

Mapping the world's degraded lands

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ABSTRACT

Degraded lands have often been suggested as a solution to issues of land scarcity and as an ideal way to meet mounting global demands for agricultural goods, but their locations and conditions are not well known. Four approaches have been used to assess degraded lands at the global scale: expert opinion, satellite observation, biophysical models, and taking inventory of abandoned agricultural lands. We review prominent databases and methodologies used to estimate the area of degraded land, translate these data into a common framework for comparison, and highlight reasons for discrepancies between the numbers. Global estimates of total degraded area vary from less than 1 billion ha to over 6 billion ha, with equally wide disagreement in their spatial distribution. The risk of overestimating the availability and productive potential of these areas is severe, as it may divert attention from efforts to reduce food and agricultural waste or the demand for land-intensive commodities.

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Introduction

Degraded lands are the center of much attention as global demands for food, feed and fuel continue to increase at unprecedented rates, while the agricultural land base needed for production is shrinking in many parts of the world (Bruinsma, 2003; Food and Agriculture Organization of the United Nations [FAO], 2005; Gelfand et al., 2013; Lambin et al., 2013; Lambin & Meyfroidt, 2011; Tilman et al., 2001). Indeed, projected population increases and rapidly growing meat consumption portend a projected doubling in global demand for agricultural commodities by 2050 (FAO, 2006). We expect additional pressure on the land base for fuel production as energy policies encourage more bio-energy production (World Energy Council [WEC], 2011).

Yield increases on existing croplands will be an essential component to increased food production, but by themselves will not suffice (Godfray et al., 2010; Hubert, Rosegrant, van Boekel, & Ortiz, 2010; Ray, Mueller, West, & Foley, 2013). Though inevitable, agricultural expansion into natural ecosystems leads to significant losses of ecosystem services, such as habitat necessary to maintain biodiversity, storage of carbon, flood mitigation, and soil and watershed protection, to cite a few (Foley et al., 2005; Gibbs et al.,

2010; Lambin & Meyfroidt, 2011). Indeed, the full consequences of past and current agricultural expansion remain poorly understood, yet are likely to be dramatic. For example, Gibbs et al. (2010) found that during the 1980s and 1990s more than half of newly expanding agricultural areas in the tropics came at the expense of closed forests, with an additional third from disturbed forests. Others identify natural and planted grasslands as key sources for expanding row crops in the United States (Wright & Wimberly, 2013). Attention often focuses on steering crop expansion toward degraded or marginal lands in the hope of avoiding the environmental consequences of agricultural expansion into high-value ecosystems (e.g., Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Gibbs et al., 2008).

Environmental and aid organizations, politicians, scientists, and the agricultural and energy sectors all point to various types of underutilized or degraded land as the solution to reconcile forest conservation with increasing agricultural production (e.g., Alexandratos & Bruinsma, 2012; Deininger & Byerlee, 2011; Gallagher, 2009; Gelfand et al., 2013; Gibbs, 2012; Robertson et al., 2008; Tilman, Hill, & Lehman, 2006). Clearly, there are a host of benefits to be achieved from the idealized vision of restoring degraded lands, especially when this could spare forests and avoid competition with food crops. However, this potential is often estimated using highly uncertain data sets (Field, Campbell, & Lobell, 2008; Goldewijk & Verburg, 2013; Hoogwijk et al., 2003; Meiyappan & Jain, 2012; Nijssen, Smeets, Stehfest, & Vuuren,

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2012; Ramankutty, Heller, & Rhemtulla, 2010; vanVuuren, Vliet, & Stehfest, 2009), and tends to be overstated, with little attention given to the current status and use of these degraded lands (Lambin et al., 2013; Young, 1999). The risks of overestimating the availability and productive potential of these areas is severe, as it may divert attention from efforts to reduce waste or the demand for land-intensive commodities such as beef.

Lack of understanding of the location, area, and condition of degraded land is a significant roadblock to a more reality-based strategy. Current estimates of potential production on degraded lands are greatly hindered by missing and often unreliable information (Grainger, 2009; Lewis & Kelly, 2014; Zucca, Peruta, Salvia, Sommer, & Cherlet, 2012). Indeed, no clear consensus exists as to the extent of degraded land, not only globally, but even within a particular country (Bindraban et al., 2012; FAO, 2008; Lepers et al., 2005). There are few if any routine assessments of degradation at the country level that keep track of pre-existing or changing conditions, nor is there any agreement on how to conduct such assessments (Bruinsma, 2003).

Simply to define “degradation” is challenging and likely contributes to the apparent variance in estimates. The term degradation is often used as an umbrella term that encompasses a wide variety of land conditions, such as desertification, salinization, erosion, compaction, or encroachment of invasive species. Conversely, it is sometimes used to refer to only a subset of these conditions. For example, many degradation studies focus only on drylands, so their results are difficult to compare with broader studies that include temperate and humid domains. In addition, there is disagreement between degradation data that include natural processes and those that have been induced solely through human activity (Weigmann, Hennenberg, & Fritsche, 2008), and it is often difficult to distinguish between these causes. Moreover, many of the specific circumstances behind degradation have different implications for rehabilitation, conservation, and productive potential. For example, in Indonesia a logged forest and highly eroded grassland may both be defined as degraded areas

despite the clear distinctions between those land categories (Koh et al., 2010).

However, there is nearly universal consensus that degradation can be defined as a reduction in productivity of the land or soil due to human activity (Holm, Cridland, & Roderick, 2003; Kniivila, 2004; Oldeman, Hakkeling, & Sombroek, 1990). Yet studies focus on temporal and spatial scales of this process that differ, which leads to much confusion when interpreting the results. Indeed, while some estimates of degradation have focused on the end condition of the land, others consider the ongoing process of degradation itself (e.g., Bai, Dent, Olsson, & Schaepman, 2008; Cai, Zhang, & Wang, 2011), and even the perceived risk of degradation, adding more confusion to the term. Another challenge is that lands with naturally low productivity, such as heathlands or naturally saline soils, may also be described as degraded. Finally, while most seminal efforts have focused on soil degradation (Nijssen et al., 2012; Oldeman et al., 1990), more recent efforts have investigated the broader issue of land degradation from an ecosystem approach, which encompasses both soils and vegetation.

This paper takes the first step toward resolving these conflicts by compiling estimates of degraded lands at the global scale and providing the first geographically explicit and quantitative comparison across estimates. We review prominent databases and methodologies used to estimate degradation, translate these data into a common framework for comparison, and highlight reasons for discrepancies between the numbers.

Review of key datasets

The major approaches used to quantify degraded lands can be grouped into four broad categories: 1) expert opinion; 2) satellite-derived net primary productivity; 3) biophysical models; and 4) mapping abandoned cropland. Each offers a glimpse into the conditions on the ground but none capture the complete picture (Tables 1 and 2; Fig. 3).

Table 1
Benefits and limitations of major approaches used to map and quantify degraded lands.^a

Approach	Benefits	Limitations
Expert opinion ^{b,c,d}	• Captures degradation in the past • Measures actual and potential degradation • Can consider both soil and vegetation degradation	• Not globally consistent • Subjective and qualitative • Actual and potential degradation sometimes combined • The state and process of degradation often combined
Satellite-derived net primary productivity ^e	• Globally consistent • Quantitative • Readily repeatable • Measures actual rather than potential changes	• Neglects soil degradation • Only captures the process of degradation occurring following 1980, rather than complete status of land • Can be confounded by other biophysical conditions
Biophysical models ^f	• Globally consistent • Quantitative	• Limited to current croplands • Does not include vegetation degradation • Measures potential, rather than actual degradation
Abandoned cropland ^{g,h}	• Globally consistent • Quantitative • Captures changes 1700 onward • Measures actual rather than potential changes	• Neglects land and soil degradation outside of abandonment • Includes lands not necessarily degraded

^a Benefits and limitations refer to existing databases, not necessarily the approaches as a whole, which could be improved to overcome limitations.

^b Oldeman et al., 1990.

