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Issues in using landscape indicators to assess land changes

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ABSTRACT

Landscape indicators, when combined with information about environmental conditions (such as habitat potential, biodiversity, carbon and nutrient cycling, and erosion) and socioeconomic forces, can provide insights about changing ecosystem services. They also provide information about opportunities for improving natural resources management. Landscape indicators rely on data regarding land cover, land management and land functionality. Challenges in using landscape indicators to assess change and effects include (1) measures of land management and attributes that are reliable, robust and consistent for all areas on the Earth do not exist, and thus land cover is more frequently utilized; (2) multiple types of land cover and management are often found within a single landscape and are constantly changing, which complicates measurement and interpretation; and (3) while causal analysis is essential for understanding and interpreting changes in indicator values, the interactions among multiple causes and effects over time make accurate attribution among many drivers of change particularly difficult. Because of the complexity, sheer number of variables, and limitations of empirical data on land changes, models are often used to illustrate and estimate values for landscape indicators, and those models have several problems. Recommendations to improve our ability to assess the effects of changes in land management include refinement of questions to be more consistent with available information and the development of data sets based on systematic measurement over time of spatially explicit land qualities such as carbon and nutrient stocks, water and soil quality, net primary productivity, habitat and biodiversity. Well-defined and consistent land-classification systems that are capable of tracking changes in these and other qualities that matter to society need to be developed and deployed. Because landscapes are so dynamic, it is crucial to develop ways for the scientific community to work together to collect data and develop tools that will enable better analysis of causes and effects and to develop robust management recommendations that will increases land's capacity to meet societal needs in a changing world.

1. Introduction

Landscape indicators are measures of the size, shape, and spatial juxtaposition of particular land types as well as the complexity and configuration of all land types within an area. The diversity of landscape indicators has been discussed in many papers (e.g., McGarigal et al., 2009; Mander et al., in this issue; Alhamad et al., 2011). Landscape metrics were developed to quantify changes in the composition and configuration of landscape elements (O'Neill et al., 1988; Turner et al., 2001) and to describe changes in landscape character (such as forest fragmentation) and functionality (Wascher, 2001).

When landscape indicators are used in combination with measures of land productivity, biodiversity, greenhouse gas emissions, and soil, water and air quality, they can provide a measure of environmental sustainability (e.g., Benedek et al., 2011; McBride et al., 2011; Shiels, 2011; Mouysset et al., 2012). When landscape indicators are combined with measures of physiological stress and condition, they can provide understanding of how alterations in the land influence species (Ellis et al., 2012). They also can help assess socioeconomic sustainability when combined with measures of profitability, employment, welfare, trade, energy security, natural resource accounting, and social acceptability (Di Giulio et al., 2009; Dale et al., 2012). Landscape indicators are useful for addressing questions about land availability and capacity for providing ecosystem services such as food, fiber, fuel, biodiversity, water as well as for urban and industrial development (Millennium Ecosystem Assessment – MEA, 2005)).

By evaluating how landscape indicators change over time and space, it may be possible to document changes in specific landscape services. Landscape indicators are sometimes applied to understand the causes and effects of those changes and to further understanding about such diverse phenomenon as climate change, disease spread, urbanization, exubanization, agricultural expansion, and other natural and anthropogenic disturbances. Such assessments are essential to understand and discern relationships

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among natural events that affect the landscape and anthropogenic influences, including land management.

This paper discusses some of the obstacles that remain in the development of landscape indicators and their use to assess and interpret changes in land character and functionality over time. Although standard approaches to calculate landscape indicators exist [e.g., using FragStats (McGarigal et al., 2000)], issues persist related to the underlying data, classifications, and the approaches used to assess change. This paper focuses on three issues. (1) Measurements of clearly defined land attributes that are reliable, robust and consistent are required, but this information is difficult to obtain for all areas on the Earth, and thus simplified land-cover classes are more frequently assessed but can be misinterpreted. (2) Multiple land-cover and land-management classes overlap and are constantly in flux, which complicates their measurement and interpretation. (3) Determining cause for change is complex and challenging. These issues make it difficult to measure land conditions and changes, and thus models are often used. The paper concludes with recommendations for improvements in approaches to apply and interpret landscape indicators.

2. Major issues related to using landscape indicators to assess land changes

2.1. Measures of land-management change are needed, but land cover is more frequently assessed

Clear definitions are critical in any analysis but are particularly important in using landscape indicators to assess change. One reason for this need is that many disciplines are engaged in assessing land-management and land-cover changes, and each has its own technical language. For example, the remote sensing and geospatial analysis communities may have one understanding of land-cover data and terminology while economists and other disciplines studying land-management change may interpret the same data differently or be unaware of corresponding uncertainty and assumptions. Another problem is that lay uses of terms often differ from technical usage. Finally, scientists are not always precise in their language. Some terms that have caused confusion among different groups interested in assessing changes in land cover and management are discussed below.

