GLOBAL BIOENERGY POTENTIALS OF DEGRADED LANDS

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Outline

Summary

Bioenergy may serve to mitigate climate change, if energy needs during production, resulting from fertilizer addition and machinery operations, are limited by sustainable production methods. Using fertile lands for bioenergy production may result in carbon debts and competition with food production. Using degraded lands, characterized by a reduced agricultural productivity, serves to relieve theses issues, to achieve more green house gas reduction by storing carbon in the soil and to mitigate soil degradation. Global bioenergy potentials on degraded lands, of which no detailed studies were available, were assessed to estimate the potential of this idea to mitigate climate change.

Based on a multicriteria-analysis examining five geographically explicit large-scale degradation databases, GLASOD data of human-induced soil degradation were selected as most useful, as these were global, comprehensive and provided concrete information on the amount of degraded area and the severity of the degradation process. As GLASOD indicated the amount of degraded lands as ranges of percentages of the total land area in large polygons >5625 km^2, a downscaling procedure was applied, to obtain more information on the precise location of degraded lands and to increase detail on the amount of degraded lands. Further, the present land use of degraded lands was assessed using overlays with HYDE, IGBP and GLC land cover data. Global potential bioenergy yields for woody and grass species were derived from the IMAGE model. To account for the limiting effects of degradation on yields, general GLASOD yield reduction percentages, which were assumed to hold for annual food crops, were adjusted to be applicable for perennial energy crops. Here, qualitative data was used, as quantitative data proved to be inadequate for this. This examination validated conventional wisdom that perennial energy crops are less sensitive to degradation than annual food crops. For the identified degraded lands, potential bioenergy yields, based on soil and climate indices, were reduced with yield reduction percentages to assess bioenergy potentials on degraded lands.

Bioenergy potentials on degraded lands that were currently not in use as cropland, pastoral land, urban area or forest were considerable: 32-42 EJ/yr, equaling 7-9% of global energy demand in 2006. China was highest in total potentials and the rest of Central America highest in potential per hectare land area. A significant share of global potentials (31%) was located in developing regions, in which bioenergy production on degraded lands may serve to provide developing opportunities for the rural poor. Our estimates should be interpreted as an upper limit, as no assumptions were included on the accessibility of degraded lands. Compared to earlier studies, energy potential were similar, land area was more limited and estimated yields were higher. These higher yields were in accordance with the limited number of field studies. In conclusion, bioenergy production on degraded lands is a promising idea in the light of sustainable development as it can contribute significantly to global energy supply, serving to mitigate climate change, and it can serve to restore degraded soils, reclaiming a valuable natural resource.

Chapter 1. Introduction

1. Background

The application of bioenergy as energy source can counteract climate change, since green house gasses (GHGs) released during combustion are taken up by growing plants during production. To realize this potential, it is essential to have a sustainable production process that limits the emission of GHGs during production, which may result from land use change, agricultural operations and fertilizer application. Additional to counteracting climate change, bioenergy can serve to improve the energy security of countries, by promoting self-sufficiency in energy provision. Practical considerations are also significant in the transition to non-fossil fuel energy sources. Forecasting studies show that from a technical perspective bioenergy production can supply a significant share of the global energy demand (Berndes *et al*., 2003). Furthermore, the introduction of bioenergy on the market is facilitated by its liquid form, allowing the existing infrastructure to be used.

Recently, for several reasons the political interest in bioenergy has increased. First, world energy consumption is predicted to increase with 44% between 2006 and 2030 (International Energy Administration, 2009), while at the same time green house gas emissions need to be reduced rapidly in order to curtail climate change. Further, regional energy-security has become more important as a result of increasing oil prices and instability in fossil fuel producing countries (Van Vuuren *et al.*, 2008). These developments have inspired many policymakers to set targets for bio-energy production and to implement bioenergy promoting policies on a national level (Jill, 2007). For example, the United States government recently committed itself to a threefold increase in bioenergy production, to be realized in ten years' time (Balat & Balat 2009). Also, in other regions, e.g. China, India and the European Union, the use of bioenergy is expected to increase (European Union, 2007, GAIN 2006a, and GAIN, 2006b).

In order to realize the potential of bioenergy, several possible negative effects need to be taken into account. First of all, the land for bioenergy plantations is limited, because suitable land is to a large extent used for traditional agriculture, human settlements, forests and protected nature areas (FAO 2003). Therefore, it is expected that bioenergy and food production will compete for arable land, which may endanger an adequate food supply (Tilman *et al.*, 2006 and Campbell *et al.*, 2008). Further, large-scale bioenergy production may lead to the conversion of natural lands, which would threaten biodiversity (CBD, 2008). Also, converting lands with carbon-rich terrestrial biomass is undesirable, since this would induce net GHG emissions, thus severely delaying GHG savings of the established plantation (Campbell, 2008). Finally, it is feared that large-scale bioenergy production may increase environmental pollution by pesticides and fertilizer, and may deplete water resources (CBD, 2008).

A possible way to circumvent these negative effects is the use of degraded lands for bioenergy production. On degraded lands, competition with food production is less significant, since energy crops are thought to be less sensitive to degradation compared to food crops, resulting in a yield advantage on these lands (Campbell *et al*., 2008, Fargione *et al*., 2008, Tilman *et al*., 2006 and Van Vuuren *et al*., 2008). Further, using degraded lands decreases the risk on expansion of agricultural practice into natural lands, limiting biodiversity losses (Van Vuuren *et al*., 2008 and Tilman, 2006). The effects on biodiversity may even be positive, because planting energy crops on degraded lands can improve wildlife habitat and restore natural ecosystem functions (Cook & Beyea, 2000). Also, the risk of GHG emissions during land conversion is less significant, because degraded lands generally contain little standing biomass. Furthermore, established plantations of perennial energy crops may act as a carbon sink, by increasing soil organic matter (Borjesson, 1999). Finally, the cultivation of perennial energy crops may serve to prevent further degradation and reclaim degraded areas, thus preserving arable soil, which comprises a valuable natural resource (Hoogwijk *et al*., 2002 and Van Vuuren *et al*., 2008).

In summary, the use of degraded lands to produce bioenergy promises to be a sustainable way of reducing GHG emissions. Therefore, the focus of this study is on the global bioenergy potentials of degraded lands

2. State-of-the-art

Assessments of the global potential of degraded lands to produce bioenergy are scarce. Hoogwijk (2003) estimated a possible range of global bioenergy potentials on degraded lands of 8-110 EJ/yr, assuming 430-580 Mha degraded lands based on Hall et al. (2003), Grainger (1998) and Houghton (1991), and using spatially invariant bioenergy yields of 1-10 Mg/ha, based on FAO forest statistics. The only study to date that included geo-referenced data, which is essential to accurate yield estimates, is van Vuuren *et al*. (2009). Using the Integrated Model to Assess the Global Environment, they focused on bioenergy potentials of abandoned agricultural lands and natural grassland systems. While examining the sensitivity of these potentials to land degradation, they found that 42.83 EJ/yr was located on serious or severely degraded lands. However, the accuracy of this assessment is limited since 1) yields were not reduced as a result of the limiting effects of degradation 2) degraded lands other than abandoned agricultural lands and natural grassland systems were not included, 3) data on degradation were obtained from the GLASOD-database, which is relatively old (1991) and includes significant uncertainty as a result of high level of aggregation and 4) the severity indicator of this database was used, even though this lacks accurate information on the degree and area affected (van Vuuren *et al*., 2008, Bai *et al*., 2008). Further, several efforts are currently undertaken to estimate regional bioenergy potentials on degraded lands (OKO).

The scarcity of accurate bioenergy potential assessments of degraded lands stems from a limited data availability on the amount of degraded lands and the bioenergy yields that can be obtained on those lands. Globally, there are only a few geo-referenced large-scale degradation databases, which were developed within the Land Degradation Assessment in Drylands (LADA) project, the Millennium Ecosystem Assessment (MEA), the Soil degradation assessment in Central and Eastern Europe (SOVEUR), the Assessment of the Status of human-induced soil degradation in South and South-East Asia (ASSOD) and the Global Assessment Of Degradation (GLASOD), (Bai *et al*., 2008, Lepers *et al*., 2005, van Lynden & Oldeman, 1997 and van Lynden & Oldeman 2000a, Oldeman, 1991). Other degradation data are spatially invariant, reporting global numbers, or are limited to national coverage (e.g. Dregne & Chou, 1994 and Hall, 1993). Also, data on the yields of energy crops are limited, since large-scale commercial experience with these crops is lacking (van den Broek, 2001 and Jongschaap *et al.*, 2007). Experimental data for production on degraded lands are also scarce, although a reasonable body of experimental yield data on non-degraded lands is available for some energy crops (Heaton, 2004). In the discussion of energy yields on degraded lands, a yield advantage of energy crops compared to food crops is often claimed (e.g. Sexton, 2008, Sanderson, 2008, Parrish & Fike, 2005 and Samson & Omielan, 1994), although scientifically sound evidence seems to be lacking

3. Research questions

Main question:

What is the global potential of bioenergy production on degraded lands?

Sub-questions

1. *Degraded lands*

a. What is the present extent of land degradation globally, where are these degraded lands located and what is the current use of these areas?

b. Which type and degree of degradation characterize these lands and which yield reductions can be expected as a result of degradation?

2. Y*ields*

a. Which bioenergy yields can be obtained on land subject to different types and degrees of degradation?

b. Differ annual food crops from perennial energy crops in the effects of degradation on yields and what is the quantitative significance of this difference?

3. *Calculating potential*

What global potential of bio-energy production on degraded lands can be calculated using the obtained knowledge?

Chapter 2. Approach

This section describes the approach that was used to assess global bioenergy potentials. The content and function of the different chapters is described.

1. Review and selection of degradation data (chapter 3)

As soil type and climate vary locally and are critical to expected yields, degradation data that were geographically explicit were examined on their appropriateness to assess global bioenergy potentials based on a set of criteria. The GLASOD database was selected to identify degraded lands globally, providing information on the amount of degraded area, the degree of degradation, the type of degradation and the cause(s) of degradation. To define degradation, the expert guidelines of the GLASOD assessment were consulted (Oldeman, 1988), since these indicated the meaning of the degradation data most clearly.

Degraded land was defined as: **land that is characterized by a reduced agricultural productivity of the soil as a result of human practices, requiring significant efforts for restoration.**

In the literature studied, numerous definitions of land degradation were found; these varied significantly, frequently leading to misinterpretations and misunderstandings within the scientific community (Eswaran *et al*., 2001). The definition, applied here, is limited to human-induced soil degradation and includes a main focus on the agricultural productivity function of the soil. Further, degradation is characterized by the need for efforts in order to restore the soil.

2. Downscaling the GLASOD database of degradation (chapter 4)

The GLASOD database of degradation expressed the amount of degraded lands as percentages of large polygons (>5625 km^2), lacking information on the precise location of degraded lands. To facilitate overlays with other maps, the GLASOD data were downscaled using a sub-pixel allocation procedure, improving the level of detail on the location of degraded lands. Using allocation rules to indicate the chance of cells to be degraded, the degraded land was assigned to 5 minute cells in a polygon. This provided a global map indicating degraded areas at a 5 minute scale.

3. Comparing the effect of degradation on yields of perennial energy crops and annual food crops (chapter 5)

The GLASOD database was linked to general yield reduction percentages for the different degrees of degradation by its main author (Oldeman, 2000). These percentages indicated the significance of the limiting effects of degradation for agricultural yields. As these general percentages were assumed to hold for annual food crops, a literature study was undertaken to determine convenient percentages for perennial energy crops, by comparing the relative yield reduction due to degradation for annual food crops and perennial energy crops. A period of ten years was chosen to examine yield differences between crops, which in some cases emerged gradually during time. Differences varied for different types and degrees of degradation. This examination was also done to validate ‘conventional wisdom’ that energy crops are less susceptible to degradation than food crops.
For this step, the energy crops chosen, agronomic choices and the management level were crucial. In literature, several bioenergy crops were proposed as promising for cultivation on degraded lands.

The most important of these were:

- Perennial rhizomatous grasses, such as switchgrass and elephantgrass, harvested yearly while providing permanent vegetation cover (Heaton, 2004)
- Short rotation forestry crops, such as willow and poplar, cultivated in harvest cycles of 8-15 years (Boehmel, 2004)

This research focuses on these crops and production systems, since these have been researched extensively and are quoted frequently in the light of using degraded lands for bioenergy production. A relatively extensive production system was assumed with equal management levels for all crops, as this is most efficient for cultivation of perennial energy crops and results in the sustainable usage of degraded soils (Parrish & Fike, 2005). For a more detailed description of the agronomy of switchgrass, elephantgrass, willow and poplar, see Moller *et al.,* (2007), Christian & Haase (2001), Dickman (2006), Sanderson (2008) and Parrish & Fike (2005). Although *Jatropha Curcas* is also thought to be productive on degraded lands, it was not included because only a limited amount of research has been done on this crop's potential (Jongschaap, *et al*., 2007). The results of literature study to *Jatropha Curcas* are presented separately.

4. Calculating global bioenergy potentials (chapter 6)

To determine global bioenergy yield potentials of degraded lands, 1) the results of the GLASOD downscaling, indicating degraded lands, type and degree of degradation, were combined with 2) potential yield maps, indicating maximum yields based on climate and soil type, and 3) with the yield reduction percentages for perennial energy crops, which were specific for different types and degrees of degradation. Further, the current land use of degraded lands was examined, as this is of major importance for the practical feasibility of bioenergy production on these lands. Here, forest, cropland, pastoral land and other land use were included.

Chapter 3. Review and selection of data on soil degradation

Degradation data were essential in assessing the global bioenergy potential of degraded lands. These data were needed to indicate the amount of degraded land and to provide information on these degraded lands, such as the type and the degree of degradation, which were relevant to yields of energy crops. Therefore, a review was performed on existing studies and current projects that provided geographically explicit information on degraded areas at large scales.

1. Methods

Using literature study, geographically explicit degradation data with global or regional coverage were examined with respect to 6 criteria, relevant for the usefulness of data in assessing global bioenergy potentials.

Examined degradation sources:

- GLASOD: The Global Assessment of human-induced Soil Degradation (Oldeman, 1991)
- ASSOD: The Assessment of the Status of human-induced soil degradation in South and South-East Asia (van Lynden & Oldeman, 1997)
- SOVEUR: Soil degradation assessment in Central and Eastern Europe (van Lynden, 2000a)
- MEA: Millennium Ecosystem Assessment (Lepers *et al*., 2005)
- GLADA: Global Assessment of Land degradation and improvement in Drylands (Bai *et al*., 2008)

Criteria:

- Present situation (data of the actual state of degradation were required)
- Up-to-date (data of recent times were required)
- Reliability (data with limited uncertainty were required)
- Level of detail (data were required with a high level of detail)
- Coverage (data with global coverage were required)
- Comprehensiveness (data were required that included all types of soil degradation)

		GLASOD	**ASSOD**	**SOVEUR**
Main definition of degradation		“A region where the balance between the attacking forces of climate and the natural resistance of the terrain against these forces has been broken by human intervention, resulting in a decreased current and/or future capacity of the soil to support life” (Oldeman, 1988).	“The partial or entire loss of one or more functions of the soil” (van Lynden & Oldeman, 1995). For this assessment the emphasis was on the production function of the soil.	“The partial or entire loss of one or more functions of the soil” (van Lynden, 2000a). Six soil functions were assessed for polluted areas and for other types of degradation only the productivity function.
Methods		A base map was prepared by correlators for their region and checked with national institutions. Expert consultation of a large amount of soil scientist, using uniform guidelines, was used to assess the extent and degree of different types of degradation.	A base map was compiled using SOTER methodology. National institutions assessed degradation by expert judgment using uniform guidelines. After delivering final reports, corrections were proposed, which were partly implemented by national institutes.	National institutes compiled a base map using SOTER (FAO Soil Terrain database) methodology. National institutions assessed degradation by expert judgment using uniform guidelines. After delivering final reports, corrections were proposed, which were partly implemented by national institutes
Indicator(s)		The degree of degradation was based on the severity of the process. For 7 of 12 types expert instructions included type-specific physical semi-quantitative criteria and for the other types general criteria referring to the agricultural suitability, the productivity, efforts needed for restoration and other biotic functions of the soil were used.	The degree of degradation was based on the change in productivity over the last 25 years, compensated for the level of management. The change in productivity was determined using quantitative data if available. This was adjusted for the management level, which was assessed qualitatively.	The degree of degradation was based on the severity of the process (resembling GLASOD) and the impact on productivity (resembling ASSOD). Differences with methodology of earlier projects include general criteria, referring only to efforts needed for restoration and a quantitative assessment of management level.
Determining degraded areas		The degree of degradation (severity of the process), combined with the extent of degradation (percentage of the unit affected, 5 classes) can be used to identify degraded lands. Assumptions are needed to account for the percentage classes. The exact location of degradation was not known, which causes problems in overlaying maps. The type of degradation may serve to identify particularly attractive areas[1].	The degree of degradation (the impact on productivity, 5 classes) can be combined with the extent of degradation (percentage of the unit affected, rounded to nearest 5%) to identify bioenergy attractive areas. The exact location of degradation was not known, which causes problems in overlaying maps. The type of degradation may serve to identify particularly attractive areas[1].	The degree of degradation, expressed as the severity of the process or impact on productivity can be combined with the extent of degradation (percentage of the unit affected, rounded to nearest 5%) to identify bioenergy attractive areas. The type of degradation may serve to identify particularly attractive areas[1].
Usefulness of the data, 6 criteria:	Coverage	**5.** Global coverage	**3.** South and Southeast Asia, 17 countries	**3.** Central and Eastern Europe, 13 countries
	Present state	**4.** The present state of degradation is assessed, except for salinization.	**1.** The change during the last 25 years is assessed. It is not know if information on the present state is available.	**1./4.** Number depending on the usage of the GLASOD-based severity or the ASSOD-based impact on productivity.
	Level of detail	**1**. The map has an average scale of 1:10 Million and mapped units have a minimum size of 5625 km^2, as a result of cartographic restrictions.	**2.** The map has a scale of 1:5 Million. Cartographic restrictions were lacking and mapped units were smaller than for GLASOD (for India 600 units instead of 50 units).	**3.** The map has a scale of 1:2.5 Million. Base map compiled by well-informed national institutes and mapped units were smaller than for GLASSOD and ASSOD.
	Up-to-date	**1.** Assessment performed in 1989-1990 (Data from 1980-1990)	**2.** Assessment performed in 1995-1996 (data from 1970-1995)	**2.** Assessment performed in 1998-1999 (data from 1973-1998)
	Comprehensive -ness	**3.** Only human-induced degradation was included. Doubts on the extent to which human-induced degradation is covered.	**4.** Only human-induced degradation was included. More types of degradation included than in GLASOD, but possibility of missing types remains.	**4.** Only human-induced degradation was included. More types of degradation included than in GLASOD, similar to ASSOD. The possibility of missing types remains.
	Reliability of data	**1.** Uncertainty as a result of subjectivity due to expert judgment, cartographic restrictions, low quality remote sensing data and arbitrary decisions.	**2.** Uncertainty as a result of subjectivity due to expert judgment (less than for GLASOD), arbitrary decisions, missing data.	**2.** Uncertainty as a result of subjectivity due to expert judgment (less than for GLASOD and ASSOD), arbitrary decisions, missing data.

Table 3.1: Overview of characteristics of different large-scale degradation datasets that were examined to assess the global potential of degraded lands to produce bioenergy. Criteria for the usefulness are assessed with a number, ranging from a minimum score of 1 to a maximum of 5.

[1] Some types of degradation may cause a comparative advantage of bioenergy production over food production, making an area particularly interesting for bioenergy production.

		Millennium Ecosystem Assessment	**GLADA**
Main definition of degradation		A variety of definitions were used in the different sources of information (Safriel, 2007).	“A long-term loss in ecosystem function and productivity that requires progressively greater inputs to repair the situation” (Bai *et al*., 2008).
Methods		Data of 14 global, regional and sub-regional studies that indicated degradation were compiled to develop a GIS-database. Data control was strict, using extensive consultation within the scientific community and evaluating validation research for remote sensing data.	Remote sensing data for the period of 1981-2003 was used. Hotspots of degradation were identified by a combination of negative trends in net primary production (NPP) and a rainfall adjusted indicator (Rain Use Efficiency or RESTREND). Urban areas and areas where NPP decreased and RUE increased were excluded from analysis. Differences in growing season were taken into account.
Indicator(s)		Indicators varied between studies and are not reported.	The annual sum of Normal Difference Vegetation Index (ratio of red and near infrared light) was used to determine NPP. A first indicator, the rain use efficiency (RUE) was calculated using NPP and rainfall, observed by local stations. Secondly, residual trends (RESTREND) were calculated as the difference between the expected NPP of a year, and the observed in that year NPP. The expected NPP was determined using the statistical relation between yearly rainfall and yearly NPP.
Determining degraded areas		Only severe degraded areas are indicated, which were irreclaimable and beyond restoration.	Hotspots of degradation can be used and an indication for the degree of degradation can be derived from the strength of the negative trends. The present state of productivity can be derived from the current NPP value. No information is available on the types of degradation.
Usefulness of the data, 6 criteria:	Coverage	**3**. 62% of global drylands	**5.** Global coverage
	Present state	**?** The study aimed to indicate the current state of degradation. Since precise methods are not known, it cannot be said if all datasets assessed the present state.	**3.** Identification of degradation was originally based on trends, which lack information on the present situation. Areas with high current productivity were excluded to account for the present state.
	Level of detail	**4.** Gridcells of 100 km^2 are used. No information was given on the extent of degradation within a gridcell.	**3.** Gridcells of 32 km^2 are used. The level of detail of information on the severity of degradation is problematic, since the NDVI signal of a gridcell may represent different situations with respect to the severity and extent in the gridcell.
	Up-to-date	**2.** Data from the period of 1980-2000.	**5.** Trends are determined using data from 1981-2003. Data from 2003 could be used to integrate the present state of degradation.
	Comprehensiveness	**2.** Only degradation in drylands and hyperarid zones is included, excluding degradation in other ecosystem types. Other limitations depend on the studies which were used as data source.	**1.** Areas that became degraded before 1981 and areas with early-state degradation (no vegetation losses yet) were excluded. Non-degraded areas may be included in the analysis because fluctuations in net radiation, changes in land-use or management practices, natural disturbances and structural climate change may cause trends in NPP, RUE and RESTREND, while no degradation occurred.
	Reliability of data	**3.** Largely unknown, because precise methods for data compilation are lacking. The strict data control suggests a relatively high reliability.	**4.** No expert judgment included. Remote sensing data was validated successfully for some areas. Uncertainty was related to possible underestimation of cloudy areas, less precision for strongly vegetated areas and scarce rainfall observations for some areas. Last, rainfall indicators were inconvenient if rainfall structurally changed during period.

Table 3.1: continuation

2. Results

Table 3.1 presents a comparison of the examined degradation datasets. To provide some background of the data, information is presented on the chosen definition of degradation, the applied methodology, the used indicators for degradation and the way data can be used to identify degraded lands. Further, an assessment of the datasets is included, based on six criteria. A more extensive description of the dataset analysis is included in Annex I.

GLASOD (Oldeman, 1991 and Oldeman, 1988)

The GLASOD project, the first uniform source of global land degradation data, assessed in 1990 the global extent of human-induced soil degradation based on the judgment of over 250 experts, who were guided by uniform guidelines. The results were first presented on a map and later digitized into a GIS-database.

Although data were qualitative and the base map is coarse, convenient information was included on the type and the degree of degradation. Five degrees were distinguished, based on the reduction in agricultural productivity of the land. Crosson (1997) related arbitrarily chosen percentages yield reduction to the different degrees. Oldeman (2000), the author of GLASOD, adopted these percentages, which suggests a reasonable estimate, facilitating assessment of energy crop yields on those lands. Since no information was provided on the crops involved, these percentages were assumed to hold for annual food crops, which were common in agriculture during the GLASOD assessment. Table 3.2 presents the different degrees of degradation, the general description given by the GLASOD report and the general reduction agricultural reduction percentages (Oldeman, 2000).

Degree	**GLASOD description**	**General yield reduction** (Crosson, 1997 and Oldeman, 2000)	
		Low estimate	**High estimate**
None	There is no sign of present degradation from water or wind erosion, from chemical, physical or biological deterioration; all original biotic functions are intact. Such land is considerable stable.	0%	0%
Light	The terrain is suitable for use in local farming systems, but has somewhat reduced agricultural suitability. Restoration to full productivity is possible by modifications of the management system. Original biotic functions are still largely intact.	5%	15%
Moderate	The terrain is still suitable for use in local farming systems, but has greatly reduced agricultural productivity. Major improvements are required to restore productivity. Original biotic functions are partially destroyed	18%	35%
Strong	The terrain is non reclaimable at farm level. Major engineering works are required for terrain restoration. Original biotic functions are largely destroyed.	50%	75%
Extreme	The terrain is irreclaimable and beyond restoration. Original biotic functions are fully destroyed.	Not indicated	Not indicated

Table 3.2. The different GLASOD degrees of degradation, their general description (Oldeman, 1988) and the general percentages yield reduction that were adopted by Oldeman (2000), including a high and a low estimate

The GLASOD guidelines for experts included all relevant types of human-induced degradation, but during compilation of the data 8 of the 20 subtypes were excluded without motivation, raising doubts on comprehensiveness of the study. Further, data for degradation due to salinization were inconvenient since the change in salt content instead of the actual level was assessed. Table 3.3 presents the different types of degradation that were included in the GLASOD data.

Main type	Subtype	Description
Water erosion	Loss of topsoil	The uniform displacement of topsoil by wind action.
	Terrain definition/mass movement	An irregular displacement of soil materials, characterized by major rills, gullies, or mass movement.
Wind erosion	Loss of topsoil	The uniform displacement of topsoil by wind action.
	Terrain deformation	The uneven displacement of soil material by wind action and leads to deflation, hollows and dunes.
	Overblowing	Encroachment of structures and roads buildings and/or sand blasting. This is an off-site effect of the wind erosion types mentioned above.
Chemical deterioration	Loss of nutrients and/or organic matter	Often leading to seriously reduced production.
	Salinization	Caused by human induced activities such as irrigation.
	Pollution	Pollution from bio-industrial sources. Excessive addition of chemicals.
	Acidification	Acidification from bio-industrial sources. Excessive addition of chemicals.
Physical deterioration	Compaction, sealing and crusting	Compaction caused by heavy machinery on a soil with weak structure stability, or on soils in which humus is depleted.
	Water logging	Human-induced soil hydromorphism, flooding and submergence (excluding paddy fields)
	Subsidence	Subsidence of organic soils (by drainage, oxidation).

