

An evaluation of the global potential of bioenergy production on degraded lands

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Abstract

In this article the global potential of energy crop production on degraded lands was estimated using detailed, spatially explicit data about the area, type and extent of degradation derived from the Global Assessment of Land Degradation Dataset, and by combining this dataset with various spatially explicit data sets. Next, an estimate was made of the possible yield of perennial energy crops on the degraded areas as a function of the type and degree of degradation. Lightly degraded areas were not included, as these areas might be suitable for conventional food production. The total global potential energy production on degraded lands was assessed to be slightly above 150 and 190 EJ yr⁻¹, for grassy and woody energy crops, respectively. Most of this potential, however, is on areas currently classified as forest, cropland or pastoral land, leaving a potential of around 25 and 32 EJ yr⁻¹ on other land cover categories. Most of the potential energy crop production on degraded land is located in developing regions. China has a total potential of 30 EJ yr⁻¹, of which 4 EJ yr⁻¹ from areas classified as other land. Also USA, Brazil, West Africa, East Africa, Russia and India have substantial potentials of 12–18 EJ yr⁻¹, with up to 30% of the potential from areas classified as other land.

Keywords: bioenergy, degradation, potential, short rotation coppice

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Introduction

Many studies on future energy systems expect an important role for bioenergy (Fisher *et al.*, 2007; Dornburg *et al.*, 2010; Van Vuuren *et al.*, 2007). Bioenergy also forms a crucial element of the agriculture and energy policy in many countries. Reasons to promote large-scale bioenergy use include ambitions to reduce the emissions of greenhouse gases (GHG), to reduce reliance on (imported) fossil fuels and to improve the opportunities for development of the agricultural sector. However, there could also be disadvantages to large-scale bioenergy production. Land use for energy crops could (directly or indirectly) lead to the conversion of natural vegetation to agricultural land, with associated impacts on biodiversity and GHG emissions (Searchinger *et al.*, 2008). Bioenergy production may also lead to other GHG emissions such as the emissions of nitrous oxide (N₂O) due to the application of nitrogen fertilizers (Smeets *et al.*, 2009). Further, establishing bioenergy plantations on productive lands will also lead to compe-

tition for land, water, capital and labour with the production of food (Eickhout *et al.*, 2008; Rosegrant, 2008).

Several studies have argued that the use of degraded soils for the production of perennial energy crops could reduce competition with food production, as perennial energy crops would be less susceptible for soil degradation compared to (annual) food crops (Tilman *et al.*, 2006; Campbell *et al.*, 2008; Fargione *et al.*, 2008; Samson & Omielan, 1994; Parrish & Fike, 2005; Sanderson & Adler, 2008; Sexton & Zilberman, 2008). In other words, the option of growing perennial bio-energy crops could significantly increase the productivity of these lands. Bioenergy production on these soil would potentially have little negative impacts on biodiversity and the GHG balance. In fact, authors have argued that cultivation of perennial energy crops could increase the carbon sequestered in degraded soils (Mehdi *et al.*, 1998; Ma *et al.*, 2000; Tolbert *et al.*, 2002), increase the quality of these soils (McLaughlin & Walsh, 1998; Mann & Tolbert, 2000) and improve wildlife habitat and restore natural ecosystem functions (Cook & Beyea, 2000; Semere & Slater, 2007).

Despite these claimed benefits of bioenergy production on degraded areas, few studies have been carried out on the global potential of bioenergy production on degraded lands. Reasons for this include the lack of

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recent, detailed data about soil degradation at a global scale and about the impact of degradation on energy crop yields. In fact, only a few spatially explicit, estimates of soil degradation are available at a global scale. These include databases developed in the Global Assessment of Human-induced Soil Degradation (GLASOD) (Oldeman *et al.*, 1991), the Global Land Degradation Assessment in Drylands (GLADA) project (Bai *et al.*, 2008) and the Millennium Ecosystem Assessment (MEA) (Lepers *et al.*, 2005), (see also section *Determination of degraded lands worldwide*). Other degradation data are spatially invariant or have a national or regional coverage (e.g. Hall *et al.*, 1993; Dregne & Chou, 1994; Van Lynden & Oldeman, 1997; Van Lynden, 2000). Data on the actual impact of soil degradation on soil quality, let alone energy crop yields is even harder to obtain, and often single field data are used, as large-scale, commercial experience with crops on degraded soil is lacking (Van den Broek *et al.*, 2001).

The lack of information can also be noticed within the studies on bio-energy potential. Hoogwijk *et al.* (2003) estimated the global potential from degraded lands to range from 8 to 110 EJ yr⁻¹, assuming 430–580 Mha degraded land and a yield range of 1–10 Mg ha⁻¹ yr⁻¹. The range of degraded land was taken from several relatively old, crude estimates by Lashof & Tirpak (1990), Houghton *et al.* (1993), Hall *et al.* (1993) and Grainger (1988). Tilman *et al.* (2006) estimated global bioenergy potentials on degraded lands to equal 45 EJ yr⁻¹, based on 500 Mha degraded lands and an average yield of 4.5 Mg ha⁻¹ yr⁻¹. This study reported this estimate to be 'rough' without further discussion. The average yield was taken from several field experiments, but without further attention to climate, soil type and degree of degradation. The only study that includes geo-referenced data is Van Vuuren *et al.* (2009), in which the potential of bioenergy production on degraded abandoned agricultural land and natural grasslands is evaluated. Van Vuuren *et al.* (2009) found a global potential of 43 EJ yr⁻¹ on degraded soils. However, three important limitations to this study are that (1) only degraded abandoned agricultural and degraded natural grassland were included, (2) the GLASOD data was aggregated into only three degradation classes and (3) the yields of perennial crops were estimated using a crop growth model but the impact of soil degradation on soil quality was thereby not considered.

Based on the situation described above, the goal of this study was to provide a better estimate of the global potential of bioenergy production on degraded lands. For this purpose, spatially explicit data about the global extent of soil degradation was used, and an overlap was made with maps on current use of these lands. Next, the yield of perennial woody and grassy energy crops on

these areas was estimated using spatially explicit data on soil and climate, and taking into account the severity and the type of soil degradation. Herein, we especially focus on the difference in sensitivity for soil degradation of energy and food crops, as this difference forms a key argument in the discussion on allocating energy crops to degraded lands. Spatially explicit degradation and yield estimates were then combined to estimate global potential of bio-energy on degraded land. Finally, conclusions were drawn and discussed.

Methodology

As indicated in the introduction, the estimates on bio-energy potentials on degraded areas are hampered by poor data availability for soil degradation and crop yields on degraded soils. In this article, we therefore combined available data sources and literature derived assumptions on degradation-yield relationships to derive bio-energy potentials on degraded lands. The procedure is summarized in Fig. 1 and consists of four steps.

1. Selection of dataset on soil degradation: First, various spatially explicit databases on soil degradation were reviewed to identify the most suitable database for our study (*Selection of degradation data*).
2. Downscaling of soil degradation database: The resolution of the soil degradation database (selected in the first step) was insufficient to be able to estimate the yield of energy crops on the basis of local soil and climate characteristics. Therefore, the database needed to be downscaled using different spatially explicit data sources (*Downscaling of the GLASOD database*). This step resulted in a detailed map on global soil degradation. In this step, we also made an overlay of the degradation map and maps of current land use (*Overlay between land use and degradation map*).
3. Calculation of the yield of perennial energy crops: In the third step, we focussed on perennial energy crops, such as grasses (switch grass and elephant grass) and (short rotation) woody energy crops (willow and poplar), as these crops are especially suitable for cultivation on degraded soils (Boehmel *et al.*, 2008; Heaton *et al.*, 2004). The yield of these crops was calculated as a function of the degree and type of degradation. The estimates are done in three steps. First, for each cell we determined the potential yield under non-degraded circumstances based on climate and soil type (*Yield of perennial energy crops under non-degraded circumstances*). Second, these potential yields were reduced by a 'generic degradation factor' as function of the degree of degradation (determined for food crops) (*Generic yield reduction due to degradation for food crops*). Third, we estimated the relative yield reduction for perennial energy crops compared to food crops. The 'relative' scores of perennial crops vis-à-vis food crops were used to correct the 'generic degradation factor' specifically for bio-energy crops (*Yield reduction due to degradation for perennial energy crops*).
4. Calculation of bioenergy potential on degraded soils: The results of step 2 and step 3 were combined to calculate the bioenergy potential on degraded soils, per type and severity of