^c Dregne & Chou, 1992.

^d Bot et al., 2000.

^e Bai et al., 2008.

^f Cai et al., 2011.

^g Field et al., 2008.

^h Campbell et al., 2009.

Table 2
Synthesis of continental and global scale estimates of degradation (million ha). Note the following: a.) Ramankutty and Foley (1999) did not provide country-level estimates, b.) light degradation was excluded from the estimates here, and c.) North America includes Mexico and Central America, unless otherwise noted.

Area	GLASOD	FAO TerraSTAT	Dregne and Chou (1992)	GLADA	Cai et al. (2011)	Campbell et al. (2008)	FAO Pan-tropical Landsat
Africa	321	1222	1046	660	132	69	9
Asia	453	2501	1342	912	490	118	12
Australia and Pacific	6	368	376	236	13	74	^d
Europe	158	403	94	65	104	60	^d
North America	140	796	429 ^a	469	96	79	^d
South America	139	851	306 ^b	398	156	69	56 ^b
World (Total)	1216	6140	3592	2740 ^c	991	470	76 ^d

^a Does not include Caribbean.

^b Includes some Caribbean countries.

^c Total based on country areas listed in Table 2 of Bai et al. (2008), and does not match global total listed in the same source (3506 million ha).

^d Non-tropical continents not included in this study.

Expert opinion

Solicitation of expert opinion was the first approach used to map and quantify degraded lands and maintains a leading role in assessments despite its subjective nature and inconsistencies (Dregne & Chou, 1992; Oldeman, 1994; Oldeman, Hakkeling, & Sombroek, 1990). Such expert judgments will continue to play a role, regardless of improvements in other methods, because degradation will remain a subjective quality whose benchmarks vary among locations (Sonneveld & Dent, 2007).

The Global Assessment of Soil Degradation (GLASOD) commissioned by the United Nations Environment Program was the first attempt to map human-induced degradation around the world (Oldeman, 1994; Oldeman et al., 1990) and is still used today (e.g., Nijssen et al., 2012). Oldeman et al. (1990) developed a set of relatively uniform mapping units and then asked experts to estimate the status of soil degradation in terms of the type, extent, degree, rate and causes of degradation within each mapping unit (roughly 1945–1990). The GLASOD data were assembled from over 290 national collaborators, and moderated by 23 regional leaders. The estimates are uniform in the sense that they are based upon defined mapping units and carefully structured definitions but they rely on local knowledge rather than measurements.

Due to this dependence upon local experts, the GLASOD assessment is considered subjective and has been open to disparagement (e.g., Rey, Scoones, & Toulmin, 1998, chap. 1; Thomas, 1993). Others have criticized GLASOD for the coarse spatial resolution of mapping units and the qualitative judgments whose consistency was untested. Sonneveld and Dent (2007) used GIS analysis to evaluate the consistency of the expert assessments across similar combinations of biophysical conditions and land use. They concluded that GLASOD is only moderately consistent and hardly reproducible. Further, they describe the expert assessments as “not very reliable.” Oldeman et al. (1990) were clear in pointing out these limitations, so it is only fair to emphasize that much of the concern stems from inappropriate uses of the data. GLASOD was designed to generate continental scale estimates, and the sampling procedure is not adequate to draw conclusions at the national scale (Bruinsma, 2003; Scherr & Yadav, 1996).

Despite its limitations, GLASOD remains the only complete, globally consistent information source on land degradation and has been widely used and interpreted (e.g., Bot, Nachtergaele, & Young, 2000; Crosson, 1995, 1997; Pimentel et al., 1995; Sonneveld & Dent, 2007). Bot et al. (2000), for example, liberally interpreted the GLASOD survey to provide national-level estimates as part of the TerraSTAT database they created for the FAO. They developed the TerraSTAT estimates based on the premise that using only the area of actual degradation would underestimate the problem by neglecting impacts on surrounding lands, off-site effects such as

sedimentation, and impacts on the economy as a whole. For these reasons, Bot et al. (2000) used severity classes based on both degree and extent of soil degradation from GLASOD to develop the TerraSTAT country data. In this way, TerraSTAT aimed to represent the land area affected by degradation, in contrast to the actual degraded area represented by GLASOD.

The GLASOD study estimated that nearly 2 billion ha (22.5 percent) of agricultural land, pasture, forest and woodland had been degraded since mid-twentieth century. Oldeman et al. (1990) deem roughly 2 percent of the soils so severely degraded that the damage is likely irreversible, and another 7 percent was moderately degraded to the point that on-farm investments would be required. The remaining 6 percent was classified as lightly degraded and considered correctable with good land management practices. The FAO TerraSTAT interpretation of GLASOD by Bot et al. (2000), on the other hand, finds that over 6 billion ha, 66 percent of the world's land, has been affected by degradation, leaving roughly only a third of the world's surface in good condition. The damage is divided into classes, similar to GLASOD – roughly 26 percent was severely or very severely degraded, 21 percent moderately degraded, and the remaining 18 percent lightly degraded. The areas affected by at least moderate degradation comprise 9 percent and 47 percent of the land surface, according to GLASOD and TerraSTAT, respectively (Table 2), highlighting the high degree of interpretability of these data sets.

Another study by Dregne and Chou (1992) that also relied largely on expert opinion, did aim to provide national-level information on both soil and vegetation degradation but was limited by data availability. They estimate degradation for most countries with drylands by using a combination of research reports, expert opinion, local experience and anecdotal accounts to evaluate both soil and vegetation conditions. Economic impact on plant yield was the main criterion used to determine degradation severity. Dregne and Chou (1992) described the quality of information used to create country-level estimates as “poor.” They found very extensive degradation covering roughly 3.6 billion ha (70 percent) of Earth's drylands. Indeed, they concluded that in their study region 73 percent of rangelands, 47 percent of rainfed croplands, and 30 percent of irrigated croplands were degraded. However, others posit that Dregne and Chou (1992) have greatly overestimated degradation (Helldén & Tottrup, 2008).

The expert opinion approach will continue as a mainstay until satellite-based measurements can provide more accurate and detailed information for both vegetation and soils. Many land-use mapping efforts employ expert opinion successfully (e.g., Achard et al., 2002; FAO, 2000) but are generally limited by issues of consistency and bias. It is particularly challenging to overcome these issues pertaining to degradation because precise definitions are lacking.

Satellite-based approach

Remotely-sensed data provide a major opportunity to improve our spatial representation of the locations of degraded lands in a globally consistent manner, as well as the process of degradation. However, a major challenge for this approach is to segregate areas of naturally low productivity or sparse vegetation from those that have been degraded by human impact. Satellite data are only available from the 1980s in most cases, so we have only a short time frame to observe changes in the land surface.

An on-going assessment within the FAO's Global Assessment of Lands Degradation and Improvement project (GLADA) is to quantify more degradation events during 1981–2003 by using the normalized difference vegetation index (NDVI), which is widely used to assess vegetation condition and productivity (Bai et al., 2008). The GLADA project defines land degradation as the long-term decline in ecosystem function and uses the satellite record from the Global Inventory Modeling and Mapping Studies (GIMMS) to assess these changes. Specifically, GLADA utilizes satellite-derived NDVI measurements collected from the Advanced Very High Radiometer (AVHRR, 8 km record) as a proxy for net primary productivity (NPP). Deviations from normal NDVI may indicate land degradation once other factors that may be responsible, such as rainfall, climate, and land use are taken into account.

Early GLADA results reveal a declining trend in NPP across 21 percent of the global land area, 2.7 billion ha, mainly in tropical Africa, Southeast Asia, China, north central Australia, the Pampas, and swaths of the boreal forest in Siberia and North America. Bai et al. (2008) also found that nearly one-fifth of this degraded land is cropland, an area equivalent to more than 20 percent of all cultivated areas. Roughly 40 percent of the degraded lands were found to be in forests, with another quarter in rangelands. But at the same time, they also found that 16 percent of global land area is increasing in NPP, with 20 percent of total cropland area on an upward swing. Roughly 23 percent of forests are also improving along with more than 43 percent of rangelands. The vast majority (78 percent) of degrading lands are found in humid regions, which is contrary to the popular belief that most degradation occurs in drylands. Indeed, Wessels, Van Den Bergh, and Scholes (2012) commented on the Bai et al. (2008) publication of GLADA results, and was highly critical of their methods, especially in the humid tropics where results were described as fatally flawed and misleading.