Table 3.3. The different GLASOD main types and subtypes of degradation and their description (Oldeman, 1991)

The area affected by degradation was expressed as a percentage of the total land area in a polygon. The precise percentage was not indicated, since experts were allowed to choose from 5 ranges of percentages (0-5%, 6-10%, 11-25%, 26-50% or 50-100%). Therefore, assumptions were necessary to determine the actual surface area of degraded lands. Further, information on the location of degraded lands was limited, as polygons were relatively large (>5625 km^2) and no information was provided on the location of degraded lands within polygons.

The reliability of GLASOD data was limited, mainly due to the significant influence of subjectivity, which is related to expert judgment. Furthermore, the expert guidelines left room for differences in interpretation, as these were based on semi-quantitative and qualitative criteria and gave no instructions how to deal with overlapping degradation. Sonneveld & Dent (2007) checked the consistency of GLASOD data by comparing GLASOD results of sites with identical biophysical and land use characteristics. They concluded a moderate consistency of the judgments. Beside expert judgment, other sources of uncertainty included arbitrary decisions by correlators, the usage of patchy remote sensing data and exclusion of data due to cartographic space restrictions.

ASSOD (Van Lynden & Oldeman, 1997 and Van Lynden, 1995)

As a sequel of the GLASOD project, ASSOD (1997) covered 17 countries in South and South-East Asia, aiming at a more detailed assessment of this area to increase the awareness on human-induced soil degradation. Similar to GLASOD, expert judgment was performed, but the level of detail of the assessment was significantly increased. Polygons were smaller, the extent of degradation was more accurately indicated, guidelines were more precise, more types of degradation were included and data was directly stored in a GIS database. However, uncertainty due to subjectivity, missing data and arbitrary decisions was still significant and the location of degraded lands within polygons remained unclear. Further, differing from GLASOD, a change in observed productivity, compensated for the management level, was examined to indicate degradation. This change indicator does not provide an indication of the actual state of degradation, although this was critical in determining yields of energy crops on degraded lands.

SOVEUR (Van Lynden & Oldeman, 2000a and Van Lynden & Oldeman, 2000b)

For 13 countries in Central and Eastern Europe, human-induced degradation was examined using expert judgment, slightly adjusted ASSOD guidelines and quantitative data if available. Convenient information on the degree of degradation was provided by including the severity of the process as well as the change in productivity as indicators for degradation. The level of detail was increased compared to GLASOD and ASSOD as a result of improved guidelines and a more detailed base map. Similar to GLASOD and ASSOD, information on the location of degraded lands within polygons was lacking and uncertainty due to subjective expert judgment, missing data and arbitrary decisions was significant.

MEA (Lepers *et al*., 2005)

The Millennium Ecosystem Assessment aimed to evaluate the degree to which ecosystem services were sustainable, given the many environmental stresses they faced. A synthesis of geo-referenced degradation data for 1981-2000 was included. Precise methods were not available, which complicated examination of this dataset. Although a detailed base map was used, the study covered only 62% of global drylands. Moreover, only severely degraded areas were included, which were defined as irreclaimable and beyond restoration. These, however, were not suitable for bioenergy production.

GLADA (Bai *et al*., 2008)

GLADA was the first global assessment of degradation that was totally based on remote sensing data. The project identified hotspots of degrading and improving land, to be validated with field research. The output available in January 2009 was examined, when validation results were not yet available. Data were based on a change in net primary productivity, not accounting for the actual productivity, although this is relevant to the present state of degradation. This problem can be addressed partly by excluding presently high productive areas.

The GLADA data was up-to-date, it included a detailed base-map with units of 32 km^2 and reliable remote sensing data were used. However, some non-degraded areas were included, because trends in net primary productivity, the main indicator, may be caused by several factors other than degradation. Further, areas that became degraded before 1981 and areas with early state degradation, without vegetation losses, were not included in the data.

The GLADA dataset lacked information on the degree of degradation and the amount of degraded land, while these were critical in determining bioenergy potentials of degraded lands. The GLADA report suggested that the strength of a negative trend in net primary production indicates the degree of degradation (Bai *et al*., 2008). However, these trends in NPP were measured as the average of 32 km^2 areas, an area size in which significant differences in degradation may occur. Consequently, distinction between a few km^2 of severely degrading land and multiple km^2 of moderately degrading land was not possible. Therefore, accurate bioenergy potential assessments based on GLADA data were severely complicated.

3. Discussion & conclusion

Based on the multi-criteria analysis, the different degradation datasets are considered on their usefulness for examining the global bioenergy potential of degraded lands. Although GLADA data includes some non-degraded areas and excludes some degraded areas, the dataset is of high interest, as it is up-to-date and based on objective remote sensing data, which resulted in the highest overall assessment of criteria (table 3.1). However, accurate yield assessments are complicated because the degree of degradation as well as the area affected remain unclear. Remote sensing data was aggregates to cells of 32 km^2. Consequently, it remains unclear if a small part of a cell is affected with severe degree or if a larger part is affected less severely, while this information is crucial for bioenergy potentials. Therefore, this dataset is inconvenient in assessing the global bioenergy potential of degraded lands.

The SOVEUR project, the second most appreciated database in the multi-criteria assessment, did provide convenient information; however, the efforts and assumptions needed to incorporate regional SOVEUR data in a global dataset, outweigh the additional value of this procedure. The three remaining databases, GLASOD, ASSOD en MEA, scored in the same range in the multi-criteria analysis. The MEA dataset was not comprehensive, including only degradation of severe degree and only (62%) of global drylands. Further, the regional ASSOD assessment measured degradation as a change in productivity; as a result, it lacked essential information on the actual state of degradation. Therefore, the MEA and ASSOD datasets are thought to be not convenient to assess global bioenergy potentials on degraded lands.

The GLASOD project dated back to 1990 and was limited in reliability and level of detail, but the data provided global coverage and convenient information on the degree of degradation, facilitating assessment of yields of energy crops. This database is selected as the most convenient one, since all other databases entail serious complications if they were to be used in assessing bioenergy potentials on degraded lands. However, if we are to use the GLASOD data some difficulties need to be overcome. Degradation as a result of salinization was determined relatively as the change in salt concentration during 1945-1990. Since no information is included on the actual state of degradation, these lands are excluded from the assessment. Second, as the smallest polygon comprises 5625 km^2 and the extent of degradation is indicated as a range of percentages, information on the exact location of degraded areas is limited. This complicates an accurate yield assessment, since yields depend on locally varying climate and soil indices. To address this issue, a sub-pixel allocation was performed, described in chapter 4, in which the GLASOD map was downscaled by allocating the area affected by degradation to a more detailed grid.

Chapter 4. Downscaling the GLASOD database of degradation

The GLASOD database lacks information on the location of degraded lands within polygons, complicating overlays with other maps that are essential in estimating energy crop yields accurate and complicating evaluation of the current land use of degraded areas. Therefore, here we describe a downscaling of the GLASOD data to obtain more detailed information on the location of degraded lands. This may, further, serve to improve detail on the area affected by degradation, narrowing down the range of percentages, which GLASOD indicated as the extent of degradation.

1. Methods

The GLASOD database was downscaled using a sub-pixel allocation procedure. Information derived from the GLASOD database was combined with information available on a more detailed 5 minute grid, to determine the likelihood that cells were assessed as degraded during the GLASOD assessment. Based on this, the degraded area of GLASOD polygons was allocated to the 5 minute cells within that polygon.

The main information provided by GLASOD was the severity of the degradation process and the extent of degraded area per polygon. Also, additional information was included about the degraded area, such as the cause(s) of degradation, the type of degradation and the rate of the degradation process. This information was available (where relevant) not only for the most important source of degradation but also for the second most important source in a polygon. The downscaling procedure was developed so that these two sources of degradation were, if possible, allocated simultaneously based on their own characteristics. This was done to prevent arbitrary priorization of one as a result of their order in the procedure.

To determine the likelihood that cells were degraded, information from the GLASOD database was combined with other geographically explicit data sources. Since Oldeman (1998), the main author of GLASOD, states that soil degradation occurring in the period 1945-1989 was covered, information from this period was needed. Information was selected that indicated the chance that 5 minute cells were degraded based on a straightforward relation and that differentiated significantly between 5 minute cells.

GLASOD indicated the extent to which a polygon was affected by degradation as a range of percentages (0-5%, 6-10%, 11-25%, 26-50% or 51-100%), lacking information on the actual affected area in polygons. The upper-limit, the lower-limit and the average of these ranges were applied in the downscaling procedure, to facilitate sensitivity analysis of these assumptions in the global bioenergy potential of degraded lands. During the procedure, exclusion rules, which are described in section 2.2, identified 5 minute cells of which assessment as degraded during GLASOD was thought to be highly unlikely. If the available area in a polygon that was left after exclusion of these non-degraded cells was not sufficient to allocate the degraded area (upper limit, lower limit or average of percentage range), the percentage affected was adjusted downwards, leading to a narrowing of GLASOD extent ranges of percentages.

From here onwards, the methodology of the downscaling procedure is further explained by, first, clarifying the allocation rules and their rationale. Then, the datasets are described that were used to implement these rules. Last, the procedure is discussed to apply the rules, during allocation of degraded area to 5 minute cells within polygons.

1.1 The allocation rules

The distribution of degraded area within polygons was based on the likelihood that cells were assessed as degraded during GLASOD, which was determined using three sets of allocation rules.

1. Degraded area is allocated to cropland and/or pastoral lands if the cause is agricultural activities and overgrazing.

The guidelines for the GLASOD assessment, which served as a manual for experts, included over-intensive annual cropping and overgrazing of pasturol lands as causes of degradation (Oldeman, 1988). Degraded area often exceeded cropland/pastoral areas in a polygon and the GLASOD report expressed serious doubts on the accuracy of information on causes (Oldeman, 1991). Therefore, in case of degradation due to agricultural activities or overgrazing, degraded area was prioritized to cropland/pastoral areas. Afterwards, remaining degraded area (if any) was distributed over other areas.

2. Degraded area is not allocated to urban areas, non-soil areas, bioreserves and protected areas. Further, closed canopy areas have a reduced chance to accommodate degraded area.

Urban areas were neglected during GLASOD (pers. comm. G. van der Lynden), bioreserves and protected areas fell into the non-degraded category ‘stable terrain under natural conditions’ and non-soil areas belonged to the non-degraded category ‘wastelands’ (Oldeman, 1991). Therefore, degraded area was not allocated to these areas.

It is very unlikely that closed canopy soils were degraded during the GLASOD assessment. Closed canopy ecosystems are generally healthy, as indicated by their ecological climax state. Such a state is improbable in the presence of soil degradation. However, in theory, violation of the undergrowth by humans can degrade the soil, while the canopy is still intact. Therefore, these areas had a 70% reduced chance to accommodate degraded area.

3. Degraded area is more allocated to wind/water erosion sensitive areas if the indicated category is wind/water erosion. Degraded area is more allocated to areas with a decrease in climate adjusted NDVI if the indicated category is ‘deforestation or removal of natural vegetation’.

Inherent soil and climatic properties of land have been shown to be a major factor in the degradation process for wind and water erosion (Kirschke, 1999 and Reich *et al*., 2001). Based on these properties the sensitivity of land to erosion can be assessed. Degradation of the type erosion was more allocated to areas with high erosion sensitivity, based on these properties.

Degradation due to deforestation or removal of natural vegetation induces a decrease in vegetation cover. The normalized difference vegetation index (NDVI) is a proxy for vegetation cover, which is measured by remote sensing as the ratio of red and near-infrared light, reflected by the land (Bai *et al*., 2008). When adjusted for variations in climate, a loss in NDVI, adjusted for variations in climate, can indicate the likelihood that an area was degraded as a result of deforestation. Therefore, if the type of degradation was deforestation or removal of natural vegetation, more degraded area was allocated to areas that showed a decrease in NDVI. The differentiating strength of this ruleset was varied between runs in the light of sensitivity analysis. The setting of involved parameters is described later on, when discussing the procedure.

Inconvenient indicators

Several indicators seemed promising at first hand, but ultimately failed to meet the criteria to be used in the allocation procedure:

- The positive relation between population density and environmental pressure, which is often used in the light of predicting degradation, was not consistent for all situations and, more importantly, provided differentiation on a regional rather than local scale (Muchena *et al*., 2005, Lal, 1997 and Wood *et al*., 1998).
- Livestock density, which is often related to degradation due to overgrazing (e.g. Kruska *et al*., 1995), was inconvenient for use on a global scale due to the high level of exceptions (Rowtree *et al*., 2004). Furthermore, convenient data was lacking for this indicator.

1.2 Datasets

To implement the rules, datasets were needed that provided geographically explicit information, on a more detailed scale than GLASOD. Table 4.1 shows the different datasets that were used and their main characteristics. Datasets were selected on reliability, appropriateness of information and the convenience of the timeframe covered. Regarding this latter criterion, exceptions have been made. For example, while data for prioritization of degraded area to cropland/pastoral areas should include all areas with (temporal) pastoral/cropland cover between 1945 and 1989, data was used for the year 1980, as reliable data for earlier years was lacking. Since most required information was relatively stable trough time, the error generated by such inconsistencies was limited. Only for the NDVI data this problem was more significant, as areas with a decreasing NDVI between 1945-1988 were needed, while data was only available for 1980-2000. Since distribution based on a decreasing NDVI was more uncertain, this rule gain less influence in the allocation procedure.

The wind and water erosion sensitivity datasets included only dryland areas. Humid and hyper arid areas were excluded from sensitivity estimates. We have assumed that humid and hyperarid cells have a medium susceptibility to erosion if they co-occur with dryland cells in a polygon. A general comparison between those soil types on erosion sensitivity, which would provide a more substantiated assumption, was beyond the scope of this research.

Information	Ruleset	Data from	Data source	Original scale	More info available
GLASOD, degree, type, extent and causes of degradation	3 & 4	1989	GLASOD	Polygon 1: 10.000.000	Oldeman (1991)
Pastoral areas (surface per gridcell)	3	1980	HYDE pastoral areas	5 minutes (fractions)	Klein Goldewijk *et al*. (2007)
Cropland areas (surface per gridcell)	3	1980	HYDE cropland area	5 minutes (fractions)	Klein Goldewijk *et al*. (2007)
Bioreserves and protected areas	1	1990	HYDE bioreserves	0.5 degree	Klein Goldewijk *et al*. (2007)
Closed canopy areas	2	1992-1993 and 1995-1996	FAO global forest cover	1 km resolution	Zhu and Waller (2000)
Non-soil units: shifting dunes, rock outcrops, glaciers and salt flats	1	1991	FAO soil map of the world	1 km resolution	FAO (1992)
Areas that decreased in NDVI	5	1980-2000	Rain-adjusted NDVI data	32 km^2 gridcells	Bai *et al*., (2008)
Wind erosion sensitivity	4	Inherent properties constant through time	USDA Wind erosion sensitivity data	2 minutes	Reich *et al*., (2001)
Water erosion sensitivity	4	Inherent properties, constant through time	USDA Wind erosion sensitivity data	2 minutes	Reich *et al*., (2001)

Table 4.1: overview of datasets that were used and their characteristics

Consistency of scale and land-sea boundaries

All datasets were converted to a 5 minute scale, using Adobe Arcgis version 14. Data was transformed by means of the dominant category, except for the FAO global forest cover map, which was transformed to the fraction of closed canopy in a 5 minute cell to preserve detail. The land-sea boundaries of all data were made consistent, using the HYDE land-sea mask. In case coastal grid cells did not contain data in the original database, these cells were filled with values derived from neighboring cells. If neighboring cells were empty, this was indicated and no value was assigned.

1.3 The procedure

The allocation was performed using a simple allocation program, which distributed per polygon a specified surface area to the 5 minute cells in that polygon, based on a map of available area and a weight distribution map (see figure 4.1 for a simple example). The program performed multiple loops in which degraded area was assigned to cells that contained area available for allocation, guided by the relative weight distribution of these cells. Runs continued until all degraded area was allocated or all available space was filled.

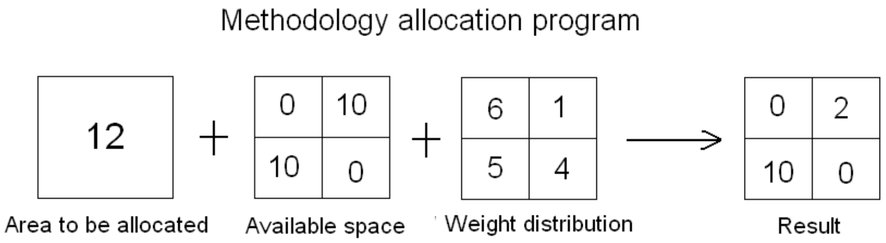

Figure 4.1. A simple example of the methodology of the allocation program. A surface area of degraded land was allocated, guided by a map of available space and a weight distribution map. As in this example, only two cells contain available area, degraded area is assigned to these, based on their relative weight distribution.

The procedure existed of four steps in which the allocation program was used to implement the different rulesets as specified under 2.2, using the datasets as described in 2.3. The procedure was designed to allocate two sources of degradation in a polygon simultaneously, preventing prioritization of one of these as a result of the chosen order.

The main line of the procedure

Figure 4.2 presents a general overview of the procedure, showing the four main steps, the implementation of the rulesets and the data transfer between steps. Table 4.2 presents the allocation runs that were performed in different steps, giving more specific information on the applied input maps. Keeping in mind these overview figures

In step 1, allocation of degraded area caused by overgrazing/agricultural activities was prioritized to cropland/pastoral areas. Then, the expected allocation space fort he remaining part of degraded area was determined by allocating the sum of the two sources in step 2. For this step information of the type of degradation of both sources was combined into one distribution map. Further, non-degraded areas were excluded from the available area map. The results of this step were not used as allocation results, but as expected allocation space for the next step, since the use of a combined distribution map leads to undesirable anomalies. In step 3, the primary and the secondary source of degradation were allocated separately based on their degradation type, using the expected allocation space as available area, derived from step 2. Limiting available space to the results of step 2 prevented large scale exceeding of total available area by total allocated area, i.e. the sum of the separate runs for the primary and secondary source. As this problem still occurred incidentally, in step 4 surplus area of individual cells was redistributed over cells in the same polygon with available area left. For this step precedence was arbitrary given to the primary source.

The procedure was performed for different assumptions on the extent of degradation and different parameter sets, which were needed to implement rules. Table 4.3 shows the parameter sets that were used, varying from a sharp differentiation between cells that are liable to and less prone to degradation to a more smooth distribution of degraded area.

Adjusting GLASOD ranges of percentages

If total available area, after exclusion of non-degraded areas, was less than the degraded area in a polygon, not all degraded area could be allocated. In this case, two things were possible, creating extra space by allocating to areas, identified as non-degraded or decreasing total degraded area. The latter was chosen, because setting the percentage degraded land downwards was still in accordance with GLASOD data, which indicated the affected area as a range of percentages of the polygon area. This resulted in a narrowing of this range by redefining the upper limit.

Following, the different steps are discussed in more detail to clarify specific choices and difficulties that were encountered.

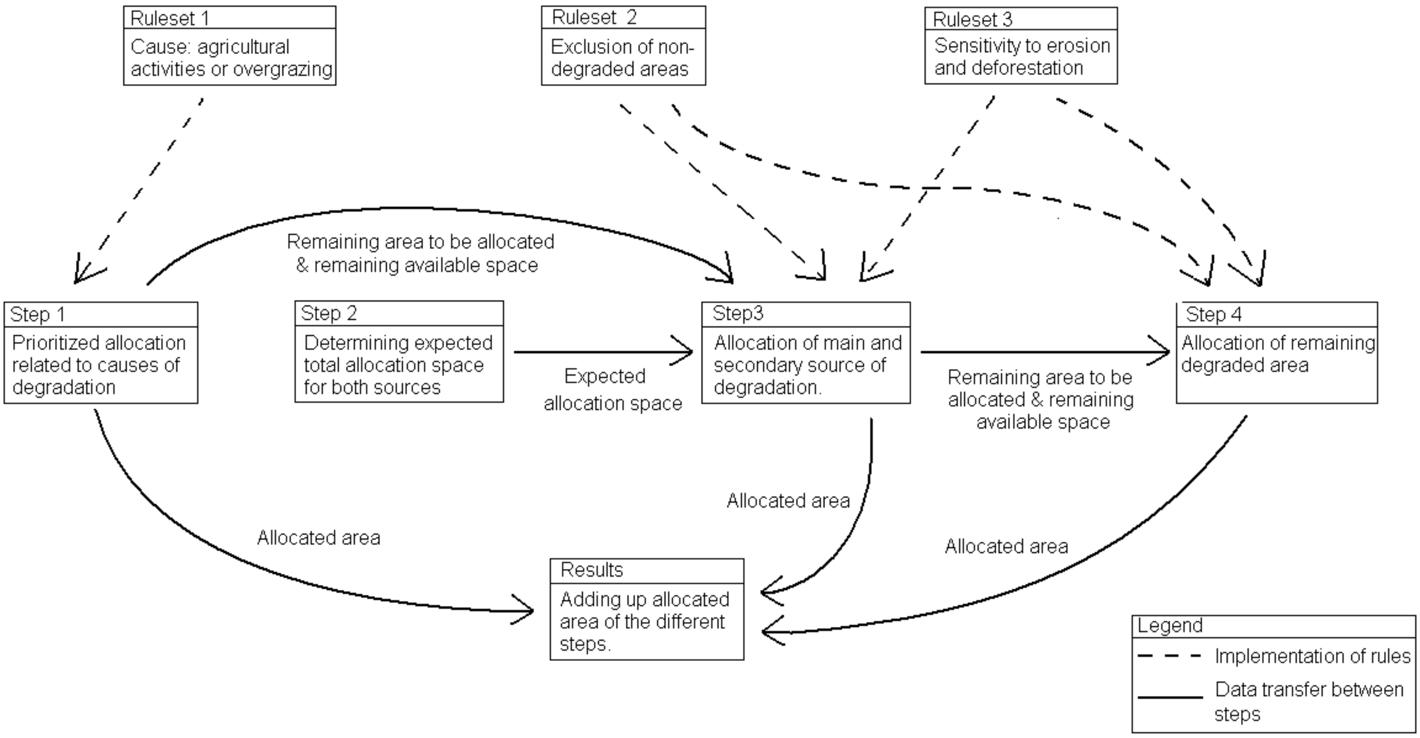

Figure 4.2. The main line of the allocation procedure. Four steps were performed, in which three rulesets were implemented. Results of step 1,3 and 4 were added up to obtain final results. During the procedure, allocation results were transferred to next steps, to subtract already occupied already from available space and to determine remaining area to be allocated.

Step	Available area	Weight distribution	Area to be allocated
1. Prioritized allocation related to causes of degradation.	Cropland/pastoral areas if related cause was indicated. Half of those areas if a second alternative cause was indicated.	Distribution based on cause (deforestation chance) and a combination of the types of both inputs (erosion sensitivity).	Total degraded area.
2. Preliminary procedure to facilitate simultaneous allocation.	Total area minus miscellaneous land units, urban areas, bioreserves, part of closed canopy areas and the area allocated during first step.	The sum of the distribution weight maps based on input 1 and input 2, both proportional to the degraded area of those inputs.	Total degraded area minus area allocated during procedure 1.
3a/b. Allocation of main and secondary source of degradation	The result of procedure 2.	Weight distribution based on cause (deforestation) and type of source 1/2 (erosion sensitivity).	The remaining part of source 1/2 after procedure 1.
4a/b. Allocation of remaining part of degraded area	The remaining part of available area after subtraction of the result of step 1, 3& 4, and exclusion of non-degraded areas	Weight distribution based on cause (deforestation) and type of input 1/2 (erosion sensitivity).	Source 1/2 fraction of surplus, if total allocated area exceeded available area

Table 4.2. overview of the inputs for different runs in the allocation procedure.

	Distribution (distribution value range)			Exclusion (percentage excluded)			Prioritization (percentage priorized)	
	NDVI range	Wind erosion	Water erosion	Closed canopy forest	Miscella-neous land units and urban areas	Cause deforestation, pastoral and cropland areas	Cropland areas (if cause: agricultural activities)	Pastoral areas (if cause: overgrazing cause)
1. Rigid	1-100	0.01-100	0.01-100	70%	100%	100%	100%	100%
2. Moderate	1-10	0.1-10	0.1-10	70%	100%	100%	100%	100%
3. Loose	1-2	0.5-2	0.5-2	70%	100%	75%	75%	75%

Table 4.3. Sets of parameters used. For distribution, values are relative to 1, which was assigned to all cells that were not affected by rules.

Step 1: Allocation of degradation due to overgrazing and agricultural activities.

The first step was designed to priorities allocation due to agricultural activities to cropland areas and degradation due to overgrazing to pastoral areas. Therefore, only pastoral/cropland areas in polygons for which GLASOD indicated agricultural activities/overgrazing as cause of degradation were available for allocation, as indicated in table 4.4. GLASOD indicated one or two causes for polygons in which degradation was identified. If two causes were indicated, it was not known which of these was more important for the identified degradation processes. Further, in contrast to the type of degradation and the extent of degradation, causes were not related to a specific source of degradation (Oldeman, 1991). Therefore, in case of two causes, these were each assumed to be responsible for half of the degraded area of the source(s) (see table 4.4). As an exception, if agricultural activities as well as overgrazing were indicated as causes, pastoral and cropland areas were added up, assuming the influence of causes to be similar to the distribution of both related land types in the polygon.