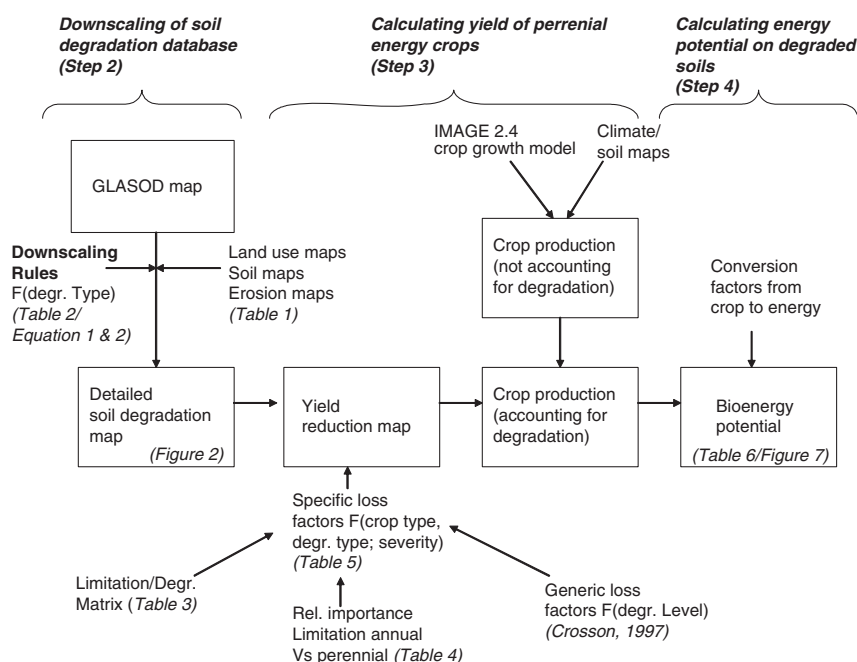


Fig. 1 Overview of the method used to estimate the potential of the production of perennial energy crops produced on degraded soils.

degradation, per land use type or vegetation cover and per region¹ (*The bioenergy potential from degraded land*).

Determination of degraded lands worldwide

Selection of degradation data. Three global datasets about land degradation are available: The GLADA (Bai *et al.*, 2008), the MEA (Lepers *et al.*, 2005) and the GLASOD (Oldeman, 1988; Oldeman *et al.*, 1991). For the purpose of determining bioenergy potential on degraded areas these dataset would need to have the following attributes: geographical detail, a high degree of accuracy, and detailed information on the severity and type of degradation. We evaluated each of these three datasets against these criteria.

1. The GLADA (Bai *et al.*, 2008). The GLADA database is relatively recent, but the approach used to compile this dataset is not useful for the purpose of this study. The GLADA database is derived from remote sensing data that show the photosynthetic activity (i.e. gross primary productivity), while the focus in this study is on soil degradation. The resolution of the GLADA database is relatively high 32 km²

cell size). However, only the occurrence, not the fraction of degradation in a grid cell, is reported. Further, the GLADA database is not validated by field research (Bai *et al.*, 2008). We concluded that the GLADA database provides insufficiently detailed information.

2. The MEA (Lepers *et al.*, 2005). The MEA database indicates the level of soil degradation on a 100 km² raster grid and is based on a synthesis of geo-referenced data of the period 1980–2000. However, the database only includes 62% of the areas classified as dry lands and indicates only extremely degraded lands that are beyond restoration. Hence, the database does not provide sufficient coverage of land types and degrees of degradation.
3. The GLASOD (Oldeman, 1988; Oldeman *et al.*, 1991). The GLASOD project assessed human-induced soil degradation of the period 1945–1990 using expert consultation of a large number of soil scientists, based on standardized reporting guidelines and based on the reduction in suitability of the soil for agriculture and based on the efforts needed for restoration (Oldeman, 1988). The GLASOD database provides data on the severity of degradation (indicated by five qualitative degrees) and the area that is affected (indicated by five ranges of percentages) of the most and second most important type of degradation in each mapping unit. An important disadvantage of the GLASOD database is that it is relatively old and that the applied expert method has limitations in reliability and detail (Sonneveld & Dent, 2009).

The GLASOD database is found to be the most useful for the application in this study, despite its age and the limited geographical detail. The latter was a reason to downscale the GLASOD data further.

¹The following regions are distinguished (Bouwman *et al.*, 2006): Canada, USA, Mexico, Rest of Central America (RCAM), Brazil, Rest South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, Western Europe, Central Europe, Turkey, Ukraine+, Asia-Stan, Russia+, Middle East, India+, Korea, China+, Southeastern Asia, Indonesia+, Japan, Oceania and Greenland.

Downscaling of the GLASOD database. The smallest mapping unit (polygon) of the GLASOD database is 5652 km² – and most polygons are much larger. In other words, for combining the degradation map with detailed yield calculation based on soil and climate characteristics more detailed information is needed than depicted by GLASOD. Therefore, we downscaled the GLASOD database to a 5 min grid level, using various spatially explicit databases (Table 1). It should be noted that the purpose of this downscaling is not to provide a final ‘soil degradation product’ at this detailed level, but only to use this map as an intermediate step in our calculations. For the downscaling, all maps were in terms of land-sea boundaries made consistent with the HYDE dataset Klein Goldewijk *et al.* (2007). The category salinized land was excluded from the GLASOD data, because no suitable detailed data were found to be used in downscaling.

Below, we describe the set of rules used to downscale the existing GLASOD data to a detailed grid. In the GLASOD dataset, we have information for each polygon on the affected area (five ranges for the percentage of total area), the severity of degradation (five classes) and the two main causes of degradation. This implies that in each polygon we need to allocate the affected area to the 5 min within the polygon. We use downscaling rules dependent on the cause of degradation (i.e. overgrazing/agriculture, deforestation) as this allows us to use geographically explicit information on these causes. At the same time, we assume the degradation type and cause to be independent, as also the GLASOD database provides no information about such link.

The downscaling is based on a set of five assumptions. First, we assume urban areas and shifting dunes, rock outcrops, glaciers and salt flats areas to be not subject to degradation (and therefore, we exclude these areas in the allocation rules). Second, we also assume protected areas, bioserves and areas with closed forest canopy cover to be non-degraded, except when the cause of degradation was overgrazing, since grazing is often permitted in protected area. Third, we assume that areas degraded by agriculture or overgrazing according to GLASOD are used as cropland and pastures, respectively. Fourth, we assume that degradation by deforestation results in a decrease in vegetation cover. And finally, we assume that degradation by water or wind erosion occurs on areas classified as sensitive to water or wind erosion.

Based on these assumptions, the following allocation procedure was applied (within each GLASOD polygon):

1. Available area per grid cell is corrected for those land use/land cover types that are assumed to be not subject to degradation, or have a reduced chance to be degraded (for forests cells (closed canopy) it is assumed that still up to 30% can be degraded given the definition of forests on land cover maps) (Eqn 1).
2. Next, degraded areas were allocated as follows (Eqn 2):
 - a. If the first and second causes of soil degradation are ‘overgrazing’ and/or ‘agriculture’, the degraded area was allocated to the pasture and cropland cells in the polygon.
 - b. If only one of two of the indicated causes are ‘overgrazing’ or ‘agriculture’, instead 50% of the degraded areas in the polygon was allocated to the pasture and cropland cells, respectively.
 - c. For all other forms of degradation, Eqn (2) is used that uses weight factors for the different causes and geographically explicit information of each grid cell.

3. In case the degraded area in a polygon of the GLASOD database could not fully be allocated, then it was assumed that the same reduction ratio to the area was applied to both degradation types. This is a valid assumption, because the results show that the total degraded area remained within the ranges given in the GLASOD database.

$$\text{AvailArea}_i = \text{Area}_i - \text{Urban}_i - \text{BareSoil}_i - 0.7 \times \text{ClosedCanopy}_i - \text{Protected}_i \quad (1)$$

$$\text{DegrA}_{i,t,c} = \text{PolygonDegA}_t \times \frac{\text{AvailArea}_i}{\sum_{i=1}^I (\text{AvailArea}_i)} \times \frac{\text{CauseWeight}_{i,c}}{\sum_{i=1}^I (\text{CauseWeight}_{i,c})} \times \frac{\text{TypeWeight}_{i,t}}{\sum_{i=1}^I (\text{TypeWeight}_{i,t})} \quad (2)$$

The sensitivity of results to these parameters in the equation above was tested using the values in Table 2. Area_i = land area of grid cell i ; Urban_i = urban area of grid cell i (Table 1); BareSoil_i = bare soil area of grid cell i (Table 1); Protected_i = protected area of grid cell i (Table 1); ClosedCanopy_i = closed canopy area of grid cell i (Table 1); $\text{CauseWeight}_{i,c}$ = allocation weight of grid cell i if cause of degradation is c (Table 2); $\text{TypeWeight}_{i,t}$ = allocation weight of grid cell i if type of degradation is t (Table 2); $\text{PolygonDegA}_{t,c}$ = degraded area in polygon of type t and cause c , available for the one or two most important types and the one or two most important causes; i, I = grid cell and the total number of grid cells per polygon.