Land in itself causes confusion. Both landscape indicators and land changes usually refer not only to land areas but also to the water bodies they contain. Topography, variability among data sources, technologies and projection systems and differing orders of classification hierarchy can lead to significant differences in measured areas of land. Changes in sea and ice, coastal flooding, volcanic eruptions and other factors also lead to varying measures of total land area on Earth. The definition of “land” that is adopted here is “a part of the Earth’s surface that is used for a particular purpose” (Encarta Dictionary).

Land cover and *land use* are often confused. *Land cover* refers to the ecological state and physical appearance of the land surface based on a classification system (e.g., forests, grasslands, or savannahs) (Turner and Meyer, 1994). Change in land cover reflects a shift based on a defined classification, regardless of land use. Changes in land-cover classification can result from how data are interpreted or aggregated, the scale and order of analysis, as well as from actual physical changes that cross the threshold values that define a given land-cover class.

Land use refers to its human purpose (e.g., agriculture, pasture, forestry, or human settlements) (Turner and Meyer, 1994). Change in land use is not always concurrent with alteration in land cover and vice versa. For example, while primal forest reserves and plantations have different uses, both are categorized as forest land cover. Furthermore, recent clear cuts are classified as forest-land use, but satellite imagery and in situ inspection of such areas do not depict forested land cover. Additionally and perhaps more importantly, land use is often simplified to refer to a single primary human use of an area, and yet nearly all lands serve multiple human purposes simultaneously. Furthermore, even the primary purpose may change frequently or vary depending on how stakeholders are defined. Because “land use” is so subjective and ambiguous, alone it offers little value as an indicator.

Land management in this paper refers to human actions that affect land characteristics. Land management is sometimes described as the “how” associated with a land use. Land management associated with a given land cover or use can vary widely among types, intensities and technologies and their combined influences on land elements, attributes and functions. A review of the literature on “land-use change” identifies divergent definitions for “land use” and suggests that concerns are predominantly related to management effects on land attributes and functions. Land management can serve multiple uses. Some management tools, such as fire, can significantly affect land attributes and functions through either its suppression or its active use. While specific land-management practices can be shown to cause measurable changes in land attributes and functions over time, there is not yet consensus on detailed definitions to permit consistent classification of land management.

Understanding how human action (management) affects land’s capacity to provide services is vital, and yet land cover is more frequently assessed because of the many challenges in assessing land management (as discussed above). Land-management and land-cover data originate from different sources and inventory techniques. Data on historical and current land management often do not exist or are available only at coarse scales or for specified points in time, especially in developing countries. Misinterpretations of landscape indicators arise if users of the information do not realize the differences among data sources and measurement uncertainties (Lenz and Peters, 2006). Clear exposition of terms, sources, processing procedures and uncertainties is especially important whenever analysis involves estimating changes over time because the classes, definitions, instruments, technologies and procedures for collecting data are rapidly evolving. Thus, actual physical change in land cover or land management as measured at two points in time can be confounded by changes in data collection and processing.

Each source of data, whether from remotely sensed images or ground-based surveys, has its own domain of applicability and quality standards. Many changes in land qualities, management and use cannot be detected by land-cover data. Using remotely sensed land-cover data to calculate changes in use and management can lead to erroneous estimates of change and effects (Grainger, 2008) and misinterpretation of landscape indicators. It is not possible to identify the purposes (uses) and management systems being applied in a landscape based on satellite imagery alone. Attempts to do so can generate uncertain use classifications and misleading conclusions about change.

Land-cover data are commonly derived from remote-sensing images, surveys, or censuses (and those survey and census data are focused largely on highly valued activities or intensively managed areas). At the global scale, remotely sensed data collected using MODIS and Landsat technologies provide estimates of the extent of some cover types and changes in large aggregate classes such as a transformation from forest to cropland. However, those data cannot provide accurate estimates of changes among land-cover types that have variable canopy cover such as shrubland, savanna, and grasslands, nor can they assess many qualitative changes that may occur within a large class such as forest or agriculture lands. Interpretation of data can be confounded when large and

Table 1
Estimates of land area available for future agricultural expansion (including bioenergy expansion) without deforestation.

Source	Description	Low estimate (millions of hectares)	High or only estimate (millions of hectares)
Gallagher (2008)	Fallow agricultural land (low) and pasture with high ag potential (high)	150	1215
FAO (2008)	Potentially available for expanded crop production	250	800
Campbell et al. (2008)	"Abandoned agricultural land"	385	472
Cai et al. (2011) Table 2	Mixed crop and natural vegetation land with marginal productivity	320	1411
Bruinsma (2009)	Arable land not currently under cultivation		up to 2600
FAO-IIASA (2007) Table 4.7	Rural land suited for rainfed agriculture (good to marginal suitability classes, assuming 1600 in current use)	1683	3743

significant changes occur within a class and go undetected while small changes that cross a threshold are interpreted as class transformations. And remotely sensed data have no ability to identify and assess the wide variety of multiple uses of land by local people.