It is important to note that while satellite-based assessments may capture recent or on-going degradation by measuring changes in productivity, they will not capture the full picture of all degraded lands. Rather they depict only those being actively affected by the processes of degradation. This means that lands degraded long ago, such as parts of West Africa or India, will not be represented by most satellite studies. Satellite data will also struggle to distinguish the fine gradients that exist between degraded and non-degraded grasslands and may be further limited by potentially confounding biophysical conditions (e.g., seasonality in drylands and environmental trends; Wessels et al., 2012). Furthermore, improved technology applied to croplands may mask the effects of degradation, making it difficult for satellite data sets to reveal them. Thus, it is unlikely that remote sensing will be able to map all cases of land degradation unequivocally, but the approach does provide valuable clues and has the potential to identify hotspots of ongoing degradation (Alcantara, Kuemmerle, Prishchepov, & Radeloff, 2012; Prince, Becker-Reshef, & Rishmawi, 2009; Wessels, Prince, & Reshef, 2008). Moreover, future advances in remote sensing, including hyperspectral data, may allow finer distinctions between land cover classes to be made, thereby enabling a more complete mapping of vegetation and soil degradation. Still, extensive ground

data, currently unavailable, will be required to produce reliable estimates of degraded areas from remote sensing at broad scales (Kniivila, 2004).

Biophysical models

Biophysical modeling has been broadly used to assess the potential vegetative productivity of global land areas (e.g. Fischer, van Velthuisen, Shah, & Nachtergaele, 2002). Common approaches include global data sets describing climate patterns and soil types to define classes of potential productivity. Such studies may incorporate empirical knowledge and expert opinion, using models to extend these into a globally consistent estimate.

Recent work has indicated that these biophysical models may be combined with observations of land use to map degradation. The spatial and temporal extent, as well as the type of degradation considered, is dependent upon the input data sets for the modeling process. In a recent and prominent example, Cai et al. (2011) used a biophysical model of agricultural productivity to map marginal lands, including degraded lands, by tuning the model to match the distribution of cropland in a global land cover map and areas of pasture land in the FAO database. The biophysical model was based upon spatial descriptions of soil type, topography, average air temperature and precipitation. By combining these data sets with expert opinions and global land cover data sets, they mapped three classes of land productivity globally: low, marginal, and regular.

Cai et al. (2011) identified degraded or low-quality cropland through coincidence between maps of modeled marginal productivity and cropland. Marginal areas with low-productivity cropping were designated as abandoned, idle, or wasted, while marginal areas with full cropping were designated as degraded. Thus, the study assesses the extent of degradation due to over-utilization of lands of marginal productivity, and focuses on capturing the process of degradation, rather than the cumulative result. Marginal productivity is assumed to be an indicator of land fragility or sensitivity to over-utilization. Further work could advance the application of biophysical modeling to assessment of land degradation by focusing on direct assessment of land vulnerability, rather than using marginality as a proxy.

In the study by Cai et al. (2011), early application of biophysical models to assess land degradation estimated nearly 1 billion ha of degraded and abandoned lands globally. Results asserted that Asia (China and India only) contained most of the land degradation, 490 million ha (Table 2).

The biophysical approach to assessing land degradation is a recent development. In general, biophysical models may indicate land degradation by combining their prediction of the cropping suitability of land with observation of their current productivity. As the Cai et al. (2011) study focuses on lands of marginal productivity currently being cropped, it excludes previously abandoned lands, lands that were experiencing full productivity when the data were developed, and non-agricultural degradation. Thus, these results do not yield a complete picture of global land degradation. However, the biophysical approach may be applicable to more contexts if the definition of degradation is expanded, and the methods adjusted accordingly. Unfortunately, however, modeling approaches that rely on models will inevitably be influenced by any inherent error. For example, the estimate of nearly 1 billion ha of degraded land by Cai et al. (2011) includes any areas that have high productivity yet were incorrectly assigned marginal productivity by their model. Thus, the accuracy of the biophysical approach will be influenced by the quality of the data used for calibration and the suitability of the model selected, which can be especially

challenging when trying to manage conditions that vary locally at the global scale.

Abandonment of agricultural lands

Another way to identify degraded lands is to look for areas that were once croplands but have since been abandoned because of decreased productivity, or due to political and economic reasons. The benefit of focusing on these lands is that it captures the longer time frame of the expert opinion approach but quantifies the *actual* conditions rather than estimating potential risk. Moreover, this approach is empirically driven, as it relies on the details of agricultural census data combined with the global consistency provided by satellite mapping.

Recent satellite advances have enabled new global scale datasets of agricultural land cover, which have been developed by merging satellite derived land cover maps with ground level agricultural inventory data sets (Cardille, Foley, & Costa, 2002; Goldewijk, 2001; Ramankutty & Foley, 1999). Early work by Ramankutty and Foley (1999) pioneered the development of a statistical “data fusion” technique to merge national and sub-national agricultural statistics with land cover maps to create global maps of the world’s croplands in the early 1990s and their historical changes since the year 1700. They found that the extent of cropland abandonment increased greatly from roughly 65 million ha in the 1950s to 225 million ha in 1990, and the rate of abandonment increased as well. Most cropland abandonment occurred in eastern North America during the early 1900s but expanded to China, southern South America and Europe by mid-century. Toward the end of the last century, abandonment was limited to the eastern portion of the U.S., parts of the Amazon basin and southern South America.

A second database produced using satellite and census data, the History Database of Global Environment 3.0 (HYDE), has also been used to assess the area of abandoned cropland (Goldewijk, 2001; Goldewijk, Bouwman, & Dreht, 2007). The HYDE database also provides information on pastures not captured by Ramankutty and Foley (1999). Field et al. (2008) quantified abandoned areas of each map grid cell in HYDE where agricultural area was decreasing over time. Areas of agricultural land that now support forests or have become urbanized were removed from the abandoned cropland estimates by masking the data with a MODIS land cover map. Campbell, Lobell, Genova, and Field (2008) refined this approach by addressing transitions between pasture and cropland in a more internally consistent way. They also quantified the extent of abandoned cropland around the world (Table 2). The analysis of the HYDE database by Campbell, Lobell, and Field (2009) found that over the last three centuries, 269 million ha of cropland and 479 million ha of pastureland were abandoned. However, after accounting for forest regrowth and urbanization, the total area of abandoned agricultural land ranged from 385 to 472 million ha. This study also found that about one-quarter of these abandoned agricultural lands (125 million ha) were across the pan-tropics.

The pan-tropical Landsat analysis led by the United Nations Food and Agricultural Organization (FAO) can also shed light on agricultural abandonment in recent decades. The FAO employed a statistical survey using high-resolution Landsat imagery (30 m by 30 m) at 117 sample locations across the tropics. Unlike most satellite-based studies that identify only the locations of cropland, the manual interdependent change detection method used by the FAO tracks land parcel transitions from one land cover class to another. The FAO Landsat analysis indicated that across the tropics, 77 million ha of cropland and pasture had been abandoned either temporarily or permanently during the 1990s (FAO, 2001; Gibbs et al., 2010). No woody plantation land was abandoned. The vast majority of the agricultural abandonment occurred in Latin

America, where over 56 million ha of land became ‘idle’ during the 1990s. Tropical Asia accounts for 12 million ha and Africa for the remaining 9 million ha of abandoned land.

