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Corresponding Author: Dr. Virginia Dale, Ph.D.

Corresponding Author's Institution: Oak Ridge National Lab

First Author: Virginia H Dale, PhD

Order of Authors: Virginia H Dale, PhD; Keith L Kline

Abstract: Landscape indicators when combined with information about environmental conditions (such as habitat potential, biodiversity, greenhouse gas emissions, and erosion) can provide useful insights about changing ecosystem services. They also provide information about opportunities for humans to use natural resources as well as implications of that use. Landscape indicators rely on data regarding land cover and land use. There are three major challenges in using landscape indicators to assess land change and effects. (1) Measures of land-use change that are reliable, robust and consistent for all areas on the Earth do not exist, and thus land cover is more frequently utilized. (2) Both land cover and land use are constantly changing, which complicates their measurement and interpretation. (3) While causal analysis is essential for understanding and interpreting changes in indicator values, determining causes of land-use change is particularly challenging. These three issues lead to the need for land modeling, which produces results that vary depending upon assumptions, input data, and modeling approach. Recommendations to improve our ability to assess land-use change and effects include the development of data sets based on systematic measurement over time of spatially explicit land qualities that matter to society, such as carbon stocks, nutrient cycling, water and soil quality, net primary productivity, habitat and biodiversity. In addition, standardized means of measuring management practices and their intensity are needed. Well-defined, robust and consistent land classification systems need to be developed, adopted, and deployed. The assumptions, scales, any masking, and baseline conditions of the underlying data should be clear. Because landscapes are so dynamic, it is crucial to develop ways for the scientific community to work together to collect the data and develop the tools to be able to assess landscape effects and suggest ways to improve management of resources.

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Dr. Virginia H. Dale
Environmental Sciences Division
Phone: 865-576-8043
Fax: 865-576-8543
Email: dalevh@ornl,gov

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Ecological Indicators
Prof. Dr. Felix Müller
Institute of Nature and Resource Conservation
Dept. of Ecosystem Management
Ecology Centre
University of Kiel
Olshausenstrasse 75
D 24118 Kiel

Dear Editor,

I am submitting a manuscript to *Ecological Indicators* as part of an Invited Feature on "**10 Years ECOLOGICAL INDICATORS**" to celebrate the 10th anniversary of our journal. Our paper is titled **Issues in using landscape indicators to assess land changes** and the authors are Virginia H. Dale and Keith L. Kline of the Environmental Sciences Division at Oak Ridge National Laboratory.

Thank you for the timely review of this manuscript.

Sincerely,

Virginia Dale
Corporate Fellow

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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 a landscape. The diversity of landscape indicators has been discussed in many papers (e.g., Mander et al., 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 and functionality (Wascher, 2001). When landscape indicators are used 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). They also can be used to assess socioeconomic sustainability when combined with measures of profitability, employment, welfare, trade, energy security, natural resource accounting, and social acceptability (Dale et al., in prep). By evaluating how landscape indicators change over time and space, it may be possible to document changes in specific landscape services. The ultimate utility of these indicators is to understand the causes and effects of those changes. Such assessments are essential to understand how natural and anthropogenic events affect the landscape and how management practices can influence those changes.

Landscape indicators are useful for addressing questions about the use and availability of the land for providing ecosystem services such as food, fiber, fuel, biodiversity, water as well as for urban and industrial development [Millennium Ecosystem Assessment (MEA, 2005)]. Although standard approaches to calculate landscape indicators exist (McGarigal et al., 2000), some issues related to the underlying data described above remain unresolved. Knowledge about land changes is essential to such diverse phenomenon as understanding drivers and implication of

climate change, disease spread, urbanization, exubanization, agricultural expansion, and other natural and anthropogenic disturbances. These indicators are also useful for understanding and defining opportunities to conserve and improve ecosystem services.

This paper presents major obstacles that remain in the development and deployment of landscape indicators and their use to assess land changes. To simplify the language, we use the term “land-change indictors” to refer to this process. Major issues related to land-change indicators are (1) that there is need for measures of land-use change that are reliable, robust and consistent, but this information is difficult to obtain for all areas on the Earth, and thus land cover is more frequently assessed, (2) the fact that both land cover and land use are constantly in flux, which complicates their measurement and its interpretation, and (3) that determining causes of land-use change is complex and challenging. These issues make it difficult to measure land conditions, and thus models are often used. The paper concludes with recommendations for improvements to provide more empirical knowledge on which to base future land-change indicators are interpretations.