Situation	**Cause**	**Available space indicated**
One cause indicated	Overgrazing	Pastoral area
	Agricultural activities	Cropland area
Two causes indicated	One of these: overgrazing	Half of pastoral area
	One of these: agricultural activities	Half of cropland area
	Overgrazing and agricultural activities	Pastoral area plus cropland area available

Table 4.4: map of available area to implement cause related rules

In this step, it was not possible to use separate distribution maps for both sources of degradation that were based on their type of degradation within the limits of this research. Therefore, a combined distribution map was used. This combined distribution map was developed by summing up separate distribution maps (the compilation of these is explained later), each multiplied by the share of the source of degradation in the total degraded area of the polygon, as follows:

$$\text{Combined distribution} = \left(\frac{\text{Total degr, area in polygon}}{\text{Degraded area source 1}}\right) * \text{Distribution based on source 1} + \left(\frac{\text{Total degr, area in polygon}}{\text{Degraded area source 2}}\right) * \text{Distribution based on source 2}$$

In order to distribute proportional to the available space in 5 minute cells, the combined distribution map was multiplied with the map of available area. This step was performed for all distribution maps applied during the procedure.

The sum of both sources of degradation was allocated, after which the allocated area was separated in both sources again, using their ratio. Remaining degraded area, which could not be allocated, since cropland/pastoral areas were insufficient or since causes other than overgrazing/ agricultural activities were indicated, was transferred to step 2.

Step 2: facilitating simultaneous allocation

This step was performed in order to determine the expected area to be filled by the allocation of both sources of degradation. This was needed to be able to allocate the sources separately based on their own type of degradation, without exceeding on a large scale total available space in cells when results for both sources were added up.

The map of available space was adapted by excluding non-degraded areas. For this, surface area covered by urban areas, non-soil areas, bioreserves, closed canopy areas (70%) and protected areas was subtracted from a map that indicated the square kilometer land area per gridcell. Here, one should be aware of the effect of possible overlaps between datasets. Overlaps for non-soil areas, bioreserves or protected areas were not problematic, since these datasets work on the level of complete grid cells. Therefore, if a cell was indicated as non-degraded by multiple datasets, the result remained no available area for allocation. The fractional datasets, urban areas and closed canopy areas, were assumed to be mutually exclusive and, therefore, not to overlap. Therefore, fractions of these datasets were added up, allowing exclusion of urban areas and closed canopy areas in one cell. The remaining area (if any) indicated the available area for allocation per gridcell. In case of degradation due to overgrazing, an unclear situation occurred if protected areas were pastoral as well, as this situation left room for different interpretation by GLASOD experts. Protected areas belonged to the category ‘stable terrain under natural conditions’, which was clarified as areas with little human influence. However, this clarification does not hold for protected areas that were managed as pastoral lands and, therefore, subject to human influence. Since it could not be retained which categorization was adopted by experts, exclusion of half of these areas was chosen. The allocation program was run with the combined weight distribution map, similar to step 1, allocating the degraded area remaining after step 1.

Step 3: **Allocation of main and secondary source of degradation**

In the steps 3a and 3b the preparatory work of step 2 is used to perform separate allocations for the two sources, allocating the remaining part of the degraded area, using source-specific distribution maps. The available space for both allocation runs consisted of the area allocated in step 2, to prevent large scale exceeding of total available area in cells that were characterized by a high susceptibility to both sources of degradation.

Fort the two sources, different distribution maps were created based on the type of degradation (if water/wind erosion) and the cause(s) of degradation (if deforestation or removal of natural vegetation). As explained before, the distribution map determined the share of degraded area that was distributed to individual cells. Cells for which no degradation sensitivity information was available gained a moderate distribution value, which was chosen to be one, so that these cells gained a moderate share of degraded area (see table 4.3). If degradation was caused by deforestation or removal of natural vegetation and if a loss in NDVI occurred between 1980-2000, the weight distribution factor was increased proportional to the amount of loss in NDVI. If deforestation or removal of natural vegetation was accompanied by another cause, the increase was halved. The factor of increase was arbitrarily chosen and, therefore, varied between runs (see table 4.3). Further, if degradation was due to wind or water erosion, the weight factor was increased or decreased depending on the qualitative sensitivity of a cell to this type of degradation, which ranged from neglible to extreme (see table 4.3). If the cause as well as the type of degradation affected the weight factor, both values were summed up. This choice was made, since it allows regulation of the relative influence of both factors. Also, multiplication would lead to underappreciation of the extreme values of the spectrum.

Step 4: **Allocation of remaining part of degraded area**

If the expected allocation space (from step 2) was more than half of the available land area in a cell and this space was filled during both separate allocations, the total available area in a cell was exceeded. A correction was performed to account for these situations. If the sum of allocated area of both sources exceeded available land area, it was reduced to the available land area in a gridcell, by subtracting surplus area of the primary and secondary source, relative to their proportion in the cell. The subtracted area was reallocated using the remaining available space, accounting for non-degraded areas and using separate distribution maps for both sources. Arbitrary, the primary source was allocated first, because simultaneous allocation was not possible in this step. The error generated by this imperfection was limited, since the correction was only necessary in a limited amount of cases.

2. Results

2.1 The effect of rules

The quality of allocation rules and the influence of those rules comprise major factors in the results of a sub-pixel allocation procedure. The quality of allocation rules depends on the rationale and the datasets that were used, which were described in the section methods. The influence of rules is determined by their differentiation capacity, regulated by the parameters applied, and by the area that is affected by the allocation rules and by the datasets involved. Table 4.5 shows the extent to which rules affected the allocation of degraded area, indicating a significant influence of rules.

Rules	**Affected**
Rule 1 & 2: Exclusion of non-degraded area	18.99% of the area in degraded polygons excluded
Rule 3: Cause overgrazing & agricultural activities, pastoral & cropland areas	70.91% of degraded polygons affected
Rule 4 & 5: Distribution based on wind and water erosion sensitivity and deforestation:	88.37% of degraded polygons affected

Table 4.5. the effect of the different rules.

The effect of allocation rules is, further, illustrated by 4.3 figure 4.4, and figure 4.5, which show the exclusion of non-degraded areas (figure 4.3), the available area in polygons affected by overgrazing or agricultural activities (figure 4.4) and the weight distribution map, based on erosion sensitivity and decrease in NDVI (figure 4.5). These figures, also, give insight in the components that guided the allocation procedure. Areas in which no degradation occurred were not relevant to rules (indicated with blue).

In figure 4.3, the non-degraded area per gridcell is shown that was subtracted from available space for allocation. The exclusion of non-degraded areas varied from 0% to 100% per gridcell and covered all world regions. In woody regions, such as the Amazon region, exclusion was extensive, since in these regions, closed canopy areas, protected areas and bioreserves were abundant. Regions with extensive non-soil areas, such as shifting dunes, rock outcrops, glaciers and salt flats, were also significantly affected, such as the edges of the Sahara. The Sahara was, beside these edges, unaffected by human-induced soil degradation according to GLASOD. Last, more scattered exclusion can be observed in densely populated areas such as Europe, due to a high level of urbanization.

In figure 4.4 the area, prioritized for allocation of degradation due to overgrazing or agricultural activities, is indicated. In 29% of the polygons, affected by degradation, these rules had no influence since other causes were involved. Affected areas showed significant variation between cells and, generally, a significant amount of pastoral/cropland area was available for allocation. An exception occurred in Sweden, where degradation was due to overgrazing although pastoral areas were scarce, limiting the effect of priorization of these.

In figure 4.5, the effect of ruleset 3 is presented. This figure was based on the loss in NDVI if deforestation was involved as cause and the sensitivity to water and wind erosion for areas affected by erosive degradation. Ruleset 3 resulted in considerable variation in 88% of the polygons, affected by degradation. The remaining 12% of the degraded polygons was not affected, either because deforestation or erosion were not involved (8%), or because, though erosive, the cells were not included in erosion sensitivity data (4%).

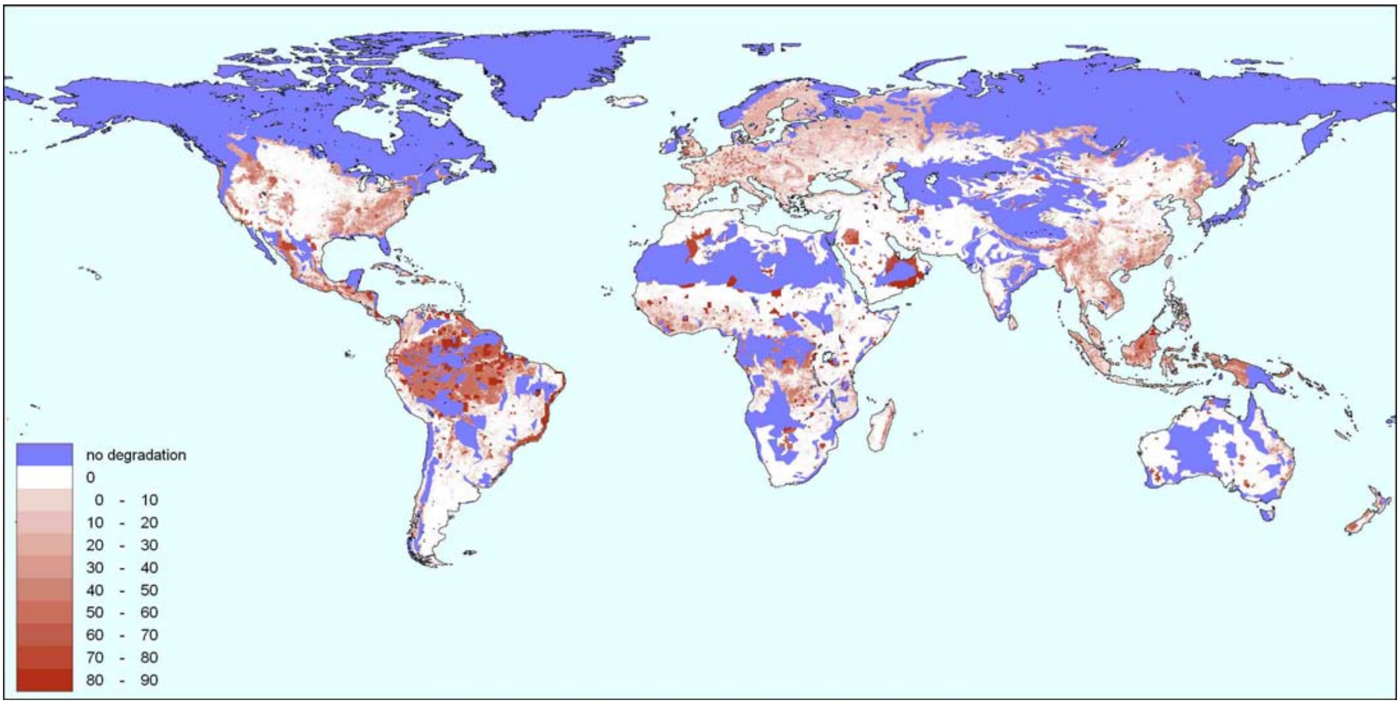

Figure 4.3. The exclusion of non-degraded areas is shown in square kilometer per cell. Blue areas contained no degradation and were, therefore, unaffected.

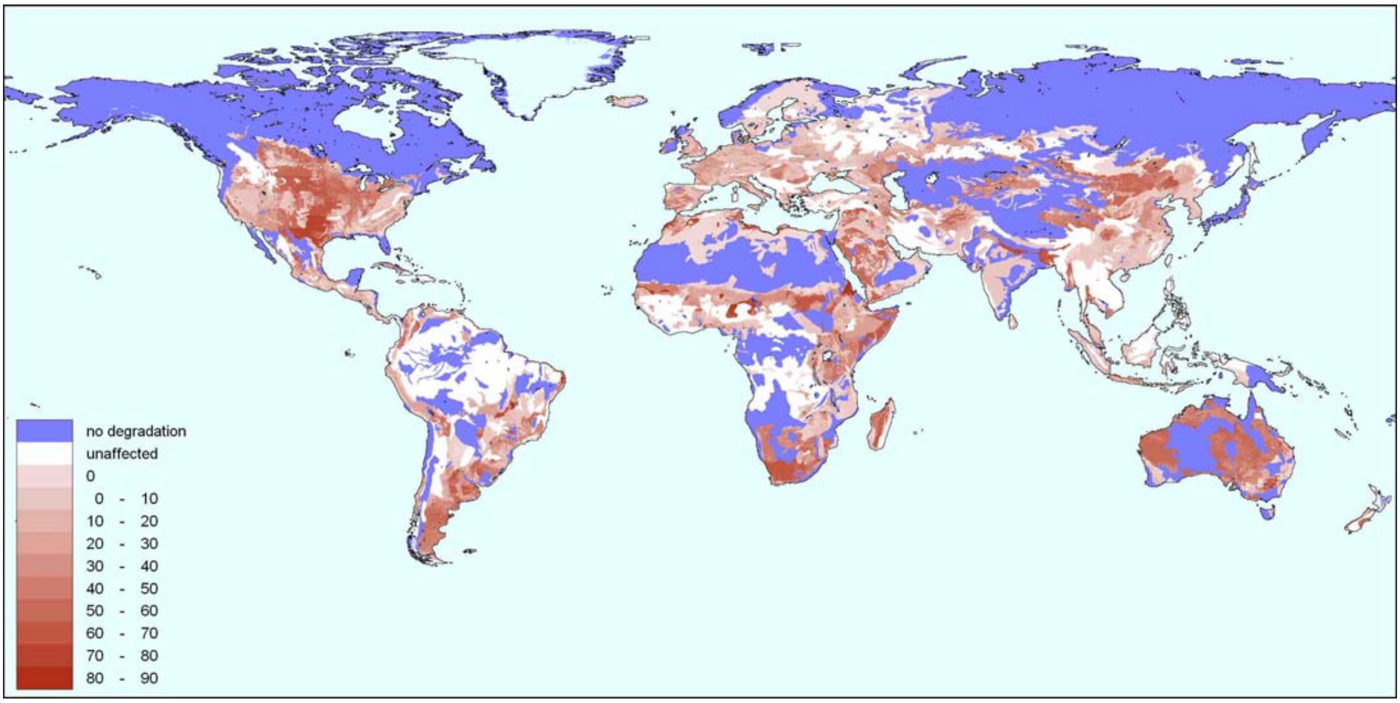

Figure 4.4. The effect of allocation of degradation due to overgrazing and agricultural activities to pastoral areas and cropland areas respectively is presented. All cells with a shade of red are affected by this allocation rule. The darkness indicates the available space (square kilometers) for allocation of degraded area due to agricultural activities and overgrazing. Blue cells contained no degradation, while white cells contained degradation due to other causes that agricultural activities or overgrazing.

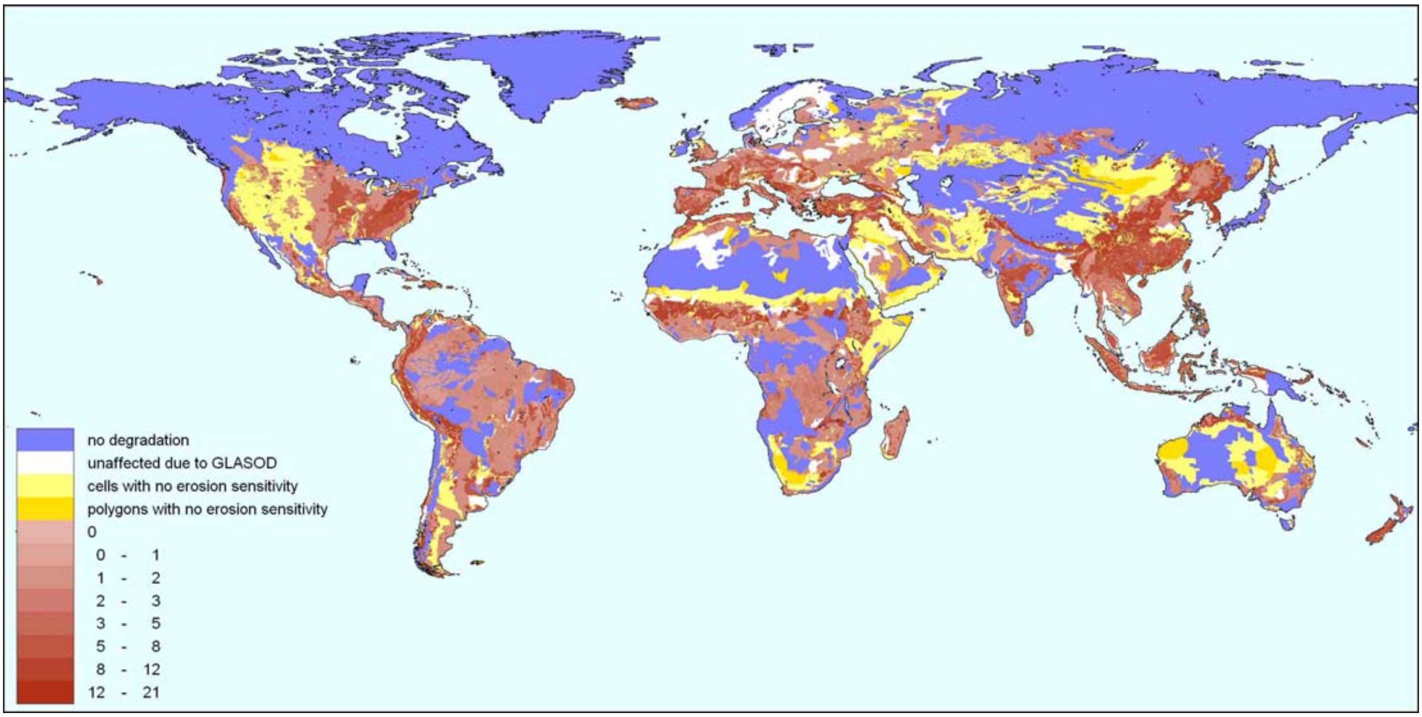

Figure 4.5. The significance of susceptibility to erosion and deforestation (rule 3 & 4) for the allocation procedure is presented. A distribution map combining information of both GLASOD entries is shown, produced using moderate parameters. All areas affected by erosion sensitivity or susceptibility to deforestation are indicated by a shade of red, showing their weight factor. Some areas were not affected due to differing reasons. Blue areas contained no degradation; white areas contained degradation due to other causes than deforestation or erosion and yellow areas were humid or hyper arid, so that they were not included in the erosion sensitivity maps. For this latter category, dark yellow cells were totally unaffected since their whole polygon lacked influence, while light yellow cells were affected indirectly, since part of their polygon was included in the erosion sensitivity map.

2.2 Results of the downscaling

The overall effect of the three rulesets is indicated in figure 4.6, which shows the difference between the original GLASOD data and downscaling results. This effect was significant for nearly all cells in polygons that were affected by degradation. Generally, the effect amounted to an increase or a decrease of 0-10 km of degraded area per grid cell.

Figure 4.7 shows an overview of global allocation results and original GLASOD data (4.7e-f) and exemplifies the effects of the downscaling by zooming in on a specific area for different parametersets (4.7a-d). More rigid rules induced more variation between individual cells, resulting in a higher level of clustering of degraded area to susceptible cells. The effects of the downscaling were limited to the distribution of degraded area within GLASOD polygons. Therefore, on a regional or global scale the effects were marginal (figure 4.7e and 4,7f).

Figure 4.8 indicates regional degraded area, for different assumptions on the extent of degradation. These assumptions were significant for results, as applying the upper limit resulted in a factor 2.23 more degraded area than applying the lower limit. This figure also shows that degraded area varied regionally, with most extensive areas in China, while in Canada, Japan, Greenland and Korea degraded lands were limited.

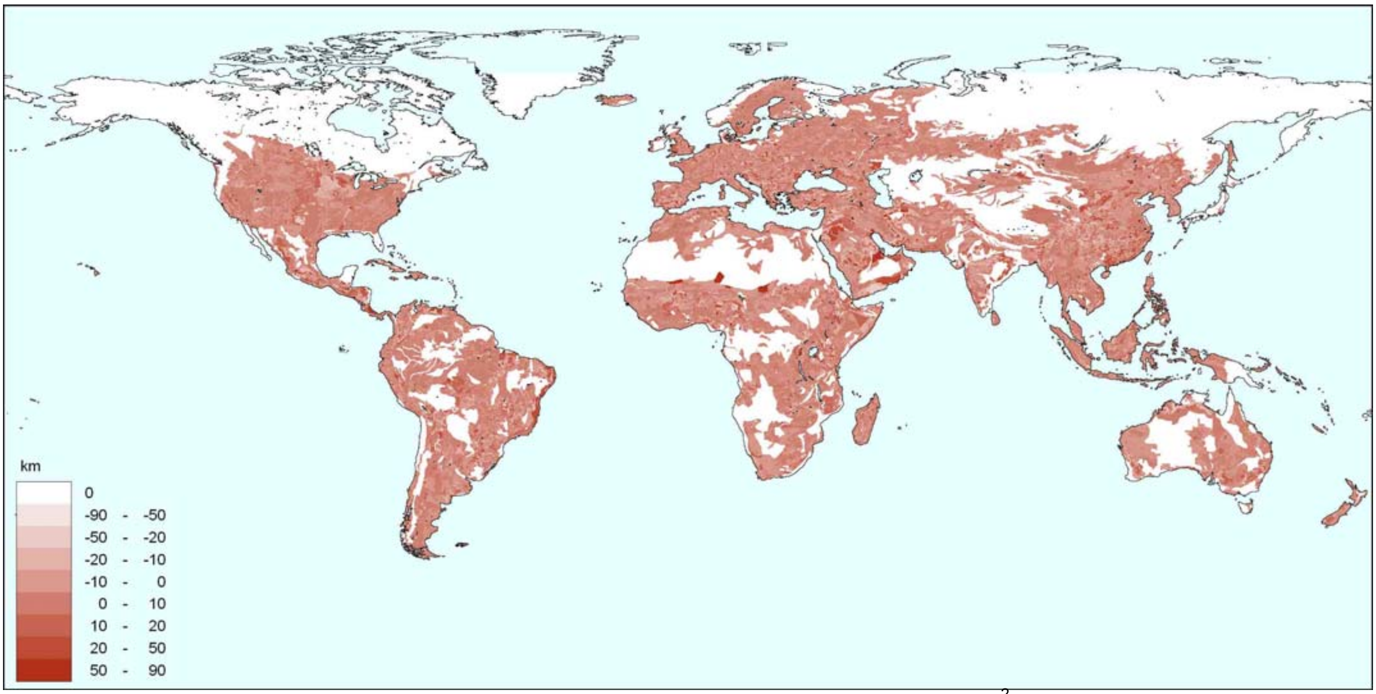

Figure 4.6 The difference between the original GLASOD data and the downscaling data in km^2 per grid cell applying moderate parameterset and the average of ranges of percentages.

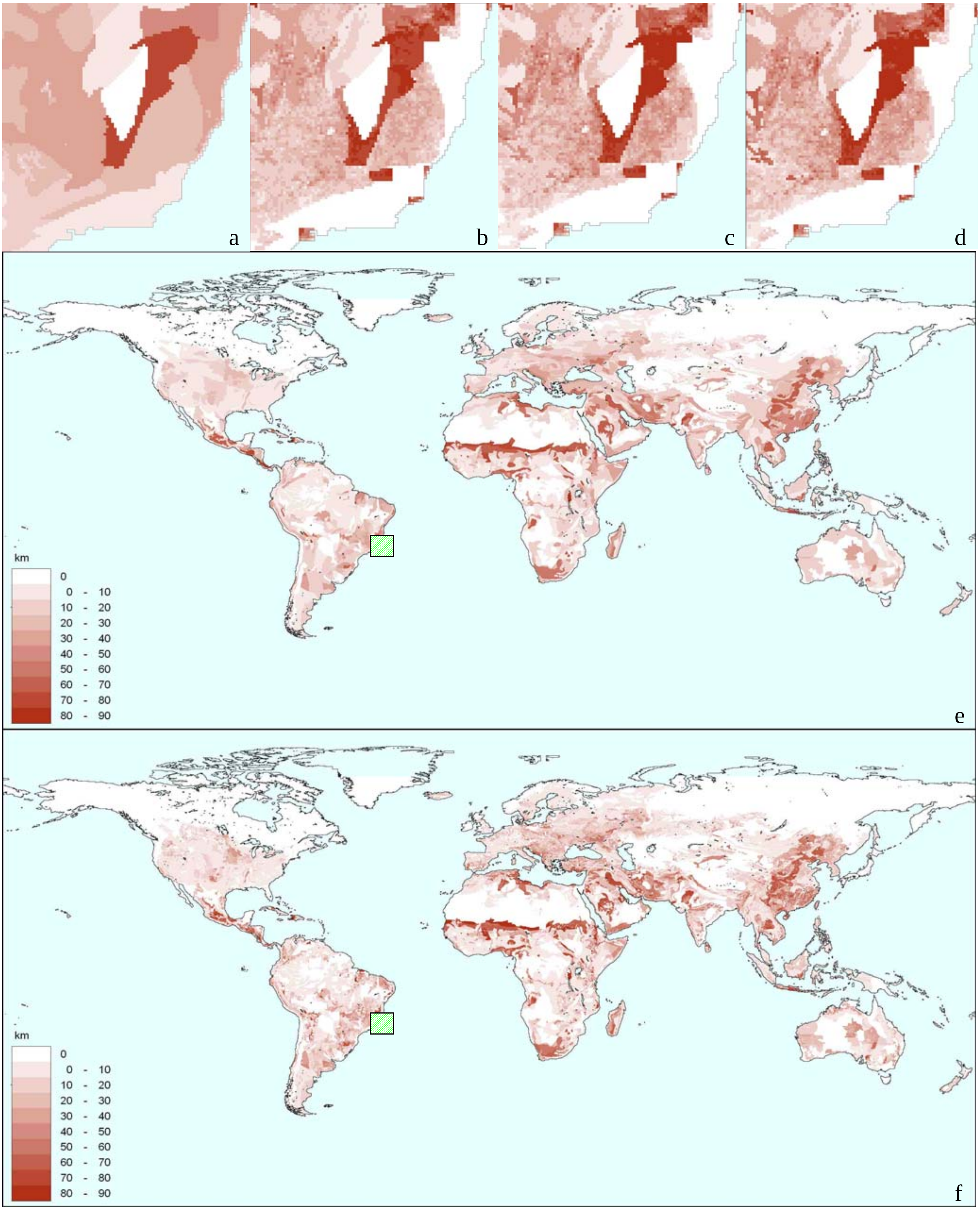

Figure 4.7. overview of the allocation results for degradation of moderate degree. The darkness of color indicates the amount of square kilometers of degraded area in a cell. Figure 4.7a to 4.7d show a detailed picture of an area in the United States, using different parameter sets ranging from no allocation rules (4.7a) to rigid allocation rules (4.7d) (shown in table 4.3). The enlarged area is indicated in green in figure 4.7e and 4.7f, which show a global view of the original GLASOD map and the result of the most rigid allocation procedure respectively.

