy analysis, the analysis of impacts of increased use of biofuels, REDD (Kindermann et al. 2008) and ex-ante evaluation of agricultural policy (Verburg et al. 2009b).

These assessments are all based on global-level quantitative analysis of the current state of relevant environmental indicators and future scenario outlooks. For this purpose global level datasets are compiled and simulation models are employed to investigate how changes in socio-economic scenarios translate into changes in the environmental indicators of interest.

Whether these indicators relate to carbon sequestration, greenhouse gas emissions, the water cycle, biodiversity or ecosystem service value, they all, somehow, are dependent on the structure and functioning of landscapes. To what extent is the spatial structure and function of these landscapes reflected in these global scale assessment methods?

All these assessments have in common that they use a numerical model, or a series of models, to translate the socio-economic scenarios into changes in land cover (Lotze-Campen et al. 2008; Smith et al. 2010; van Vuuren et al. 2010). Macro-economic assessments at world region level are used to capture demand–supply relations of commodity consumption, production and global trade in these commodities (Meijl et al. 2006; Britz and Hertel 2011). Such models include the IMPACT model (Rosegrant et al. 2002; Rosegrant and Cline 2003), MagPie

(Lotze-Campen et al. 2010), GLOBIOM (Schneider et al. 2011), GCAM (Wise et al. 2009) and the GTAP model (Hertel et al. 1997; Meijl et al. 2006; Hertel et al. 2010). Spatial allocation of land change within world regions accounting for the physical suitabilities of land resources and impacts of climate change are simulated by components of integrated assessment models such as IMAGE (Bouwman et al. 2006), or G4M (Rokityanskiy et al. 2007). The physical impacts on vegetation characteristics, crop growth and biogeochemistry are accounted for by process-based expert models (e.g. LPJmL (Bondeau et al. 2007)) while climate models are used to evaluate the impacts of land cover change on climate (Pitman et al. 2009). Given the global scope and complexity of these model systems the spatial resolution is often limited to pixels measuring approximately 50 × 50 km (0.5°; (Bouwman et al. 2006; Lotze-Campen et al. 2010)) or even larger units such as the 'homogeneous response units' used by the GLOBIOM model (Schneider et al. 2011); other assessment models do not go beyond large world regions and only use simple downscaling algorithms to represent land cover data for smaller geographic regions (Thomson et al. 2010). Land cover is represented in most of the spatially explicit models by designating the dominant land cover type in a pixel or land unit. Land management is often represented by a homogenous management factor per world region and further spatial variation is not accounted for. Impacts on environmental indicators are calculated using this representation of land cover/use as an input. In case of biodiversity impact assessment, the GLOBIO model downscales world-region level land cover changes based on the current fractional cover of the different land cover types within the pixels (Alkemade et al. 2009). The coarse spatial resolution, the use of dominant land cover types to represent the landscape at this resolution and the uniformity assumed in the downscaling methods clearly disrespect the importance attached to the spatial structure of landscapes to explain its ecological functioning. Figure 1 illustrates the common representation of land cover in global assessments by a comparison with more detailed data of land cover for the same regions. Not only the simplification due to the increased spatial resolution is leading to problems, also the prevalence of the different land cover types is affected by the aggregation procedure (Schmit et al. 2006).

While acknowledging the underlying reasons and needs for using such simplifications in the representation of landscapes at the global scale, the implications of this representation are seldom documented (Verburg et al. 2011c). The sensitivity of the reported impact indicators to the spatial representation of the landscape depends on the specific indicator and context, but has not been studied in a structured way. With the increasing range of applications that global scale models are currently used for, these simplified landscape representations may have increased impacts. Initially most global scale integrated assessment models were used to study vegetation dynamics, carbon balance, crop growth and greenhouse gas emissions in order to capture important trends in climate and land use, and their feedbacks. However, with global land use scenarios being available from these models, they started to be applied for an increasing number of indicators, from global flood modelling to biodiversity and ecosystem service assessment. For these indicators, which strongly depend on the spatial structure of landscapes, the use of the simplified landscape representations in global models may be questionable.