Overlay between land use and degradation map. In the downscaling for some forms of degradation information on land use has been used. Still, the area affected by degradation can be downscaled to grid cells with different land use and land cover attributed (now or in the future). In our calculation, we report the available bio-energy in degraded areas classified as natural grid cells and grid cells used for agriculture separately. In this light, it should be noted that information on current land use is clearly uncertain among others because there is gradient from intensively used agricultural cells to light-use and extensive forms of grazing to finally, mostly natural cells. Also for areas that are degraded or have marginal yields, often different uses exist to sustain rural livelihoods. The land is thus not necessarily an idle resource just waiting for cultivation. The purpose of this article is to provide a rough estimate based on global information, and more detailed studies are needed at the local scale to evaluate these estimates. As discussed further, perennial energy crops may in these areas provide a better opportunity to use the potential of the soil than annual food crops.

Table 1 Datasets used during the downscaling of the Global Assessment of Land Degradation Dataset (GLASOD) database and for the evaluation of the current use of degraded areas

Data source	Information	Reference year	Resolution	Unit	Reference
GLASOD downscaling HYDE database	Pasture area	1980	5'	Area in a grid cell	Klein Goldewijk <i>et al.</i> (2007)
	Cropland area	1980	5'	Area in a grid cell	Klein Goldewijk <i>et al.</i> (2007)
	Urban area	1990	5'	Area as fraction of grid cell	Klein Goldewijk <i>et al.</i> (2007)
	Bioreserve and protected area	1990	0.5°	Boolean, 50%	Klein Goldewijk <i>et al.</i> (2007)
FAO global forest cover	Closed canopy forests area	1992–1993 and 1995–1996	1 km ²	Boolean, reclassified to area per 5' grid cell	Zhu & Waller (2001)
FAO soil map of the world	Non-soil units (shifting dunes, rock outcrops, glaciers and salt flats)	1991	1 km ²	Boolean, reclassified to area per 5' grid cell	FAO (1992)
GLADA database	Decrease in rainfall-adjusted NDVI	1980–2000	32 km ²	Percentage reduction, reclassified to NDVI decrease index between 1 and 10 per 5' grid cell	Bai <i>et al.</i> (2008)
Wind erosion sensitivity data	Wind erosion sensitivity	Inherent properties, constant through time	2'	Dominant class per 5' grid cell, reclassified to sensitivity index 0.1–10	Reich <i>et al.</i> (2001)
USDA water erosion sensitivity data	Water erosion sensitivity	Inherent properties, constant through time	2'	Dominant class per 5' grid cell, reclassified to sensitivity index 0.1–10	Reich <i>et al.</i> (2001)
Land use examination IGBP DISCover Global Land Cover 2000	Forest area (all categories)	1992–1993	1 km ²	Dominant class per 5' grid cell	Loveland <i>et al.</i> (2000)
	Forest area (all tree cover categories except 'tree cover burnt')	2000	1 km ²	Dominant class per 5' grid cell	Bartholome & Belward (2005)
HYDE database	Pasture area	1980 and 2000	5'	Area as fraction of grid cell	Klein Goldewijk <i>et al.</i> (2007)
HYDE database	Cropland area	1980 and 2000	5'	Area as fraction of grid cell	Klein Goldewijk <i>et al.</i> (2007)

GLADA, Global Land Degradation Assessment in Drylands; NDVI, normalized difference vegetation index.

Table 2 The weighting factors used for the causes and the types of degradation which are assumed to influence the location of degradation (if relevant), for default setting, and more or less stringent effects

Cause/type of degradation	Value from map	Default value	Stringent value	Loose value
CauseWeight _{Deforestation}	Decrease in NDVI (Table 1)	10×	100×	10×
TypeWeight _{WindErosion}	Wind erosion sensitivity 0.1–10 (Table 1)	100×	10 000×	10×
TypeWeight _{WaterErosion}	Wind erosion sensitivity 0.1–10 (Table 1)	100×	10 000×	10×
Allocation to cropland/pasture if cause is Agricultural activity/overgrazing	Cropland/pasture area (Table 1)	100%	100%	75% (preferential allocation of step 1 only to 75% of cropland/pasture area)

NDVI, normalized difference vegetation index.

Growth of energy crops on degraded lands

Yield of perennial energy crops under non-degraded circumstances. In our calculations of the potential for bio-energy production on degraded soils, we assume that extensive production systems are used for the production of perennial energy crops with limited fertilizer input and no irrigation. The main reasons is that intensive energy crop production systems on degraded soils are likely to be not economically viable under current conditions (Parrish & Fike, 2005). For calculating the production at cell level, we used data from the Crop and Grass Production Model (CGPM) part of the Integrated Model to Assess the Global Environment (IMAGE) (Leemans & van den Born, 1994; Alcamo *et al.*, 1998; Bouwman *et al.*, 2006). The CGPM is a crop and tree growth model that estimates the yields based on soil and climate data – and which is primarily based on FAO-AEZ model. In this article, we use the model to estimate the yields of woody and grass-system energy crops as a function of soil and current climate. With respect to the estimates for grass-crops, it should be noted that the current model does not include highly specialized energy crops, but instead provides information for mixed grass systems. The CGPM results represent the yield under non-degraded circumstances and so the results need to be corrected for impact of soil degradation, which is further described in the sections Generic yield reduction due to degradation for food crops and Yield reduction due to degradation for perennial energy. An energy content of 19 GJ per oven dry ton (odt) was used to calculate bioenergy potentials.

Generic yield reduction due to degradation for food crops. The GLASOD database itself provides no information about the impact of soil degradation on crop yields. However, Crosson (1997) estimated the yield reduction percentages as a function of the degree of degradation in GLASOD and these figures have in fact also been used by GLASOD database developers (Oldeman, 1998). For each GLASOD severity class, Crosson estimated a high and low yield reduction percentage, namely 5% and 15% for light degradation, 18% and 35% for moderate degradation and 50% and 75% for strong degradation. No

estimates were given by Crosson for extreme degradation, but it can be safely assumed that this category leads to a 100% yield loss, based on the GLASOD classification of extreme degraded soils ‘irreclaimable and beyond restoration’ (Oldeman, 1988). These reduction factors introduced by Crosson are ‘generic’ and are valid for C₃ annual food crops, such as wheat.

Yield reduction due to degradation for perennial energy crops. To estimate the specific yield reduction for perennial energy crops, we carried out a literature review to compare the sensitivity of food crops and perennial crops to degradation, and converted the findings into operational information. While the general procedure is described herein, the resulting factors are reported under the results section “Growth of energy crops on degraded soils”.

Based on our literature review, several reasons were identified as to why the yield of perennial energy crops could be less sensitive to soil degradation than annual food crops. The two most important reasons are (1) perennial energy crops have certain characteristics, such as an extensive root system, potential to go into a dormant state, that result in higher stress tolerance, higher survival rates, i.e. less *limitations to growth*, and higher yields and (2) perennial energy crops can increase the soil organic matter (SOM) and can thereby improve *soil quality* and thereby the yield.

We introduced the better performance of perennial crops by introducing relative performance factors that adjust the generic reduction factors based on the better performance of perennial crops on degraded soils after about 10 years of production. This is done for each of the five types and four degrees of degradation indicated by the GLASOD database, because each combination may affect annual food crops and perennial energy crops differently.

In our analysis, we assessed the impact of soil degradation on five types of growth limiting factors: nutrients, water, toxicity, agronomy and gas exchange. For each of these factors, we assumed two levels of limitations: namely (1) light-moderate and (2) strong-extreme. For each factor the difference between food crops and perennial crops is estimated based on the differences in plant characteristics. Finally, the impact of different

types of degradation on the yield of annual and perennial crops is estimated for each level of degradation. These assessments lead to a set of factors that determine the relative performance of perennial crops compared to normal food crops for each GLASOD score.