In addition, the utility of land-cover data derived from remote-sensing imagery is limited by the use of different sensors over time, changing classification schemes over time, and alternative definitions of land-cover classes among regions and data products. Improved technologies may provide more comprehensive or meaningful information pertinent to landscape indicators. The accuracy of global-scale land-cover data varies due a number of factors (Friedl et al., 2002, and http://www-modis.bu.edu/landcover/userguidelc/consistent.htm). The Millennium Ecosystem Assessment (MEA, 2005) noted a lack of reliability and high variability in satellite-based estimates of total cropland (cultivated systems) at global scales. MODIS and other global land-cover products are limited in their ability to provide accurate assessments of the extent of underutilized and "marginal" lands (much less the degree of underutilization of such areas) (Wardlow and Egbert, 2008).

"Marginal" lands are defined economically as areas that generate little profit; yet they often provide critical provisioning and sustaining services to local people as well as ecosystem services of value to wider populations. Considerable uncertainty exists about the size and characterization of "marginal" land areas. Hence interpretation of landscape indicators pertinent to this important category is particularly troublesome. Areas of "idle" and "marginal" croplands are often reported to be pasture and can range from 210 million to over 2 billion hectares globally (Monfreda et al., 2008; MEA, 2005, respectively). In Table 1, data are summarized from a variety of analyses examining land available and suited for agricultural expansion without requiring deforestation. Estimates depend on assumptions and methods used and range from a low of 150 million hectares if focused only on the recuperation of abandoned agricultural lands to over 5 billion hectares if extensive areas of grassland and pasture are considered among lands offering opportunities for expanding or intensifying agricultural production.

The studies of land available for agricultural expansion (Table 1) highlight another common issue affecting land assessments, *masking*, which refers to the need to define what land areas and land types are excluded from an analysis (Verburg et al., 2004; Heistermann et al., 2006; Rindfuss et al., 2008). For example, most studies looking at potential for agricultural expansion begin by eliminating areas assumed to be "in use" for other purposes such as urban and protected areas, as well as lands assumed to be unsuited for agricultural production based on assumptions and criteria related to factors such as soils, slope, climate, technologies and tenure. Projects that focus on forestry or agriculture may omit information pertinent to landscape indicators if they do not consider urban forests or urban agriculture, for those areas can contribute greatly both to ecosystem processes such as carbon flux (Nowak and Crane, 2002) and to socioeconomic sustainability such as food security (Madaleno, 2002). A majority of the Earth's population have now moved to urban areas bringing agroforestry practices with them; however urban areas are usually masked out of analyses of forest and agriculture areas. Many changes that occur in small areas or that occur within a class may be significant but are often masked out of an analysis either explicitly or as a result of data resolution, processing or aggregation procedures. Masking is an important topic to change analysis because areas assumed to have no effects may experience significant alterations and implications and thus affect landscape indicators and their interpretation.

The *classification* of land-use categories to which indicators are applied is an important topic in itself. It determines what land-use types can be considered (e.g., are both active and idle cropland considered to be in agriculture land use?) but inevitably depends on human interpretations of classifications across highly divergent cultural systems and levels of data quality (e.g., idle cropland may be alternatively classified as pasture, grassland, shrubland, or immature forest). In recent decades, the technologies used to collect data and the methods applied to assign land-cover classes have been in constant evolution. Misinterpretations of land indicators can occur as a result of changing classification schemes over time.

How the land-management type is determined also affects its categorization; for example, satellite imagery cannot detect differences between intended land uses such as fallow crop land, natural grassland reserve, pasture, land held speculatively for non-agricultural development, and some newly planted crops. This problem underscores the limitations of "land use" categories without further specifying management and other land attributes. While satellite data have been used to measure changes in area for basic land-cover types such as forests, other factors, such as forest structure and density, may correlate stronger with changes in total biomass and other ecosystem attributes than do forest area (Rautiainen et al., 2011). Furthermore, landscape indicators derived from remote-sensing data may not provide adequate information to guide decisions to address concerns about the loss of biodiversity, increases in carbon release, and reduced ecosystem services when landscapes are changed by repeated use of fire, and yet fire is the most pervasive form of land management in the world (MEA, 2005).

2.2. Poor understanding of ongoing changes in land cover, use and management

The constant flux in land cover, use and management requires care in interpreting changes in landscape indicators. Multiple influences on change may be occurring simultaneously at different spatial and temporal scales, and some of these changes occur in cycles. Thus, any change analysis is highly dependent upon the specific points or ranges in time and space selected for analysis. For example, a land-cover change from type A to B may be identified in one analysis but may be occurring in a regular cycle and identified as a change from type B to A in the same place but over a