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

2.1 Measures of land-use 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 land changes. One reason is that many disciples are involved in the topic, and each has its own technical language. Another reason is that lay uses of terms may differ from technical uses. Finally, scientists are not always precise in their language. Some of the most often confused terms 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. Changes in sea and ice, coastal flooding, volcanic eruptions and other factors lead to varying measures of total land area on Earth. Thus 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), and change in land cover reflects a shift based on a defined classification, regardless of its use. Changes in land cover classification can result from how data are interpreted or aggregated, as well as from physical transformations that may be a result of human activities or natural events, such as a volcanic eruption. One of the challenges in attributing changes to anthropogenic versus natural events is that some phenomena, such as fire, can be instigated by a variety of factors that run the gamut from being fully natural to being entirely human instigated and include everything in between, with natural and human systems interacting in ways that may intensify or mitigate the observed effects.

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 (but aspects of this distinction depend on the details in the categorization). For example, both primal forest reserves and plantations might be categorized as forest land cover. Furthermore, land that has recently been clear cut and that is planned to be used for silviculture would remain forest in terms of land use, but satellite imagery would depict a change in land cover. Hence it is difficult to identify land use based on satellite imagery alone. Land use is commonly simplified to refer to its primary human use, but in actuality, any given

land area may have multiple simultaneous uses for different groups of people as well as other species.

Land-use and land-cover data originate from different sources and inventory techniques. Historical data on actual land uses (rather than land cover) often does not exist or are available only at coarse scales or for specified points in time especially in developing countries. Most common land-cover data are derived from remote-sensing images and survey or census data, with census and survey data focused largely on high valued activities or more intensively managed areas. At the global scale, remotely sensed data collected using MODIS and Landsat technologies provide estimates of changes in the extent of some cover types (such as large areas that converted from forest to cropland) but do a poorer job with providing accurate estimates of changes among land-cover types that have more variable canopy cover such as shrubland, savanna, and grasslands. 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). Remotely sensed data have a limited ability to discriminate mixed classes characterized by a mosaic of trees, shrubs, and herbaceous vegetation.

Each source of land-use and land-cover data, whether from remotely sensed images or ground-based surveys, has its own domain of applicability and quality standards. Many changes in land use, qualities and management cannot be detected by land-cover data, which may lead to an erroneous estimation of change and effects (Grainger, 2008). 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 more limited in their ability to provide accurate assessments of the extent of underutilized and “marginal” lands (much less the degree of underutilization in such areas).

Considerable uncertainty persists about the size and characterization of "marginal" land areas. The estimates of "idle" and marginal croplands are prone to confusion with pasture and can range from 210 million to over 2 billion hectares globally (Monfreda et al., 2008, and MEA, 2005, respectively). Furthermore, marginal lands often provide critical services and value to poor people.

Data derived from satellite imagery such as MODIS have several limitations. For example, satellite data have been used to measure changes in area for basic land-cover types such as forest, but Rautiainen et al. (2011) point out that other factors, such as forest structure and density, may correlate stronger with changes in total biomass and other ecosystem attributes than the simple measure of forest area. In addition to only estimating one dimension of change, the utility of land-cover data is limited due to the use of different sensors over time, the use of varying classification schemes between years, and the use of alternative definitions of land-cover classes among regions and data products. Improved technology may provide more comprehensive or meaningful information.

The classification of land-use categories is an important topic in itself. It addresses 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 definitions across highly divergent cultural systems and levels of data quality. How the land-use type is determined also affects the categorization; for example, satellite imagery cannot typically detect differences between different land uses (such as between fallow crop land, natural grassland reserve, pasture, and some newly planted crops). Furthermore, misinterpretations of land indicators can occur if the classification scheme changes over time.