The advantage of perennial bio-energy crops over food crops is expressed as the relative difference in yield reduction per degradation type and degradation degree, and calculated from the factors related to soil quality and limitations to growth (Eqn 3). The operational results for these factors based on the literature review are described in detail in the section Growth of energy crops on degraded soils.

$$D(t,d) = I(d) + \sum_{NS} S(t) \times E(d) \quad (3)$$

$D(t,d)$ = difference in yield reduction between perennial energy crops and annual food crops for degradation type (t) and degradation degree (d) (%); $I(d)$ = difference in yield reduction on the basis of soil improvement characteristics alone (%); $S(t)$ = relative importance of each limitation per degradation type (t); $E(d)$ = difference in yield reduction related to each limitation for degradation degree (d).

In the final step, the generic yield reduction values of annual food crops (Generic yield reduction due to degradation for food crops) are used as starting point. Moderate limitation levels were thereby assumed to occur on light and moderate degraded soils and generally (accounting for 5/6) on areas classified as strongly degraded. Strong-extreme stress levels were assumed to occur on strongly degraded and incidentally (accounting for 1/6) on extremely degraded areas. The sensitivity of the results for the assumptions is tested using a best estimate, a high estimate (factor 1.5 higher) and a low estimate (factor 1.5 lower).

Results

The global extent of degraded land

The original GLASOD map includes a single, average, score for large areas with a minimum size of 5625 km². Following the downscaling procedure described above, Fig. 2 was derived that depicts the distribution of degraded areas and the severity of degradation across the world at a 5 min grid. The figure can be seen as an interpretation of the original GLASOD data based on local cell characteristics. The total area per region and severity class based on the downscaled data is shown in Fig. 3. Obviously, at regional scale the downscaled map reflects the properties of the original GLASOD map. The total global area of degraded land equals 1836 Mha. The degraded area is spread across all regions in the world. Most of the degraded land can be found in China (15%). Other regions that have significant areas of degraded land are the Middle East (9%), India+, Brazil and the region Rest of South America (RSAM). The last three regions each account for 6% of the global area of degraded land. Figure 2 also shows that most (46%) of the degraded land is moderately degraded, 37% is classified as lightly degraded and 15% and 0.5% are strongly and extremely degraded, respectively. The distribution of the severity classes is unevenly distributed across regions. Slightly and moderately affected soils are concentrated in a limited number of regions. China accounts for 15% and 17% of the slightly and moderately degraded soils. Brazil, RSAM, West Africa, East

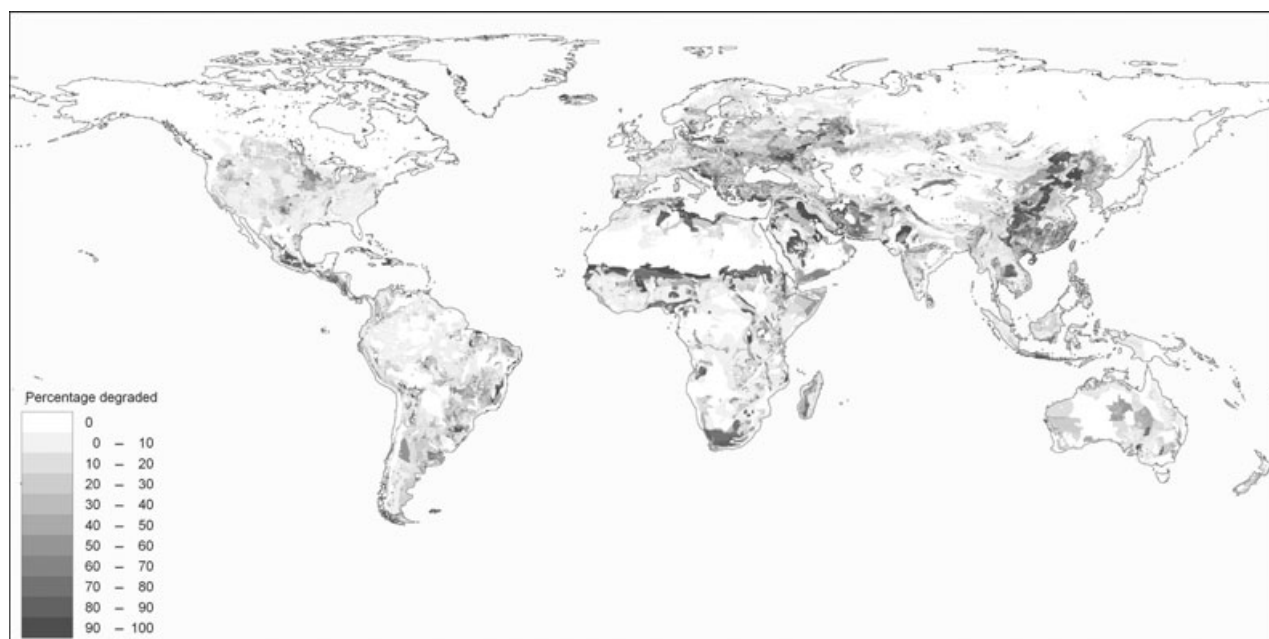


Fig. 2 Global overview of degraded lands at a 5 min scale (% of the land area that is affected by degradation).

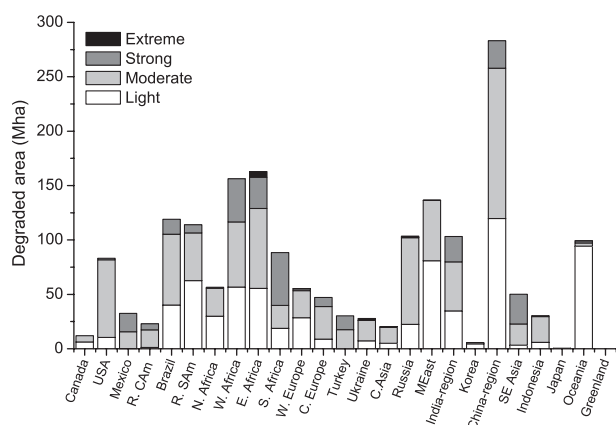


Fig. 3 The area and severity of degraded soils in different regions (in Mha).

Africa, Middle East, India+ and Oceania account together for 49% and 64% of the area. The same regions, plus the USA and Russia and except for Oceania, also account for the bulk (67%) of the strongly affected areas. Extremely degraded areas are concentrated in East Africa (56%), Ukraine (19%), and Russia (14%).

We have made an overlay of the current land-use map and the downscaled GLASOD map. Figure 4 shows the derived global distribution of degraded lands per degree and type of degradation across the current land use. Within the GLASOD data set, erosion is by far the dominant type of degradation, responsible for 87% of the land degradation. Chemical degradation is the second most important cause of degradation (8%), followed by compaction (3%), and waterlogging and subsidence. The results show that the majority of degraded lands overlays with pastoral land (43%); this is followed by cropland (25%), other land use (21%) and forest area (10%). These numbers need obviously to be interpreted with

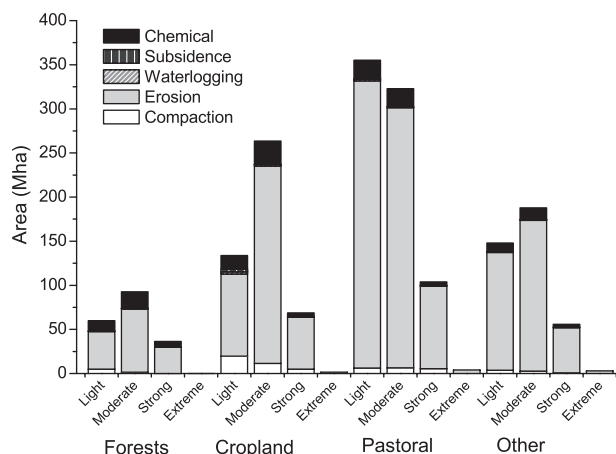


Fig. 4 The global area of degraded soils per land use type and per degree and type of degradation (in Mha).

care as they are obviously influenced by the downscaling rules that have been applied. The results suggest that degraded areas may be mainly used as pastoral areas (37–51%). The percentage of the land occupied by cropland is estimated at 19%, 30%, 26% and 17%, for areas affected by light, moderate, strong and extreme degradation, respectively. Especially interesting for the production of energy crops are the overlays with areas which are not under forest cover and which are not classified as crop and pasture land. In total, 394 Mha of degraded land is classified as being in this category (other land). As indicated in the method section, part of this land may still be used for some form of rural livelihood given the difficulties in accounting for the gradient in the intensity of land use in land use maps. Not all of these lands should therefore be regarded as idle resources. In that light, it should also be noted that slightly and moderately affected soils might still be suitable for the production of food, especially in land scarce regions (and thus potentially competition for these areas could play a role). Of the lightly, moderately and strongly degraded areas, about 21–22% is other land, while for strongly degraded areas, which are especially unattractive for the production of food crops and for grazing of cattle, 35% is classified as other land. The total degraded areas classified as other land are 148, 188, 56 and 3 Mha for soils that are slightly, moderately, strongly and extremely affected by degradation, respectively.