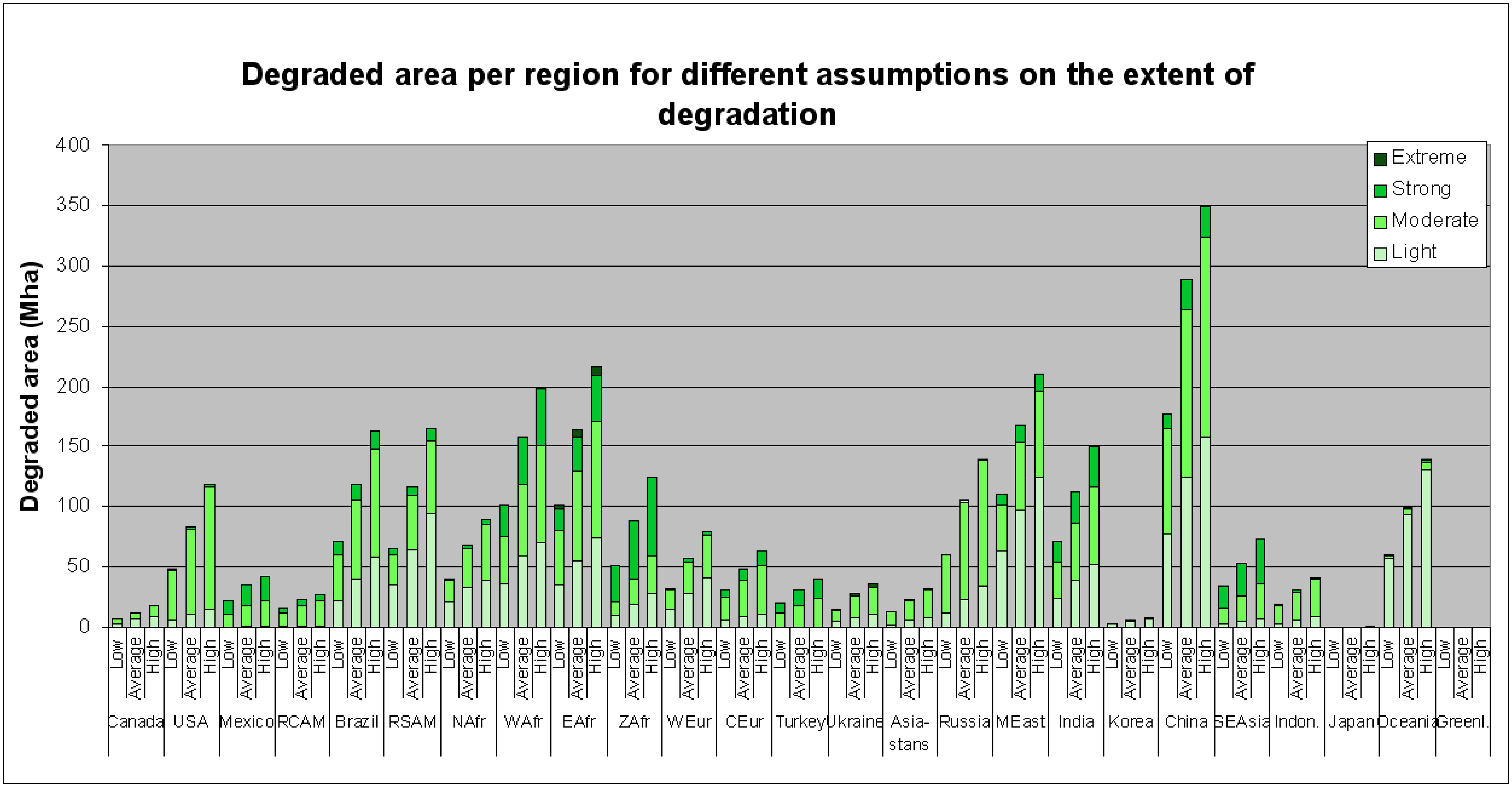

Figure 4.8 Regional degraded area, applying the moderate parametersets, taking the lower boundary, the average or the upper boundary of GLASOD extent percentage ranges.

2.3 Adjustment of degraded area

GLASOD data on the amount of degraded lands was adjusted downwards if, after exclusion of non-degraded area, a polygon offered less space than the chosen GLASOD percentage indicated as degraded area. Table 4.6 shows the total degraded area that was allocated for different parametersets and assumptions on the extent of degradation. The adjustment of degraded area is indicated by the percentage of degraded land that could be allocated during the different runs. In all runs, more than 94% of the degraded area was allocated. Allocation with rigid or moderate parameters resulted in a higher allocation percentage than allocation with loose parameters. Further, if more degraded area was assumed, then more degraded area was excluded during the procedure.

In figure 4.8 the effects of the downscaling on the surface area of degraded land are presented for 25 regions, applying moderate parameters and the average of percentages ranges. While degraded land decreased significantly as a result of the downscaling in the rest of Central America, Asia-stans, Brazil, India and West Africa, an increase in degraded area was observed in Canada, Turkey, South Africa and India.

In figure 4.9 original GLASOD data is compared with downscaled degraded area for all GLASOD polygons that were affected by degradation. For all polygons degraded area decreased or remained the same. Adjustments were most significant for degradation of moderate degree, while degraded area of extreme degree remained the same. Further, the adjustment was generally proportional to the degraded area in a polygon, as adjustments were more significant for polygons with more extensive degraded lands.

		No rules	Parameter set		
			Loose	Moderate	Rigid
Degraded area allocated	Lower limit	*	*	1.17 Gha (99.33%)	*
	Average	1.96 Gha (100%)	1.85 Gha (94.67%)	1.92 Gha (97.85%)	1.92 Gha (97.85%)
	Higher limit	*	*	2.52 Gha (95.79%)	*

Table 4.6 The total surface area that was allocated for different parametersets and different assumptions on the extent of degradation. Percentages indicate the share of degraded area that was allocated.

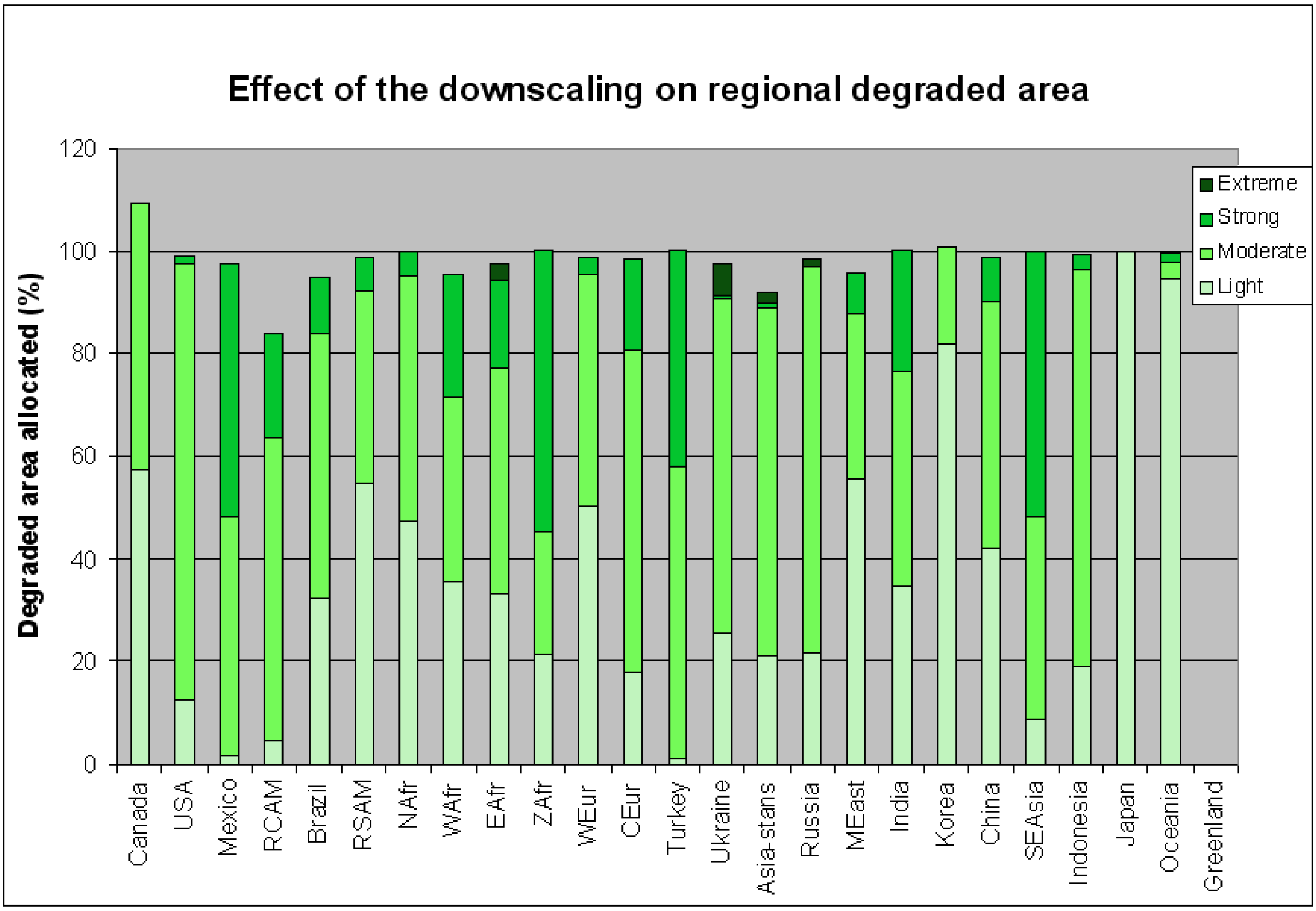

Figure 4.8 Per region, the allocated percentages of original GLASOD data is shown. As a result of relocation in GLASOD polygons that covered regional boundaries, some regions contain more degraded area than original GLASOD data.

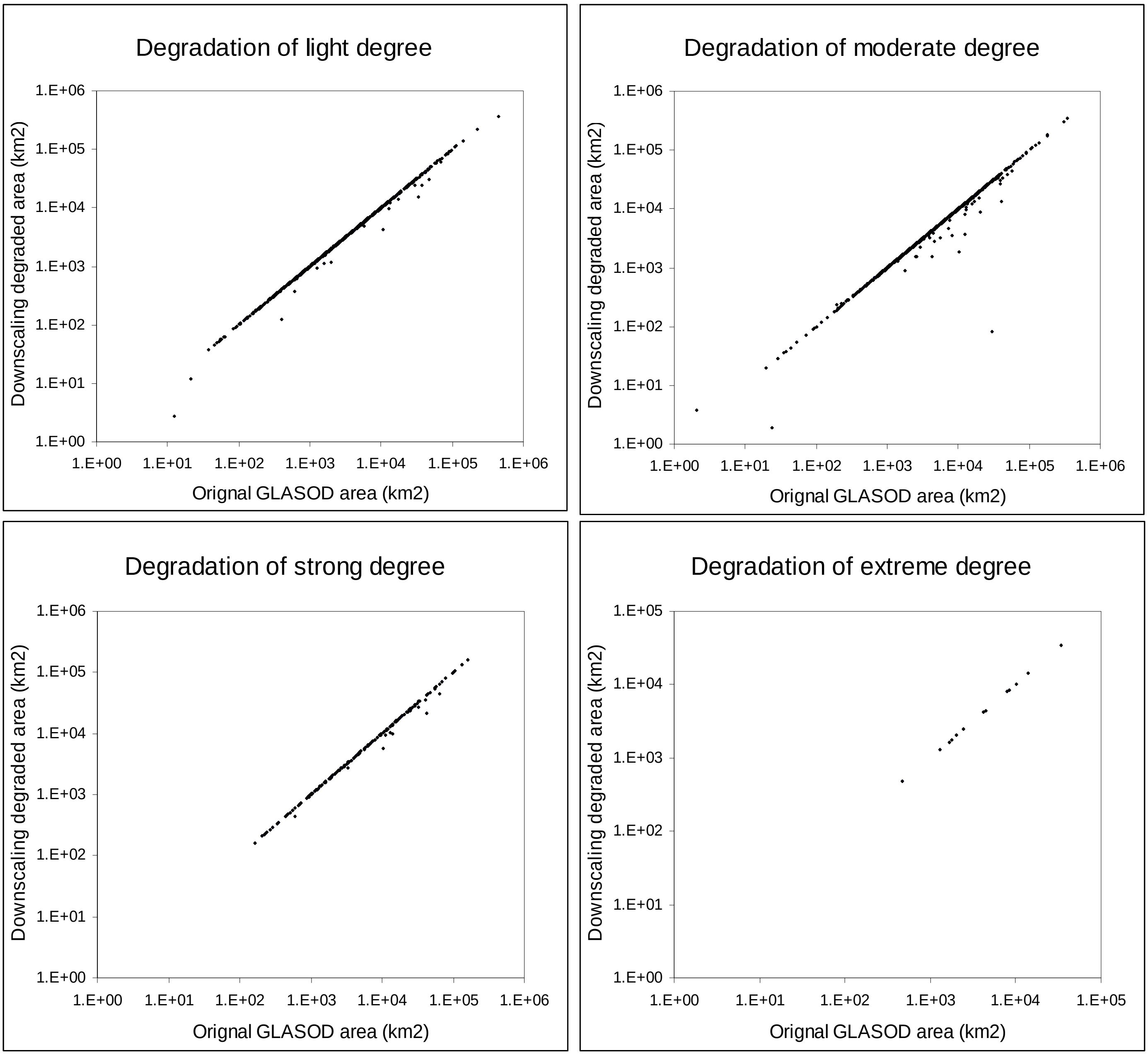

Figure 4.9. The area degraded land, as indicated by GLASOD is plotted against the area degraded land that was allocated during the downscaling procedure for the different GLASOD polygons on a logarithmic scale. Data points that deviate from the diagonal indicate an adjustment of degraded area, as a result of limited available space due to exclusion of non-degraded area.

3. Discussion & conclusion

The location of degraded lands was significantly affected by the downscaling of the GLASOD database. This effect occurred within polygons, resulting in marginal effects on larger scales. However, the more detailed information on the location of degraded lands is expected to affect global bioenergy potentials, since factors involved in energy yields, such as soil type and climate, vary on a local scale. This effect is expected to be positive, since degraded area was allocated to cropland areas and forests, if related causes were indicated, and these areas are expected to be generally located in productive areas. Moreover, degraded area was not allocated to non-soil areas, which are limited in potential yields, since these areas are characterized by extreme properties, such as high salt concentrations (salt flats) or very limited soil structure (shifting dunes).

The downscaling resulted in a decrease of original GLASOD degraded area of 2.15%, when applying moderate parameters and the average of the extent ranges of percentages. This adjustment is expected to decrease global bioenergy potentials, as less energy can be produced on a smaller area. For loose parameters the adjustment was more significant, since for this parameterset 75% instead of 100% of pastoral/cropland areas was prioritized if corresponding causes occurred. This priorization was performed not accounting for the exclusion of non-degraded area. In cells for which the datasets of cropland/pastoral areas and non-degraded areas overlapped, the 25% that was not prioritized could be excluded in the second run, if the exclusion of non-degraded areas was implemented. Therefore, loose parameters left more room for exclusion of degraded area in the procedure, resulting in a more significant adjustment of degraded area. Although total degraded areas was decreased due to the downscaling, it increased in some regions. This increase can be explained by the relocation of degraded area in polygons that extended over different regions. As was expected no polygons increased in degraded area. Beside the adjustment of degraded land due to exclusion of non-degraded area, some degraded area was excluded unintentionally as a result of difficulties with the conversion of the GLASOD database. In total the error caused by these problems equaled 0.25% of total degraded area.

The interpretation of the range of percentages, assuming the upper limit, the average or the lower limit, was of major influence in the procedure, causing maximally a factor 2.23 difference in total degraded area. The differentiating capacity, as established by the parameterset, was less significant for total degraded, amounting to maximally 3.6%. The effect of these assumptions on global bioenergy potentials is examined in chapter 6.

As the original data still limits the information that is included, the downscaled information of the GLASOD data should be used with care. However, the procedure is expected to lead to a more accurate estimate of the global potentials of degraded lands, as the detail on the location of degraded land was improved, by applying rulesets that were based on a clear rationale and mainly information of the GLASOD database itself.

Chapter 5. Comparing the effect of degradation on yields of perennial energy crops and annual food crops

1. Acknowledgements

Special thanks go out to dr. ir. A. J. Haverkort, dr. ir. H. Hengsdijk and ir. J. G. Conijn from the University of Wageningen, who provided very useful comments to improve the content of this chapter.

2. Introduction

In previous chapters, the GLASOD database of degradation was chosen to identify degraded areas globally. In this chapter yield reduction percentages are established for perennial energy crops, for the different degrees of degradation as indicated by GLASOD. Subsequently, in chapter 6 the established percentages are used to reduce potential biophysical yields in order to estimate bioenergy crop yields on degraded lands globally.

The GLASOD report presented five qualitative degrees of degradation, which were related to percentages yield reduction by Crosson (1997) that were adopted by Oldeman (2000), the main author of GLASOD. Crosson (1997) applied two different sets of percentages (presented in table 5.1), since the precise interpretation of qualitative descriptions of degradation degrees by experts during GLASOD was unknown. The two sets of percentages were not linearly related, differing a factor 3 for light degradation, a factor 2 for moderate degradation and a factor 1.33 for strong degradation. Percentages for extreme degradation were lacking in Crosson (1997) and Oldeman (2000). Degradation of extreme degree was assumed to result in 100% productivity loss, as GLASOD described this category as irreclaimable and beyond restoration. As no information was included on the crop types involved, the percentages were assumed to hold for annual food crops, since these were common in agriculture during the GLASOD assessment. To determine convenient percentages for the examined perennial energy crops, i.e. perennial rhizomatous grasses and short rotation forestry species, the effects of degradation on these crops is compared to the effects on annual food crops in this chapter.

In literature, it is frequently asserted that perennial bioenergy crop yields are less affected by degradation than annual food crop yields, although a convenient foundation is often lacking. In some cases, the rationale is restricted to postulating that perennial energy crops are better adapted to unfavourable circumstances than food crops (Sexton 2008, Sanderson 2008). In other cases, differences in plant physiologic mechanisms, nutrient and water use efficiency are posed to argue for a yield difference, neglecting the complexity attached to the effect of such factors on productivity under stress conditions (Parrish & Fike, 2005, Samson & Omielan, 1994).

In the section results, before elaborating on the available evidence for these assertions, results of the literature study to *Jatropha Curcas* are presented, which proved to be insufficient for yield estimates on degraded soils.

Percentage yield reduction	**Light degradation**	**Moderate degradation**	**Strong degradation**	**Extreme degradation**
Low estimate	5	18	50	100
High estimate	15	35	75	100

Table 5.1. The percentages yield reduction for light, moderate, strong degradation that Crosson (1997) applied to estimate productivity losses resulting from degradation based on the GLASOD database. Oldeman (1998), the main author adopted these percentages. For extreme degradation 100% reduction was assumed.

3. Methods

Percentages yield reduction for perennial energy crops can be established if on similarly degraded soils, the extent to which potential yields are reduced is compared for annual food and perennial energy crops. Therefore, the relative yield reduction was critical, i.e. the percentage to which potential yields are decreased as a result of degradation. Several lines of reasoning, which are described below, and corresponding scientific evidence were explored to examine relative yield reductions for annual food and perennial energy crops. The obtained evidence was utilized to establish convenient percentages yield reduction for perennial energy crops.

If data availability was sufficient, the examination was performed for different combination of the five types and four degrees of degradation that were indicated by GLASOD, since the difference between annual food crops and perennial energy crops may depend on those. Although site-specific conditions such as climate, soil type and pests incidence may also be influential, these were not examined separately, because such specific data were lacking. Due to this limitation, arguments for differences in relative yield reduction were restricted to a general nature, keeping in mind that exceptions may occur for certain site-specific conditions. The examination was performed taking into a period of ten years after initiation of energy production. This period was chosen as it allows perennial energy crops to establish and affect the soil, while it gives farmers a feasible term to benefit from yield advantages.

3.1 Yield data

To examine relative yield reductions as a result of degradation, one can use quantitative yield data for perennial energy and annual food crops, grown on non-degraded soils and soils that were subject to different types and degrees of degradation. Statistics on actual yields observed during commercial cultivation, the most straightforward yield data source, and experimental yield data were examined. Experiments were often not designed to determine yields. These generally served a more specific aim, in which yields were reported as by-products (van den Broek, 2001), resulting in a higher chance on anomalies within yield data. Further, experimental conditions that are significant for yields, such as experimental set-up, climate and soil type, varied between studies. To account for differences in these, studies were examined that determined annual food crop yields as well as perennial energy crop yields, keeping experimental conditions constant. Alternatively, independent energy and food yield studies were reviewed, aiming to level out the effects of variations in experimental conditions. Here, it was assumed that no relation existed between the site-specific factors of studies and the examined crop type and soil quality.

3.2 Crop growth models

Crop growth models can calculate crop growth for different situations, based on quantitative basic properties of crops and relations between these. Relative yield reductions can be compared by calculating the growth of energy and food crops on non-degraded soils and soils subject to different types and degrees of degradation. Two types of crop-growth models were examined, those modeling potential crop yields for different soil qualities and those modeling crop growth for different soil qualities.

3.3 Crop characteristics

Differences in main characteristics between crops can give a general indication of the relative yield reduction for different crops as a result of degradation. First, several differences were identified that provided general arguments in the discussion. Subsequently, to specify results for different types and degrees of degradation, the main stresses caused by different types of degradation were examined. Then, the effect of these stresses on the performance of perennial energy crops and annual food crops was examined, by analyzing relevant differences in plant characteristics. The relative yield reduction was compared for moderate stresses, limiting yields significantly, and extreme stresses that excluded reasonable yields of annual food crops. This subdivision was chosen as results differed for the performance during limiting conditions and the tolerance to extremely limiting conditions. Last, assumptions were established to estimate the quantitative difference in yield reduction, based on the qualitative findings of this method. Due to time constraints, the examination was limited to the most frequently cited plant characteristics in the light of performance on degraded soils.

4. Results

First, information found for *Jatropha Curcas* is presented. Then, results are described for the different lines of reasoning that were explored to obtain evidence for a comparison of the relative yield reduction due to degradation for perennial energy crops and annual food crops. Last, these results were combined to quantify this difference for different types and degrees of degradation.

4.1 *Jatropha Curcas*

Jonschaap et al. (2007) reviewed the state of scientific knowledge on cultivation of *Jatropha Curcas* for bioenergy production. They stated that, although evidence was found indicating that Jatropha Curcas can establish well on marginal soils and produce reasonable yields, yield data for marginal soils were largely absent, causing yield predictions to be practically impossible. In literature it is suggested that *Jatropha Curcas* can grown well on a wide range of soils as a result of low water and nutrient use, tolerance to acidic conditions and an extensive root system (e.g. Achten et al., 2008). However, until now, results in the field did not meet the expectations based on these characteristics (Jongschaap et al., 2007). Summarizing, although *Jatropha Curcas* may have some promising features to be cultivated on marginal soils, the current state of knowledge did not allow sound yield predictions. The Energy and Resources Institute (TERI) of India announced to undertake a 10-year project to cultivate *Jatropha* on wastelands (Braun, 2006), which may provide more information in the future. For perennial rhizomatous grasses and short rotation forestry crops, global potential biophysical yields were available from the IMAGE model, facilitating the assessment of yields on degraded lands.

4.2 Yield data

Statistical data yield data of large-scale commercial bioenergy production were not available, due to a limited experience with this relatively new form of agriculture (van den Broek, 2001 and Jongschaap *et al.*, 2007).

In experimental research, a wide range of yields is reported for energy crops as a result of differences in experimental conditions, such as experimental set-up, climate and soil type (Jongschaap et asl., 2007, Parrish & Fike, 2005). Three studies were found that examined energy crop yields as well as food crops yields on degraded soils keeping experiment conditions constant. Varvel *et al* (2008) found that corn and switchgrass derived ethanol yields on a marginal soil were in similar range. Tilman *et al.* (2006) concluded that low input high diversity grasslands produced higher ethanol yields on marginal soils than grain on fertile soils. Although this study was criticized by Russele *et al*. (2007) on inconsistent assumptions in methodology, Zhou *et al.*, found similar results in a sequel study. Consisting of three studies, data availability was not sufficient to provide a sound indication, as more studies are needed to account for differences in experimental conditions. Further, in these studies grain was cultivated as ethanol supplier instead of food crop, which may have affected results due to differences between ethanol and food production methods.

The alternative method to account for varying site-specific conditions, averaging out effects using a large body of independent yields studies, was also complicated by a limited data availability. The amount of yield studies for perennial energy crops on degraded soils was inconvenient for a meaningful comparison. This is confirmed by reviews, which tend to give examples of yields on degraded lands, rather than an overview or average (e.g. Parrish & Fike, 2005 and Sanderson, 2008). Further, Heaton (2004) applied a similar methodology to compare regular yields of elephantgrass and switchgrass, not focusing on degraded soils. She obtained 173 observations derived from 21 methodologically consistent studies, of which only 3 studies included yield data for marginal soils.

4.3 Crop growth models

Several crop growth models were studied to compare the effects of degradation on food and energy crops (e.g. CliftonBrown *et al*., 2005, FAO/IIASA, 2000, Kiniry *et al*., 2005, Leemans & van de Born and Schneider *et al*., 2001) However, no results were obtained, as often only few types of degradation were included, lacking chemical degradation and compaction, and as assessment of specific differences between crops was hindered by inherent high uncertainty levels of crop-growth models. Crop-growth models depend generally on assumed relations and estimated parameter values, needed as a result of limited quantitative data and a limited understanding of the processes of crop growth. Ongoing research at the University of Wageningen is specifically modeling the responses of different crops to several degradational stresses (pers comm. Conijn S, Haverkort A and Hengsdijk H). This research seems promising to indicate difference in the effects of degradation for perennial energy and annual food crops, but results were not available yet. Moreover calibration remains a problematic issue, considering the lack of data.