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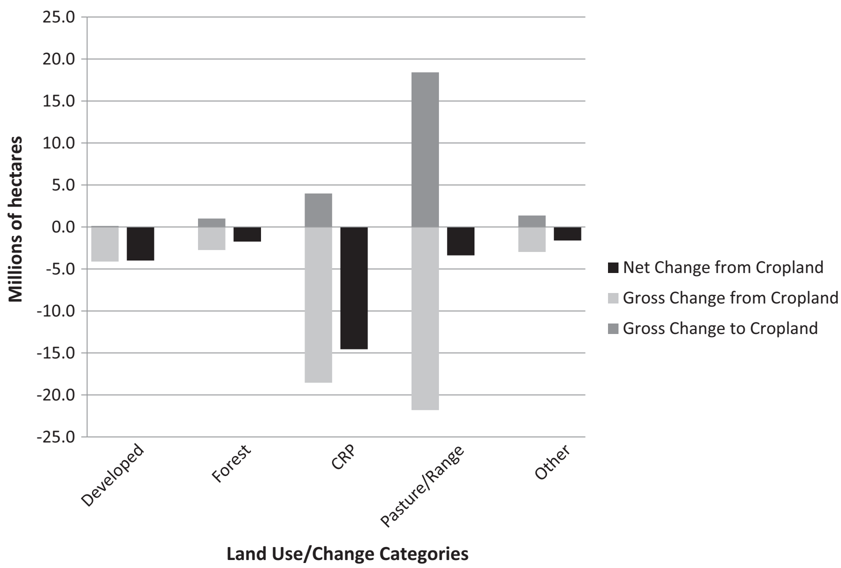

Fig. 1. Net and gross land-class change in the United States associated with cropland, based on the National Resources Inventory (NRI) from 1987 to 2007 (USDA, 2009). Gross change refers to total gross change measurable within the limitations of NRI's 5-year intervals. For example, if a given parcel of land is cropland in 1992, forest in 1997, and cropland again in 2002 and 2007, its area appears twice reflecting the two changes in the bars corresponding gross change from cropland to forest and gross change from forest to cropland (in this example, there would be zero net change). For this figure, NRI's "Pastureland" and "Rangeland" are combined as "Pasture/Range," and NRI's "Other rural land" and "Water areas & Federal land" are combined as "Other." CRP refers to land in the Conservation Reserve Program, and the maximum amount of CRP land is established by the U.S. Farm Bill. Note that for the period from 1987 to 2007, all net changes were associated with cropland losses to other land-use classes.

different time period. A longer time horizon for analysis may show no net change in land cover, even though significant alteration in other characteristics of the landscape may have occurred due to the cycles and total gross change. Gross changes are typically larger and can have greater effects than net changes, yet most analyses focus on net changes (Lubowksi et al., 2006 and Fig. 1). Furthermore many analytical approaches do not allow for reversibility (i.e., the ability of a land-cover type or use to revert back to a prior class or category). Instead, they assume change is unidirectional. As a result many ongoing changes among land classes can be overlooked. This problem has occurred frequently in analyses of forest cover, when areas that are classified as changing from forestry to another use are then masked out of further analysis even though they may revert to forestry after a disturbance. A similar example occurs in some interpretations of changes in the land in the U.S. Conservation Reserve Program (CRP). U.S. Congressional authorizations constrain the types and total area of land eligible for CRP programs. Each new Farm Bill provides new guidelines and funding levels that lead to new terms and requirements for participation. Thus, land is constantly being added to and retired from CRP and related land conservation programs. Analyses focusing only on retiring lands or single program elements often raise concerns about loss of environmental benefits of retiring CRP land but rarely consider the full range of effects from other additions or subsequent use of retired land (Dale et al., 2010).

The gamut of ongoing changes in land cover, use and management requires precise definitions and accurate information to describe the baseline conditions being considered. Baseline refers to conditions at a particular place and time, taking into account the trends that reflect rates, directions, cycles and momentum of ongoing changes. Change is then measured as a divergence from the baseline conditions. However because of the historic and current range in variability in conditions (e.g., Allen et al., 2002), a baseline is a static representation of dynamic events. Results of any change analysis are highly sensitive to the choice of baseline and how it is defined. Baseline conditions should account for natural variability and provide a means to assess effects of short-term events (Hardman-Mountford et al., 2005; Strömquist et al., 1999) as well as historical trends and context. The landscape indicators should be calculated and interpreted at spatial and temporal resolutions appropriate for the process, event or effect being assessed. Baseline conditions can be used to develop a "business as usual" case for comparison to new or different activities that are being assessed. An analysis of indicator values for the business as usual case as compared to changed conditions should reveal effects of those changes. Sometimes when starting values of indicators are not available, baseline conditions are measured in reference areas that are thought to be similar to prior land conditions. Appropriate interpretation of most derived indicators requires that reference areas be nearby in order to ensure similar weather, topography, soils, vegetation potential and socio-economic conditions.