Growth of energy crops on degraded soils

Yield reduction due to degradation: annual food crop vs. perennial energy crops. As described in the Methodology, we carried out a literature review on the difference in sensitivity of annual food crops and perennial energy crops to soil degradation. We discuss the outcomes in the following two sections.

Soil quality: A central factor for the quality of a soil is the SOM content. The conversion of natural vegetation to cropland typically results in a decrease of the SOM content, which results in a deterioration of the chemical and physical properties of the soil for crop production (Lal, 2006). Cropland is thus typically low in SOM. In contrast, soils under perennial crop production have much higher SOM contents and can also increase the SOM content (Lal, 2006). Perennial crops limit the removal of SOM through water and wind erosion, biological oxidation and leaching, and the accumulation of litter and the extensive root systems contribute to the build up of SOM (Börjesson, 1999). Experimental studies have shown that switching from annual food crops to perennial energy crops generally results in an increase in SOM of $1 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (e.g. Ranney *et al.*, 1991; Hansen, 1993; Kort *et al.*, 1998; McLaughlin & Walsh,

1998; Mehdi *et al.*, 1998; Cook & Beyea, 2000; Ma *et al.*, 2000; Mann & Tolbert, 2000; Zan *et al.*, 2001; Tolbert *et al.*, 2002). Lal (2006) showed that for every additional t C in SOM yields can increase with 20–70 kg ha⁻¹ yr⁻¹ for wheat, 10–50 kg ha⁻¹ for rice, and 30–300 kg ha⁻¹ yr⁻¹ for maize. We related these numbers to the average global yields of these crops (maize: 5.1 t ha⁻¹ yr⁻¹, wheat 4.3 t ha⁻¹ yr⁻¹ and rice 3.0 ha⁻¹ yr⁻¹) (FAO, 2010). The average yield increase of annual crops due to increasing the SOM thus equals circa 5%. We use this figure as an average number and thus assumed an increase of 1.5%, 3.0%, 4.5% and 6.0% for light, moderate, strong and extreme degradation, respectively.

Limitations to growth: In Table 3 the five types of degradation included in the GLASOD are related to the five types of limitations that are considered in this study on the basis of a literature survey (compaction, erosion and subsidence, changes in microbial regime, waterlogging and chemical degradation). Compaction, which is characterized by a high soil bulk density, results in a poor aeration (inadequate gaseous exchange), complications with seeding and tillage (agronomic limitations), a limited root growth and a decreased infiltration rate (water and nutrient limitation) (Shestak & Busse, 2005). Erosion and subsidence leads to the loss of the fertile top soil layer, including SOM. This in turn results in a decrease of the rooting depth, the nutrient availability and the microbial activity (Lal, 1990; Den Biggelaar *et al.*, 2001). Changes in microbial regime can result in toxic nitrate ammonium concentrations (Hakansson & Voorhees, 1997). Waterlogging impedes adequate gaseous exchange for crops and affects a wide variety of chemical processes, resulting in an inappropriate nutrient balance and disturbed gaseous exchange (Fausey & Lal, 1990). Furthermore, water logging may complicate seeding and tillage (agronomic limitations). Chemical degradation results in a disturbance of the natural chemical properties of the soil, which can result in

nutrient stress, toxic conditions or a disturbed pH balance (Logan, 1990).

We have estimated the relative difference in yield responses due to degradation between perennial (energy) crops and annual food crops based on literature review (Table 4). The indices in Table 4 are derived from an evaluation of the biophysiological differences between the two crop types as described below.

- **Nutrients.** It can be assumed that perennial (energy) crops are less limited by nutrients compared to food crops. An important reason is that perennial crops are more efficient in using the available nutrients. First, annual crops are often harvested completely, including storage organs and leaves, while perennial energy crops in temperate rations are typically harvested in late autumn, winter or in early spring, i.e. after litter fall and after translocation of the nutrients to roots (Jorgense & Schelde, 2001). Second, the loss of nutrients to surface- and groundwater from perennial energy crops is lower compared to annual crops, because of the higher vegetation cover and SOM content, which results in lower soil erosion, run-off and nutrient leach-

Table 4 Differences in relative yield reduction for perennial energy crops vs. annual food crops under different limitations

Limitation	Light and moderate degradation	Strong and extreme degradation
Nutrients	++	+++
Water	–	++
Toxicity	+	+
Agronomy	++	++
Gaseous exchange	–	–

Plusses indicate the expected yield advantage of perennial energy crops over annual food crops, namely a large difference (+++), a moderate difference (++) and a small difference (+).

Table 3 The occurrence of main limitations for crop growth for the Global Assessment of Land Degradation Dataset types of degradation

Limitation	Degradation type				
	Compaction	Erosion	Waterlogging	Subsidence	Chemical
Nutrients	++	+++	++	+++	++
Water	+++	++	–	++	–
Toxicity	+	–	–	–	+++
Agronomy	++	–	+	–	–
Gaseous exchange	+	–	+++	–	–

The relative importance of different limitations is indicated as occurring frequently (+++), regularly (++) or incidentally (+). Sources: Shestak & Busse (2005), Raghavan *et al.* (1990), Mullins *et al.* (1990), Lal (1990), Hakansson & Voorhees (1997) and Den Biggelaar *et al.* (2001).

ing rates. Third, energy crops are more efficient in capturing nutrients from the soil than annual food crops, due to the more extensive root system and mycorrhizal symbiosis (Tolbert *et al.*, 2002; Parrish & Fike, 2005; Lewandowski *et al.*, 2000). Moreover, perennial energy crops usually have a longer growing period compared to annual crops. This allows for a gradual nutrient uptake rate, while the high yielding annual crop varieties, which are commonly used in commercial agriculture, are very sensitive to the availability of nutrients and water during the growing period. The growth of perennial energy crops is mainly limited by the availability of water (Moller *et al.*, 2007), while for annual food crops also the availability of nutrients is a key limiting factor. Based on the discussion above we conclude that there is a large difference between the sensitivity of the yield of perennial energy crops and annual food crops for nutrient stress.

- *Water.* The water use efficiency of perennial energy crops is generally higher compared to annual food crops. Reasons are that most perennial energy crops have a C4 photosynthetic pathway, while annual food crops, such as wheat and potatoes, have a C3 type of photosynthetic system. Theoretically, a C4 photosynthetic pathway allows more efficient use of water, but this is generally only realized under light, humid and warm conditions (Beale *et al.*, 1999; Jorgense & Schelde, 2001; Naidu *et al.*, 2003; Parrish & Fike, 2005). More important are the larger and deeper root system, which allows for higher water absorption efficiency in case of irregular rainfall, and which allows the extraction of water from deeper soil layers (Parrish & Fike, 2005). Also important are the reduced need for tillage, which limits ecosystem damage, the increase in SOM content, which improves the water holding capacity, and the higher vegetation cover, which reduces run-off. Because the growth of perennial crops is generally limited by the availability of water, it is expected that their water use related qualities are generally fully exploited on non-degraded soils. Therefore, no advantage in percentage yield reduction during moderate water stress is expected.

- *Toxicity.* Although data about the tolerance of energy crops to toxic substances are scarce, several studies show that perennial energy crops can grow under toxic conditions (Jorgense & Schelde, 2001). For example, switchgrass is used to regenerate toxic soils, such as taconite mine tailings, strip mines, lignite overburden, bauxite mines, acidic coal refuse piles, lead and zinc mines and sites denuded by zinc smelters (Parrish & Fike, 2005). Further, poplar and willow are also grown on landfills, which are characterized by methane toxicity (Nixon *et al.*, 2001). Also, mycorrhizal

symbiosis, which is facilitated by perennial energy crops, may be important for tolerance to low pH levels and high aluminium levels (Parrish & Fike, 2005). Because of the lack of data about the direct impacts we assumed a small yield difference between perennial energy crops and annual food crops.