Estimates of global GHG emissions and carbon sequestration are based on either straightforward relations between emissions, dominant land cover, climatic and soil conditions or on more complex biogeochemistry models using similar input data. Errors in these estimates caused by the simplified landscape representation can originate from scaling errors (the 'ecological fallacy') (Easterling 1997) or from a spatial mismatch between land cover and other determinants. Also, inaccuracies emerge from ignoring variations in landscape composition and the contribution of minor land use types and landscape elements to emissions. In some landscapes it is rather the non-dominant land cover types or landscape elements that make the largest contributions to GHG emissions and carbon sequestration (Falloon et al. 2004; Follain et al. 2007). A number of studies have illustrated the effects of simplifications in land cover representation on environmental impacts. Jiao et al. (2010) found that up to 18 % of the soil organic carbon in an agricultural landscape in the North China Plain was associated with built structures and the disturbed lands surrounding these structures, commonly ignored in large scale assessments. Nol et al. (2008) found that nitrous oxide emissions were overestimated by about

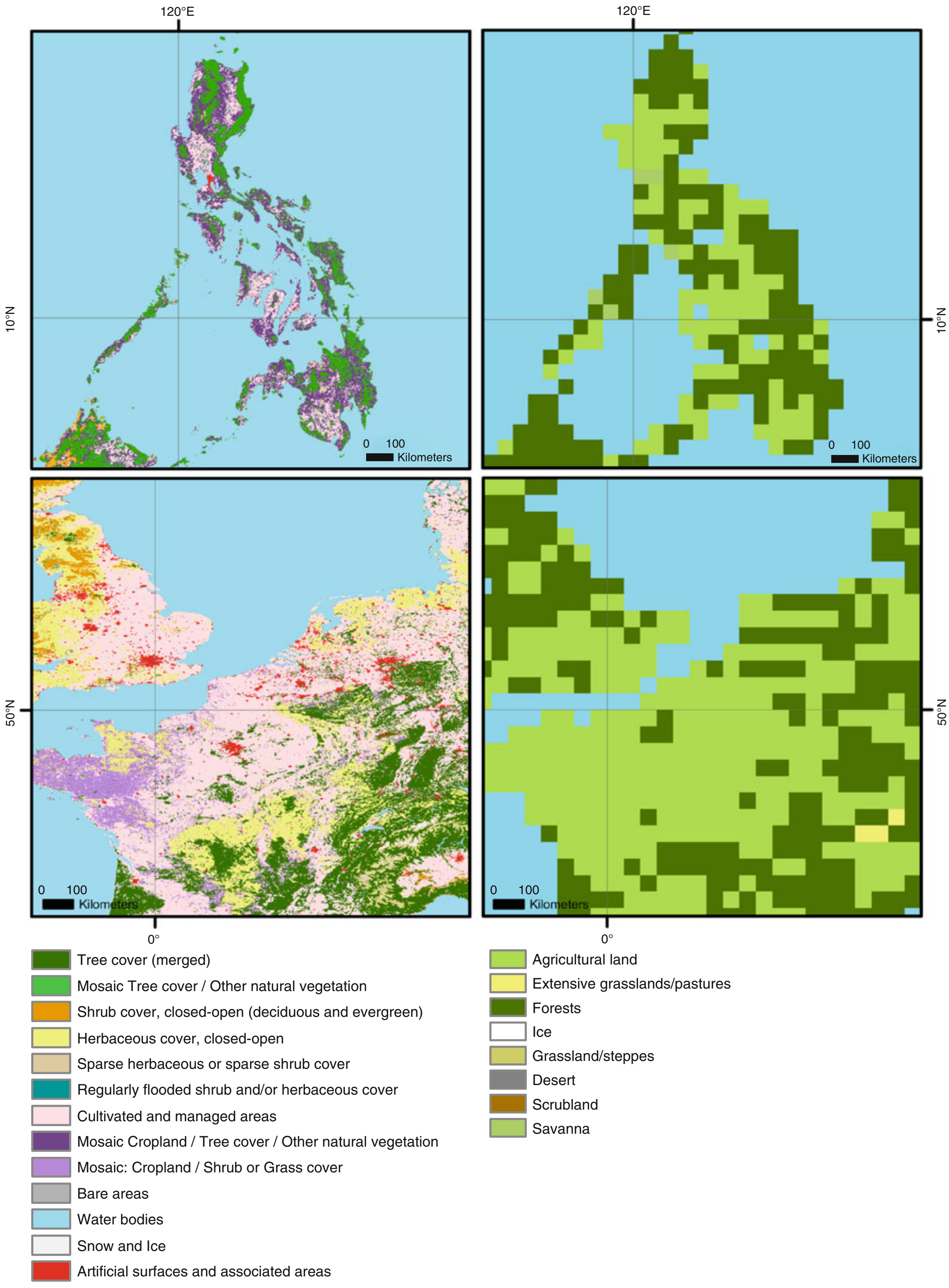

Fig. 1 Comparison of land cover representation in a high-resolution database (GLC2000) and the common representation in global scale integrated assessment models at 0.5° spatial resolution

10 % in case land cover data were used that ignored the presence of ditches in the landscape.