The results of these studies are not directly comparable due to differences in geographic domains, time periods and the types of agricultural land considered. However, it is important to note that the magnitude of reported changes are relatively similar, suggesting some degree of confirmation. A significant limitation of this approach is that it excludes degradation other than agricultural abandonment, so the numbers should be considered extremely conservative estimates of degradation. Also noteworthy is the omission of shifting cultivation derived from historical reconstructions of land use, which probably leads to underestimation of abandonment in these assessments (Meiyappan & Jain, 2012). In addition, the estimates of historical land use on which the agricultural abandonment approach is based are themselves highly uncertain (Goldewijk & Verburg, 2013; Meiyappan & Jain, 2012). In particular, the majority of inputs regarding pre-industrial landuse patterns are considered by experts to be uncertain on all continents (Goldewijk & Verburg, 2013).

Methods

The methods of mapping degraded lands discussed in the previous sections have led to notably different descriptions of their spatial distribution. To illustrate this, we removed minor differences due to data set format, units, and coordinate system. Specifically, we selected one map generated with each of the four methods discussed, and converted them into the percent of area degraded on a common equal-area grid. In so doing, we excluded degradation that was labeled as light in severity (Fig. 1). Though each data set was handled with considerations unique to it, the general process was: (1) transform the data into the equal-area projection Eckert IV with a high resolution of 1 km; (2) convert the data to units of degraded area; (3) scale the data to a lower resolution of 20 km by summing degraded areas among high-resolution cells; and (4) convert the data to units of percent area degraded by dividing the area degraded by the cell area.

The foremost example of an expert opinion assessment of global degraded lands, GLASOD, was provided in vector format. The polygons were converted to a raster format with 1 km resolution, including only degradation of moderate, strong, and extreme degrees (classes 2–4). We then converted the degradation extent classes to percent area degraded by applying the median of the range represented for each class. The extent of degradation was then used to calculate the area degraded in each cell.

The GLADA data set, provided as a raster representing the slope of linear regression of summed Rain Use Efficiency (RUE)-adjusted NDVI (ratio of vegetation production to rainfall), was used to represent satellite-estimates of degraded land (Fig. 3 of Bai et al., 2008). Following the method used by Bai et al. (2008), we assumed that any pixel with a negative trend in RUE-adjusted NDVI is degraded over its full area.

The Cai et al. (2011) data set is the only available example of mapping global degraded lands with biophysical modeling. We obtained this data set as a raster representing abandoned and degraded land area with a spatial resolution of 30 arc second geographic. We converted the data to fraction of area degraded at five arc minute resolution before transforming to Eckert IV. We noted that the total area degraded and abandoned in the data set was 42 percent higher than the area reported by Cai et al. (2011). This is because they excluded some heavily degraded areas in their report, primarily Eastern Europe and Western Russia.

To represent the global distribution of abandoned agriculture, the results from Campbell et al. (2008) were obtained as a raster

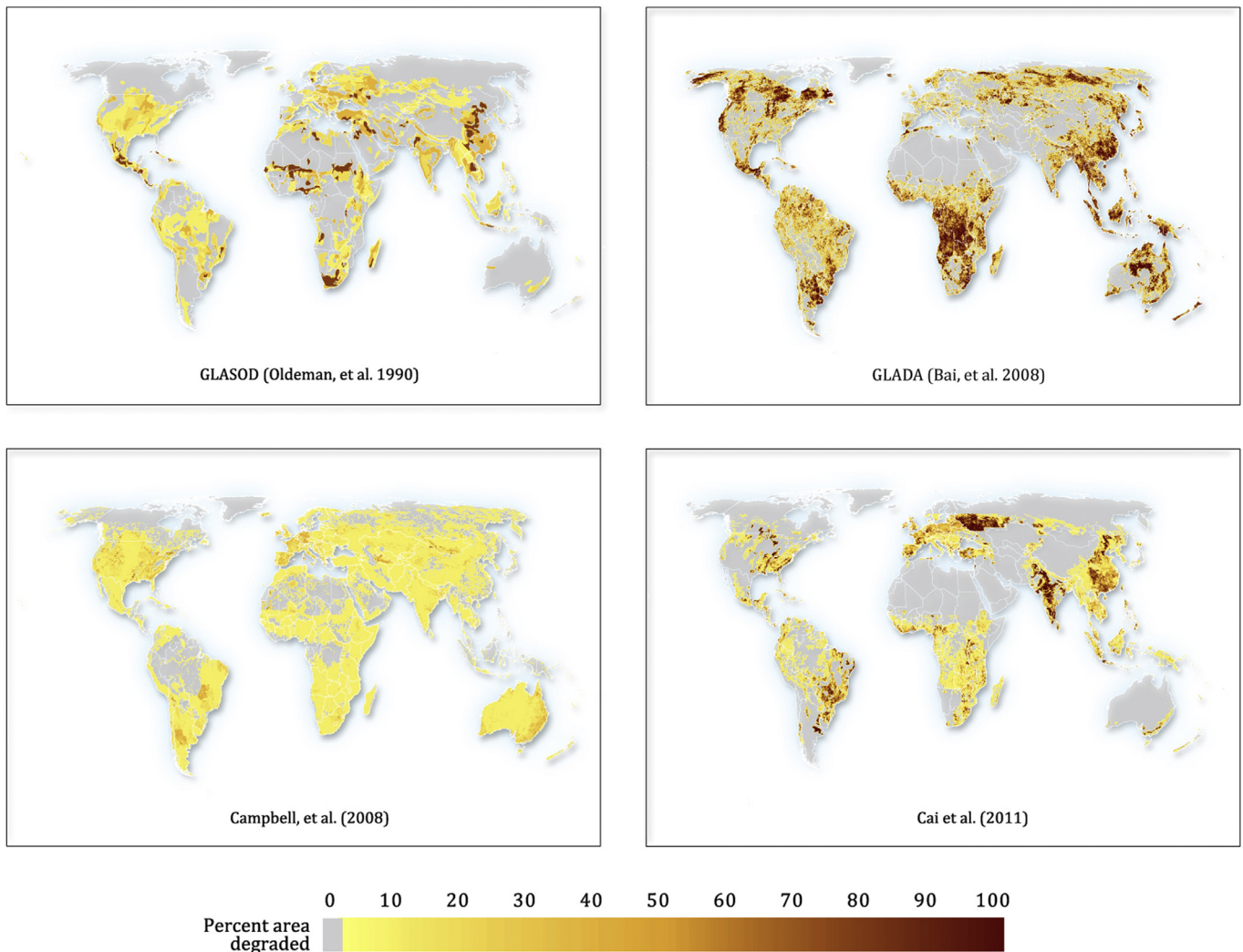


Fig. 1. Maps of land areas (percent of cell area) affected by degradation; each panel represents one of the methods described, all shown with common legend and 20 km grid.

data set. We selected the upper bound of abandoned area at five arc minute geographic resolution, because it more closely resembles other estimates of global degraded area (Table 2). As we did with Cai et al. (2011), we converted these data to the fraction of area degraded before transforming to Eckert IV.

Once the four maps were translated into the degraded area in 20 km cells in Eckert IV projection, we used four methods to assess their similarities and differences: visual comparison (Fig. 1); identification of the number of data sets in agreement (Fig. 2); linear regression among each pair of data sets; and the standard deviation, σ , among all four data sets in each 20 km cell (Fig. 3). Visual comparison was useful in identifying large differences between maps at the global scale. The number of data sets in agreement revealed places where the majority of data sets diverged in their appraisal of degradation effects. Linear regression indicated the presence or absence of any relationships between specific pairs of degradation mapping methods (e.g. expert opinion versus abandoned agriculture). Standard deviation, calculated independently for each 20 km cell, indicated the spread of the values that the four mapping methods ascribe to degraded area.