- *Agronomy.* Perennial energy crops require less tillage than annual food crops, as perennial crops do not need to be re-established. Therefore, if certain agronomic limitations complicate tillage operations, then perennial crops are less affected than annual crops.

- *Inadequate gaseous exchange.* Regarding inadequate gaseous exchange no indications were found for a difference in performance between annual food crops and perennial energy crops. We therefore assume a moderate yield difference for agronomic limitation and no yield difference for gaseous exchange.

The yield reduction classification shown in Table 4 is included in the calculations, by assuming a 3.75% difference in yield reduction in case of a small difference in yields (+), 7.50% for a moderate difference (++) and 11.25% for a large difference (+++). This range is derived from the literature. For strong degradation, yield advantages under moderate and extreme degradation were combined with a 5/6 and 1/6 weighting, respectively.

The results in Tables 3 and 4 are combined in Table 5, which shows the difference in relative yield reduction (following Eqn 3), percentage yield reduction for annual food crops, and the resulting percentage yield reduction for perennial energy crops per type and degree of degradation. The yield reduction factors for annual food crops are taken from Crosson (1997) (see *Generic yield reduction due to degradation for food crops*). The yield of perennial energy crops is 5.3–16.3% less sensitive for degradation compared to annual food crops, which equals a 0.3–1.1%-point lower yield reduction for light degradation, 1.6–3.0%, 4.5–8.2% and 11.0–16.3%-point for moderate, strong and extreme degradation, respectively.

Yield of perennial energy crops on degraded soils. Figure 5 shows the average yield of woody and grassy energy crops according to the Crop and Grass Production Model (CGPM) of the IMAGE model. The higher end of each bar indicates the yield not accounting for degradation. In the lower side of each bar, the impact of degradation on soils has been accounted for. The average yield of woody and grassy species grown on degraded soils was calculated at 8.9 and 6.8 oven dry ton (odt) $\text{ha}^{-1} \text{yr}^{-1}$, respectively. Across the different soil type categories, the yield of woody crops varied between 2.7 to 10.1 odt $\text{ha}^{-1} \text{yr}^{-1}$ and 2.2 and 6.6 odt $\text{ha}^{-1} \text{yr}^{-1}$ for

Table 5 The difference in relative yield reduction between perennial energy crops and annual food crops (based on Eqn 3 and Tables 3 and 4), applied to the yield reduction for annual food crops (a high and a low estimate, see Generic yield reduction due to degradation for food crops), resulting in estimated yield reduction for perennial energy crops (a high and a low estimate) for all types and degrees of degradation

Yield reduction percentages	Compaction		Erosion		Water logging		Subsidence		Chemical	
	Low	High	Low	High	Low	High	Low	High	Low	High
Light degradation										
Difference in relative yield reduction	5.3		6		5.3		7.1		6.8	
Annual food crops	5.0	15.0	5.0	15.0	5.0	15.0	5.0	15.0	5.0	15.0
Perennial energy crops	4.7	14.2	4.7	14.1	4.7	14.2	4.6	13.9	4.7	14.0
Moderate degradation										
Difference in relative yield reduction	6.8		7.5		6.8		8.6		8.3	
Annual food crops	18.0	35.0	18.0	35.0	18.0	35.0	18.0	35.0	18.0	35.0
Perennial energy crops	16.8	32.6	16.7	32.4	16.8	32.6	16.4	32.0	16.5	32.1
Strong degradation										
Difference in relative yield reduction	8.7		9.9		8.5		10.9		10	
Annual food crops	50.0	75.0	50.0	75.0	50.0	75.0	50.0	75.0	50.0	75.0
Perennial energy crops	45.7	68.5	45.1	67.6	45.8	68.7	44.5	66.8	45.0	67.5
Extreme degradation										
Difference in relative yield reduction	12.3		15.8		11		16.3		12.8	
Annual food crops	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Perennial energy crops	87.7	87.7	84.3	84.3	89.0	89.0	83.7	83.7	87.2	87.2

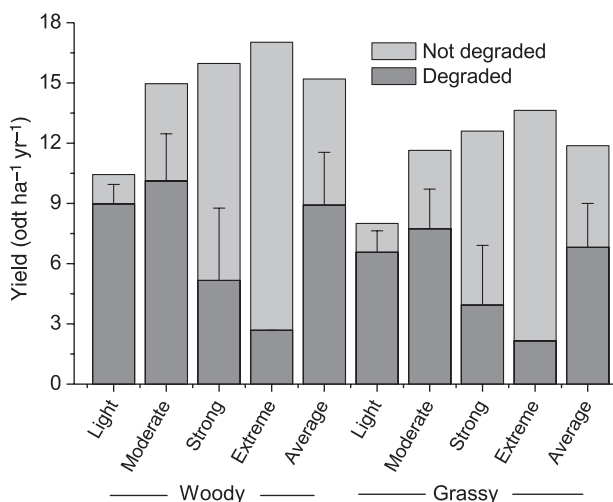


Fig. 5 The yield of woody and grassy energy crops on not degraded soils and on various levels of severity of soil degradation (in odt ha⁻¹ yr⁻¹). The weighed average is estimated excluding lightly degraded soils. The yield figures were calculated using the high yield reduction factor. The error bars indicate the yield in case the low yield reduction factor was used.

grassy energy crops on extremely and moderately degraded areas, respectively. Note that the uncorrected yields seem to anti-correlate with the severity of degradation. This is in fact due to our downscaling rules that lead to a higher degree of degradation assigned to soils that have been used as agricultural area (and thus have

relatively high yields). The corrected yields, however, are strongly influenced by the degree of degradation. Further, the CGPM that is used to estimate the yields also showed that the yield of woody energy crops would be circa 30% higher than the yield of grassy energy crops. It has to be noted that some special herbaceous energy crops like miscanthus can achieve higher yields than woody energy crops (Pellis *et al.*, 2004; Hastings *et al.*, 2009; IEA, 2009). The model for grassland production applied herein does, however, represent average grassland systems. Moreover, the results presented in Fig. 5 cover the entire global area of degraded lands, i.e. also include areas where only marginal grasslands exist. For these reasons, woody crops perform slightly better on average than grassy energy crops, despite the possibility of high miscanthus yields at specific locations.

Figure 6 shows the distribution of yields per region across different yield classes. Regions with a relatively high yield (>15 odt ha⁻¹ yr⁻¹) are the USA, RCAM, Ukraine, Oceania, Korea and Indonesia. However, in many parts of the world, in the Middle East, South Africa, East Africa, West Africa Turkey, yields are lower than 5 odt ha⁻¹ yr⁻¹. The bulk of the areas have a yield between 5 and 15 odt ha⁻¹ yr⁻¹.

The bioenergy potential from degraded land

The total potential of the production of perennial energy crops on moderately, strongly and extremely

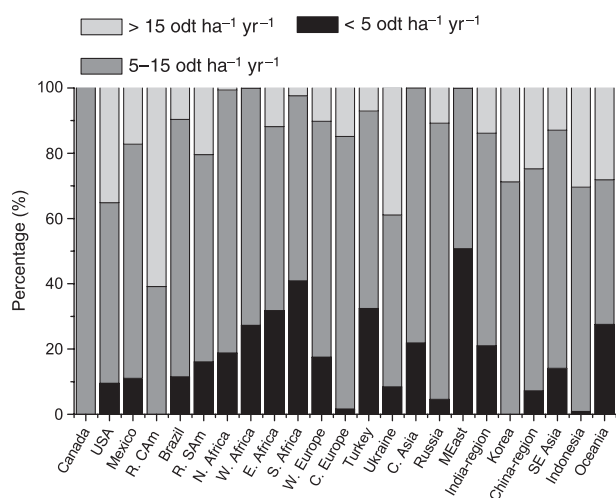


Fig. 6 The potential of woody energy crops on degraded lands per region per yield class for 0–5, 5–15 and >15 odt ha⁻¹ yr⁻¹ (as % of total potential).

degraded soils was estimated at 193 EJ yr⁻¹ for woody crops and 151 EJ yr⁻¹ for grassy species, respectively (Table 6). In these estimates, lightly degraded soils have been excluded, as these soils are potentially still suitable for the production of food. Within the total potential for woody crops, moderately degraded areas account for 86% (or 166 EJ yr⁻¹), strong degraded areas

for 26 EJ yr⁻¹ and extremely degraded areas for 0.4 EJ yr⁻¹.