Focusing on ongoing changes also requires defining the scale at which those changes are considered. Both the temporal and spatial extent and resolution determine how change can be assessed. The extent of the analysis defines the length of time and the size of the region for which land changes are measured. Temporal extent may be on the order of minutes, days, years, decades, or centuries, and spatial extent may be for local areas, regions, nations, continents, or the entire world. Both the extent and resolution for any assessment depend on the characteristics of available data and questions being addressed [and those questions define the extent as well as other aspects of the context being considered (Efroymson et al., 2013)]. All of these aspects of a change assessment affect interpretation of the landscape indicators. For example, assessment of land-management decisions typically focuses on local areas or regions and a decade or less because most decisions are made at a local level and with a relative short-term perspective (Dale et al., 2000). At the other extreme, questions about causes of increased atmospheric CO_2 concentration and subsequent climate change focus at the global scale and over decades or longer.

Data resolution determines the level of detail at which interpretation of landscape indicators can occur. While greater resolution provides more details, that information is not always necessary. The appropriate resolution for analysis ideally includes one step lower and one above the scale at which major processes operate or the questions being addressed (O'Neill et al., 1986). For example, to use landscape indicators to assess changes that occur over a season, daily data are appropriate for the lower temporal resolution and annual data may provide an upper limit. Spectral resolution of the satellite imagery underlying landscape indicators can significantly affect maps as well as indicators and their interpretation (Vannier et al., 2011).

2.3. Determining causes of change in land attributes is complicated and challenging

The interpretation of landscape indicators is affected by the complexity of interacting factors that make determining attribution of the causes for change difficult, if not impossible. Identifying causes requires consideration of a large number of potential drivers that operate at different scales, and, in most situations, it is impossible to attribute land-cover changes to a single cause. Changes reflect relationships and feedbacks among many anthropogenic and natural events. Furthermore, natural and human systems interact in ways that may intensify or mitigate effects over time (e.g., as with fire). Indeed, when Europeans colonized the Americas, few realized that the landscapes encountered were a product of centuries of management using fire. And later, when policies were applied to control and prevent fire in the U.S., few public officials realized that these efforts would lead to fuel accumulation and more intense, destructive and uncontrollable future fires.

Important drivers of change affecting landscape indicators include governance capacity, population change, land-tenure regimes, macroeconomic and trade policy, environmental policy, infrastructure, land suitability, domestic and international markets, climate conditions, technology, poverty, cultural beliefs and many others that may be highly specific to localized situations (Allen and Barnes, 1985; Lambin et al., 2003). Yet without an understanding of the cause of change, the landscape indicator is merely a descriptor with limited value for analysis. This problem can be addressed by reporting changes not only in the landscape indicator but also in potential drivers of change. For example, it is useful to know about changes in governmental policies, affluence, transportation systems and other infrastructure, human population, extractive industries, environmental regulations, tenure customs, etc. Such information should be provided at the same spatial and temporal scale and with identical baseline conditions as the land change is reported. For example, Yang et al. (2012) related landscape indicators on patterns in land-cover types to erosion rates by also having information on rainfall, topography, sources of sediment, and flow length in the subwatersheds as well as soil conservation practices in each land-cover type.

Furthermore, the predominant drivers of *initial* land transformation differ from the primary causes of *subsequent or ongoing* changes (Dale and Kline, in press; Fig. 2). Yet this difference is rarely noted when assessing change and applying indicators. *Initial transformation* refers to occupation and purpose-driven change of attributes that convert a landscape dominated by natural systems to one dominated by disturbance and appropriation of resources by humans. The few large areas that remain in natural and mostly undisturbed conditions tend to be located in inaccessible or inhospitable regions or are protected (Miles et al., 2006). For example, much of the Amazon rain forest and many national park lands contain lands with minimal disturbance. However, even landmark protected areas such as the Great Smoky Mountain National Park in the United States are predominantly composed of landscapes in various states of secondary growth and recovery under management for a different set of services than those desired when initial transformation took place. *Initial* conversion is a key concern and often results in large impacts on biodiversity and ecosystem services. Therefore it is important to understand the specific factors that determine if and where initial transformation takes place.