Taken together, the maps of the number of data sets in agreement, and the standard deviation among all four mapping methods, are very informative. Where all four values indicate degradation of

similar extent (up to 20 percent of cell area), there are four data sets in agreement (dark green in Fig. 2) and the standard deviation is low (yellow or green in Fig. 3). Where three data sets indicate a similar degree of degradation, but one set diverges, there are three data sets in agreement (light green in Fig. 2) and the standard deviation reflects the degree of divergence. Similarly, where two data sets indicate a similar state of degradation, and the other two indicate different degrees of degradation, there are two data sets in agreement (yellow in Fig. 2), and the standard deviation reflects how far the two differing sets diverge from the two in agreement. Finally, where all four data sets indicate different states of degradation, there is only one data set in agreement (red in Fig. 2), and the standard deviation is high (red in Fig. 3). (For interpretation of the references to color in this paragraph, the reader is referred to the web version of this article.)

Discussion

None of the assessments described here provided direct measurement of degradation. All studies relied on proxies in the form of satellite-derived indices, expert opinion, agricultural abandonment, or modeling. No single estimate accurately captures all degraded lands, but each does contribute to the overall discussion.

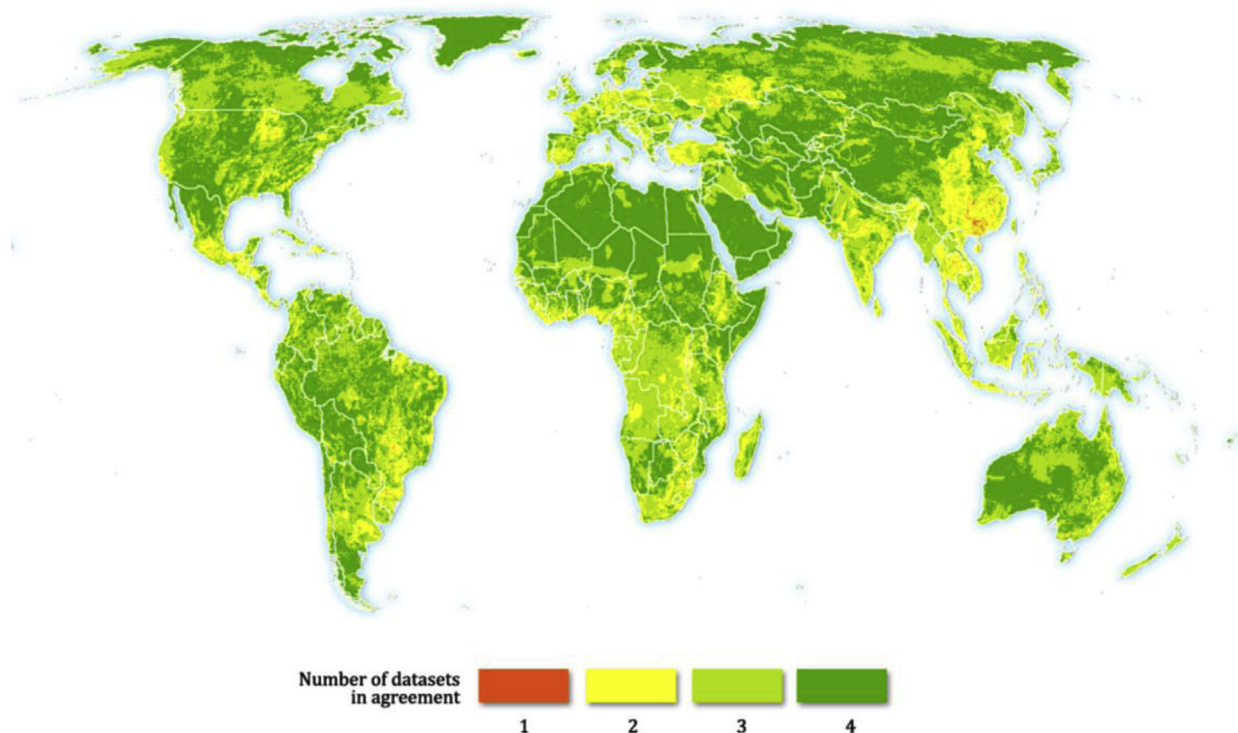


Fig. 2. Number of data sets in agreement ($\pm 20\%$) of area of degraded land. In red areas, no data sets are within 20% of one another; in yellow areas, two data sets are within 20% of one another; in light green areas, three data sets are within 20% of one another; and in dark green areas, all four data sets are within 20% of one another. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Quantifying the error or uncertainty in these estimates is difficult, perhaps impossible, because there are no accepted values against which to make comparisons.

There is general agreement among the data sets regarding areas with little to no degradation. Of the cells that show agreement among all four data sets, 89 percent have an average extent of degradation that is less than 5 percent of the cell area. Thus, it is far less common for all of the data sets to agree that an area is degraded than to concur that it is not.

The greatest disagreement occurs in Asia where only two data sets show agreement and standard deviation among the data sets is greater than 30 percent of cell area for large areas of China and Southeast Asia. There is also a large area of disagreement in Central Africa, with >40 percent standard deviations. In Europe, the greatest disagreement is in Western Russia. In North America, it is in Southern Mexico and the Upper Midwestern US. In South America, the largest disagreement is in the Pampas of Argentina, in Uruguay, and in Southern Brazil.

Part of the variation is expected, due to different definitions, methodologies, time periods and domains. For example, there is very little agreement between GLADA and GLASOD when considered spatially ($R^2 = 0.00$ for percent area degraded in 20 km cells) in part because GLASOD considered soil degradation over centuries while GLADA considered only vegetation degradation over decades.

It is possible to note areas mapped as degraded in the GLASOD data set alone. Specifically, several areas in the Sahel (in Mali, Burkina Faso, Niger and Sudan) are mapped as degraded in GLASOD, but not captured using the other approaches. This discrepancy leads to only three data sets agreeing in these regions and standard deviations of about 30 percent of cell area.

GLADA alone observed degradation in several areas, leading to patches of disagreement in Eastern Argentina, Quebec and Ontario in Eastern Canada, much of Central Africa, the Northern Territory in Australia, and the Central Siberian Plateau. In these regions, it is

likely that vegetation degradation has occurred in recent decades, without the associated soil degradation that the other approaches would have captured.

The [Cai et al. \(2011\)](#) data set observes heavy degradation in the area around Moscow, in Western Russia. It is unclear whether the unique identification of heavy degradation in this area is an artifact of the biophysical modeling approach or an indication of recent ongoing over-utilization of lands of marginal productivity that is sure to lead to degradation.

The [Campbell et al. \(2008\)](#) data set does not appear to contribute to high standard deviations among the four sets because it does not contain large areas of concentrated abandonment. Rather, any areas mapped as greater than 50 percent abandoned agriculture are smaller ($\leq 6400 \text{ km}^2$) than those areas of disagreement discussed above. Indeed, the large spreads of low concentration abandonment in [Campbell et al. \(2008\)](#) highlights an additional concern in applying these datasets to the estimation of biofuel production: additional infrastructure needs for production on small areas spread over much of the Earth's surface would be inhibitive, at best. The two global agricultural databases are also difficult to compare because [Ramankutty and Foley \(1999\)](#) do not consider abandonment of pastureland, which is part of the [Campbell et al. \(2009\)](#) estimate.

Other than the cropland abandonment estimates, many of the datasets contain estimates that are likely too high. Consider, for example, that during these periods of widespread degradation covering upward of 75 percent of the world's land surface, we have continued to increase our agricultural production. This is undoubtedly due in part to increased inputs to compensate for soil nutrient depletion and erosion, but nonetheless it does draw into question the extremely high estimates by GLADA, FAO TerraSTAT, and [Dregne and Chou \(1992\)](#).