For other indicators a potential problem of the commonly used representation of landscapes by the dominant land cover resides in the absence of a representation of the spatial structure and possibilities to account for spatial interactions that are so important for ecosystem functioning. To deal with this lack of spatial information some assessments have tried to capture elements of spatial structure by using more detailed data available for the current conditions. Given the importance of patch size for biodiversity (Dengler 2009), the GLOBIO model uses the initial patch size of ecosystems based on high resolution land cover data to calculate average patch size per 0.5 degree pixel (Alkemade et al. 2009). For scenario simulations these patch sizes are modified proportionally to the total amount of land change in a world region. A similar approach was taken in the quantitative assessment of the TEEB assessment in determining the monetary value of ecosystems (Hussain et al. 2011). Here, patch size and abundance of the same ecosystem in the neighborhood are a major determinant of ecosystem values. While for the current state estimates are used based on high resolution land cover maps these can only be proportionally modified for future scenarios given the lack of spatial detail in the land change assessment models. This way some of the spatial characteristics of landscapes important to ecosystem function are incorporated. However, due to the simplified representations in integrated assessment models very arbitrary assumptions underlie the scenario calculations. Other spatial landscape characteristics of importance such as connectivity cannot be accounted for at all. Schulp and Alkemade (2011) provide a quantitative analysis of the impacts of land cover representation on the quantification of ecosystem services. Their study illustrates the large dependency of assessments of pollination services to the representation of land cover data, especially in mosaic landscapes.

In all global assessments ecosystems and landscapes are designated by land cover types. Land cover information can be derived from remote sensing directly and one-to-one relations between land cover and ecosystem types are used. As no remote sensing information is available on the spatial distribution of land management and human intervention in the ecosystem (Verburg et al. 2009a), integrated assessment models mostly represent agricultural management, forest management, grazing intensity and other disturbances as homogenous within a region or country. As a consequence, the heterogeneity of these landscape characteristics—though of prime importance to environmental impact assessment—cannot be accounted for.

Ways forward

It is inevitable that in global scale assessments simplifications and aggregations in the representation of landscapes need to be made. However, the oversight presented in the previous sections indicates that many critical elements of landscape composition and structure are lost in the representation of landscapes in current assessments. Aggregation of the underlying detailed land cover data causes an underrepresentation of land cover types with a relatively low prevalence, landscape structure and (linear) landscape elements are not represented at all, and the level of human interaction and management in the landscape is not integrally assessed. Depending on the specific indicator and context these omissions may have large consequences for the accuracy of the environmental impact indicators that are calculated. At the same time, it restricts the capacity of global assessments to account for changes in land management and landscape architecture as a means of mitigating and adapting global change impacts. How can some of the important landscape characteristics and elements of landscape function be preserved in global scale assessment methodologies?

A straightforward solution seems to be an increase in spatial resolution of the data and model representation. The common 0.5° pixels classified by their dominant land cover are insufficient and can be replaced by units with a higher resolution. Many global studies now aim at a 5 arcminute ($\sim$10 $\times$ 10 km) spatial resolution consistent with many recent datasets (Monfreda et al. 2008; Licker et al. 2010; Neumann et al. 2010; Siebert and Döll 2010). This higher resolution leads to a much better representation of the variation in land cover and especially to a better representation of the smaller land cover types that are hardly ever dominant at the 0.5 degree resolution. However, it basically suffers from the same limitations as noted above (Shao and Wu 2008). While land cover data are available at even higher resolutions, a further increase in spatial resolution would lead to high demands on computational capacity and a poor fit with other data that are not available at higher spatial resolutions. Many of the physical and socio-economic data that are used as drivers of land change, or data needed to assess impacts of land change on environmental indicators, are limited in their spatial resolution (Verburg et al. 2011b). Recent advances in the development of such datasets may move the possibilities to increase spatial resolution forward (Robinson et al. 2007; Siebert et al. 2010; Verburg et al. 2011a). Only increasing the resolution of the land cover data, however, does not necessarily lead to more accuracy. Increasing the resolution of land cover data does not necessarily allow us to represent those characteristics of landscapes essential for its functioning which only become apparent at relatively high spatial resolutions.