4.4 Plant characteristics

Differences in mechanisms and main characteristics between species can give an indication of their performance on degraded soils. To start with, the harvest-index yield relation, risks on harvest failure and improvements in soil quality are described, since these comprised more general arguments in the discussion, which are not related to a certain stress or limitation. Then, the stresses and limitations caused by different types of degradation are discussed. Subsequently, differences in plant characteristics between perennial energy and annual food crops are described that are relevant to the relative yield reduction, resulting from these dergadational stresses and limitations.

4.4.1 Harvest index-yield relation and harvest failure

The harvest-index yield relation and risks on harvest failure were relevant in the discussion, but failed to provide legitimate arguments in either direction. The harvest index, the harvestable share of aboveground biomass, decreases for food crops at lower yields (IPCC, 2006), while the aboveground biomass of perennial energy crops is harvested entirely, avoiding this loss (see figure 5.1). However, at lower yields, which occur during degradation, perennial energy crops may invest more in an extensive root system to avoid stress than annual food crops. Therefore, at lower yields the relative investment in aboveground biomass production may be decreased, counteracting the advantage of an unaffected harvest index (Clifton-Brown & Lewandowski, 2000). Furthermore, the stover of food crops may be used for bioenergy production and is increasingly produced at lower yields.

On degraded lands conditions are more harsh, increasing chances on harvest failure. Therefore, the susceptibility of crops to harvest failure may be important for their performance on degraded soils. However, also regarding the susceptibility to harvest failure, arguments pointed in both directions. During years with harsh conditions, annual food crops may fail to establish resulting in no production, while perennial energy crops may still produce limited yields, as these crops are already established. However, during extreme harsh years, perennial energy crops may not survive, resulting in several years of limited production during the establishment phase before optimal production is reached. Food crops, at the other hand, can produce optimally in the year afterwards.

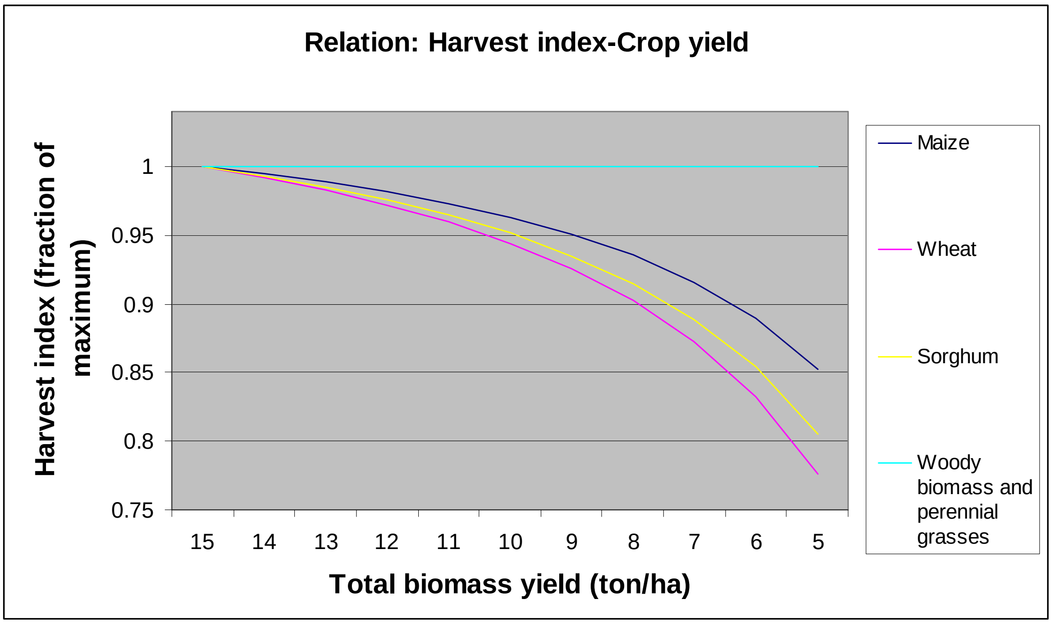

Figure 5.1. The relation between the total biomass yield and the harvest index, relative to the maximum value, of different food crops and energy crops. Derived from IPCC (2006), table 11.2.

4.4.2 Soil quality improvements

In contrast to annual food crops, perennial energy crops improve soil quality, limiting the effects of a reduced soil quality due to degradation on yields. Figure 5.2 gives an indication of the main factors and relations involved in this difference. Perennial energy crops serve to enhance nutrient and water holding capacity, to increase soil fertility, to enhance infiltration and to improve general soil structure and chemistry (e.g. stabilizing carbon fractions) (Tolbert, 2002)). In contrast, annual food crops tend to reduce soil quality by depleting the soil organic matter pool, degenerating soil physical and chemical properties (Lal, 2006). These effects were generally observed, but exceptions may occur due to differences in crop characteristics, site characteristics, management and former land use.

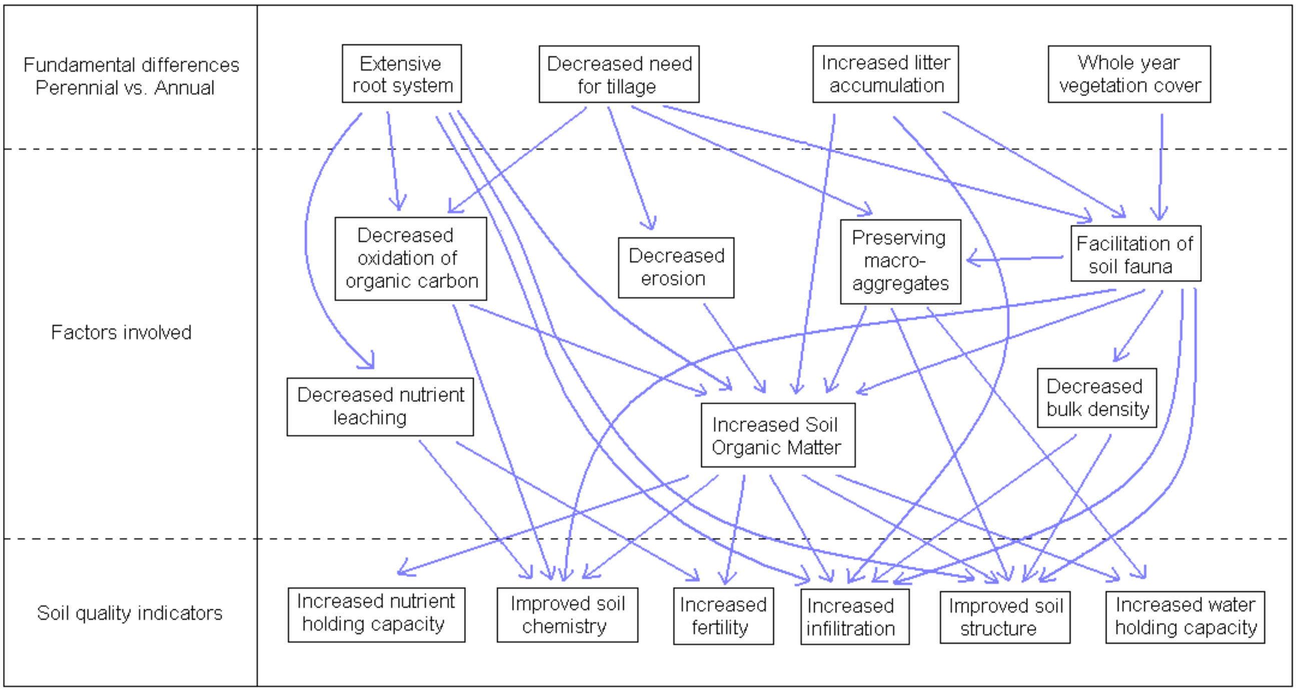

Figure 5.2. Conceptual model of the main factors and relations involved in differences between perennial and annual crops in terms of their effects on soil quality. Feedbacks related to increasing SOM are not indicated for the sake of clarity. Based on Borjesson (1999), Fenton (2008), Jongschaap *et al.,* (2007), Kort (1998), Lal (2006), McLaughlin & Walsh (1999), Lemus & Lal (2005), Mann (2000), McCallum *et al.* (2004), Ranney & Mann (1994) and Tolbert (2002).

A central factor in soil quality comprises the soil organic matter pool (SOM), which is important for many soil quality indicators (figure 5.2). Cultivation of perennial energy crops decreases removal of SOM from the soil, by limiting erosion, biological oxidation and leaching. Furthermore, these crops enhance the addition of SOM to the soil by increased litter accumulation and root mass compared to annual food crops (Borjesson, 1999). Switching from annual food crops to perennial energy crops generally results in an increase in SOM of 1-2 Mg C ha $^{-1}$ yr $^{-}$1, depending on site-specific conditions (e.g. Cook & Beyea 2000, Hansen 1993, Kenny 1993, Ma *et al.* 2000, Mann & Walsh 2000, Mehdi *et al*. 1998, Kort 1998, McLaughlin & Walsh 1998, Ranney *et al.* 1991, Tolbert 2002, Zan *et al.* 2001). Incidentally, an increase was not observed (e.g. Grival & Bergeson, 1998). Lal (2006) reviewed literature on the effect of increasing SOM on yields. He found that increasing SOM affected yields positively. For every additional Mg C in the SOM pool yields increased with 20–70 kg ha^{-1} for wheat, 10–50 kg ha^{-1} for rice, and 30–300 kg ha^{-1} for maize. In contrast, during prolonged food production on already degrading lands, yields can be expected to decrease due to progressing soil degradation. Therefore, this differences indicates a comparative yield advantage of perennial energy crops over food crops during the years following initiation of production.

4.4.3 Stresses caused by different types of soil degradation

Soil degradation results in a reduced productivity of the soil, limiting agronomic yields (Oldeman, 1991). This reduction can become evident in several ways. First, soil degradation can affect the services of the soil to crops, i.e. providing nutrients, moisture and gaseous exchange (Den Biggelaar, 2001). Although during agriculture, a limited nutrient supply is generally mitigated by fertilizer additions, this stress still occurs, as soil degradation can prevent fertilizer additions from reaching crops. Second, environmental variables can be disrupted in a way that limits growth, e.g. toxic concentrations of chemicals and highly acidic or alkaline conditions. Last, soil degradation can reduce yields indirectly by complicating agronomic management operations, e.g. by a weak soil structure, hindering heavy machinery manoeuvres.

Table 5.2 shows a general overview of the relative importance of several main stresses for different types of degradation. The occurrence of these stresses may vary depending on site-specific conditions (Hakansson & Voorhees, 1997 and Shestak & Busse, 2005). The rate of plant growth is often controlled by one limiting factor. Therefore, table 5.2 indicates the probability of a stress to be limiting rather than the continuous share of a stress in inhibiting crop growth. The indicated types of degradation were derived from the GLASOD degradation database, which served as basis for the assessment of global bioenergy potentials (Oldeman, 1991).

	Compaction	**Erosion**	**Waterlogging**	**Subsidence**	**Chemical**
Nutrient stress	++	+++	++	+++	++
Water stress	+++	++	-	+	-
Toxic conditions	+	-	-	-	+++
Agronomic limitations	++	-	+	-	-
Limited gaseous exchange	+	-	+++	-	-

Table 5.2. The stresses or limitations caused by different types of degradation (derived from Oldeman, 1991). The relative importance of different stress or limitation is indicated as occurring frequently (+++), regularly (++) or incidentally (+) (information is based on Shestak and Busse, 2005, Raghavan *et al.*, 1990, Mullins *et al.*, 1990, Lal 1990, Hakansson and Voorhees, 1997 and Den Biggelaar, 2001)

Compaction is characterized by a soil with a high bulk density, which causes reductions in root depth, root density and infiltration rate, a poor aeration and complication with seeding and tillage (Hakansson & Voorhees 1997 and Shestak & Busse, 2005, Mullins *et al.*, 1990). The resulting limited root growth and poor infiltration rates frequently cause water stress and regularly cause nutrient stress (Shestak &

Busse, 2005). Further, changes in microbial regime can cause high nitrate ammonium concentrations that impede growth (Hakansson & Voorhees 1997).

During erosion the fertile toplayer of the soil is removed, decreasing potential rooting depth, nutrient availability, soil organic matter and biologic activity (Den Biggelaar *et al.*, 2001 and Lal, 1990). As explained earlier (figure 5.2), this loss of SOM decreases nutrient and water holding capacity, resulting in water and nutrient stress for crops.

Subsidence comprises the removal of organic matter from the fertile topsoil as a result of biological oxidation. Loss of fertile topsoil is also the main effect of erosion. Therefore, stresses are similar for both degradation types.

As a result of waterlogging the soil is excluded from air, preventing adequate gaseous exchange for crops. This anaerobiosis of the soil affects a wide variety of chemical processes, resulting in an inappropriate nutrient balance, in which some nutrients may occur in toxic quantities while others are depleted (Fausey & Lal, 1990).

Chemical degradation includes acidification, nutrient depletion, pollution and salinization. These types of degradation all affect chemical systems in the soil, generally resulting in nutrient shortage, toxicity or a disturbed pH value, which hinder crop growth (Logan, 1990).

4.4.4 Differences in plant characteristics

Table 5.3 shows the extent to which a difference in relative yield reduction between perennial energy crops and annual food crops can be expected based on differences in plant characteristics. The presence and significance of this difference is presented for nutrient stress, water stress, toxic conditions, agricultural limitations and limited gaseous exchange and for moderate stresses, limiting yield significantly, and extreme stresses, excluding reasonable yields of annual food crops. The relation between these stress levels and the different degrees of degradation is discussed in section 4,4, when establishing percentages yield reduction for perennial energy crops. First, the rationale for the expectations in table 5.3 is explained per stress or limitation. Expected soil improvements resulting from cultivation of perennial energy species, which gradually reduce these stresses are not included in this discussion.

	Moderate	**Extreme**
Nutrient stress	++	+++
Water stress	-	++ *
Toxic conditions	+	+
Agricultural limitations	++	++
Limited gaseous exchange	-	-

Table 5.3. Differences in relative yield reduction for perennial energy crops vs. annual food crops as a result of nutrient stress, water stress, environmental limitations, agricultural limitations and limited gaseous exchange are presented. Plusses indicated an expected yield advantage for perennial energy crops as follows: +++: substantial difference, ++ moderate difference, + marginal difference. * only valid for comparison of perennial energy crops and C3 food crops.

Nutrient stress

Since nutrient stress occurs during all types of degradation (table 5.2), performance of crops during poor nutrient conditions is significant for their overall performance on degraded soils. Several characteristics are discussed that may provide arguments, indicating that perennial energy crops are less affected by nutrient stress than annual food crops on extremely and on moderately nutrient poor soils.

Extreme nutrient stress

Cultivation of perennial energy crops results in a more efficient use of nutrients, which gives them a comparative yield advantage on extremely degraded soils, where annual food crops are not able to produce reasonable yields. Crops affect three factors that are important when considering the efficiency of a production system to produce on a nutrient poor soil: 1) the efficiency of converting absorbed nutrients into harvestable biomass, 2) the loss of nutrients from the system to the environment and 3) the capacity of crops to capture nutrients from the soil. Regarding those three factors perennial energy crops are in advantage compared to food crops.

First, perennial energy crops are more efficient in converting absorbed nutrients into harvestable biomass. Perennial energy crops are harvested after translocation of nutrients to roots and, unlike food crops, storage organs are not harvested, limiting removal of nutrients from the field (Jorgense &

Schelde, 2001). In accordance, the Nutrient Use Efficiency (NUE), i.e. the amount of essential nutrients a crop needs to produce biomass, is significantly lower for perennial energy crops than for annual food crops (see Jorgense & Schelde (2001) for an overview of NUEs). Second, unlike food crops, perennial energy crops significantly limit the loss of nutrients to the environment, by decreasing run-off, biological oxidation, erosion and leaching from nutrients (see figure 5.2). Third, energy crops are more efficient in capturing nutrients from the soil than annual food crops. Perennial energy crops produce a more extensive root system, increasing their range and total surface area to collect nutrients (Heaton, 2004 and Sanderson 2008). Also, perennial energy crops facilitate mycorhizal symbiosis, enhancing phosphor-uptake (Lewandowski 2006, Heaton 2004, Clifton-Brown *et al.*, 2001). Thus, due to a more efficient use of nutrients in the system, energy crops tolerate lower fertility levels, resulting in a yield advantage on extremely nutrient poor soils compared to annual food crops.

Moderate nutrient stress

To examine the sensitivity of yields to moderate nutrient stress for perennial energy crops and annual food crops, 1) the effects of a more efficient system level nutrient use on performance during moderate stress and 2) differences in total nutrient requirements were considered.
A more efficient nutrient use is not necessarily related to maintenance of high yields on soils with moderate nutrient stress, as also on fertile soils energy crops exploit their efficient nutrient use. Amongst other factors, this allows perennial energy crops to, generally, achieve higher total biomass production than annual food crops, which is critical to obtain convenient energy yields (table 5.4). Therefore, to determine the sensitivity of yields to moderate nutrient stress, the effect of a more efficient use of nutrients in the system on the relative yield reduction was examined.

Crop	**Average annual aboveground biomass production**	**Type of research**
Source: Fischer *et al*., 2005 for yields and IPCC, 2006 for harvest index		
Grain	14.61 Mg ha^{-1}	Crop-growth model, average yield on very suitable land
Willow & poplar	16.25 Mg ha^{-1}	Crop-growth model, average yield on very suitable land
Elephantgrass	25.50 Mg ha^{-1}	Crop-growth model, average yield on very suitable land
Source: McLaughlin *et al*., 2006		
Maize	12-14 Mg ha^{-1}	Commercial statistics US
Switchgrass	13-23 Mg ha $^{-1}$	Experimental studies US

Table 5.4. Total annual aboveground biomass production of annual food vs. perennial energy crops. As a wide range of yields is reported in literature due to differences in site-specific conditions, data was derived from 2 sources to be comparable.

On non-degraded soils, several factors other than nutrient availability can be limiting for growth. For example, yields of poplars, willows, switchgrass and elephantgrass are generally limited by water availability (Moller, 2007). Therefore, one could argue that perennial energy crops possess additional nutrient use related qualities compared to annual crops, which are not fully exploited on non-degraded soils. Thus, during increased nutrient stress, these crops are better equipped to maintain high yields, reducing relative yield reduction. Further, mycorhizal symbiosis, which is facilitated by perennial energy crops, is only beneficial during nutrient limited conditions, since on fertile soils the costs outweigh the benefits (Parrish & Fike, 2005). This comprises an additional advantage for energy crops during nutrient stress, which is lacking for annual food crops.

Additional to the effects of a more efficient nutrient use, total nutrient requirements can indicate the sensitivity of crop yields to moderate nutrient stress, since a less nutrient demanding system can be expected to be less affected by poor nutrient conditions. Total nutrient requirements were considered by examining the input of nutrients as a result of fertilizer additions. Fertilizer additions comprise the main crop-specific nutrient influx in agricultural systems. Nitrogen deposition, the other significant influx, is independent of crop type (Propheter 2009, Mann 2000). The efflux of nutrients was not quantified, as it consists several crop-specific nutrient fluxes, such as erosion, leaching, increasing SOM, biological oxidation and removal of nutrients by harvest, for which quantitative data are limited. As with many ecological issues, fertilizer requirements can be expected to vary depending on site-specific conditions. However, general application rates can give an indication of average nutrient requirements.

In literature a low fertilizer demand is often quoted as an advantage of perennial energy crops compared to annual food crops (e.g. Boehmel, Sanderson 2008 Clifton Brown, 2001 Tilman, 2006 Hill 2006 Ignaciuk, 2006). However, quantitative data on fertilizer requirements of perennial energy crops is limited (Parrish & Fike, 2005 and Moller *et al.*, 2007, Lewandowski 2000). Some studies reported marginal responses to fertilizer additions, suggesting minor application to be adequate. Others found fertilizer requirements similar to or higher than maize (Lewandowski, 2003). A review by Brejda (2000) on fertilizer response of switchgrass showed greatly varying results and also more recent research failed to provide consensus (Parrish & Fike, 2005). As field studies were inadequate to provide general application rates, fertilizer recommendations were considered (see table 5.5 for an overview of results). Recommendations were in similar range for food and energy crops, indicating no significant difference in total nutrient requirements between annual food crops and perennial energy crops. The effect of a more efficient use of absorbed nutrients by perennial energy crops seems to be compensated by their higher biomass production compared to annual food crops.

Crop	Recommended annual fertilizer application			Source
	N	P	K	
Food crops				
Wheat	60 kg	35 kg	45 kg	Ranney (1994)
Maize	135 kg	60 kg	80 kg	Ranney (1994)
Soybeans	20 kg	45 kg	70 kg	Ranney (1994)
Sorghum	90 kg	60 kg	60 kg	Ranney (1994)
Energy crops				
Switchgrass	50 kg	60 kg	60 kg	Ranney (1994)
	50-100 kg	-	-	Lewandowski (2003)
	40-120 kg	-	-	Mc Laughlin & Kzos (2005) in Parrish & Fike (2005)
	50-100 kg	-	-	Moder & Vogel (1995) in Parrish & Fike (2005)
	67-110 kg	-	-	Brejda (2000) in Parrish & Fike (2005)
Poplar	90-150 kg	-	-	Moller *et al.* (2007)
Willow	60-100 kg	9-15 kg	40-65	Perttu (1998)
Short rotation woody crops	60 kg	15 kg	15 kg	Ranney (1994)

Table 5.5. Recommendation of fertilizer application for different food and energy crops. Generally, ranges are presented, since recommendations vary for different site-specific conditions, such as climate or soil type.

Water stress

Water stress occurs as a result of compaction, erosion and subsidence (table 5.2). Differences in plant characteristics, relevant to the relative yield reduction of perennial energy crops and annual food crops on soils with extreme and moderate water stress are described.

Extreme water stress

Perennial energy crops generally induce a more efficient use of water on the system level compared to annual food crops, resulting in an improved tolerance of extremely water limiting conditions. Crops affect several factors involved in the efficiency of water use in an agricultural system: 1) the efficiency of using absorbed water by crops, 2) the retention capacity of the system and 3) the efficiency of crops in capturing water from the soil. Perennial crops generally are in advantages compared to annual food crops regarding these factors, which gives them a yield advantage over annual food crops during extremely water limiting conditions.

First, perennial energy crops, covered here, are characterized by a C4 photosynthetic pathway, while several annual food crops apply a C3 photosynthetic pathway, such as wheat, grain and potatoes. A C4 photosynthetic pathway is, in theory, related to improved efficiency in using water and nutrients to assimilate biomass, although this advantage is generally only realized in high light, humid and warm environments (Beale *et al.*, 1999, Jorgense & Schelde, 2001, Naidu *et al.*, 2003 and Parrish & Fike, 2005). Compared to C4 annual food crops, such as maize and sorghum, this difference is lacking. However, elephantgrass showed to achieve higher efficiencies in a broader range of conditions than maize, e.g. in temperate climates of Northern Europe (Beale *et al.*, 1999, Naidu *et al.*, 2003).

Second, unlike annual food crops, perennial energy crops result in a high infiltration rate and a high water holding capacity of the soil, preventing water deficiency during limited water supply to the soil. The differences involved in this are already described in the section 4.4.2 (see also figure 5.2). These include a more extensive root system, a decreased need for tillage, increased litter accumulation and whole year vegetation cover of perennial energy crops.

Third, the more extensive root system of perennial energy crops serves to reach deeper soil layers and increases surface area for water collection and, therefore, the capacity to take up water during incidental rainfall. Thus, perennial energy crops are expected to tolerate more limiting water conditions than annual food crops (especially C3), which results in a yield advantage during extreme water stress.

In literature, the Water Use Efficiency (WUE), the ratio of water used and produced biomass, is often cited regarding performance of crops during water stress (Blum, 1996). However, WUE is inappropriate as indicator, since variations in WUE are generally explained by variations in water use rather than variations in the efficiency of a plant in using this water. Plants with a reduced water use and often high WUE, are generally limited in the capacity to take up water during a short time span. However, this capacity is critical to performance during dry conditions, when water supply is often irregular due to incidental rainfall. Plants with a great capacity to take up water are generally characterized by higher water use during wet conditions, resulting in lower WUE efficiency (Blum, 1996). Therefore, based on this indicator no conclusion can be drawn on the performance of crops during dry conditions.

Moderate water stress

To compare for annual food and perennial energy crops the extent to which yields are affected by moderate water stress, the effects of a more efficient water use and assertions on general drought tolerance were examined. More specific differences in plant physiologic mechanisms involved in water stress sensitivity, such as osmotic adjustment, were not considered, since such differences were multiple, decreasing the straightforwardness of their effects. (Blum, 1996).

The higher efficiency in water use on the system level of perennial energy crops, is not necessarily related to a decreased yield sensitivity to water stress. Yields of poplar, willows, switchgrass and elephantgrass on non-degraded soils are generally water-limited (Moller, 2007, Fike *et al.*, 2006 and Beale, 1999). This suggests that perennial energy crops depend on their water use related qualities to produce high biomass yields on non-degraded soils (see table 5.4). Therefore, an additional yield advantage during water limiting conditions cannot be identified based on the more efficient water use of perennial energy crops.

The drought tolerance of a crop can be used to indicate the extent to which a plant is affected by water stress. In literature, some authors suggest perennial species to be drought tolerant compared to annual food crops. Elephant grass is generally cited to be less affected by water stress than annual food crops (Beale *et al.*, 1999 and Moller *et al.*, 2007). For switchgrass results varied. Muir *et al* (2001) found that switchgrass yields were extremely affected by drought, while Heaton (2004) and Parrish & Fike (2005) suggest switchgrass to be drought tolerant. Poplars and willow are generally thought to be more drought susceptible. However, beside the results of Muir *et al* (2001), no field data were presented to substantiate these statements, weakening their legitimacy. Therefore, no indication on a difference in relative yield reduction could be derived.