Our uncertain knowledge of degraded lands is not surprising given the significant measurement challenges of capturing a

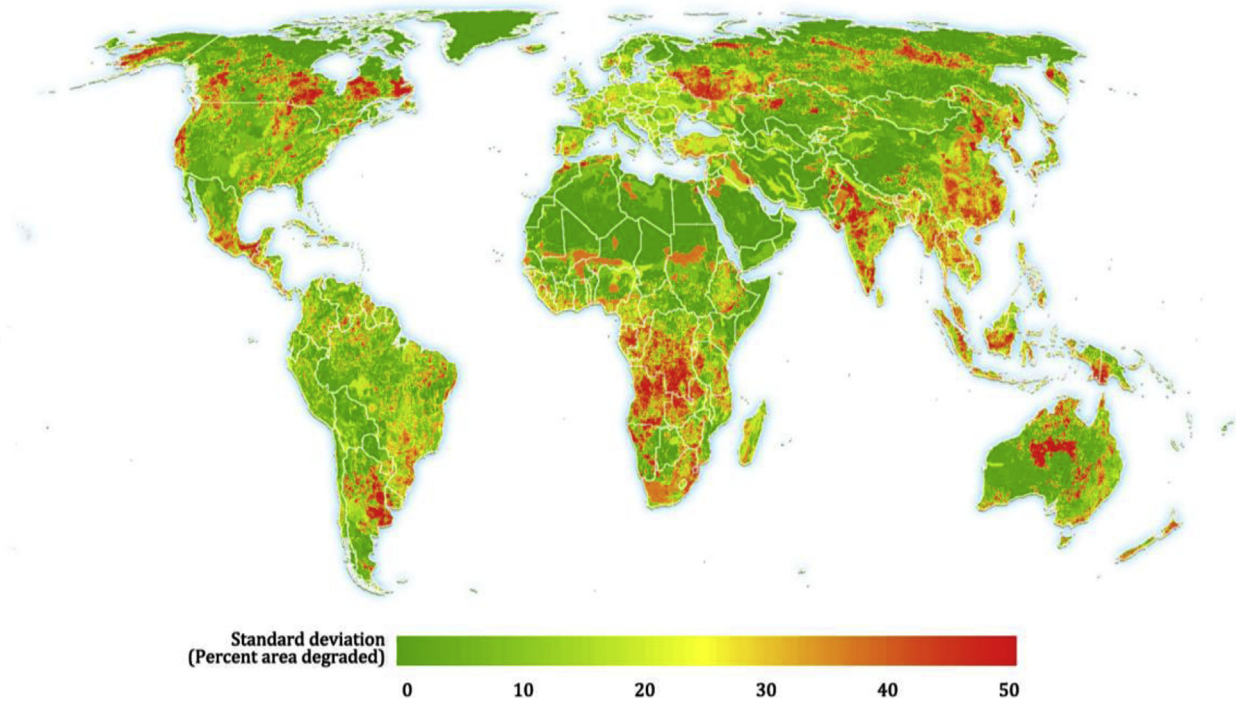


Fig. 3. Map of standard deviation (percent of cell area) among the four prominent global databases of degraded lands.

dynamic and subjective condition. Site-specific context, such as soil type, topography, farming practices and land use history, all influence degradation. Context can also be time-specific in terms of rainfall patterns, fire regimes and changes in land management. Some types of degradation such as soil compaction or acidification are particularly difficult to discern even at the field level, much less across larger spatial scales. Moreover, the on-site impacts of degradation can be masked by inputs or by improving land management or technology. Degradation in one area may have ripple effects on other areas that are not readily evident from observations (e.g., siltation, chemical contamination). Scaling up to national or regional levels is clearly challenging, but is also precisely the information that is needed by policymakers.

Development of relevant and consistent definitions of degradation is increasingly important as we attempt to establish policy and market-based incentives to encourage production on these lands. Definitions that are constrained or region-specific will be needed to avoid unintended consequences. For example, in Indonesia, very low-productivity grasslands and logged forests are both categorized as degraded despite huge differences in their current use and the environmental impacts of conversion (Edwards et al., 2011; Fairhurst & McLaughlin, 2009; Woodcock et al., 2011).

Emphasis on the specific modes of degradation could be another approach. For example, The FAO/IIASA analysis of Global Agro-EcoZones (GAEZ) estimates that 1.39 billion ha are affected by excess salts, leading to moderate, severe, or very severe constraints (FAO/IIASA 2012). Though this data set does not indicate the cause of salinization, it could yet suggest more about the improvability of the land than the more general term 'degraded.'

Efforts to map degraded lands often aim to identify regions that could be converted to uses deemed more productive, particularly biofuel production. However, most studies ignore the social and environmental constraints and tradeoffs associated with using such lands. Even a precise map of the physical area of degraded land would significantly overestimate its potential by neglecting its myriad social, environmental, and political constraints (Lambin

et al., 2013; Young, 1999). Moreover, the recoverability of degraded lands is not in linear relationship with its degradation pressure. Specifically, degraded land may be reasonably recoverable until it reaches a tipping point. Beyond this threshold, the resources needed to recover the land may no longer justify its improvement.

Lambin et al. (2013) emphasize that the physical availability of degraded land is only part of the story. We must also consider the human role in decisions to invest in these lands (Swinton, Babcock, James, & Bandaru, 2011). Economic incentives will be needed to encourage production on degraded lands in many cases (Swinton et al., 2011). To grow crops or animals on lands with reduced productivity will be a low profit–high cost enterprise that is unlikely to happen without strong economic incentives to farmers and agro-industry. For example, additional inputs of fertilizer and pesticides will require fossil energy for production and transportation and may lead to downstream impacts of increased eutrophication or chemical toxicity. Irrigation will undoubtedly be needed in many degraded regions and this will stress our already tenuous worldwide water supply.

Conclusion

Restoration of degraded lands does offer a lower-carbon expansion pathway, and could provide some respite for forest conversion or increase food production in key locales (Gibbs et al., 2008). However, restoring and cultivating degraded lands near forests may erode their passive protection due to the increased infrastructure development. Some degraded lands were once forests or savannas and may be better suited to restoration to those ecosystems, and their associated carbon sinks, rather than undergoing further development for agriculture (Houghton & Hackler, 2006; Piñeiro, Jobbágy, Baker, Murray, & Jackson, 2009). Leakage may also occur as communities evicted from such degraded areas are pushed into the forest frontier, or they could face reduced livelihoods if pushed onto even lower quality lands. Emphasizing

and mapping these vulnerable regions may also facilitate large-scale economic land acquisitions, as countries perceived to have more cultivable land are likely to be more attractive to investment by others (Deininger & Byerlee, 2011). In many ways our focus on using degraded lands is a distraction; it lulls us into complacency by implying that we can easily continue meeting global demands for agricultural commodities. Even degraded lands do not offer a “free ride” (Lambin et al., 2013).

Despite uncertainties in these estimates of degraded areas and their ideal uses, improved understanding of our global land base is necessary to address worldwide land scarcity, and to develop policies around bioenergy and large-scale land acquisitions (Lambin & Meyfroidt, 2011; Lambin et al., 2013). The estimates provided here provide a starting point for considering the potential of degraded land. More importantly, they emphasize the urgency for new approaches that will likely require a combination of innovative satellite data analysis and extensive field inventories.