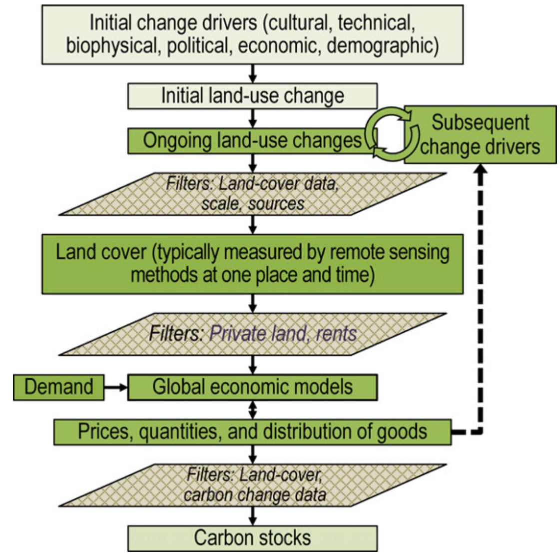

Fig. 2. Flow chart reflecting drivers and data sets associated with typical analyses of land-use changes (adapted from CBES, 2010). Cultural, technical, biophysical, political, economic, and demographic forces are prime drivers of *initial* transformation. Transformed land subsequently experiences ongoing changes as a function of those drivers along with influence from economic forces as productive systems are increasingly integrated with global markets. How changes in land cover and mangement are measured and interpreted is filtered by (1) the types and scales of land-cover data that are available and (2) the fact that global economic forces are modeled based on assumptions about private land ownership and management to maximize rents. Other filters may be applied depending on the model and the objectives of analysis. For example, when the output of global economic models are used to estimate changes in carbon stocks associated with land-use change, global land is grouped into a limited number of simple classes or ecological zones with assumed productivity and carbon stocks that reflect averages of estimates or aggregated values.

Ongoing land-use change (Fig. 2) occurs when areas previously subjected to anthropogenic disturbances are further altered by human activities. Ongoing change may include a process of adaptation and “improvement” (e.g., plots burned and planted among ashes and stumps transitioning to pasture, to planted pasture, to cultivated row crops, and to irrigated row crops). Or ongoing land-use change may involve secondary conversion following long fallow periods between short periods of active management. The social, economic and political drivers that determine first time transformation, e.g. *if* land is occupied and cleared, are distinct from those that determine ongoing land-use changes reflected by management and use decisions *after* land was cleared (Fig. 2). Changing market opportunities influences what crops are grown at any particular point in time after land is brought into production but may have had little bearing on the local forces related to land claims, tenure, road infrastructure and colonization policies that often determine if a parcel of land is initially cleared.

Most economic models are driven by relative prices, supply and demand associated with capital, labor and availability of natural resources. Land is outside the model and only enters the equation as a factor that generates rent and, therefore, reflects effects of *ongoing land-use change*. Indeed, most economic models begin with assumptions about private ownership and access to markets and price information that are not applicable to conditions when and where initial transformation occurs. Effects of ongoing land-use changes on biodiversity and ecosystem services largely depend on the status of the system before a change takes place (reflecting baseline conditions and business as usual cases) compared to the conditions after the change. Ongoing land-use changes typically alter management practices. If new market opportunities allow for investment in improved equipment and technologies, the land-use

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change may reduce or eliminate the use of traditional management approaches involving fire. Hence to address such situations, it is essential to report not only the changes in the landscape indicators but also the baseline conditions against which the change is being measured.

The attempt to identify the role of biofuels in land-use changes in the Brazilian Amazon provides an example of the complications of determining attribution for first time land transformation and hence the difficulty of interpreting changes in landscape indicators for those cases. Sixteen field-based regional and local studies in the Brazilian Amazon suggest that deforestation (initial transformation) is predominantly a result of four policy-driven forces:

(1) Regional economic opportunities and credit [cattle ranching (Brown et al., 2005; Morton et al., 2006), crop profitability (Jones et al., 1995), or emerging urban markets in the Amazon (Browder and Godfrey, 1997)].
(2) Transportation infrastructure [roads (Laurance et al., 2001, 2002; Nepstad et al., 2001; Alves, 2002; Kirby et al., 2006)].
(3) Political and social forces [national colonization programs (Carvalho et al., 2002), migration (Perz, 2002a,b), or life-cycle of households (Walker et al., 2002, Moran et al., 2003)].
(4) Environmental and social conditions [lot size, land-use history, and land-use choices (Dale et al., 1993; Moran et al., 2002)].

Furthermore, Scouvart et al. (2007) conducted causal analysis of seven local case studies at three time periods within the same region of the Brazilian Amazon using a meta-analysis approach. A major result of their study is that deforestation in the Brazilian Amazon cannot be explained by any one single dominant factor or by simple causal patterns. They find that primary drivers of deforestation are roads combined with biophysical conditions and the occurrence of local and regional activities. The main biophysical constraints are soil conditions and the length of the dry season that may favor agricultural expansion. Local and regional activities include extractive enterprises for timber and minerals as well as local development programs aimed at building economic growth associated with livestock and agriculture. These local and regional activities involve investments in infrastructure that facilitate occupation. Put simply, if land with good productive potential is made accessible and if government policy or local customs recognize land claims based on "improvements" that begin with clearing, then deforestation will occur. The drivers observed along active deforestation frontiers around the globe today are not so dissimilar to those that led to the initial transformation of more than one million square kilometers of land in the US under the "Homestead Act" that offered free land to settlers willing to occupy and "improve" the native landscape.

In contrast to the causal analysis studies referenced above, attempts to attribute deforestation in the Brazilian Amazon to a simplified indicator such as biofuel expansion have been based on correlation and lack causal analysis (e.g., Barona et al., 2010). Even with this lack of evidence, many analyses incorrectly assume that biofuel use induces deforestation (e.g., Djomo and Ceulemans, 2012) or, more broadly, that deforestation can be explained simply by observing what appears to replace forests after an initial transformation is identified.