In addition to increasing the resolution it is needed to move beyond the discrete representation of landscapes by the dominant land cover. In its simplest form this can be achieved by a continuous field approach that denotes the fractions of the different land cover types that make up a larger pixel (Hansen et al. 2003, 2008; Hurtt et al. 2011). Alternatively, the global land surface could be represented by a classification of landscape types. Such landscape types allow representing typical mosaics of land cover but can also include a representation of the landscape elements, the management characteristics and a characterization of the spatial structure of the landscape. Landscape typologies have been made for specific regions and also many countries have national level landscape typologies available (Peterseil et al. 2004; Van Eetvelde and Antrop 2009). Few landscape maps exist for larger scales and those that exist mainly represent physical characteristics and/or land cover (Mücher et al. 2010). An example of a landscape characterization at global scale is provided by van Asselen and Verburg (2012), building on the work by Ellis and Ramankutty (2008), and Letourneau et al. (2012). Here, high-resolution land cover information, efficiency of agricultural production and livestock statistics are combined into a typology that describes landscapes at a 5 arcminute spatial resolution in terms of the land cover mosaic, agricultural management intensity and livestock numbers (Fig. 2). Such a simple classification captures a much larger part of the specific human-environment interactions that take place in the landscape and can more easily be related to ecosystem service provision and biodiversity indicators than a representation based on land cover alone. However, implementing such a landscape representation in existing integrated assessment model is not straightforward. In current models land cover types are translated to environmental impacts using expert-rules or empirical relations. Replacing land cover representations by a landscape characterization requires a new definition of the relations between the representation of landscapes and environmental impacts. At the same time, the land cover transitions simulated in integrated assessment models can no longer be determined through a straightforward downscaling of the regional demands for agricultural areas. Instead, local pathways to either a change in the land cover mosaic or a change in the management intensity should be accounted for, as these will determine the changes in landscape type and environmental impact. An example of such algorithm is provided by Letourneau et al. (2012).

Although the classification of van Asselen and Verburg provides insight in the land cover composition of the 5 arcminute pixels and provides an indication of the intensity of agricultural management and livestock keeping, it does not provide specific information on the spatial structure of the landscapes and the landscape elements. Linear elements are very important components in landscapes and main determinants of ecosystem function (pollination, erosion, aesthetics etc.). However, even high-resolution data of land cover are not able to correctly represent this green infrastructure. In some instances very high resolution data can provide an alternative (Vannier and Hubert-Moy 2008). However, the costs and processing capacity for such analysis are high and specific landscape elements such as stone walls and other linear elements may still not be detected (Ståhl et al. 2011). Other solutions are, therefore, necessary to characterize and monitor the presence of landscape elements over larger areas. Alternative data based on ground observations may provide useful information (Dramstad et al. 2001). An example of such a dataset based on ground observations is the Land Use/Cover Area frame statistical Survey (LUCAS) database that is available for the European Union (Gallego and Bamps 2008). This dataset consists of more than 230.000 sample points for 2009 across the European Union with ground observations of land use and