Toxic conditions

To assess the sensitivity of perennial energy crops and annual food crops to toxic conditions, for example resulting from extreme pH values or toxic concentrations of metals, the tolerance levels for these conditions were examined. Differences in tolerance levels are relevant to moderate as well as extreme stresses.

In literature only few tolerance levels for environmental variables were reported for perennial energy crops. Parrish and Fike (2005) reported switchgrass to grow on sites with a pH as low as 3.7, while Lewandowski (2003) found switchgrass to generally tolerate pH-levels ranging from 4.9 to 7.6. Poplars and elephantgrass grow generally in a pH range of 5.5 to 7.5, although elephantgrass tolerates also more acidic or alkaline conditions (Moller *et al.*, 2007). The tolerance of low pH levels is suggested to be related to mycorhizal symbiosis, which is facilitated by perennial energy crops (Parrish & Fike, 2005). No quantitative data were found for the tolerance of high aluminum levels by perennial energy crops, although mycorhizal symbiosis is also thought to be beneficial for this (Parrish & Fike, 2005).

Although data on specific tolerance levels were scarce, perennial energy crops are frequently reported to grow under very limiting edaphic conditions (Jorgense & Schelde, 2001). For example, switchgrass is used to revegetate drastically disturbed areas such as sand dunes, taconite mine tailings, strip mines, sand and gravel mines, lignite overburden, bauxite mines, acidic coal refuse piles, lead and zinc mines, and sites denuded by zinc smelters (Parrish & Fike, 2005). Further, short rotation forestry can be used to produce on landfills, which are characterized by methane toxicity, drought, poor nutrient status and limited gaseous exchange (Nixon, 2001). Based on these experiences perennial energy crops are expected to be less affected by toxic conditions or extreme pH values.

Agricultural limitations

During cultivation of perennial energy crops tillage is largely eliminated, since crops do not reestablish annually such as food crops (Sanderson, 2008). Consequently, tillage complications are less significant for perennial energy crops than for annual food crops. Therefore, energy crops are expected to have an advantage in a situation with agricultural limitations, compared to annual food crops.

Limited gaseous exchange

Regarding stress due to limited gaseous exchange no indications were found for a difference in performance between annual food crops and perennial energy crops.

4.4.5 Effects on relative yield reduction due to degradation

To summarize results related to differences in plant characteristics, the relative incidence of stresses during several types of degradation (table 5.2) was combined with the expected difference in performance during these stresses (table 5.3), using the following calculation:

$$\begin{array}{l}\text{Expected yield difference}\\ \text{for a type of dergradation}\end{array} = \sum^{\text{stresses}} \frac{\text{Occurence of a stress}}{\text{Total occurence of stresses}} * \begin{array}{l}\text{Expected yield difference}\\ \text{related to the stress}\end{array}$$

For calculations, the qualitative results were translated to numbers, counting the amount of plusses in table 5.2 and table 5.3, and converted back to plusses for presentation. For the different types of degradation, the relative occurrence of the different stresses was multiplied by the expected differences for these stresses. Then, the outcome for the different stresses was summed up to determine the expected difference in relative yield reduction for the type of degradation. Table 5.6

shows the results, indicating that for all combinations of types of degradation and stress levels an advantage in relative yield reduction of perennial energy crops over food crops is expected.

	Compaction	Erosion	Waterlogging	Subsidence	Chemical
Moderate stress levels	+	+	+	++	+
Extreme stress levels	++*	+++*	+	+++*	++

Table 5.6. The expected difference in relative yield reduction for different types of degradation of perennial energy crops compared to annual food crops. More plusses indicate a more significant difference.

*: only valid for comparison of perennial energy crops and C3 food crops, compared to C4 food crops a + less was expected.

4.5 Yield reduction percentages for perennial energy crops

As yield data and crop-growth models were inconvenient to provide an indication of a difference between annual food crops and perennial energy crops in yield reductions resulting from degradation, estimates were based on evidence derived from differences in plant characteristics. Differences in plant characteristics indicated a difference in relative yield reduction based on 1) improvements in soil quality resulting from cultivation of perennial energy crops and 2) a difference in sensitivity to stresses or limitation caused by degradation (table 5.6). Table 5.7 presents the calculation applied to establish the difference in relative yield reduction due to degradation between perennial energy crops and annual food crops, which are presented in table 5.8. Three sets of difference percentages were calculated to account for the uncertainty, involved in the calibration of qualitative results. The calibration of qualitative results was based on the following considerations.

Improvements in soil quality

The increase in soil organic matter, induced by cultivation of perennial energy crops, played a central in the factors involved in improvements in soil quality (figure 5.2) The generally observed increase in SOM of 1-2 Mg C ha $^{-1}$ yr $^{-}$1 resulted, according to data of Lal (2006), in yield improvements amounting to tenths of percentages per year for several food crops such as wheat and rice. Beside this yield improvement, an advantage was expected as a result of avoided yield losses due to mitigated soil degradation. This advantage is estimated to be also in the range of tenths of percentages, as soil degradation is significant for yields, but also a gradual process. Further, during food production degradation can also be mitigated by taking appropriate measures. Based on this information, taking into account a timeframe of ten years, improvements in soil quality were estimated to result in a yield difference of 1.5% to 6%. The difference was expected to increase for more severe degradation, since on soils with a lower quality, effects of improvements are expected to be more significant. Estimates are of a general nature, since effects are expected to vary for different site-specific conditions,

Reduced sensitivity to degradation

Expected differences in the sensitivity of crops to degradational stresses and limitations (table 5.6) were fully based on qualitative data, as no quantitative data were available, complicating calibration of results. The identified arguments were significant for yield reductions due to degradation. Based on these arguments, differences may occur in the range of a several tens of percentages. For example, during water stress an increased root depth may allow perennial energy crops to reach a deeply situated water reservoir, causing water supply to be adequate instead of severely limited. Also, during nutrient stress, a more efficient nutrient capturing, nutrient catabolism and less nutrient losses to the environment may result in a sufficient nutrient supply, while a lack of these qualities may signficantly inhibit growth. Thus, these arguments, which indicate an advantage for perennial energy crops, can be of major importance for yields on degraded soils. However, their significance often depends on site-specific conditions. If no deeply situated water supply existed, for example, increased root depth

may be of limited important. Also, during nutrient stress mycorhizal symbiosis is only an advantage if phosphor is deficit, while positive effects are non-existing if nitrogen is depleted. Accounting for these different situations and the strength of arguments, the difference in sensitivity to stresses was estimated to result in a difference in relative yield reduction of a number of percentages. Established calculation rules resulted in percentages ranging from 3.8% to 10.3%, depending on the type and degree of degradation.
Percentages were determined by relating the different degrees of degradation to the stress levels. For degradation of light and moderate degree, moderate stress levels were assumed to occur, significantly limiting yields, but not excluding growth of annual food crops. For strong degradation, stress levels were assumed to be generally moderate, although incidentally periods in time or locations may occur that exclude growth of annual food crops. Therefore, percentages for severe degradation were for 1/6 explained by the expected difference for extreme stress levels and for 5/6 by the expected difference for moderate stress levels. For extreme degradation, only extreme stress levels were assumed to occur, as 100% yield reductions indicate exclusion of growth of annual food crops.

The differences in yield reduction, shown in table 5.7, were applied on the high and low estimates of general yield reduction percentages, to determine the percentages reduction for perennial energy crops, which are presented in table 5.8.

1. Calibration of difference in relative yield reduction based on stress-related results

Performed for each type of degradation, for moderate and extreme stress levels.

Percentage difference = 3.75 ***** expected difference (as determined in section 4.4.5)

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2. Calculation of difference in relative yield reduction for different degrees and types of degradation, based on stress-related results (see step 1) and improvements in soil quality (specific for degrees of degradation).

Performed for each type of degradation:

Light degree = MSL+**1.5**

Moderate degree = MSL + **3**

Strong degree = MSL * (5/6) + ESL (1/6) + **4.5**

Extreme degree = ESL + **6**

MSL: calibrated value for moderate stress levels (derived from step 1)
ESL: calibrated value for extreme stress levels (derived from step 1)

In bold the percentages related to improvements in soil quality

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3. Establishing a high and a low estimate based on optimal percentages as determined in step 2

Optimal estimate = results step 2

High estimate = Optimal estimate * 1.5

Low estimate = Optimal estimate / 1.5

Table 5.7 Calculation to determine quantitative differences in relative yield reduction based on qualitative results from differences in plant characteristics.

	Compaction			Erosion			Waterlogging			Subsidence			Chemical		
	L	O	H	L	O	H	L	O	H	L	O	H	L	O	H
Light degradation	3.5	5.3	7	4	6	8	3.5	5.3	7	4.8	7.1	9.5	4.5	6.8	9
Moderate degradation	4.5	6.8	9	5	7.5	10	4.5	6.8	9	5.8	8.6	11.5	5.5	8.3	11
Severe degradation	5.8	8.7	11.6	6.6	9.9	13.2	5.6	8. 5	11.3	7.3	10.9	14.5	6.7	10	13.3
Extreme degradation	8.2	12.3	16.3	10.5	15.8	21	7.3	11	14.7	10.9	16.3	21.7	8.5	12.8	17

Table 5.8.Differences between perennial energy crops and annual food crops in relative yield reduction as a result of degradation, indicated in percentages. A low estimate (L), an optimal estimate(O) and a high (H) estimate are presented for different types and degrees of degradation.

Adjusted percentages yield reduction		**Compaction**		**Erosion**		**Water logging**		**Subsidence**		**Chemical**	
		Low	High	Low	High	Low	High	Low	High	Low	High
Light degradation	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	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
Severe degradation	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	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	87.25	87.25

Table 5.8. Adjusted percentages yield reduction for perennial energy crops based on percentages for annual food crops. Results are presented for different combinations of type of degradation and degree of degradation. For annual food crops a high and a low estimate are presented. Yield reductions for perennial energy crops are calculated applying the best estimate of the difference between crops, derived from table 5.7.

5. Discussion & conclusion

Several lines of reasoning were explored to examine differences in relative yield reduction as a result of different types and degrees of degradation for annual food crops and perennial energy crops. Although in literature, a yield advantage of perennial energy crops over annual food crops is often asserted, scientific evidence proved to be limited. Statistical yield data, the most straightforward datasource, were not available for perennial energy crops, since experience with this new form of agriculture was limited. Due too limited data availability, experimental yield studies were also inconvenient to compare food and energy crop yields on degraded and non-degraded soils. Crop-growth models included high uncertainty and were not specific enough to provide a reasonable comparison between crops, although ongoing modeling efforts on the University of Wageningen seemed promising. Thus, quantitative yield data were inadequate, while these are critical in assessing the performance of perennial energy crops on degraded lands.

As more quantitative data were lacking, main differences in plant characteristics were used to compare relative yield reductions for annual food and perennial energy crops as a result of degradation. Qualitative results suggested a yield advantage for perennial energy crops for all examined types and degrees of degradation. These results were calibrated to quantitative differences, establishing three sets of assumptions. The evidence base for these assumptions was limited, mainly as a result of the need to rely on differences in main characteristics between crops. Crop performance during limiting conditions is determined by a complex system of multiple interrelated mechanisms and characteristics, which are only partly understood. Further, data was insufficient to examine the effect of variations in site-specific conditions, which may result in exceptions to expected relations. Differences were examined for a time period of ten years. For a longer period differences may be more significant, since perennial energy crops gradually improve the soil, resulting in positive effects on yields. For extreme degraded lands a rather optimistic view was chosen, since some extremely degraded soils may also exclude cultivation of energy crops, despite their broader tolerance to extremely limiting conditions.

Summarizing, based on the current state of knowledge, a yield advantage of perennial energy crops over annual food crops on degraded soils is expected, although the assessment of the significance of this difference is complicated. Getting more insight in this difference is of high importance, since it is critical to accurate bioenergy yield assessments and it comprises a main argument in the debate on the attractiveness of bioenergy production on degraded lands.

Chapter 6. Calculating global bioenergy potentials

In previous chapters ingredients were obtained to assess global bioenergy potentials on degraded lands. The GLASOD degradation database was selected to provide information on global degraded lands; a downscaling procedure was used to improve the level of detail of this information. General yield reduction percentages resulting from degradation, which were linked to this database, were then adjusted in order to make them applicable for energy crops. In this chapter these ingredients are used, together with potential yield maps of energy crops, to assess global bioenergy potentials on degraded lands. Further, the present land use of degraded lands is examined and a sensitivity analysis is performed to examine the effect of assumptions.

1. Methods

Bioenergy potentials on degraded lands for woody crops and grasses were determined by taking the potential yields, i.e. maximum attainable yields based on climate and soil type, for all degraded lands and reducing these as a result of the limiting effects of degradation. Thus data on degraded lands, potential yields and quantitative information on the limiting effects of degradation were needed. The results of the GLASOD downscaling (chapter 4) indicated the location and surface area of degraded areas. Potential yield maps of energy crops were derived from the Integrated Model to Assess the Global Environment (IMAGE), which provided potential rainfed bioenergy yields of woody species and grasses at a global scale. Percentages yield reduction, which were specific for GLASOD types and degrees of degradation, were obtained from the adjustment of general yield reduction percentages for perennial energy crops, as described earlier (chapter 5). Using these inputs, energy yield potentials of degraded lands were obtained for different regions, types of degradation and degrees of degradation. Further, the present land use of degraded area is examined, to exclude land that is currently in use as pastoral, cropland, urban or forest. For the sake of comparison with other studies, calculations were also performed for the total land area and without applying the limiting effect of degradation. Further, the sensitivity of assumptions in this procedure and the current land use of degraded lands were examined. Three parts of the procedure are now discussed in more detail: 1) the IMAGE potential yield maps, 2) the degraded land area and yield reduction factors and 3) the land use on degraded lands.

1.1 Potential yield maps

Two sources of potential yield maps were examined. Fischer et al. (2005) applied the FAO/IIASA Agro-Ecological Zones (AEZ) approach to assess crop productivity for elephantgrass, willow and poplar of 1-5 km gridcells in Eastern Europe, Northern and Central Asia. Although this study included convenient information for energy species and a high level of detail, it was not clear whether the approach was extrapolated to a global scale. Communication with the authors failed to provide more information.

The Integrated Model to Assess the Global Environment (IMAGE) was selected to provide potential bioenergy yield maps. IMAGE applied the FAOIIASA agro-ecological zones methodology to determine, at a scale of a half by a half degree, potential rainfed yields for woody species and grasses cultivated for bioenergy (Alcamo et al., 1998). For areas that were characterized by an adequate length of the growing season, a simple photosynthesis/respiration model was used to determine climate related potential yields (Alcamo et al., 1998). Then soil reduction factors were applied to account for limitations resulting from inherent properties of the soil. In this approach the adequate climate and moisture parameters and the temperature photosynthesis response curve were crop specific (Leemans & Van den Born, 1994). Rainfed yields were considered, since rainfed production is appropriate for the relatively extensive production system used when cultivating bioenergy crops on degraded lands. More specific information on the compilation of IMAGE potential yield maps can be found in Alcamo et al. (1998) and Leemans & Van der Born (1994). The potential yields indicated by IMAGE maps, expressed in tons oven dry mass. A uniform energy content of 19 GJ per ton oven dry mass was applied to calculate bioenergy potentials.

1.2 Degraded land area and yield reduction factors

The inputs for calculation that were described in chapter 4 and 5, degradation data and yield reduction percentages, included several assumptions for which different scenarios were established (as indicated in table 6.1), to be used in the sensitivity analysis.

Factor		Assumptions
Degradation data	Amount of degraded area (ranges of percentages)	Lower limit
		Average
		Upper limit
	Light degradation	Inclusion
		Exclusion
	Differentiation by allocation rules	No differentiation
		Loose
		Moderate
		Rigid
Yield reduction	Relative yield advantage of perennial energy crops over annual food crops	Low estimate
		Optimal estimate
		High estimate
	General yield reduction percentages	Low estimate
		High estimate

Table 6.1 Assumptions and different options for these. Optimal assumptions for the standard case are indicated with bold.

By using the standard case assumptions (table 6.1) we aim for a realistic estimate of the potential of bioenergy production on degraded lands. The choice for the high estimate of general percentages yield reduction instead of the low estimate was rather arbitrary, although we prefer not to overestimate the potential of bioenergy. Therefore the potentials applying the low estimate were also presented in the main section of the results and served to indicate the range of conceivable bioenergy potentials. Regarding the amount of degraded area, the differentiation by allocation rules and the relative yield advantage of perennial energy crops over annual food crops, the middle assumption was applied as a standard, since this was developed as the most suitable assumption. Lightly degraded areas were excluded from yield calculations, as on these areas the competitive yield advantage of bioenergy compared to food production was marginal (0.3%-1.6%). Therefore, these areas are potentially also suitable for conventional agriculture. See also the section on current use of degraded area. The sensitivity of assumptions was examined by considering the effects of alternative assumptions on global bioenergy potentials. For lands affected by salinization, the actual state of degradation was unknown, since the relative change in salt concentration was assessed by GLASOD experts. Therefore, information for salinized lands was insufficient to calculate bioenergy potentials and these were excluded from calculations.

1.3 Land use on degraded lands

Degraded areas were examined on their current land-use, as this indicates the accessibility of lands to be used for bioenergy production. Table 6.2 presents the data that were selected to examine four categories: cropland, pastoral land, forest, and other land. In order to remain consistent with the downscaling procedure, HYDE cropland and pastoral data were used. Forest areas were derived from IGBP and GLC land cover data, which were used for compilation of the HYDE database. A forest map was compiled taking the average of both databases, making sure that total land area was not exceeded by cropland, pastoral and forest together. The category ‘other’ was established as the remaining non-forest, non-cropland, non-pastoral land area, excluding urban areas and-non soil areas, since during the GLASOD downscaling, degraded lands were not located on these. It should be noticed that is category may be in use for other purposes and may not be fully accessible for bioenergy production.

Land use type	Data source	Categories used
Cropland	HYDE 2000	Cropland area (km^2 per 5 minute cell)
Pastoral lands	HYDE 2000	Pastoral area (km^2 per 5 minute cell)
Forest	IGBP DISCover Land Cover	IGBP: -Evergreen needle-leaf forest -Evergreen broad-leaf forest -Deciduous needle-leaf forest -Deciduous broad-leaf forest -Mixed forest Gridcells of $1km^2$
	Global Land Cover 2000	GLC: -Tree Cover, broadleaved, evergreen -Tree Cover, broadleaved, deciduous, closed -Tree Cover, broadleaved, deciduous, open -Tree Cover, needle-leaved, evergreen -Tree Cover, needle-leaved, deciduous -Tree Cover, mixed leaf type -Tree Cover regularly flooded, fresh water -Tree Cover regularly flooded, saline water Gridcells of $1km^2$
Other	HYDE 2000	Urban areas (km^2 per 5 minute cell)

Table 6.2 Datasets used to examine the current land use of degraded lands.

Three rules were applied when assigning land use types to degraded area:

- Degraded area that was allocated to cropland during the downscaling, using data for 1980, was assigned to these croplands, if still present in cropland data for 2000.
- Degraded area that was assigned to pastoral lands during the downscaling, using data for 1980, was assigned to these pastoral lands, if still present in pastoral data for 2000.
- Degraded area of extreme degree, was not allocated to cropland areas, if possible, since these lands do not allow crop production.

After applying these rules, the remaining degraded area was assigned to land use types proportional to their occurrence in 5 minute cells. For calculations including non-degraded area, the above-mentioned rules were not applied and the area was distributed proportionally to land use types in 5 minute cells.

2. Results

First, the results are presented for the major components of bioenergy potential calculations, the degraded lands and the yields on these lands. Subsequently, the resulting bioenergy potentials are discussed. We conclude this section with a report of the sensitivity analysis, examining the influence of different assumptions on the results.

2.1 Degraded area

Figure 6.1 and table 6.3 present the amount of degraded area for different land use types, degrees and types of degradation. Total degraded area comprised 1836 Mha, for which erosion was the most occurring type of degradation, responsible for 87% of degraded lands. Chemical degradation occurred on 8% percent of degraded lands, while physical degradation (compaction, waterlogging and subsidence) was the least significant type, affecting 5% of degraded lands. Salinized lands, which were excluded from calculations and are therefore not shown in the figures, comprised 4% of total degraded area. The relative occurrence of different types of degradation was in accordance with the original GLASOD data.

The procedure to determine present land use showed that degraded lands were for 43% in use as pastoral land; 25% was used as cropland, 21% belonged to the category 'other' and 10% was forested. Degradation of moderate degree occurred most (47%), followed by degradation of light degree (38%), degradation of strong degree (14%) and degradation of extreme degree (0.5%). This overall occurrence of degrees varied for lands in use as cropland and lands in use as pastoral land Compared to the overall distribution, on pastoral areas degradation of light degree was more significant, while on cropland areas degradation of moderate degree increased in significance. On forest and other area the proportions of occurring degrees was similar to the overall distribution, except that extremely degraded lands in use as forest did not occur (figure 6.1).

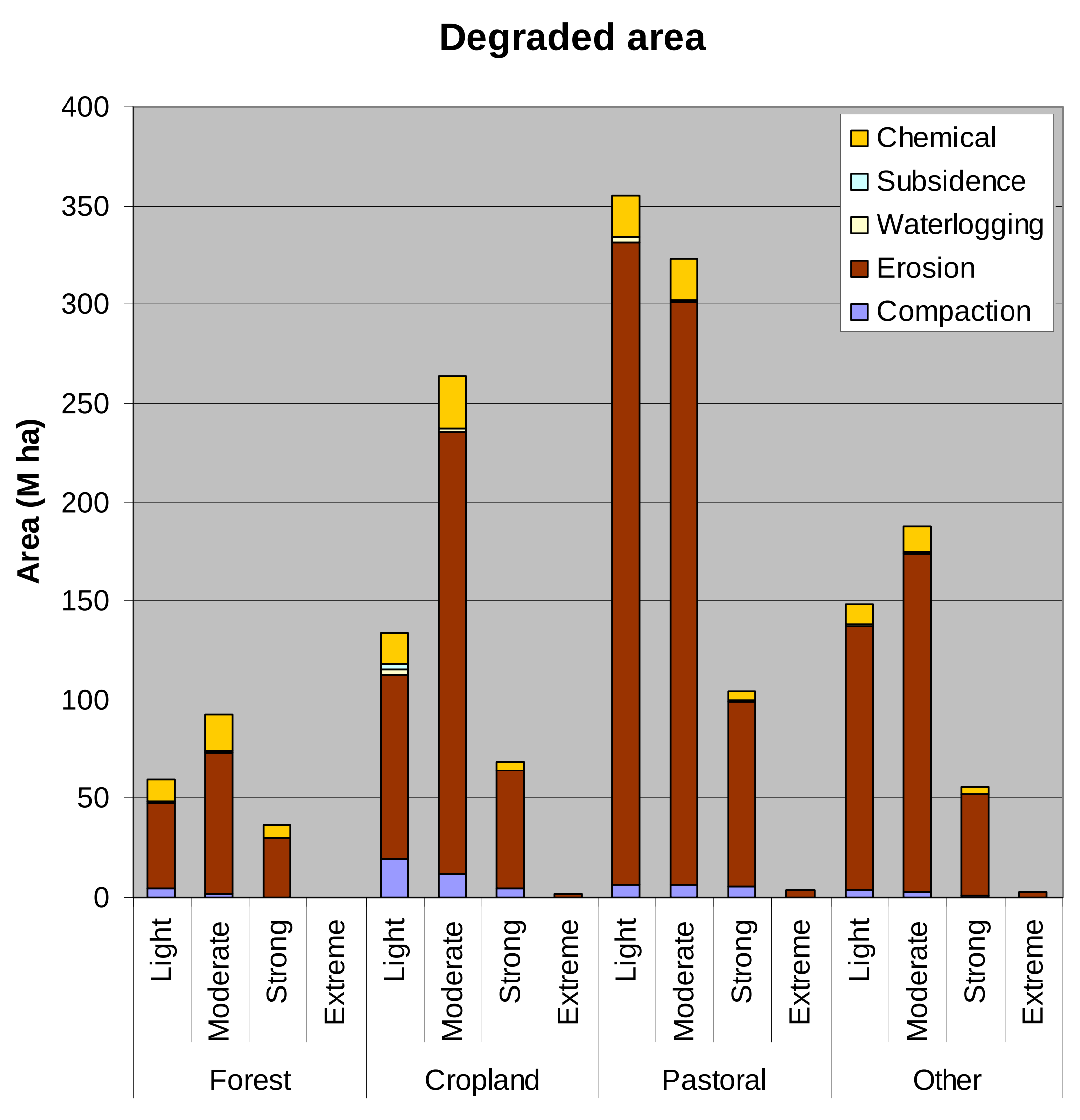

Figure 6.1 Surface area of degraded area for different land use types, degrees of degradation and types of degradation.

		Degraded area (Mha)			
		Forest	**Cropland**	**Pastoral**	**Other**
Light	**Compaction**	5,00	19,66	6,23	3,79
	Erosion	42,58	93,25	325,52	133,36
	Waterlogging	0,38	2,29	2,34	0,67
	Subsidence	0,19	3,09	0,06	0,07
	Chemical	11,57	15,40	20,95	10,04
Moderate	**Compaction**	1,53	11,57	6,58	2,78
	Erosion	71,75	223,59	294,90	170,84
	Waterlogging	0,52	1,69	0,68	0,82
	Subsidence	0,24	0,38	0,07	0,33
	Chemical	18,60	26,20	20,68	12,97
Strong	**Compaction**	0,07	4,92	5,41	0,74
	Erosion	29,93	58,82	93,81	51,28
	Waterlogging	0,10	0,21	0,36	0,09
	Subsidence	0,00	0,22	0,00	0,00
	Chemical	6,29	4,54	4,40	3,62
Extreme	**Compaction**	0,00	0,00	0,00	0,00
	Erosion	0,08	1,42	4,05	2,99
	Waterlogging	0,00	0,00	0,00	0,00
	Subsidence	0,00	0,00	0,00	0,00
	Chemical	0,00	0,00	0,00	0,00
Totals		**188,82**	**467,24**	**786,03**	**394,40**

Table 6.3 Degraded area (Mha) presented for different degrees of degradation, types of degradation and current land-use types.