The studies of initial transformation in the Amazon illustrate three cautionary principles when applying landscape indicators to assess effects: (1) correlation does not imply causation; (2) documenting and understanding drivers and effects of initial transformation (or direct land-use change) is a required prerequisite to understanding and estimating the role of indirect effects; and (3) there needs to be a causal analysis to support plausible linkages between direct and indirect changes. While some indirect effects on land-transformation trends can be estimated, they often have large and irreducible uncertainties (CARB, 2010), particularly since indirect effects often involve offsetting forces that may influence an indicator in both directions (positive and negative). Addressing causes of changes in landscape indicators requires adopting an interdisciplinary approach, considering alternative theories, and obtaining and using sufficient data to test model assumptions and projections. Having a good understand of the underlying causes of land change is essential to being able to interpret the landscape indicators that describe those changes.

3. Modeling land change

Because of the complexity, sheer number of variables, and limitations of empirical data on land changes, models are often used to illustrate and estimate values for landscape indicators, and those models have several problems. Current efforts to model changes in land management and land cover are limited by the availability of appropriate data sets and lack of knowledge on attribution, which leads to estimates being constrained by model assumptions (Kline et al., 2011). In addition, data are often used for modeling without explicitly considering the suitability of the data for the specific application and the potential bias that originates from the data inventory and editing. For example, when models mix data from different sources to assess change for a large area, the differences between those data are often ignored, and the uncertainties become impossible to quantify.

There is consensus that current models are incapable of adequately representing the social, economic, and environmental causes and effects of land-use changes (CBES, 2010). A series of international meetings, workshops, and proposed rules and regulations have underscored that policies requiring consideration of indirect LUC in environmental assessments lack the scientific support to understand and estimate such effects (Zilberman et al., 2010; Kline et al., 2011). There is growing consensus in the scientific community that current modeling approaches have unacceptably large uncertainties, fail to adequately incorporate the drivers behind initial land transformation, and must be improved (Oladosu et al., 2011). The types and sources of uncertainties need to be identified and characterized in order to address causes and effects. Classification systems need to be more robust and responsive to research needs. And modeling should consider the different ways that land can be managed to provide multiple services for stakeholders, including provision of food, feed, fiber, fuel, and a place to live, work, recreate, and protect ecosystem services.

4. Recommendations for addressing issues in using landscape indicators to assess land changes

Steps are described below to address the three issues raised in this analysis, i.e., that (1) simple land-cover classes are frequently assessed in lieu of analyses based on multiple data layers measuring land attributes at appropriate resolutions of how human activities affect landscape indicators and functionality, (2) documenting ongoing changes in land requires systematic measures of land management over time, and (3) causal analysis of land change is limited (Fig. 3). These steps lead to a proposed analysis framework (Fig. 3) designed to clarify the questions, approach, and causes of changes in landscape indicators. First the questions should be refined to reflect a scope that can be addressed based on available information, for too often unanswerable (but interesting) question are posed. This refinement should set clear and justified boundaries for the time period and place to be analyzed. Second, the analytical approach selected should fit the questions. Analysis tools such as regressions, transition models, or simulations may be employed and should consider spatial configurations and

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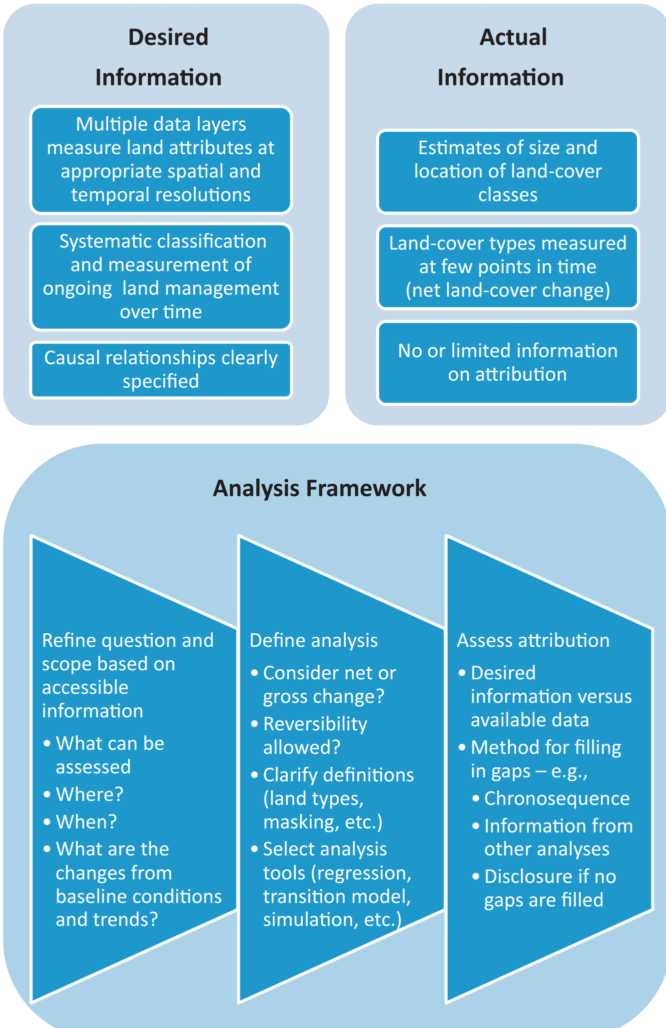