Measures of land-use change are needed to understand human and natural effects on the land, but land cover is more frequently assessed because of problems in assessing land use mentioned above. Misinterpretations of the landscape indicators arise if users of the information do not realize the differences among data sources and uncertainties in the measurements of land use and land cover (Lenz and Peters, 2006). Clarification of terms and uncertainties are especially important whenever analysis involves estimating changes over time.

The Millennium Ecosystem Assessment (MEA, 2005) noted that the majority of the world's agricultural land is used extensively, leading to fallow rotations that can vary from a single year to decades between periods of cultivation. Fire is the most common land management tool on these extensive agricultural lands and in less-developed nations. These anthropogenic fires often spread unabated to surrounding forest reserves and wild lands. There is concern over the loss of biodiversity, increases in carbon release, and reduced ecosystem services when landscapes are changed by repeated use of fire, but landscape indicators may not provide adequate information to guide decisions to address such concerns.

2.2 Ongoing changes occur in both land cover and land use

A focus on change implies consideration of dynamics in time and space. Hence there is a need to define baseline conditions and the temporal and spatial scale being considered. Baseline refers to the conditions at a particular place and time. Change is then measured as a divergence from the baseline. 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 capture natural variability and short-term events (Hardman-Mountford et al.,

2005; Strömquist et al., 1999) as well as historical trends and context. Baseline conditions are used for comparison to new or different activities that would not have occurred in the "business as usual" case. An analysis of indicator values for the baseline as compared to changed conditions should reveal marginal effects of those changes. Sometimes when initial values of indicators are not available, baseline conditions are measured in reference areas that are thought to be similar to prior land conditions. These reference areas are typically nearby in order to ensure similar weather, topography, soils, and potential vegetation.

Focusing on change also requires defining the scale at which those changes are considered. Both the temporal and spatial extent and resolution determine how change is 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 question being addressed and characteristics of available data. For example, assessment of land management decisions best focus on local areas or regions and a decade or less because most land-use 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. Thus the questions being addressed often define the extent as well as other aspects of the context being considered (Efroymson et al., in review).

Resolution is also an important component of scale, for it determines the level of detail. While greater resolution provides more details, that information is not always necessary. The appropriate resolution for analysis is ideally 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, if there is interest in changes in photoperiod response that occur over a season, then daily data are the most appropriate lowest temporal resolution. Spectral resolution of the satellite imagery underlying landscape indicators can significantly affect maps as well as indicators and their interpretation (Vannier et al. 2011).

Masking 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, some projects that focus on forestry or agriculture leave out part of the story if they do not consider urban forests or urban agriculture, for those areas can contribute greatly 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. This masking topic is important to change analysis because areas assumed to have no effects may experience significant alterations.

There are several characteristics of landscape indictors and the ways they are used that make assessing land changes problematic. Reversibility is the ability of a land cover type or use to revert back to a prior class or category, but some analytic approaches do not allow this possibility. Instead, they assume change is unidirectional. Furthermore, many ongoing changes among land classes are overlooked because of the focus on net change between two points in time. However gross changes can be larger and have greater effects than net changes (Lubowski et al., 2006, and Figure 1).

2.3 Determining causes of land-use change is complicated and challenging

Determining causes of land-use change is complicated, for it requires consideration of a large number of potential drivers that operate at different scales. Important drivers include governance capacity, population change, land tenure regimes, macroeconomic and trade policy, environmental policy, infrastructure, land suitability, domestic and international markets, climate conditions, and many others (Allen and Barnes, 1985; Lambin et al., 2003).

Furthermore, the predominant drivers of *initial* land-use change often differ from the primary causes of *subsequent, ongoing* changes (Figure 2). Yet this difference is not always made clear. *First time conversion* occurs when areas that were heretofore undisturbed by anthropogenic actions are changed by human activities. The only areas left on Earth in such 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 national park lands in the United States contain undisturbed lands. These undisturbed lands are not part of regional or global economic systems and thus are considered in economic terms as being *hollow* (i.e., having no value) (Rudel, 2002). First time conversion is a key concern and often results in large impacts on biodiversity and ecosystem services. *Secondary conversion* occurs when areas previously subjected to anthropogenic disturbances are further altered by human activities. Most economic models focus only on land that generates rent and, therefore, reflect secondary conversion. Effects of secondary conversion on biodiversity and ecosystem services largely depend on the status of the system before and after conversion including land-management practices (such as fire) and natural disturbances.