2.2 Yields

Figure 6.2 presents the average yields on degraded areas for woody and grass species for different degrees of degradation, as well as the weighed global average. The average non-limited yields on degraded lands, based on climate and soil characteristics and excluding degraded lands of light degree, was 15.21 t/ha/yr for woody biomass and 11.81 t/ha/yr for grass biomass. On average, these yields were reduced with 41% (woody) or 43% (grass) due to the limiting effects of degradation, which differed for types and degrees of degradation. This resulted in a weighed average yield on degraded lands of 8.91 t/ha/yr for woody biomass and 6.81 t/ha/yr for grass biomass. These numbers were most affected by the yields on moderately degraded lands, as these occurred significantly more than strongly, and extremely degraded lands (see section 2.1 degraded area).

Figure 6.2 shows that on moderately degraded lands average yields were higher than on lightly degraded soils: 18% (for grass) and 13% (for woody). This was unexpected, since yields were more reduced for moderately degraded soils (on average 32% yield reduction) than for lightly degraded soils (on average 14% yield reduction). The explanation for this observation lies in the non-reduced potential yields of the IMAGE maps, which were based on climate and soil type. Table 6.4 presents the average potential yields for different degrees of degradation compared to the global average. Degraded lands are located in relatively productive areas, except for lightly degraded lands. Table 6.4 shows that as degradation was more severe the productivity, based on climate and soil indices, of degraded lands was higher, increasing to a maximum for extremely degraded lands of 57% (grass) or 51% (woody) above global average.

Figure 6.2 also presents the yields for the alternative set of general yield reduction percentages, since both were equally reliable. Using the low estimate for general yield reduction percentages resulted in higher yields, increasing weighed average yields with 29% for woody and 32% for grass. More specific effects of the applied general yield reduction percentages are described in section 2.4, which concerns the sensitivity of assumptions on global bioenergy potentials.

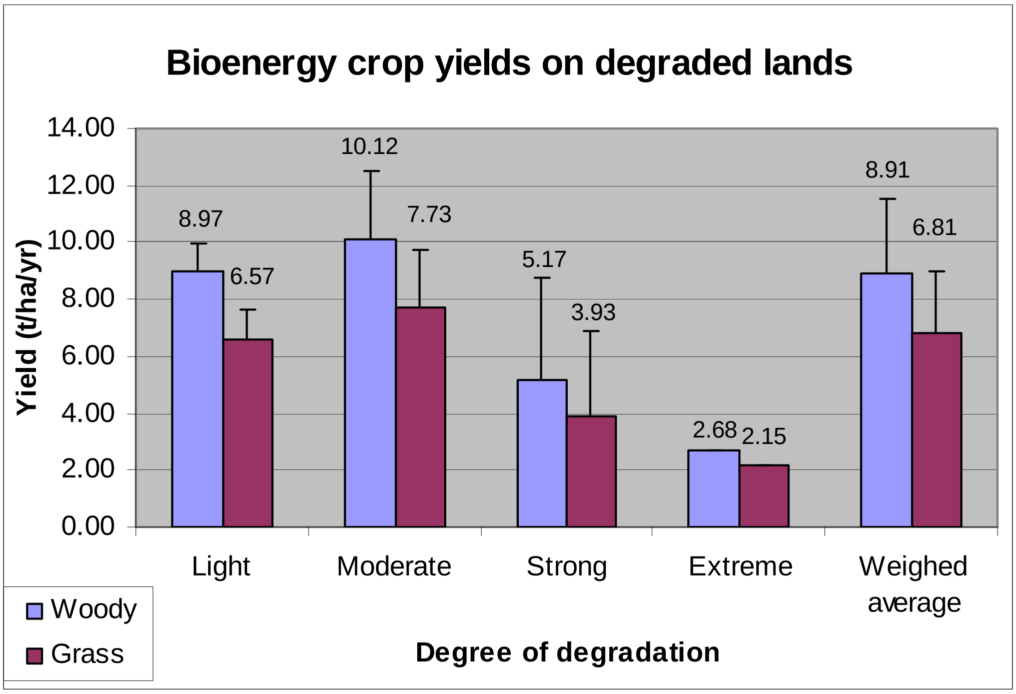

Figure 6.2 Average bioenergy crop yields (t/ha) for woody crops and grasses on degraded lands for different degrees of degradation. For the weighed average lightly degraded lands were excluded. Error bars indicate numbers if the low estimate for general yield reduction percentages was applied.

		Difference of potential non-degraded yields with global average	
		Grass	Woody
Degree of degradation	Light	-8%	-7%
	Moderate	34%	33%
	Strong	45%	42%
	Extreme	57%	51%
Weighed average (light degree excluded)		37%	35%

Table 6.4 The effect of the location of degraded land of different degrees on the potential yields, based on climate and soil indices. Except for degraded land of light degree, degraded areas occur in areas with a high potential compared to the global average.

2.3 Bioenergy potentials

We estimated global bioenergy potentials on degraded lands to equal 193 EJ/yr for woody biomass or 151 EJ/yr for grass biomass. Of these, 32 EJ/yr (woody) or 25 EJ/yr (grass) can be produced on land which is classified as ‘other land use’, i.e. which is not in use as pastoral land, cropland, forest or urban area. Figure 6.3 presents an overview of global bioenergy potentials and shows that these potentials were widely spread across regions. See figure 6.4 for an overview of the total woody and grass energy potentials for 25 different regions. China was the region with the highest potential: 23 EJ/yr for grass species or 30 EJ/yr for woody species. Other promising regions included Russia, the USA, India, Brazil, East Africa and West Africa. If only degraded lands belonging to the category other land use were included, the USA was found to be less promising, while South East Asia became more important. For Japan and Greenland bioenergy potentials on degraded lands were absent, as no or only light degradation had occurred. Globally, woody bioenergy potentials were 28% higher than grass biomass potentials.

Figure 6.5 indicates the density of bioenergy potentials on degraded lands, by presenting the potential per hectare land area in the different regions. The Rest of Central America accommodates most potentials per hectare land area, with 68 GJ/ha/yr for grass species and 83 GJ/ha/yr for woody species. Central Europe and Turkey were also characterized by high energy potentials per hectare, followed by South East Asia, Indonesia, China and Mexico.

The present land use of degraded lands varied per region (figure 6.4 and 6.5). For instance in China, the categories pastoral and cropland were similar in potential, while in the USA cropland was dominant. Also, the ratio between woody and grass bioenergy potentials differed between degraded areas, although for all areas woody potentials were higher than grass potentials.
When considering China is highest in potential with 4.9 EJ/yr (figure 6.4) and India, South East Asia, East Africa, West Africa, Brazil and Russia are promising with more than 2 EJ/yr.

Figure 6.6 shows the distribution of bioenergy potentials over yield classes and the share of different land use types in these classes. Both factors varied per region. Bioenergy potentials in the USA and the Rest of Central America were for the greatest part located on degraded lands with productivity above 15 t/ha/yr, although results suggested that in the USA these were all in use as cropland/ pastoral land or forest. Such high productive degraded lands were also significant for bioenergy potentials in Ukraine, India, South East Asia, Mexico, Oceania and China. For bioenergy potentials in Brazil and Russia degraded lands with yields of 5-15 t/ha/yr were relatively important. In Africa, degraded lands with productivity below 5 t/ha/yr had a relatively large share in bioenergy potentials, but in East Africa degraded lands with yields above 15 t/ha/yr were also significant for potentials.

As the two optional sets of general yield reduction percentages were equally reliable, error bars in figure 6.4, 6.5 and 6.7 indicate potentials, when using the alternative low estimate of general yield reduction due to degradation. The low estimate resulted in total bioenergy potentials of 250 EJ/yr for woody biomass and 195 EJ/yr for grass biomass, with 42 EJ/yr (woody) and 33 EJ/yr (grass) belonging to the category other land use. The difference between applying high or low general yield reduction percentages was similar to the difference found for yields, amounting to 29% higher potentials for woody species and 32% higher potentials for grass species.

Table 6.5, table 6.6 and figure 6.7 illustrate the energy potentials for grass and woody biomass for different land use types, different degrees of degradation and different types of degradation. Results for bioenergy potentials generally reflected results for degraded area (presented in figure 6.1 and table 6.3). Most bioenergy could be produced on degraded lands affected by erosion, followed by chemical degradation, physical degradation, including compaction, subsidence and finally water logging. Also, the significance of different degrees of degradation was in line with the degraded area results, although differences between degrees were increased since yield reduction was higher for more severe degradation. In terms of their relative significance, the moderate degree was the most important degree, followed by the strong degree; the extreme degree was least significant for total energy potentials. The significance of different land use types for bioenergy potentials differed from their significance in the amount degraded area. Compared to land use distribution of degraded area, croplands and forest increased in significance for energy potentials whereas pastoral areas and other areas decreased (table 6.6). This is explained by the fact that forests and croplands were generally located in more productive areas, characterized by climate and soil types that allow higher energy yields, compared to pastoral lands and other lands (as discussed in section 2.2 ‘yields’). Consequently, most energy potentials can be produced on areas currently in use as cropland (table 6.5), while most degraded lands are in use as pastoral areas (table 6.3).

Table 6.7 presents the bioenergy potentials for degraded lands and for the total land area, for the categories ‘other land use’ and ‘all land use types’. For the sake of comparison, the potential non-reduced yields are also presented for degraded lands. Table 6.7 shows that the share of potential non-reduced bioenergy yields on lands belonging to the category other, which were not in use as pastoral land, cropland forest or urban area, is relatively low for degraded lands (18%) compared to the total land area (22%).

Further, although 9% of the total land area is affected by degradation of a moderate, strong or extreme degree, potential yields on those lands comprise 12% of global potential yields. Thus, as has been observed while examining average yields, degraded lands are located in areas which are characterized by 37% (grass) or 35% (woody) higher productivity than the global average land productivity.

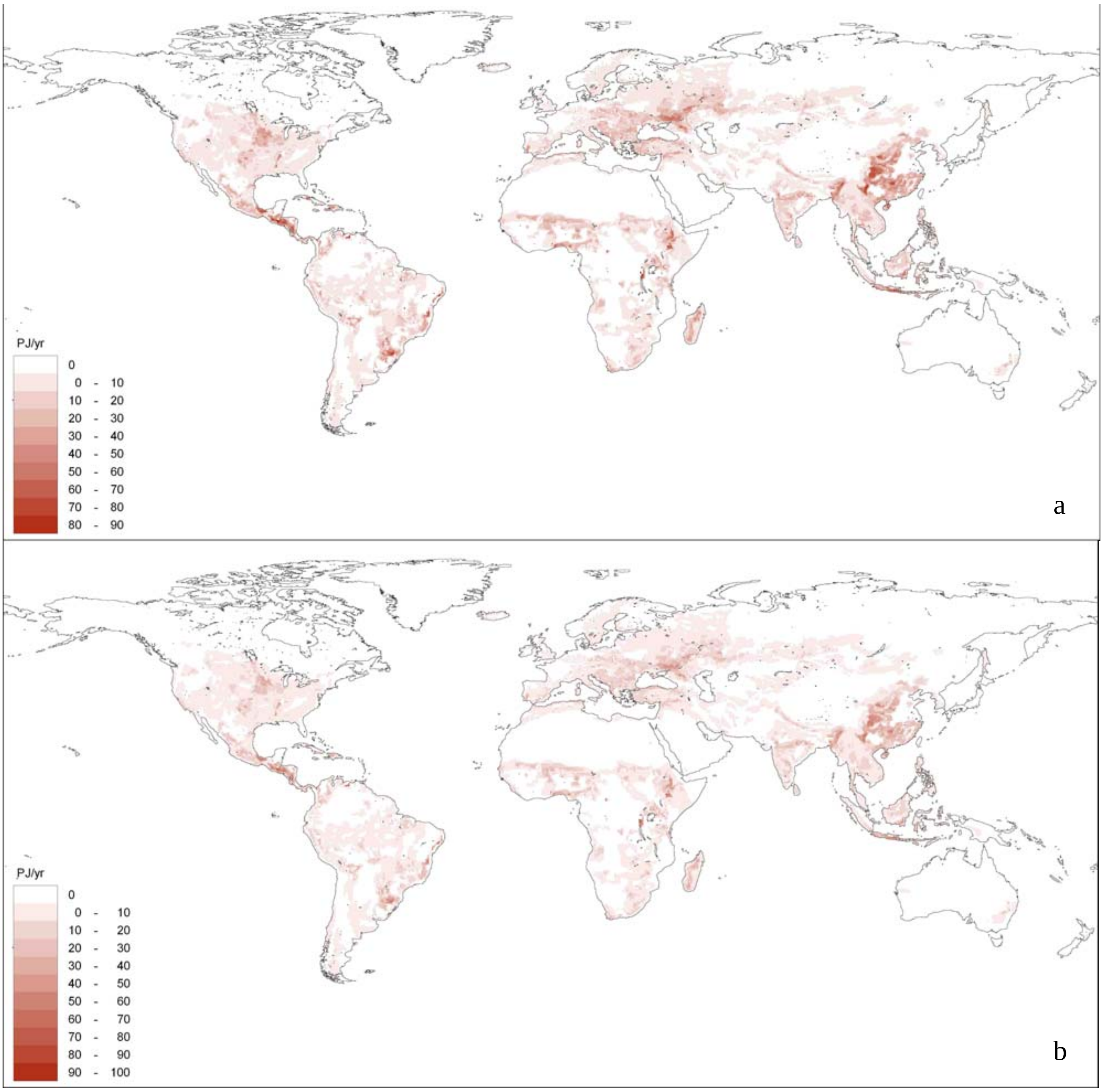

Figure 6.3 Global overview of woody (63.a) and grass (6.3b) bioenergy potentials (PJ/yr) on degraded lands, indicated for a half by a half degree grid cells.

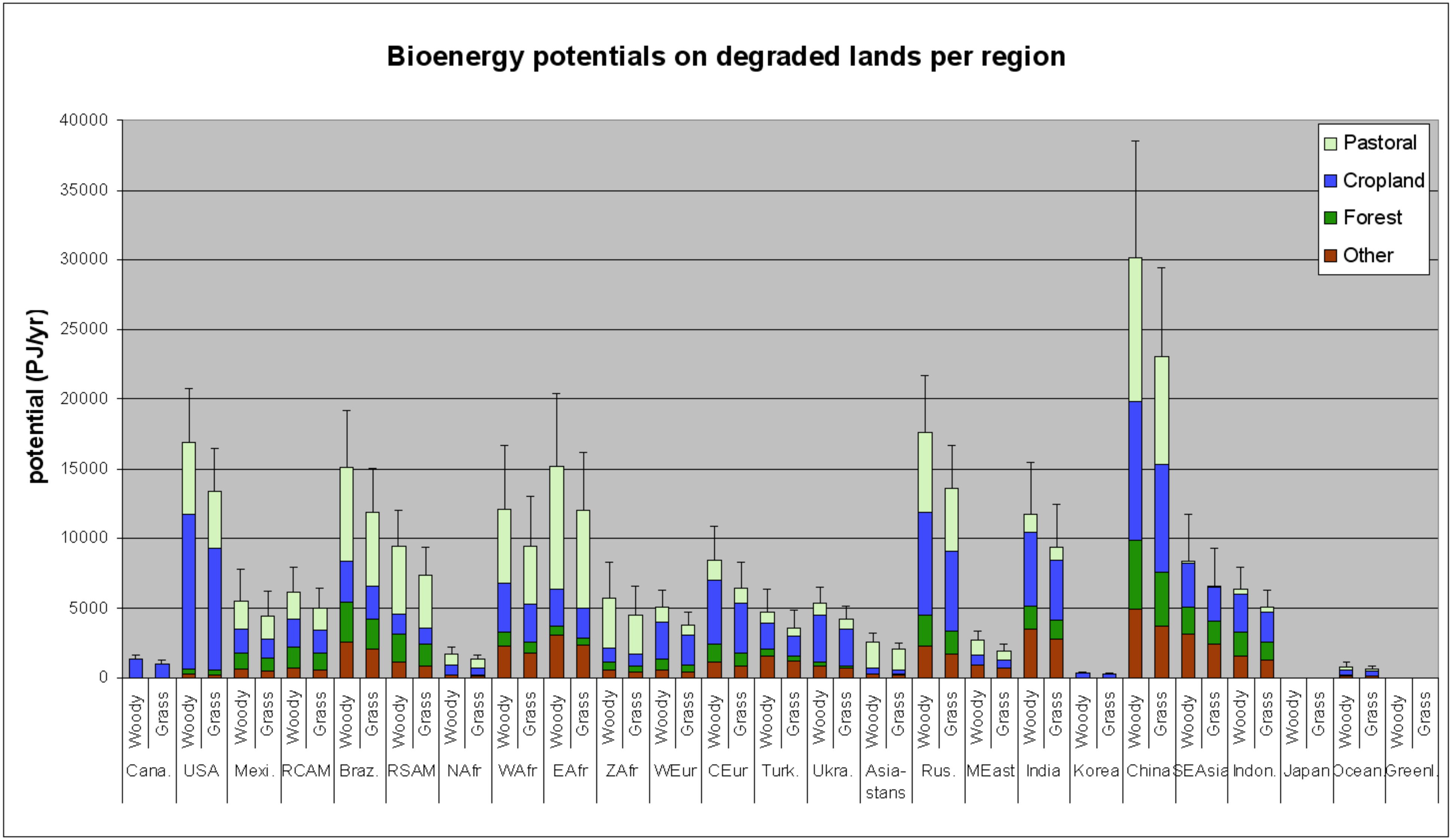

Figure 6.4 Bioenergy potentials for woody and grass species for different regions. Colors indicate the distribution of potentials for current land use. Error bars indicate total potential if the low estimate for general yield reduction percentages was applied.

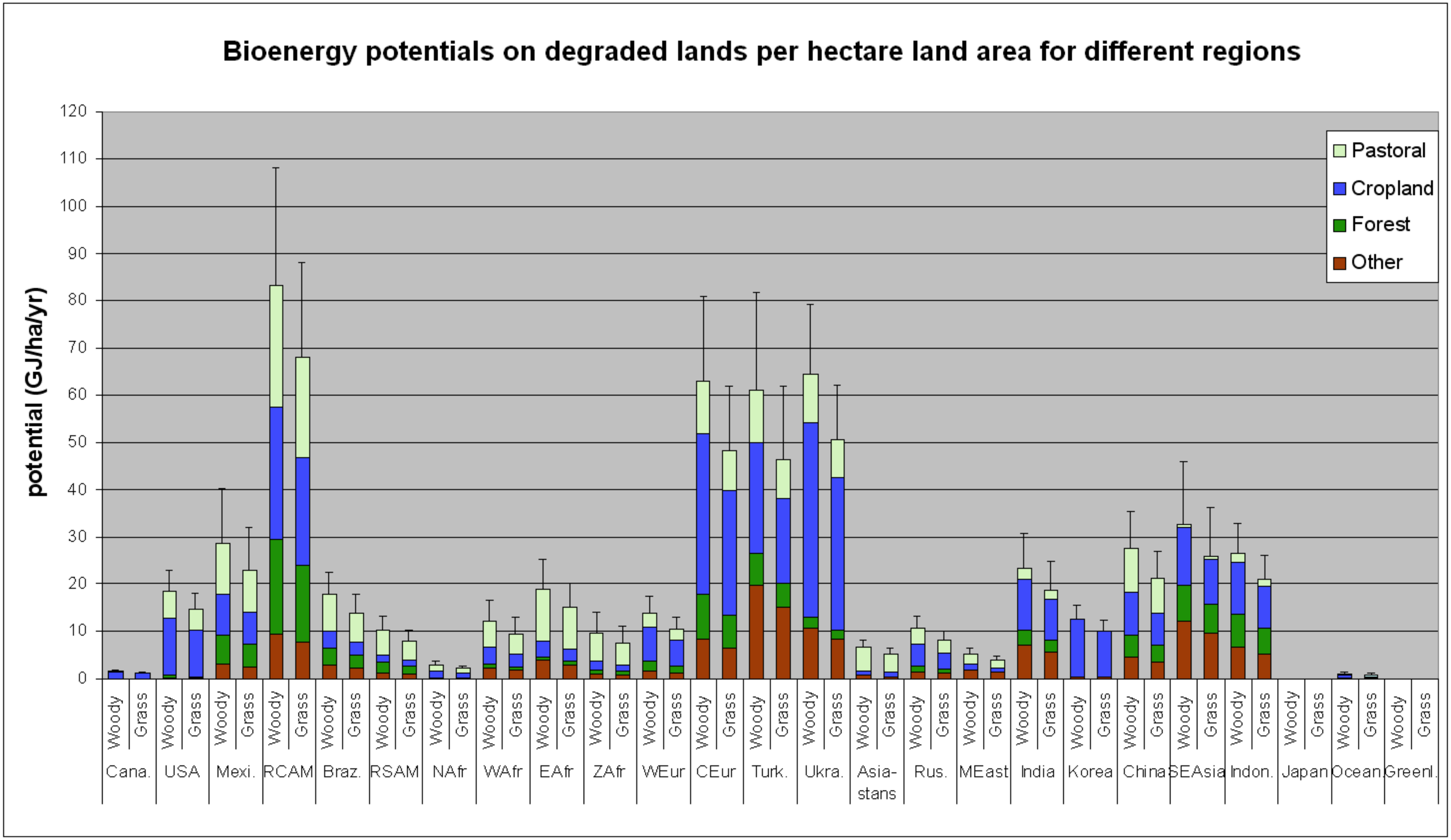

Figure 6.5. Bioenergy potentials for different regions per hectare land area in those regions, indicated for different present land use types. Error bars indicate the potentials when applying the alternative low estimate for general reduction percentages.

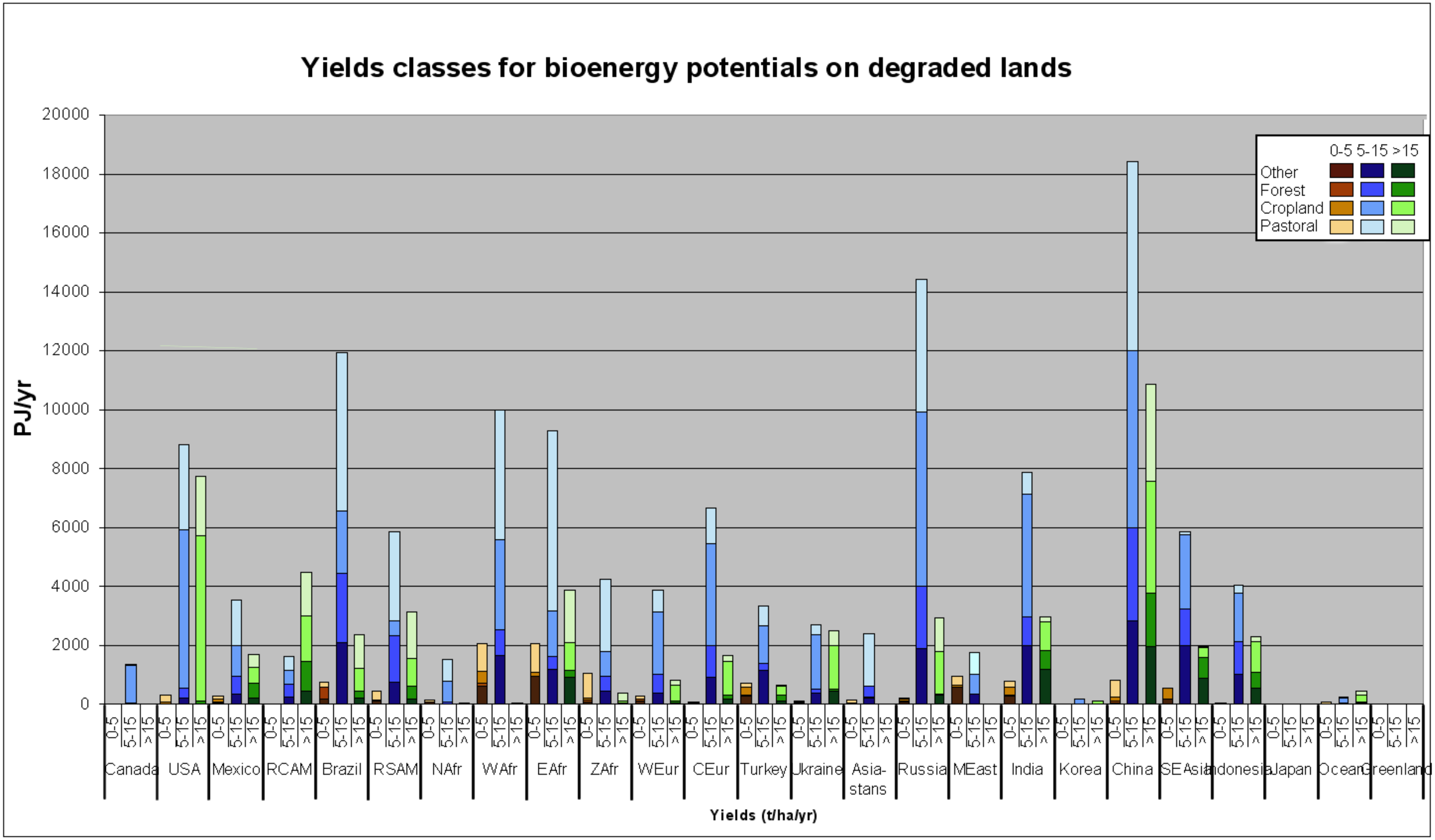

Figure 6.6 Total woody bioenergy potentials per region indicated for three yield classes: potentials that can be derived from degraded lands that produce 0-5 t/ha/yr, 5-15 t/ha/yr or more than 15 t/ha/yr.