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References

- Achard, F., Eva, H. D., Stibig, H.-J., Mayaux, P., Gallego, J., Richards, T., et al. (2002). Determination of deforestation rates of the world's humid tropical forests. *Science*, 297(5583), 999–1002. <http://dx.doi.org/10.1126/science.1070656>.
- Alcantara, C., Kuemmerle, T., Prishchepov, A. V., & Radeloff, V. C. (2012). Mapping abandoned agriculture with multi-temporal MODIS satellite data. *Remote Sensing of Environment*, 124, 334–347. <http://dx.doi.org/10.1016/j.rse.2012.05.019>.
- Alexandratou, N., & Bruinsma, J. (2012). *World agriculture towards 2030/2050: The 2012 revision*. ESA Working paper No. 12-03. Rome, FAO.
- Bai, Z. G., Dent, D. L., Olsson, L., & Schaepman, M. E. (2008). Proxy global assessment of land degradation. *Soil Use and Management*, 24(3), 223–234. <http://dx.doi.org/10.1111/j.1475-2743.2008.00169.x>.
- Bindraban, P. S., van der Velde, M., Ye, L., van den Berg, M., Materechera, S., Kiba, D. I., et al. (2012). Assessing the impact of soil degradation on food production. *Current Opinion in Environmental Sustainability*, 4(5), 478–488. <http://dx.doi.org/10.1016/j.cosust.2012.09.015>.
- Bot, A. J., Nachtergaele, F. O., & Young, A. (2000). *Land resource potential and constraints at regional and country levels* (L. a. W. D. Division, Trans.). Rome: Food and Agriculture Organization of the United Nations.
- Bruinsma, J. (Ed.). (2003). *World agriculture: Towards 2015/2030: An FAO perspective*. London, UK: Earthscan.
- Cai, X., Zhang, X., & Wang, D. (2011). Land availability for biofuel production. *Environmental Science and Technology*, 45(1), 334–339. <http://dx.doi.org/10.1021/es103338e>.
- Campbell, J. E., Lobell, D. B., & Field, C. B. (2009). Greater transportation energy and GHG offsets from bioelectricity than ethanol. *Science*, 324(5930), 1055–1057. <http://dx.doi.org/10.1126/science.1168885>.
- Campbell, J. E., Lobell, D. B., Genova, R. C., & Field, C. B. (2008). The global potential of bioenergy on abandoned agricultural lands. *Environmental Science and Technology*, 42(15), 5791–5794.
- Cardille, J. A., Foley, J. A., & Costa, M. H. (2002). Characterizing patterns of agricultural land use in Amazonia by merging satellite classifications and census data. *Global Biogeochemical Cycles*, 16(3), 18–19. <http://dx.doi.org/10.1029/2000GB001386>.
- Crosson, P. (1995). Future supplies of land and water for world agriculture. In N. Islam (Ed.), *Population and food in the early twenty-first century: Meeting future food demands of an increasing population* (pp. 143–159). Washington, DC: International Food Policy Research Institute.
- Crosson, P. (1997). Will erosion threaten agricultural productivity? *Environment: Science and Policy for Sustainable Development*, 39(8), 4–31. <http://dx.doi.org/10.1080/00139159709604756>.
- Deininger, K. W., & Byerlee, D. (2011). *Rising global interest in farmland: Can it yield sustainable and equitable benefits?* World Bank Publications.
- Dregne, H. E., & Chou, N. T. (1992). Global desertification dimensions and costs. *Degradation & Restoration of Arid Lands*, 73–92.
- Edwards, D. P., Larsen, T. H., Docherty, T. D., Ansell, F. A., Hsu, W. W., Derhé, M. A., et al. (2011). Degraded lands worth protecting: the biological importance of Southeast Asia's repeatedly logged forests. *Proceedings of the Royal Society B*, 278(1702), 82–90. <http://dx.doi.org/10.1098/rspb.2010.1062>.
- Fairhurst, T., & McLaughlin, D. (2009). *Sustainable oil palm development on degraded land in Kalimantan*. Washington, DC: World Wildlife Fund.
- Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science*, 319(5867), 1235–1238. <http://dx.doi.org/10.1126/science.1152747>.
- Field, C. B., Campbell, J. E., & Lobell, D. B. (2008). Biomass energy: the scale of the potential resource. *Trends in Ecology & Evolution*, 23(2), 65–72. <http://dx.doi.org/10.1016/j.tree.2007.12.001>.
- Fischer, G., van Velthuisen, H. T., Shah, M. M., & Nachtergaele, F. O. (2002). *Global agro-ecological assessment for agriculture in the 21st Century: Methodology and results*. Laxenburg, Austria: International Institute for Applied Systems Analysis.
- Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., et al. (2005). Global consequences of land use. *Science*, 309(5734), 570–574. <http://dx.doi.org/10.1126/science.1111772>.
- Food and Agriculture Organization. (2001). *Global Forest resources assessment 2000*. FAO Forestry Paper 140 (p. 479). Rome, Italy.
- Food and Agriculture Organization. (2005). *The state of food insecurity in the world 2005: Eradicating world hunger – key to achieving the millennium development goals*.
- Food and Agriculture Organization. (2006). *The state of food and agriculture, 2006: Food aid for food security?* (No. 37).
- Food and Agriculture Organization. (September, 2008). *The state of food and agriculture, 2008. Biofuels: Prospects, risks and opportunities* (pp. 1–138).
- Gallagher, P. W. (2009). Roles for evolving markets, policies, and technology improvements in US corn ethanol industry development. *Regional Economic Development*, 5(1), 12–33.
- Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R. C., Gross, K. L., & Robertson, G. P. (2013). Sustainable bioenergy production from marginal lands in the US Midwest. *Nature*, 493(7433), 514–517.
- Gibbs, H. K. (2012). Trading forests for yields in the Peruvian Amazon. *Environmental Research Letters*, 7(1), 011007. <http://dx.doi.org/10.1088/1748-9326/7/1/011007>.
- Gibbs, H. K., Johnston, M., Foley, J. A., Holloway, T., Monfreda, C., Ramankutty, N., et al. (2008). Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. *Environmental Research Letters*, 3(3), 034001. <http://dx.doi.org/10.1088/1748-9326/3/3/034001>.
- Gibbs, H. K., Ruesch, A. S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N., et al. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings of the National Academy of Sciences*, 107(38), 16732–16737. <http://dx.doi.org/10.1073/pnas.0910275107>.
- Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., et al. (2010). Food security: the challenge of feeding 9 billion people. *Science*, 327(5967), 812–818. <http://dx.doi.org/10.1126/science.1185383>.
- Goldewijk, K. K. (2001). Estimating global land use change over the past 300 years: the HYDE database. *Global Biogeochemical Cycles*, 15(2), 417–433. <http://dx.doi.org/10.1029/1999GB001232>.
- Goldewijk, K. K., Van Dreht, G., & Bouwman, A. F. (2007). Mapping contemporary global cropland and grassland distributions on a 5×5 minute resolution. *Journal of Land Use Science*, 2(3), 167–190. <http://dx.doi.org/10.1080/17474230701622940>.
- Goldewijk, K. K., & Verburg, P. H. (2013). Uncertainties in global-scale reconstructions of historical land use: an illustration using the HYDE data set. *Landscape Ecology*, 28(5), 861–877. <http://dx.doi.org/10.1007/s10980-013-9877-x>.
- Grainger, A. (2009). The role of science in implementing international environmental agreements: the case of desertification. *Land Degradation & Development*, 20(4), 410–430. <http://dx.doi.org/10.1002/ldr.898>.
- Helldén, U., & Tottrup, C. (2008). Regional desertification: a global synthesis. *Globe and Planetary Change*, 64(3), 169–176. <http://dx.doi.org/10.1016/j.gloplacha.2008.10.006>.
- Holm, A., Cridland, S., & Roderick, M. (2003). The use of time-integrated NOAA NDVI data and rainfall to assess landscape degradation in the arid shrubland of western Australia. *Remote Sensing of Environment*, 85(2), 145–158. [http://dx.doi.org/10.1016/S0034-4257\(02\)00199-2](http://dx.doi.org/10.1016/S0034-4257(02)00199-2).
- Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D., & Turkenburg, W. (2003). Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy*, 25(2), 119–133. [http://dx.doi.org/10.1016/S0961-9534\(02\)00191-5](http://dx.doi.org/10.1016/S0961-9534(02)00191-5).
- Houghton, R. A., & Hackler, J. L. (2006). Emissions of carbon from land use change in sub-Saharan Africa. *Journal of Geophysical Research: Biogeoscience* (2005–2012), 111(G2). <http://dx.doi.org/10.1029/2005JG000076>.
- Hubert, B., Rosegrant, M., van Boekel, M. A., & Ortiz, R. (2010). The future of food: scenarios for 2050. *Crop Science*, 50(Suppl. 1), S-33. <http://dx.doi.org/10.2135/cropsci2009.09.0530>.
- IIASA, FAO. (2012). *Global Agro-Ecological Zones—model documentation* (GAEZ v. 3.0). International Institute of Applied Systems Analysis & Food and Agricultural Organization, Laxenburg, Austria & Rome, Italy.
- Kniivilä, M. (2004). *Land degradation and land use/cover data sources*. Working Document. United Nations: Department of Economic and Social Affairs, Statistics Division.
- Koh, L. P., Ghazoul, J., Butler, R. A., Laurance, W. F., Sodhi, N. S., Mateo-Vega, J., et al. (2010). Wash and spin cycle threats to tropical biodiversity. *Biotropica*, 42(1), 67–71. <http://dx.doi.org/10.1111/j.1744-7429.2009.00588.x>.
- Lambin, E. F., Gibbs, H. K., Ferrel, L., Grau, R., Mayaux, P., Meyfroidt, P., et al. (2013). Estimating the world's potentially available cropland using a bottom-up