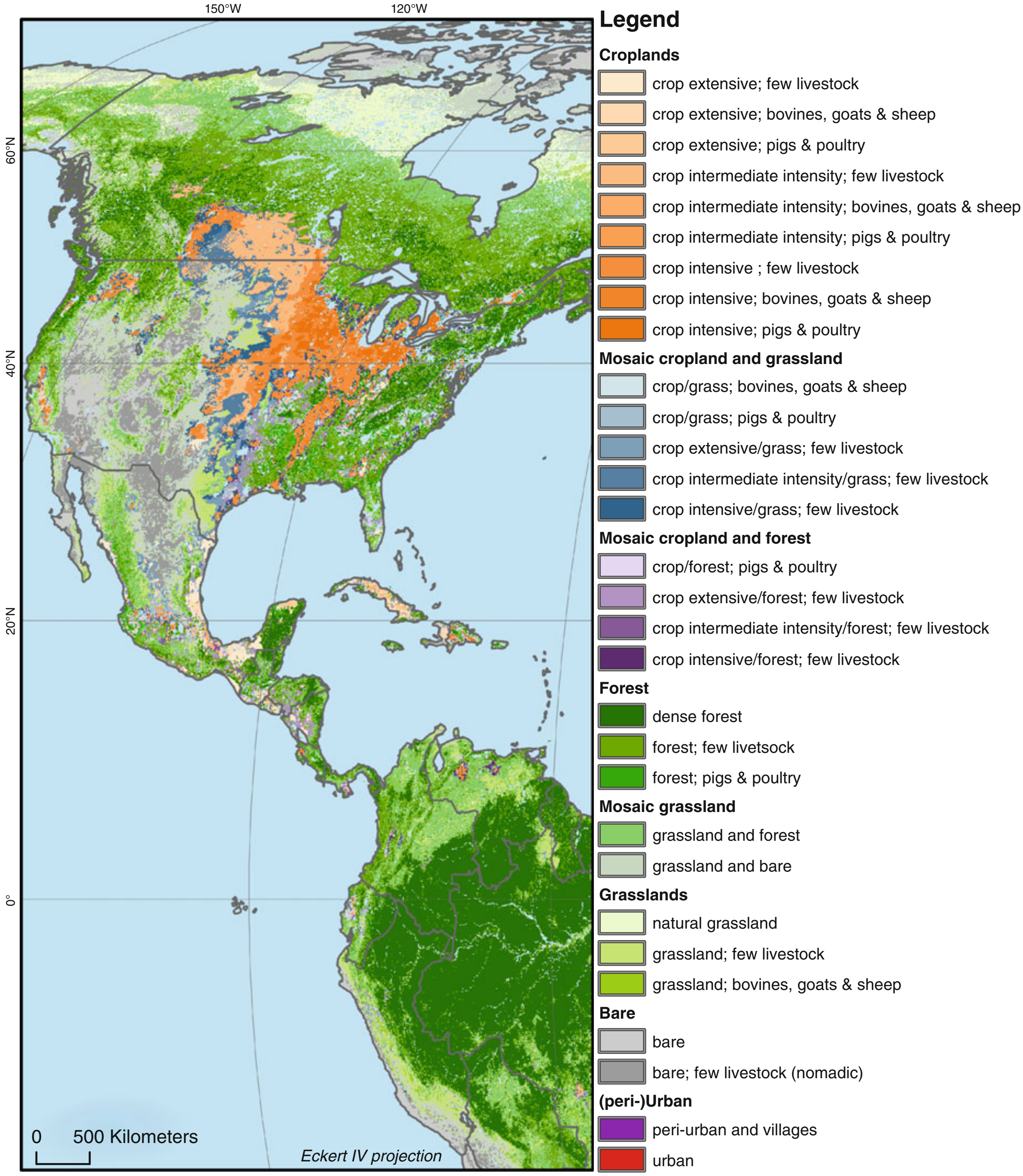

Fig. 2 Representation of landscapes by the land cover mosaic, agricultural management intensity and livestock density as presented by van Asselen and Verburg (2012)

landscape. Data recorded include amongst others land cover, parcel size and the number and type of landscape element crossed while walking a 250 meter transect. In addition, multi-directional photographs are made at each sample point. These transect data are of special interest as they provide an indication of the presence of 19 different types of landscape elements, such as grass margins, hedgerows, stone walls and ditches. Figure 3 provides a simple interpolation of the density of linear landscape elements in agricultural areas in Europe by assigning the 2009 observations to agricultural landscape units based on the European landscape unit map (Mücher et al. 2010; Wascher et al. 2010). This map provides an indication of the green infrastructure in agricultural areas in Europe not accounted for in earlier assessments. The intensive ground survey underlying this map may not be feasible world-wide. However, new approaches such as crowd-sourcing (citizen observatories) have indicated that the collection of large collections of ground information is now feasible (Schuurman 2009; Heipke 2010; Goodchild 2007). Recent efforts have shown the potential to use citizen observed data to validate land cover maps (Iwao et al. 2006; Fritz et al. 2009). Similar efforts have the potential to provide the input to enhance our characterization of landscape structure information at larger scales. The number of landscape pictures contributed by citizens worldwide available in georeferenced databases such as Panaramio indicates the potential of such an approach. Alternative approaches include the combination of broad-scale landscape typologies with more detailed case studies where the characteristics of the landscape composition and structure are described in more detail (Nol et al. 2008; Ellis et al. 2009). Next to making parameters of landscape structure available at the global scale, the second challenge would be to further develop models that actually use the data, taking into account the effect of these structures on e.g. crop growth, soil processes, water retention, biodiversity, and the broad range of ecosystem service indicators. In addition, changes in landscape structure in response to changes in driving factors of landscape change need to be explicitly addressed. Representing these processes requires moving beyond the current approaches of addressing land change in global modelling. Currently these are mostly driven by economic equilibrium approaches based on trade relations and profit optimizing behavior. A deeper understanding of the decision making processes of actors is needed to represent the changes in landscape structure and elements, requiring novel ways of landscape change modelling (Rounsevell and Arneth 2011).