Fig. 3. The difference between actual and desired information on land changes leads to a new analysis framework. The approach is targeted to assess the causes for changes in land cover and management, effects on land attributes, and how these relationships guide intrepretation of landscape indicators. The framework emphasizes the need to refine the question based on what can be assessed and the spatial and temporal characteristics of available information. The analysis specifies the types of change considered (e.g., gross, net, reversible), defines key terms, and justifies a selected approach. In contrast to this framework, too often the analysis tool is selected first and then an attempt is made to mold the questions and available information to fit that tool. Since the framework focuses on a key weakness in current land-change analysis, attribution, the final step is to assess how available data inform causal analysis. Since there are always disparities between desired information and available data in such analyses, it is important to note if gaps are addressed, and, if so, what approach is used. Hence the question, analysis approach, and ability to assess causes of land changes all affect the interpretation of the landscape indicators.

relationships. Finally the attribution of changes in landscape indicators should be assessed by considering available information as well as ways to address its gaps. There are several approaches available to deal with the challenge of understanding changes over long time periods. For example, a chronosequnece approach assumes that different places experienced identical pressures over time (e.g., Osland et al., 2012). In other cases the attribution may rely solely on results from another study (and then the difference between the two situations should be made clear). Too often, there is no attempt to fill in missing attribution information, and the absence of causal analysis is not discussed.

Landscape indicators need to be related to accurate and robust geospatial data on socioeconomic conditions, management practices and ecosystem attributes such as carbon stocks, nutrient cycling, water and soil quality, net primary productivity, habitat and biodiversity. These attributes and ecosystem characteristics should be measured in a consistent and repeatable manner over the time period and spatial extent pertinent to the issue being considered. There is great potential to manage landscapes more efficiently that would enhance multiple services, but at the present time there are insufficient data to test hypotheses about effects of land-management alternatives. For example, having relevant geospatial data over time could help guide management that supports the capacity of the land to provide improved ecosystem services such as flood control and drought mitigation. Better data could help us develop recommended management practices that increase the ability to sequester carbon while simultaneously improving other ecosystem services such as food provision and clean water (Lal, 2010).

At the same time, standardized definitions and methods are needed to describe and measure management practices and their effects, including information on their duration, extent and intensity. For example, energy and raw materials used to support land preparation, depth and timing of tillage, other cultivation activities, harvest and extraction of resources, and other management practices should be documented in order to assess how these activities can influence change in landscape and ecosystem indicators (Grainger, 2009). Well-defined and robust classification systems with appropriate detail in the scale of analysis are necessary for consistent application of landscape indicators and measures of change over time.

Use of landscape indicators also requires clarity in specifying the assumptions, scales, hierarchy, masking, sources and baseline conditions associated with the data being utilized. The goals and context of the analysis determine data requirements.

Current land-change models need improvements (CBES, 2010) to apply and interpret landscape indicators. Interactions and feedbacks both within and between the social, environmental, and other model components are poorly represented. Uncertainties associated with design assumptions, scenarios, combining data from different scales, and the results of sub-models should be more clearly disclosed, quantified and reduced. Global equilibrium models require better representation of regional drivers of initial transformation and subsequent changes in land cover and management. Furthermore, models should be validated and calibrated for the particular land-use change effects being estimated. Land modeling efforts could be improved by the availability of long-term, fine-scale, multi-dimensional data sets that contain the social, economic, environmental, cultural and political factors that influence land use. These models could then provide some understanding of the causal factors of land-use change that is necessary to interpret landscape indicators derived from their projections.

Addressing the many issues associated with developing and applying effective landscape indicators is difficult. A priority for the scientific community is, therefore, to increase the level of collaboration and work toward consensus in definitions and methodology. For example, one goal could be having field experts contribute to conceptual frameworks of land change in particular situations that identify which drivers "cause" *initial* transformation versus the contributing factors that may accelerate or diminish the pace of conversion. Another priority would be the acquisition of consistent and reliable inventories of land attributes, uses and management practices that would permit land-change analysis at local, regional, and global scales. A third priority could be to develop or adopt modeling approaches that better represent issues of initial transformation, ongoing change dynamics, and how policy options interact with the driving forces of change for specific cases, rather than relying on available models developed for different purposes that

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lack the ability to assess and attribute causes of changes. Because landscapes are so dynamic, it is crucial to determine ways for the scientific community to work together to collect the data and develop the tools to better assess, understand and communicate how land management affects landscape indicators and to suggest alternative management practices to meet the evolving needs of society in an ever-changing world.

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