- approach. *Global Environmental Change*, 23(5). <http://dx.doi.org/10.1016/j.gloenvcha.2013.05.005>.
- Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences*, 108(9), 3465–3472. <http://dx.doi.org/10.1073/pnas.1100480108>.
- Lepers, E., Lambin, E. F., Janetos, A. C., DeFries, R., Achard, F., Ramankutty, N., et al. (2005). A synthesis of information on rapid land-cover change for the period 1981–2000. *BioScience*, 55(2), 115–124.
- Lewis, S. M., & Kelly, M. (2014). Mapping the potential for biofuel production on marginal lands: differences in definitions, data and models across scales. *ISPRS International Journal of Geo-Information*, 3, 430–459.
- Meiyappan, P., & Jain, A. K. (2012). Three distinct global estimates of historical land-cover change and land-use conversions for over 200 years. *Frontiers of Earth Science*, 6(2), 122–139. <http://dx.doi.org/10.1007/s11707-012-0314-2>.
- Nielsen, M., Smeets, E., Stehfest, E., & Vuuren, D. P. (2012). An evaluation of the global potential of bioenergy production on degraded lands. *GCB Bioenergy*, 4(2), 130–147. <http://dx.doi.org/10.1111/j.1757-1707.2011.01121.x>.
- Oldeman, L. R. (1994). The global extent of soil degradation. *Soil Resilience and Sustainable Land Use*, 99–118.
- Oldeman, L. R., Hakkeling, R. U., & Sombroek, W. G. (1990). *World map of the status of human-induced soil degradation: An explanatory note*. Wageningen: International Soil Reference and Information Centre.
- Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., et al. (1995). Environmental and economic costs of soil erosion and conservation benefits. *Science*, 267(5201), 1117–1123. <http://dx.doi.org/10.1126/science.267.5201.1117>.
- Piñeiro, G., Jobbágy, E. G., Baker, J., Murray, B. C., & Jackson, R. B. (2009). Set-asides can be better climate investment than corn ethanol. *Ecological Applications*, 19(2), 277–282. <http://dx.doi.org/10.1890/08-0645.1>.
- Prince, S. D., Becker-Reshef, I., & Rishmawi, K. (2009). Detection and mapping of long-term land degradation using local net production scaling: application to Zimbabwe. *Remote Sensing of Environment*, 113(5), 1046–1057. <http://dx.doi.org/10.1016/j.rse.2009.01.016>.
- Ramankutty, N., & Foley, J. A. (1999). Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochemical Cycles*, 13(4), 997–1027. <http://dx.doi.org/10.1029/1999GB900046>.
- Ramankutty, N., Heller, E., & Rhemtulla, J. (2010). Prevailing myths about agricultural abandonment and forest regrowth in the United States. *Annals of the Association of American Geographers*, 100(3), 502–512. <http://dx.doi.org/10.1080/00045601003788876>.
- Ray, D. K., Mueller, N. D., West, P. C., & Foley, J. A. (2013). Yield trends are insufficient to double global crop production by 2050. *PloS One*, 8(6). <http://dx.doi.org/10.1371/journal.pone.0066428>.
- Rey, C., Scoones, I., & Toulmin, C. (1998). Sustaining the soil: indigenous soil and water conservation in Africa. In *Sustaining the soil* (pp. 1–27). [http://dx.doi.org/10.1002/\(SICI\)1099-145X\(199807/08\)9:4<369::AID-LDR280>3.0.CO;2-H](http://dx.doi.org/10.1002/(SICI)1099-145X(199807/08)9:4<369::AID-LDR280>3.0.CO;2-H).
- Robertson, G. P., Dale, V. H., Doering, O. C., Hamburg, S. P., Melillo, J. M., Wander, M. M., et al. (2008). Sustainable biofuels redux. *Science*, 322(5898), 49–50. <http://dx.doi.org/10.1126/science.1161525>.
- Scherr, S. J., & Yadav, S. N. (1996). *Land degrading in the developing world: Implications for food, agriculture, and the environment to 2020*. International Food Policy Research Institute.
- Sonneveld, B. G. J. S., & Dent, D. L. (2007). How good is GLASOD? *Journal of Environmental Management*, 90(1), 274–283. <http://dx.doi.org/10.1016/j.jenvman.2007.09.008>.
- Swinton, S. M., Babcock, B. A., James, L. K., & Bandaru, V. (2011). Higher US crop prices trigger little area expansion so marginal land for biofuel crops is limited. *Energy Policy*, 39(9), 5254–5258. <http://dx.doi.org/10.1016/j.enpol.2011.05.039>.
- Thomas, D. S. (1993). Sandstorm in a teacup? Understanding desertification. *Geographical Journal*, 159(3), 318–331.
- Tilman, D., Hill, J., & Lehman, C. (2006). Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science*, 314(5805), 1598–1600. <http://dx.doi.org/10.1126/science.1133306>.
- Tilman, D., Reich, P. B., Knops, J., Wedin, D., Mielke, T., & Lehman, C. (2001). Diversity and productivity in a long-term grassland experiment. *Science*, 294(5543), 843–845. <http://dx.doi.org/10.1126/science.1060391>.
- vanVuuren, D. P., van Vliet, J., & Stehfest, E. (2009). Future bio-energy potential under various natural constraints. *Energy Policy*, 37(11), 4220–4230. <http://dx.doi.org/10.1016/j.enpol.2009.05.029>.
- Wessels, K. J., Prince, S. D., & Reshef, I. (2008). Mapping land degradation by comparison of vegetation production to spatially derived estimates of potential production. *Journal of Arid Environments*, 72(10), 1940–1949. <http://dx.doi.org/10.1016/j.jaridenv.2008.05.011>.
- Wessels, K. J., Van Den Bergh, F., & Scholes, R. J. (2012). Limits to detectability of land degradation by trend analysis of vegetation index data. *Remote Sensing of Environment*, 125, 10–22. <http://dx.doi.org/10.1016/j.rse.2012.06.022>.
- Wiegmann, K., Hennenberg, K. J., Fritsche, U. R. (2008). Degraded land and sustainable bioenergy feedstock production. Paper presented at the joint international workshop on high natural value criteria and potential for sustainable use of degraded Lands, Paris.
- Woodcock, P., Edwards, D. P., Fayle, T. M., Newton, R. J., Khen, C. V., Bottrell, S. H., et al. (2011). The conservation value of South East Asia's highly degraded forests: evidence from leaf-litter ants. *Philosophical Transactions of the Royal Society of London: Biological Sciences*, 366(1582), 3256–3264. <http://dx.doi.org/10.1098/rstb.2011.0031>.
- World Energy Council. (2011). *Global transport scenarios 2050*. London, UK: World Energy Council.
- Wright, C. K., & Wimberly, M. C. (2013). Recent land use change in the Western Corn Belt threatens grasslands and wetlands. *Proceedings of the National Academy of Sciences*, 110(10), 4134–4139.
- Young, A. (1999). Is there really spare land? A critique of estimates of available cultivable land in developing countries. *Environment, Development and Sustainability*, 1(1), 3–18.
- Zucca, C., Peruta, R. D., Salvia, R., Sommer, S., & Cherlet, M. (2012). Towards a world desertification atlas. Relating and selecting indicators and data sets to represent complex issues. *Ecological Indicators*, 15(1), 157–170. <http://dx.doi.org/10.1016/j.ecolind.2011.09.012>.