Different global assessments require different typologies of landscapes. For biodiversity different landscape structures and elements need be represented as for assessments of greenhouse gas emissions. This requires a higher level of flexibility in our representation of the earth surface. Instead of trying to standardize classification systems of land cover towards a uniform, accepted, compromise, we need to find ways in which we can include those

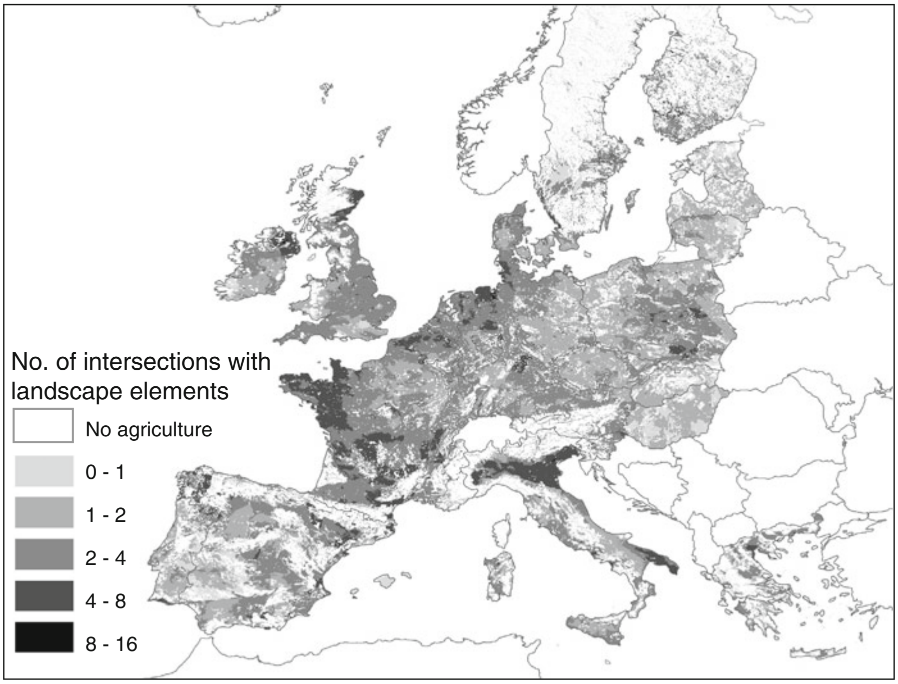

Fig. 3 Average number of landscape elements crossed on a 250 m transect per landscape unit based on observations in the LUCAS database

characteristics of the landscape that are critical for a specific assessment.

Unfortunately we cannot quantitatively determine the advances of alternative ways of representing landscapes on the accuracy of global assessments. However, recent experiments with earth system models have illustrated the sensitivity of model outcomes in terms of climate change for land cover change (Lawrence and Chase 2010; de Noblet-Ducoudré et al. 2012). Such results are indicative for the possible advances that can be made through improving the representation of the land surface in such models.

Conclusion

Changes in landscape composition and structure are the result of changing human-environment interactions and a driver of global environmental change. Landscape ecologists have focused on understanding landscape functioning and contribute their knowledge to landscape level environmental management and spatial planning. However, their knowledge of the role of landscape composition and spatial structure can also make an important contribution to global environmental change assessments. Adaptation to global change and mitigation of its negative consequences requires measures that modify landscape characteristics to be more resilient against global change impacts and mitigate further change. This requires knowledge of the links between local landscape architecture and global environmental change processes. A representation of landscapes in global assessments that does justice to their functioning is needed to accomplish such a link. Such representation of landscape diversity in global models not only requires an increase in spatial resolution of the land cover maps but rather a representation of the landscape characteristics itself in terms of composition, spatial structure and management. While this paper has mainly focused on issues related to the spatial and thematic representation of landscapes, similar considerations apply to temporal aspects (including seasonality, crop rotations etc.). This all requires novel and flexible representations of landscapes and a shift away from uniform classifications based on dominant land cover types. Landscape ecology is in a good position to contribute to such novel representations and move beyond the level of individual landscapes. By better integrating the landscape into global scale assessments, landscape ecologists can make a contribution to global sustainability science and earth system governance (Gardner et al. 2008).

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