The attempt to identify the role of biofuels and indirect land-use changes in the Brazilian Amazon provides a useful example of the complications of selecting the appropriate theory of land-use change for first time conversion. Sixteen field-based regional and local studies in the

Brazilian Amazon suggest that deforestation (first time conversion) 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)]; and

(4) environmental and social conditions [lot size, land-use history, and land-use choices (Dale et al., 1993, Moran et al., 2002)].

Furthermore, Scouvant 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 prime causes 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. In contrast, 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).

These studies illustrate three key attributes of first time conversion in the Amazon. (1) Correlation does not imply causation. (2) Understanding and documenting direct land-use change

is required prior to estimating indirect effects. (3) There needs to be a causal analysis to support plausible linkages between direct and indirect changes. While indirect relationships can be estimated, they have large and irreducible uncertainties (CARB, 2010). Addressing the importance of this issue requires adopting an interdisciplinary approach, considering alternative theories, and obtaining and using data to test model assumptions and projections. Scouvant et al. (2007) aptly summarize that "none of the theoretical explanations available in the literature on deforestation is better than the others. They are rather complementary as they each apply in different contexts." 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.

4. Modeling land change

Because of the problems in empirical data on land changes, models are often used to provide the information used in calculating landscape indicators. Current efforts to model changes in land use or land cover are limited by the availability of appropriate data sets and knowledge of driving factors of land-use change and outputs are constrained by initial 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. Furthermore, 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, 2009). A series of international meetings, workshops, and proposed rules and regulations over the past year 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 of land use, and must be improved (Oladosu et al., 2011). Yet these uncertainties need to be identified and characterized in order to address causes and effects and to consider ways that the land can best meet stakeholder objectives (those objectives can include provision of food, feed, fiber, fuel, a place to live, work, recreate, and protect ecosystem services).

Current land-change models have several areas in which improvement are needed (CBES, 2009). Interactions and feedbacks both within and between the social, environmental, and other model components are often poorly represented. Uncertainties associated with design assumptions, scenarios, and the results of sub-models should be reduced. There need to be adequate reference cases and potential future scenarios relevant to each application of the models. Global equilibrium models require sub-models that represent regional drivers of land-use changes. 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 the landscape indicators derived from their projections.

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, e.g. that (1) land cover is more frequently assessed yet the interest is in land-use change, (2) ongoing changes are constant, and (3) there is only limited causal analysis of land change. Landscape indicators need to be related to accurate and robust geospatial data on ecosystem attributes such as carbon stock, nutrient cycling, water and soil quality, net primary productivity, habitat and biodiversity. This information about the land 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 a huge potential to manage landscapes to more efficiently provide multiple services, but at the present time there are insufficient data to test hypotheses about ways to manage the land and other resources. For example, having relevant geospatial data over time could build guide management that builds the capacity of the land to provide ecosystem services. Better data could help us develop *best 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 means are needed to measure the effects of management practices including duration, extent and intensity. For example, energy and raw materials used to support cultivation, 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.

Well-defined, robust and consistent land classification systems need to be developed, adopted, and deployed. These categories should include information on land characteristics such as the intensity at which land is used (Grainger 2009). Having clear land classification systems is necessary for consistent and well-documented landscape indicators over time.

Use of landscape indicators also requires clarity in specifying the assumptions, scales, any masking, and baseline conditions of the underlying data. The goals and context of the analysis often determine the appropriate conditions for the data. These basic assumptions need to be communicated to users of the indicators.

Working to achieve these steps is difficult. A priority for the scientific community is therefore to increase the level of collaboration and work toward consensus. For example, one goal could be for experts to come to contribute to a conceptual framework of the factors that drive land-use change and particularly the causal factors behind *initial* conversion in specific regional contexts. Another priority would be the acquisition of reliable global land-use inventories. A third priority could be to develop land-use-change models that addresses the specific issue at hand rather than adapting other models developed for different purposes or models that lack the ability to attribute causes of changes. Because landscapes are so dynamic, it is crucial to develop ways for the scientific community to work together to collect the data and develop the tools to be able to assess landscape effects and suggest ways to improve management of resources.