It is important to note that from the total potential of woody crops at degraded soils, 25, 71 and 64 EJ yr⁻¹ come from areas covered by forests, cropland and pastures, respectively, and 32 EJ yr⁻¹ is classified as other land (see previous remarks on the potential use of this land). More than 80% of these potentials come from moderately affected soils.

Figure 7 shows the potential of woody and grassy energy crops per region and per land use type. The bulk of the potential was calculated for Asia (45%), Africa (18%) and Central and South America (19%). The largest potential, 16% of the total global potential or 30 EJ yr⁻¹, was projected for China, whereby 16% of this potential came from 'other land', while 33% and 34% came from cropland and pastures, respectively, and the remaining from forests. But the potentials of other regions were also considerable. The USA, Brazil, West Africa, East Africa, Russia and India each have potentials above 10 EJ yr⁻¹. However, large differences were found with respect to the availability of the degraded areas. In the USA, 1% of the potential came from areas classified as 'other land', while in India this figure was 30%. Cropland and pastures occupy 56–96% of the potential in these countries, which shows that agriculture can be a major limiting factor for the availability of degraded land for energy crop production.

Table 6 Bioenergy potentials (EJ yr⁻¹) for grass and woody species, presented for different degrees of degradation, types of degradation and current land-use types

	Grass bioenergy potentials				Woody bioenergy potentials			
	Forest	Cropland	Pastoral	Other	Forest	Cropland	Pastoral	Other
Moderate								
Compaction	0.2	1.9	0.7	0.3	0.3	2.5	1.0	0.3
Erosion	13.2	43.0	39.4	17.4	17.0	54.7	50.7	22.5
Waterlogging	0.1	0.4	0.2	0.2	0.2	0.5	0.2	0.2
Subsidence	0.0	0.1	0.0	0.1	0.1	0.1	0.0	0.1
Chemical	2.9	4.7	3.1	2.0	3.8	6.1	3.9	2.6
Strong								
Compaction	0.0	0.4	0.3	0.1	0.0	0.5	0.4	0.1
Erosion	2.8	5.1	6.0	4.3	3.6	6.5	7.7	5.5
Waterlogging	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Subsidence	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chemical	0.5	0.3	0.3	0.2	0.6	0.4	0.4	0.3
Extreme								
Compaction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Erosion	0.0	0.1	0.1	0.1	0.0	0.1	0.2	0.2
Waterlogging	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Subsidence	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chemical	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	19.8	56.0	50.2	24.7	25.5	71.4	64.5	31.8

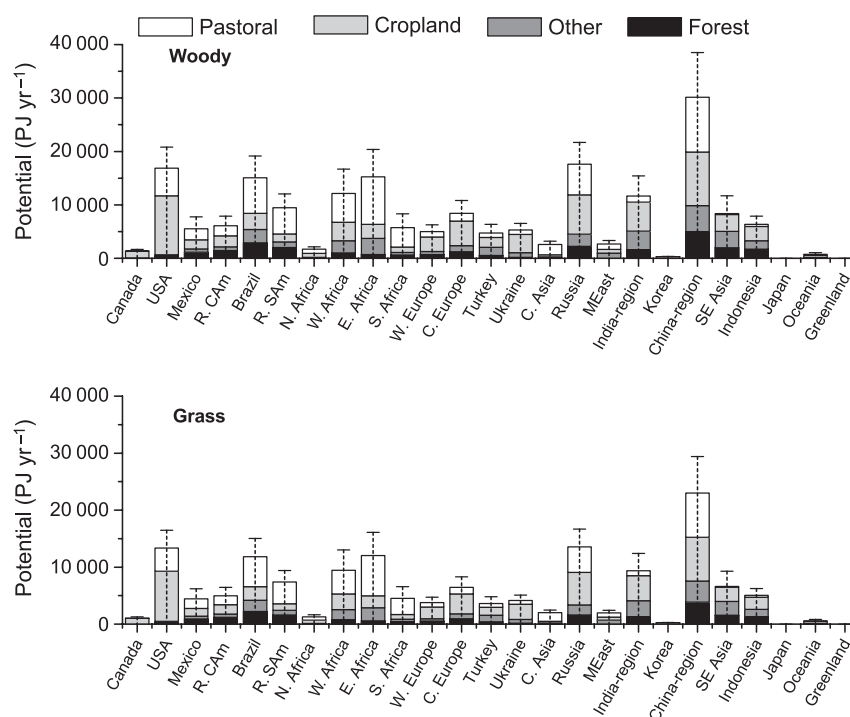


Fig. 7 The potential of woody and grassy energy crops on degraded lands per region and per current land-use type (in PJ yr⁻¹). Error bars indicate total potential in case the low yield reduction percentage was applied.

Sensitivity analysis

Obviously, the calculation of the bioenergy potentials on degraded lands in this article involved several assumptions. We have tested the sensitivity of our results for the key assumptions, using the values in Table 7. In case the low yield reduction percentages were used instead of high reduction values (Table 5), the global potential increased by 29%. Including lightly degraded lands,

which are less attractive for bioenergy production because of the limited yield advantage over food crops, increased the potential by 40%. Using the upper or lower limit included in the GLASOD, instead of the average, also significantly influenced the results and changed the potential by +30% to -27%. However, it is obviously rather unlikely that the upper or lower values would apply to all polygons. Changing the allocation rules during the downscaling procedure had two effects

Table 7 The effect of varying assumptions or factors on total bioenergy potentials

Assumption/factor	Standard	Alternative	Sensitivity (percentage difference with standard case)
Degraded area			
Area affected by degradation	Average	Lower limit	-27
		Upper limit	+30
Differentiation by downscaling rules	Moderate	No differentiation	+2
		Loose rules	-3
		Rigid rules	-0.04
Light degradation	Excluded	Included	+40
Yield reduction			
General yield reduction percentages	High estimate	Low estimate	+29
Relative yield advantage of perennial energy crops over annual food crops	Optimal estimate	Low estimate	-2
		High estimate	+2

Calculations were performed for grass potentials. The sensitivity of woody potentials was similar (maximum 2.2% difference).

on the results. First of all, not only did the area allocated change, but also the location of degraded lands changed. The latter aspect could influence the potential if the degraded areas would be allocated to areas with other climate and soil characteristics. The overall effect of changing the allocation rules was, however, limited to -3.0% or less. Last, the effect of alternative yield reduction percentages was found to be of limited importance ($-/+2\%$). In other words, the most important uncertainties are the assumed yield reduction values and the question which of the degraded areas are included.

Discussion and conclusions

In this study the global potential of perennial energy crop production on degraded soils was evaluated, including an assessment of the current use of these areas. A comparison on available products on degraded areas showed the GLASOD map to be the most appropriate starting point. More recent products exist but these could not be used directly. Further research is desired on developing better land degradation maps (our sensitivity analysis identified the degradation map as an important source of uncertainty). The GLASOD was downscaled to a 5 min resolution. The yield of grass and woody energy species on degraded soils was estimated using a crop growth model. The effect of degradation on the yield of woody and grassy crops were evaluated and applied for different types and degrees of degradation.

The potential of moderately, strongly and extremely degraded areas was estimated at 166, 26 and 0.4 EJ yr^{-1} , respectively. Within these areas, a total 32 EJ yr^{-1} comes from areas not classified as forest, cropland and pastoral land. While, given the quality of land use maps, it may not be ruled out that this other land is to some degree used for marginal agricultural purposes, the use of perennial energy crops may be very attractive on these areas and it might therefore be a reasonable indicative number for the potential of bioenergy production on degraded areas worldwide. Obviously, this needs to be studied in more detail on the basis of local studies. The potential of forest, cropland and pastoral land was estimated at 25, 71 and 64 EJ yr^{-1} , respectively (possibly some of the pastoral lands are interesting for energy crop production, assuming that not all pastoral areas are used to their carrying capacity). Regarding the type of degradation, erosive areas were dominant in bioenergy potentials in all regions. Regions with a high potential for bioenergy from degraded lands are China, the USA, Brazil, West Africa, East Africa, Russia and India.

The results are based on our finding from literature assessment that the yields of perennial energy crops are

less sensitive to soil degradation compared to conventional (annual) food crops. As a consequence, bioenergy production on degraded lands might be a promising option as it possibly combines the restoration of degraded soils with the potential to increase energy security, and mitigate climate change.