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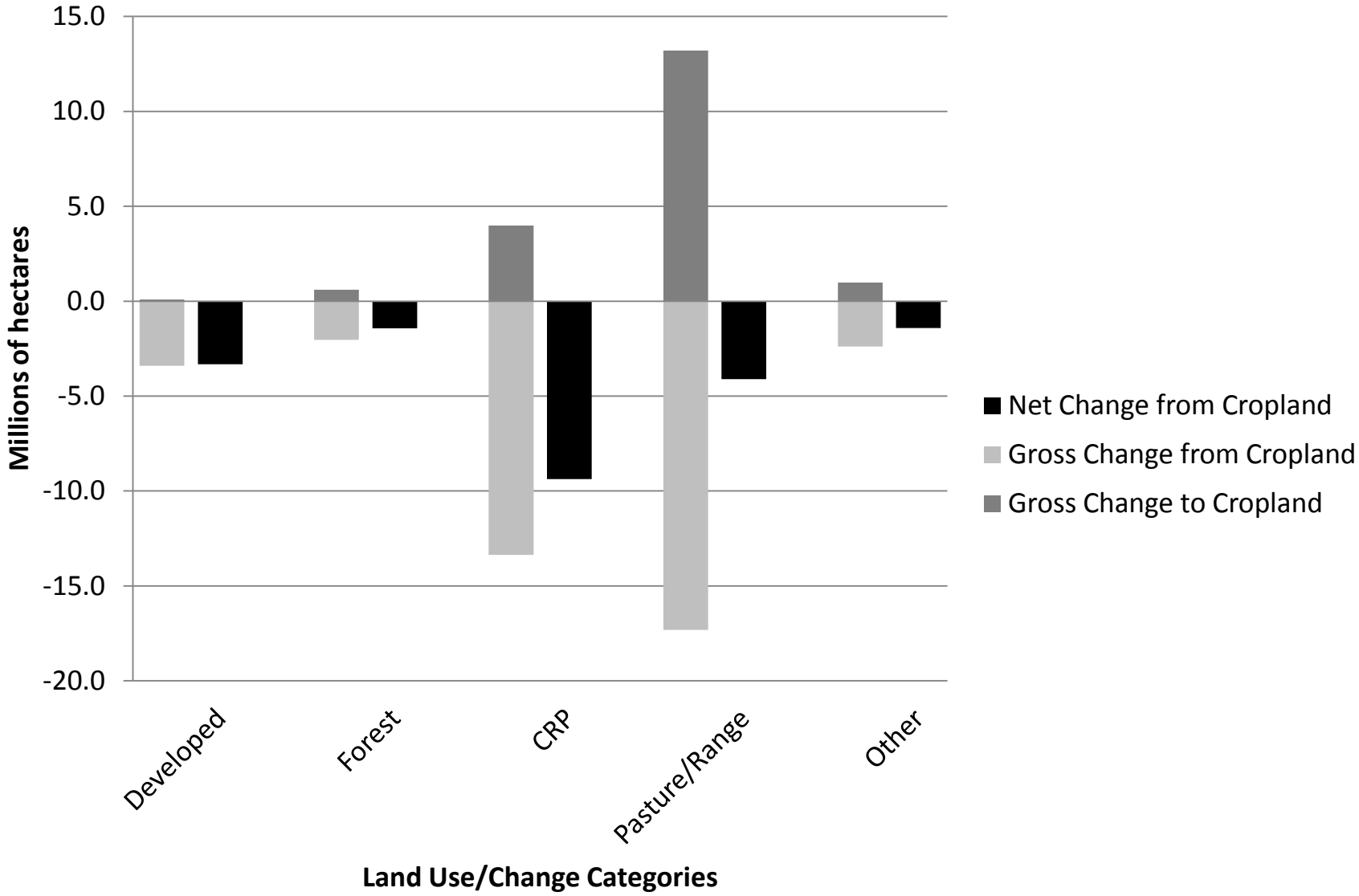
Figure captions