Obviously, important assumptions have been made in our calculations. For instance, using the low yield reduction percentages (instead of the medium ones) would increase the global potential by 29%, but similarly, the potential would decrease if higher reductions were used. Interestingly, comparison with earlier assessments (Table 8) shows that the potentials calculated in this study are comparable to values reported earlier in the literature (using less comprehensive methodologies). We discuss the comparison with these studies in more detail for both yields and the extent of degraded areas considered.

The yields estimated in this study (8.9 and $6.8 \text{ odt ha}^{-1} \text{ yr}^{-1}$ on average for woody and grassy energy crops, respectively) are within the range of $1\text{--}10 \text{ odt ha}^{-1} \text{ yr}^{-1}$ assumed by Hoogwijk *et al.* (2003). The yield figures in the study of Hoogwijk are also derived from the CGPM model, but no geographically explicit calculations were made. The assumptions on crop management form another difference. While Hoogwijk *et al.* (2003) multiplied potential rainfed yields by a factor of 0.7 (to represent imperfect management), this study used potential rainfed yields themselves (factor of 1). The study by Van Vuuren *et al.* (2009) used similar yields as the yields in this study (and also derived from the CGPM model). An important point here is that the effects of degradation on yields are not accounted for by Van Vuuren *et al.* (2009). Here, the yields are, in fact, reduced by 4.6–88% depending on the degree and type of degradation (and with an average of 29%). On the other hand, Van Vuuren *et al.* (2009) accounted for imperfect management by using time, crop and region dependent factors ranging from 0.5–1.3 in the year 2050. A final reason for the difference in yields between this study and that of Van Vuuren *et al.* (2009) is their use of the combined severity and degree of degradation indicator, compared to the spatially explicit soil and climate data used in this study. Totally independent studies have been performed by Tilman *et al.* (2006) and Campbell *et al.* (2008). Here, a direct comparison is more difficult due to differences in the type of land that is considered. Tilman and his co-workers estimated the yield of grassland at $4.7 \text{ odt ha}^{-1} \text{ yr}^{-1}$, based on field experiments. This figure is comparable to the $4.3 \text{ odt ha}^{-1} \text{ yr}^{-1}$ calculated for abandoned agricultural land by Campbell *et al.* (2008). Campbell estimated the biomass yield with a natural production model, using data on climate, surface insulation, soil texture, land cover and

the normalized difference vegetation index (NDVI). Campbell *et al.* (2008) state that the NDVI input may be sensitive to degradation which may decrease yields. The higher yield estimated in this study can partially be explained by differences in the areas that are considered, although this probably does not fully explain the difference. A more detailed comparison between the two models with the results of Tilman *et al.* (2006) would be desirable. Still, the yields found in this study are in accordance with field studies on energy production on degraded lands (McElroy & Dawson, 1986; Ettala, 1988; Husain *et al.*, 1998; Bungart & Huttl, 2001; Mulkey *et al.*, 2006; Tilman *et al.*, 2006; Schmer *et al.*, 2008).

Also important are differences in the area of degraded soils taken into account (Table 8). Hoogwijk *et al.* (2003) estimated the amount of degraded area a factor two higher than in this study based on other studies that provided rough, global numbers. Tilman

et al. (2006) only considered abandoned agricultural land, and therefore their results are not directly comparable. In both cases, it is difficult to compare numbers as little detail is provided behind the aggregated numbers. Van Vuuren *et al.* (2009) also used the GLASOD database so the total area is similar (although Van Vuuren *et al.* (2007) used somewhat different rules excluding different land use types). It can be concluded that in this study the assessment of the impact of degradation on yields was performed using some simple, generic rules and based on a qualitative literature review. This provides a first-order level estimate, but more accurate and consistent field data are urgently needed to further substantiate and quantify the competitive advantage of perennial biofuels over annual food crops on these lands.

Obviously, our calculations also heavily depend on the available information on degraded areas. Unfortu-

Table 8 The main results of existing assessments of bioenergy potentials on degraded lands are shown, indicating the amount of degraded area, the estimated bioenergy yields on these lands and the resulting bioenergy potential

Source	Methodology	Lands included	Assessment		
			Area (Mha)	Yields (odt ha ⁻¹ yr ⁻¹)	Potential (EJ)
This study	Geographically explicit assessment based on downscaled GLASOD degradation data, yield reduction percentages and IMAGE potential yield maps	Global degraded lands not in use as forest, cropland, pastoral land or urban area	247	10.2	25–32
Van Vuuren <i>et al.</i> (2009)	Geographically explicit assessment of global bioenergy potentials for different SRES scenarios and yield developments in 2050. The share of these potentials that was located on degraded lands was identified	Abandoned agricultural land (accessibility of 75% assumed) and degraded natural grassland systems (accessibility of 50% assumed) overlapping with the GLASOD map of degraded areas	–	2.5–33	31 from severely degraded and 12 from extremely degraded soils
Hoogwijk <i>et al.</i> (2003)	To explore the ranges of bioenergy potentials, studies assessing available area were reviewed (Grainger, 1988; Lashof & Tirpak, 1990; Houghton <i>et al.</i> , 1991; Hall <i>et al.</i> , 1993) A crop growth model was used to examine yields	Degraded lands (degradation of soil and/or vegetation), which can be used for bioenergy production	430–580	1–10	8–110 (in 2050)
Tilman <i>et al.</i> (2006)	Rough global estimate based on a yield study to assess Low Input High Diversity grass systems on degraded soils	Agriculturally abandoned and degraded lands	500	4.7	45

GLASOD, Global Assessment of Land Degradation Dataset.

nately, the best suitable assessment of degraded areas for this study is rather old (see Methodology). The GLASOD is based on expert judgement and the spatial level of detail is limited. Sonneveld and Dent (2009) tested the consistency of GLASOD by comparing expert judgments on soil degradation hazard for similar combinations of biophysical conditions and land use. Reproducibility is evaluated by estimating a model that relates the land degradation classes to information on explanatory variables, the results of which can be used to assess the land degradation at unvisited sites. The GLASOD assessments proved to be only moderately consistent and hardly reproducible, while the counter-intuitive trend with crop production reveals the complexity of the production–degradation relationship. The authors argue that the GLASOD approach can be improved by resolving the differences in conceptualization among experts and by defining the boundaries of the ordered classes in the same units as independent, quantitative land degradation data. In any case, the GLASOD data are relatively old (1990) and thus developments in degraded area during the last two decades have not been included. Consequently, the potential of energy crops on degraded soils as presented in this article could be an underestimation, although the ranges given in GLASOD are quite large.

Further, it should also be noted that GLASOD focuses only on human-induced soil degradation. However, naturally degraded lands may also be interesting for bioenergy production. The potential of energy crop production from naturally occurring degraded areas is not known. Yet, some observations suggest that this potential could be (very) large. For example, 76 Mha are degraded through salinization according to GLASOD, but which are not included in this study. Wicke *et al.* (2011) estimated the total area of saline and sodic soils, using data from the Harmonised World Soil Database (HWSD; FAO *et al.*, 2008) at 735, 228, 52 and 113 Mha, for slightly, moderately, highly and extremely affected soils. The HWSD includes both human degradation through salinization, and naturally occurring salt-affected soils. So there might be an overlap between the potentials projected by Wicke *et al.* (2011) and the potentials calculated in this article, but the determination of the extent of this overlap requires further research.

The results above clearly show that further research efforts are needed. Specifically, the following areas require additional information:

- The yields of energy crops as function of the type and degree of degradation and the tree and crop management system; these yields also need to be tested against field data.

- The information on degraded areas, including information on the exact location, amount, degree and current land use, since current datasets rely especially on expert judgement.
- The economic viability of bioenergy production on degraded lands and policy options to provide economic incentives that promote sustainable development.
- The risks associated with production of bio-energy on degraded soils related to depletion of water resources, pollution and invasiveness of energy species.

In this article, we have made a first global, detailed attempt to estimate the bio-energy potential on degraded areas. Depending on crop type, the potential was estimated to amount to 190 EJ world wide, of which around 25–32 EJ on land not classified at the moment as crop or pasture land or as forests (this is equal to about 5–10% of current global primary energy use). The areas do hold a promise of bio-energy production with little negative impacts on food production, biodiversity or GHG emissions. For a clearer estimate, however, more ground level, empirical data would be needed.

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