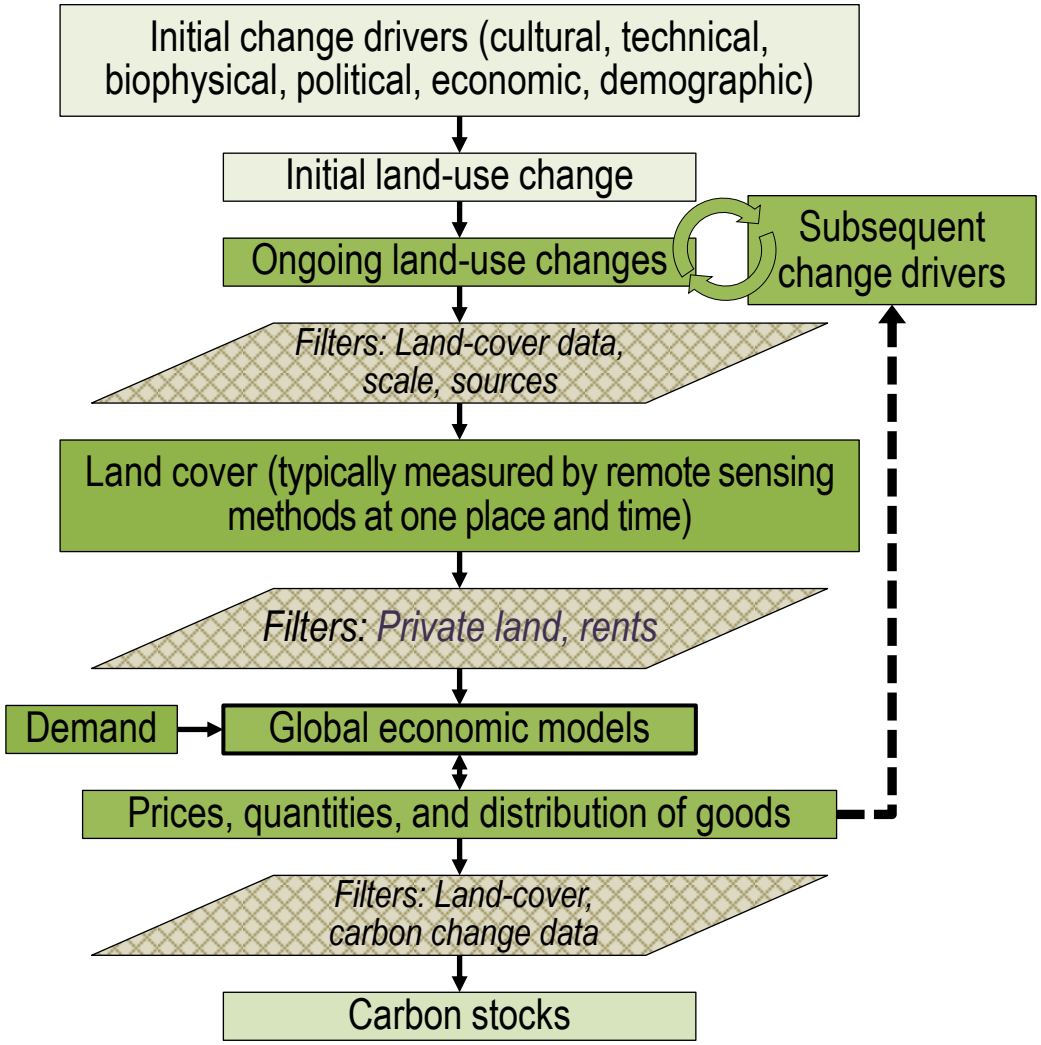
Figure 1. Net and gross land class change in the United States associated with cropland, based on National Resources Inventory (NRI) data from 1987 to 2007) (USDA 2009). Gross change refers to total gross change measurable within the limitations of NRI's 5-year intervals. For example, if a given parcel of land is cropland in 1992, forest in 1997, and cropland again in 2002, its area appears twice in the corresponding bars. 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".

Figure 2. Diagram of causes of land-use changes (revised from CBES 2009).

Figure(s)


15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
Millions of hectares
Developed
Forest
CRP
Pasture/Range
Other
Land Use/Change Categories
Net Change from Cropland
Gross Change from Cropland
Gross Change to Cropland

Figure(s)



Source: CBES 2010
(http://www.ornl.gov/sci/besd/cbes/)