		Grass bioenergy potentials (PJ/yr)				**Woody bioenergy potentials (PJ/yr)**			
		Forest	***Cropland***	***Pastoral***	***Other***	***Forest***	***Cropland***	***Pastoral***	***Other***
Moderate	***Compaction***	227	1918	742	264	294	2468	954	339
	Erosion	13197	42952	39384	17366	17019	54744	50699	22493
	Waterlogging	119	371	154	186	150	468	193	233
	Subsidence	39	62	11	55	50	79	14	69
	Chemical	2909	4712	3050	2030	3757	6062	3925	2624
Strong	***Compaction***	6	417	283	52	8	519	356	67
	Erosion	2819	5116	6049	4317	3588	6483	7683	5455
	Waterlogging	8	19	33	8	10	23	41	10
	Subsidence	0	19	0	0	0	24	0	0
	Chemical	460	319	337	246	594	404	426	316
Extreme	***Compaction***	0	0	0	0	0	0	0	0
	Erosion	4	71	133	141	5	88	168	174
	Waterlogging	0	0	0	0	0	0	0	0
	Subsidence	0	0	0	0	0	0	0	0
	Chemical	0	0	0	0	0	0	0	0
Totals		**19789**	**55976**	**50176**	**24665**	**25475**	**71362**	**64459**	**31780**

Table 6.5 Bioenergy potentials (PJ/yr) for grass and woody species, presented for different degrees of degradation, types of degradation and current land-use types.

	Forest	**Cropland**	**Pastoral**	**Other**
Degraded area	11,32 %	29,26 %	37,80 %	21,62 %
Grass	13,14 %	37,17 %	33,32 %	16,38 %
Woody	13,19 %	36,96 %	33,39 %	16,46 %

Table 6.6 Relative importance of land use types for degraded area, grass energy potentials and woody energy potentials

Bioenergy potentials in EJ/yr		Grass		Woody	
		Reduced yields	Potential yields	Reduced yields	Potential yields
Degraded lands	Only land use ‘other’	24.67	45.70	31.78	58.69
	All land use types	150.61	257.37	193.08	329.43
Total land area	Only land use ‘other’	-	470.67	-	620.87
	All land use types	-	2147.06	-	2789.71

Table 6.7 Comparing bioenergy potentials (EJ/yr), reduced and non-reduced, for degraded lands and total land area, including only ‘other’ land use or all land use types.

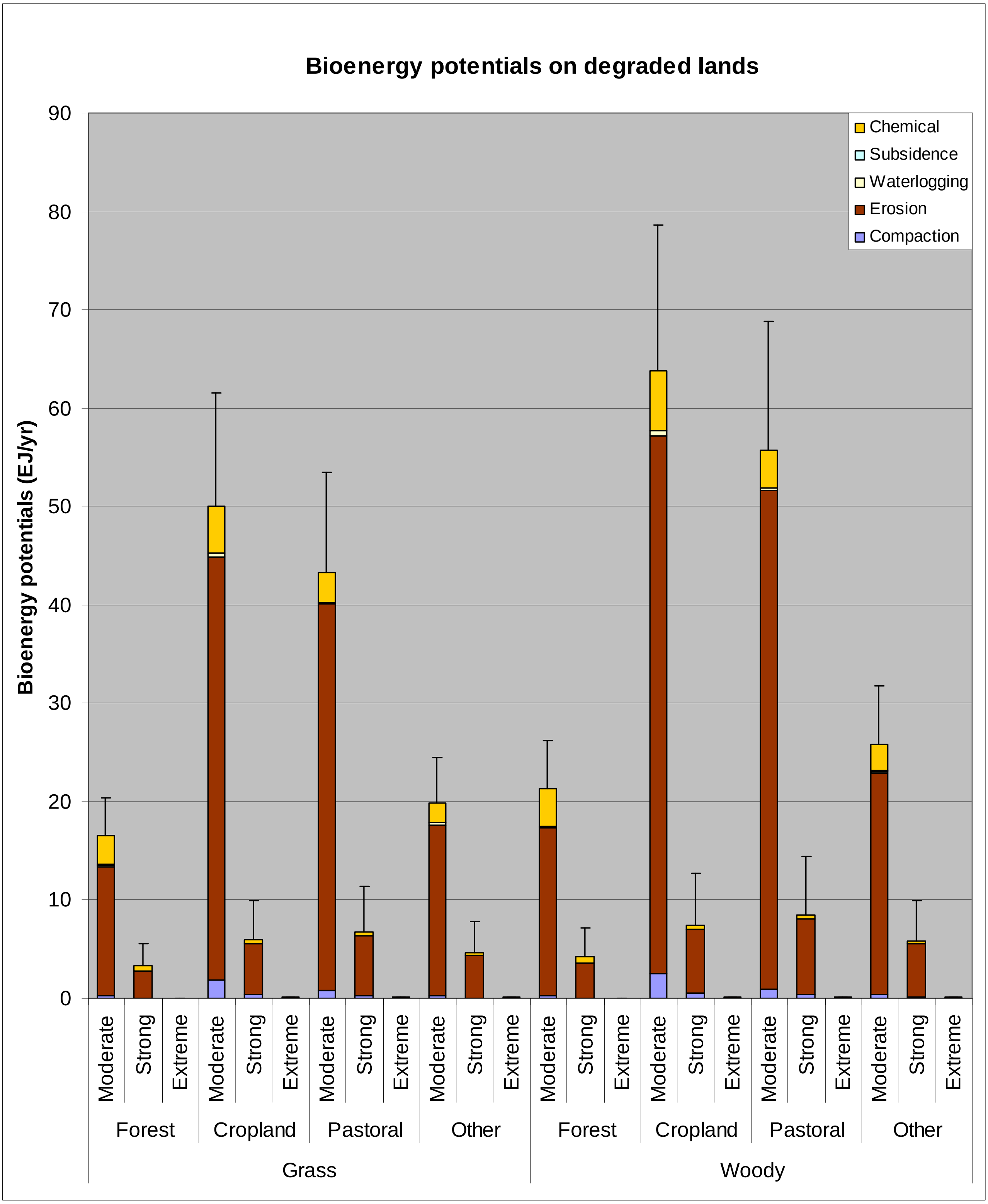

Figure 6.7. Grass and woody biomass potentials, illustrated for different present land uses, degrees of degradation and types of degradation. Error bars indicate total potential if the low estimate for general yield reduction percentages was applied.

2.4 Sensitivity

Table 6.8 shows the sensitivity of global bioenergy potentials on degraded lands to several choices that were made during the assessment procedure. Three factors were of major importance for the results, affecting total potentials by more than 29%: the area affected by degradation, the general yield reduction percentages, and the exclusion of lightly degraded lands. Less significant were the differentiation by downscaling rules and the relative yield advantage of perennial energy crops over annual food crops, as these were found to influence the global bioenergy potentials with less than 3%.

- Applying the upper limit of the range of percentages that GLASOD indicated as the area affected by degradation was more significant (+30%) for potentials than applying the lower limit (-27%). This difference resulted from the fact that percentage classes were not linearly related.
- The downscaling procedure had two effects on the results. First, the area affected was adjusted downwards. Second, downscaling rules affected the location of degraded lands, which may cause a difference in their productivity as a result of the different climate and soil characteristics. These effects together resulted in a difference of +1.97% higher potentials using the original GLASOD data, compared to applying moderate parameters. When applying loosely differentiating rules, the decrease in potentials was greater (additional 3.17%). A main cause of this was that loose rules resulted in a greater decrease of degraded area during the downscaling procedure. The difference between applying moderate rules and rigid rules was marginal (-0.04%).
- The effect of excluding lightly degraded lands resulted in a decrease of energy potentials with 39.88%. Bioenergy potentials on lightly degraded lands are presented for different present land uses, degrees of degradation and types of degradation in table 6.9. The proportions in this table were similar to those observed for the other degrees (table 6.5).
- The effect of alternative general yield reduction percentages, which equaled 29% (table 6.8), varied for different degrees of degradation, as the two sets of percentages were not linearly linked (see table 6.10). For the extreme degree no difference occurred, since for extreme degraded lands both sets of percentages were similar, excluding annual food crop yields.

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	+1.97%
			Loose rules	-3.17%
			Rigid rules	-0.04%
	Light degradation	Excluded	Included	+39.88%
Yield reduction	General yield reduction percentages	High estimate	Low estimate	+29.43%
	Relative yield advantage of perennial energy crops over annual food crops	Optimal estimate	Low estimate	-2.23%
			High estimate	+2.23%

Table 6.8 The effect of varying different assumptions or factors for total bioenergy potentials. Calculations were performed for grass potentials. The sensitivity of woody potentials was similar (maximum 2.2% difference).

Degradation of light degree		Forest	Cropland	Pastoral	Other
Woody bioenergy potentials (PJ/yr))	*Compaction*	1036	5864	1775	889
	Erosion	11549	27080	39882	13594
	Waterlogging	66	759	727	196
	Subsidence	45	926	14	17
	Chemical	2750	4307	4750	2411
	Total	**15446**	**38935**	**47148**	**17106**
Grass bioenergy potentials (PJ/yr)	*Compaction*	751	4453	1388	661
	Erosion	8948	21059	30269	10268
	Waterlogging	49	604	580	156
	Subsidence	34	706	10	12
	Chemical	2127	3380	3733	1892
	Total	**11909**	**30202**	**35980**	**12989**

Table 6.9 Degraded area (km^2), woody biomass potential and grass biomass potentials (PJ/yr) for lightly degraded areas, which were excluded from main calculations.

	Sensitivity of general reduction percentages (%)
Moderate	+23.23%
Strong	+69.69%
Extreme	--
Weighed average	+29.43%

Table 6.10 The sensitivity of bioenergy potentials to alternative general yield reduction percentages (high estimate) for different degrees of degradation.

3. Discussion & conclusion

The main aim of this study was to assess global bioenergy potentials on degraded lands. Degraded lands that are presently used as cropland, pastoral land and forest are less attractive for bioenergy production, since 1) abandoning present land use is often undesirable, 2) practical implementation is difficult due to conflicting interests with land owners and regional policies and 3) using forests can cause a carbon debt and biodiversity losses. Therefore first we focus on bioenergy potentials on degraded lands characterized by other land use. We estimated global bioenergy potentials on lands to equal 32-42 EJ/yr. Of this potential, 10-13 EJ/yr was located in developing regions such as Africa, South America, Indonesia and South East Asia. In these regions bioenergy production on degraded lands may be particularly interesting, as it may provide developing opportunities and jobs in poor rural areas. In India and China, countries with quickly developing economies but also poor rural areas, bioenergy potentials on degraded lands amounted to 8-11 EJ/yr. In the extensive area covered by Europe, Northern America and the remaining part of Asia, total bioenergy potentials on degraded lands classified with other land use were relatively low, amounting to 9-12 EJ/yr. However, these regions did include some promising areas with a high density of energy potentials. The Rest of Central America, Central Europe and Turkey were high in bioenergy potentials on degraded land per land area. These estimates were based on woody biomass species, since these were more productive than grass species for all identified degraded areas.

Degraded lands that are not in use as cropland, pastoral land, forest or urban area are most promising with respect to the practical implementation of bioenergy production. Nevertheless, these lands may be also in use for other purposes than those included in the land use examination. This land use, although limited in efficiency, may still be valuable and therefore undesirable to abandon. Therefore, these lands are expected to be only partly accessible for bioenergy production. Hence, results should be interpreted as an upper limit of the potential of bioenergy production on degraded lands. On degraded lands that are in theory attractive for bioenergy production, practical consideration such as issues with current landowners and regional policies may hinder implementation. A factor which may be important in this is the economic viability of bioenergy production. It is impossible to accurately predict the yields needed to make bioenergy production profitable in the future, for instance because production costs differ per region and bioenergy promoting policies may also be influential. Generally, however, degraded lands with high energy yields are economically more viable than degraded lands with low energy yields. The results showed that high yields, of more than 15 t/ha/yr, were relatively important in the potential of India, China, South East Asia, Indonesia, Mexico, Oceania and Ukraine, increasing chances on profitable bioenergy production. In Africa yields below 5 t/ha/yr were relatively significant, which is less problematic since production costs are generally low in this continent.

Results showed that degraded lands were generally in use as cropland, pastoral land, forest or urban area (79%). This was to be expected, since we focused on human-induced degradation, which involves a function of the land for humans before it became degraded. Only if this function was abandoned the land may be not in use, but often the original function may be preserved, although the productivity is limited by the effects of degradation. Further, degraded lands were generally located in highly productive areas where incentives to keep exploiting the land may continue to exist, despite the limited efficiency due to degradation.

Beside degraded lands belonging to the category other land use, degraded lands that are currently in use as cropland can be attractive to use for bioenergy production. Although implementation may be difficult, bioenergy production on these lands can increase productivity, as it may result in soil quality improvements and as energy crops are better suited for low quality soils than annual food crops. Furthermore, perennial energy crops may provide protection against further degradation. We estimated that degraded croplands can provide up to 71 EJ/yr. The transition to bioenergy production may, however, be hard to realize as a result of the conflicting interests of landowners and regional policies. Moreover, although limited in efficiency, the current agricultural activities may still be important, for example for food production, and therefore undesirable to abandon. Although the feasibility of using these lands for bioenergy is limited, in some cases a transition from cropland or pastoral land to bioenergy production may be realized.

As stated before, degraded lands were located in highly productive areas, based on climate and soil type, compared to average global productivity. This was partly expected as degradation data excluded non-soil areas, such as deserts, shifting dunes or salt flats, which are generally characterized by marginal productivities. However, the results also showed that land with more severe degradation was located in areas with even higher natural productivity. This observation can be explained in several ways. Lands affected by soil degradation may be generally exploited until agricultural productivities decrease to such a low level that landowners begin to implement measures to cease degradation. For highly productive areas this level may not be reached until the land is severely degraded, i.e. until its productivity is decreased strongly, while for moderately productive soils a less significant decrease in agricultural productivity may already result in the implementation of protective measures. Second, the slightly reduced productivity that occurs during the initial stages of degradation can easily be explained by one of the many other factors that affect yields, such as the yearly changing climate conditions. Land owners may not expect highly productive lands, which have been successfully used in the past for agriculture, to be affected by soil degradation; as a result their reaction may be delayed, allowing soil degradation to progress to a more severe state.

The potential yields on degraded lands, based on climate and soil type, differed for different categories of present land use. Croplands and forests were generally located in areas with higher productivity than pastoral lands and lands with other functions. This was expected, since forests or croplands are more intensive in use and demand a higher productivity than pastoral lands or lands with other use. The higher yields of degraded croplands suggests that using these for bioenergy production is more efficient than using lands with other land use.

Sensitivity results showed that the assumptions regarding the area affected by degradation, the general yield reduction percentages and the exclusion of lightly degraded lands were important for the final results. The effect of general yield reduction percentages was accounted for in the presented ranges of bioenergy yields. Regarding the extent of degradation, we examined as alternatives to the average, the extremes of ranges of percentages, taking the upper or the lower limit of ranges of percentages. Assuming a normal distribution of chances, these extremes seem unlikely. However, it may be that on average the actual area affected diverged somewhat from the average percentage of ranges. This error is, however, limited to a few percentages of bioenergy potentials and therefore not included in the presented ranges of energy potentials.

During the calculations some difficulties were encountered. Estimates of bioenergy potentials on degraded lands did not include the Northern part of Greenland and the Northern part of Russia, as these were lacking in the GLASOD degradation data. However, exclusion of these areas is expected to have no influence on bioenergy potentials, since climate and soil types in these regions do not allow bioenergy production. Second, IMAGE potential yield maps included soil reduction factors, which were similar for all crops, although in reality crops are adapted to different circumstances (Leemans & Van der Born, 1994). This causes the difference between estimates for grass and woody biomass to be less significant.

Further, during the procedure to examine present land use, some extremely degraded lands were determined to be cropland, since other land uses were not available, although this was not preferred in the methodology. Also, whilst results of the present land use of degraded lands were in accordance with our expectations, it should be noticed that our method provided only an indication of present land use, as the degradation data as well as the HYDE cropland and pastoral maps were based on a downscaling procedure, which inherently leads to significant data uncertainty. Last, areas that became urban during 1990-2000 were not accounted for; this problem is thought to be of marginal importance, since the development of urban areas occurs over longer timescales and the extent of urban areas is limited.

Chapter 7. Discussion and conclusion

In this chapter the main results of the study are discussed by 1) comparing results with existing studies, 2) indicating the main limitations of the assessment, 3) discussing the implications of obtained bioenergy potentials and 4) placing the idea of bioenergy production on degraded lands in a sustainability perspective. Last, some future recommendations are presented.

1. Comparison with existing studies

This study assessed bioenergy potentials on degraded lands, not in use as forest, urban area, cropland or pastoral area to be in the range of 32-42 EJ/yr. Several other studies estimated global bioenergy potentials on degraded lands. Table 7.1 summarizes these, indicating the main methodology, the included land types, the amount of global degraded lands, the bioenergy yields on these lands and the resulting bioenergy potentials. Table 7.1 indicates also two studies that assessed bioenergy potentials on abandoned lands, which were reported to be often affected by degradation.

1.1 Assessments of bioenergy potentials on degraded lands

Van Vuuren et al. (2009) was the only study that examined bioenergy potentials on degraded lands using geographically explicit data, which is critical to provide an accurate estimate. They estimated the share of the global bioenergy potentials located on degraded area in order to assess the influence of land degradation on global bioenergy potentials. Similar to this study, Van Vuuren et al. (2009) also used the GLASOD degradation database and the IMAGE bioenergy potential yield maps for its calculations.

The results of Van Vuuren et al. are similar to those reported here, although the yields as well as the land areas differed significantly (table 7.1). The yield estimates of Van Vuuren et al. (2009) reported in table 7.1 are their overall yields (so not specific to degraded areas). Still they were significantly higher then the ones used here, as Van Vuuren et al. used IMAGE yields directly, while we decreased these as a result of the limiting effects of degradation (yield reductions of 18-89%). Further, the area used by Van Vuuren et al. (2009) was more limited, as this assessment included only abandoned degraded lands and natural grassland systems and it used accessibility factors, to account that areas are unlikely to be fully available for bioenergy production. Summarizing, the differences between this study and Van Vuuren et al. (2009) are significant, but compensate each other. Accounting for the accessibility of degraded lands can be expected to reduce bioenergy potentials considerably. However, the precise significance of this reduction is highly uncertain, as it depends on complex factors such as economy, politics and local landowner issues. Therefore, we did not include accessibility as a restraint, focusing on an upper limit of bioenergy potentials of degraded lands.

Three studies were found that used spatially invariant data to estimate global bioenergy potentials on degraded lands: i.e. Hoogwijk et al., 2003, Tilman et al., 2006 and WI, 2006. Presented bioenergy potentials were in similar range as our results, although, the estimated yields and the amount of degraded lands differed significantly (table 7.1). Hoogwijk et al. (2003) and Tilman et al. (2006) estimated the amount of degraded area to be approximately a factor two higher than our results suggested. The degraded area estimate of Hoogwijk (2003) was based on assumptions derived from relatively old studies, of which reports were not available (i.e. Grainger, 1988, Hall et al., 1993, Houghton et al., 1991 and Lasse & Tirpak, 1990). The degraded area estimate of Tilman et al. (2006) was reported to be a rough estimate and not further clarified. The yield estimate of Tilman et al. (2006) was a factor two lower than our average result and was based on field experiments examining one degraded soil. In addition to the low number of experiments, also differences in crop type may have affected results. Hoogwijk et al. (2003) predicted average yields of 1-10 t/ha/yr. The average yield we have found (10.22 t/ha/yr) is somewhat higher. Hoogwijk et al. (2003) clarify their estimate by referring to woody energy yields on less suitable terrain derived from the IMAGE crop growth model, although the exact rationale about their precise range remained unclear. The higher amount of marginal lands and the lower yields presented by WI (2006) could not be clarified, as the methodology for these estimates was lacking (WI, 2006). Among others, it was not clear which definition of marginal lands was applied.

Source	Methodology	Lands included	Assessment		
			Area	Yields	Potential
Degraded lands					
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 Mha	Range: 2.68-11.54 t/ha/yr Average: 10.22 t/ha/yr	32-42 EJ
Van Vuuren et al., 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	-	Range: 2.5-33 t/ha/yr	31 EJ: severe 12 EJ: extreme (degradation degree)
Hoogwijk et al., 2003	To explore the ranges of bioenergy potentials, studies assessing available area were reviewed (Grainger, 1988, Hall et al., 1993, Houghton et al., 1991 and Lasse & Tirpak, 1990) 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 Mha	1-10 t/ha/yr	8-110 EJ (2050)
Tilman et al., 2006	Rough global estimate based on a yield study to Low Input High Diversity grass systems on degraded soils.	Agriculturally abandoned and degraded lands	500 Mha	4.74 t/ha/yr	45 EJ
WI, 2006	Methodology not clear, estimate for potentials in 2050.	Marginal lands	1579 Mha	2-5 t/ha/yr	60-150 EJ (in 2050)
Abandoned agricultural lands					
Field et al., 2008	Assessment of area based on geographically explicit HYDE historical land use data. Net primary productivity data were used to assess yields.	Abandoned pastoral lands and croplands not in use as urban or forest (often degraded)	386 Mha	3.55 t/ha/yr on average	27 EJ[1]
Campbell et al., 2008	Assessment of area based on geographically explicit HYDE historical land use data. A crop growth model was used to assess yields	Abandoned pastoral lands and croplands not in use as urban or forest (often degraded)	385-472 Mha	4.3 t/ha/yr on average	32-41 EJ[1]

Table 7.1 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. Further, shaded with grey, several estimates are shown of bioenergy potentials including non-degraded areas, which were also calculated for this study for the sake of comparison. A '-' is shown if the study did not provide the required information.

[1] Field et al. (2008) and Campbell et al., (2008 applied a heating efficiency of 20 GJ per ton dry matter, while the other studies applied a heating efficiency of 19 GJ per ton dry matter.

1.2 Assessments of bioenergy potentials on abandoned agricultural lands

Table 7.1 presents two estimates of current bioenergy potentials on abandoned croplands and pastures based on geographically explicit data (Campbell et al., 2008 and Field et al., 2008). These lands may be degraded, as a reduced productivity comprises an important reason for abandonment. However, abandonment may also be for other reasons than degradation (leading to a larger area). At the same time, as lands may be degraded as a result of industrial activities or deforestation, the abandoned agricultural lands can also be shorter. Although, the overlap between abandoned agricultural lands and degraded lands is unknown, the results for abandoned agricultural lands may provide an interesting comparison. Table 7.1 shows that the amount of abandoned lands identified by both the study of Campbell et al. and Field et al. was significantly higher than our estimate of degraded lands, while the bioenergy yields on these lands were significantly lower than we assessed, resulting in comparable bioenergy potential estimates. Two factors may explain the differences in yield estimates. First, Campbell et al. (2008) and Field et al. (2008) were more conservative in estimating potential yields than the IMAGE estimates underlying our study. However, we showed that perennial energy crops can produce, in some situations, yields higher than current natural productivity, as a result of soil improvements and specific qualities of perennial energy crops to grow on low quality soils.

1.3 Yields and yield reductions

Although research on yields on degraded soils proved to be insufficient to estimate bioenergy yields globally (as a function of climate, soil and degradation, chapter 5), we use the results now to validate the range of observed yields. Table 7.2 shows that result of different studies (field studies and one modeling study) were in similar range as our yield estimates. The detailed data ranges from 3-15 t/ha/yr but most of the data is around 5-6 t/ha/yr. Our estimate ranged from 2.68-11.54 t/ha/yr. It is difficult to obtain further insight as more detailed information for the empirical data is missing.

Source	**Crop**	**Soil**	**Methods**	**Average yields**
Tilman et al. (2006)	Low input high diversity grassland	Degraded nitrogen poor sandy soil	In total 152 plots, 11 years study. No fertilization	4.74 t/ha/yr (best species composition)
Mulkey et al. (2006)	Switchgrass	Set aside land of the conservation reserve program	3 plots, 56 Kg NO^3 ha/yr.	3-5.3 t/ha/yr
Schmer et al. (2008)	Switchgrass	Marginal lands of the conservation reserve program	On-farm, 10 fields across US, 74 kg N ha/yr, 5 harvest years	5.2-11.1 t/ha/yr
McElroy and Dawson (1986)	Willow	Degraded surface water mineral gleys	9 years, litter recycling for N in Ireland	12-15 t/ha/yr
Ettala (1988)	Willow	Landfill caps	5 years, six landfills in Finland, irrigated with leachate from landfills	7.3-12.5 t/ha/yr
Bungart and Huttl (2001)	Poplar	Clayey-sandy nutrient poor soil	4 years, intial fertilization 100 kg N/K/P	9.2 t/ha/yr
Husain et al. (1998)	Poplar	Marginal lands	Modeling study examining yields in Minnesota	4.5-11.2 t/ha/yr

Table 7.2 Results of research to yields of bioenergy crops on degraded soils.

Earlier, we also concluded that studies on yield reductions as a result of degradation were not sufficient in assessing general yield reductions as a function of different types and degrees of degradation. Again, we use the data here to compare available data to our results. As a result of a lack of data, quantitative studies on the effects of degradation on agricultural productivity were limited and speculative (Den Biggelaar et al., 2004). Table 7.3 presents results of Lal (1998), who reviewed the quantitative effects of soil erosion and compaction on agronomic productivity based on experiences in agriculture. Results are in similar range compared to our estimates. However, the range presented by Lal (1998) for erosion is lower than suggested by GLASOD data, which indicates occurrence of extreme degree erosion, resulting in yield losses of 100% (for annual food crops). While, GLASOD data indicates the occurrence of compaction (as a cause of degradation) up to strong degree, which were estimated to result in yield losses of maximally 75%, Lal (1998) indicates losses up to 90%.

Source	**Relevance**	**Yield reduction**	
		Low estimate	**High estimate**
This study	Erosion, globally	5-100%	15-100%
	Compaction, globally	5-50%	15-75%
Lal (1998)	Erosion in Midwest, USA, Africa and Asia	2-40%	
	Compaction in Europe and Africa	40-90%	

Table 7.3 Yield reductions due to degradation for annual food crops.

2. Discussion of research limitations

In our study, we have estimated the global bioenergy potentials on degraded lands based on the amount of degraded lands and the expected yields of perennial energy crops on those lands. To indicate the exact scope of this study, limitations of the examination of both factors are discussed. Further, the main sources of data uncertainty are discussed to give insight in the reliability of the assessment.

2.1 Assessment of degraded lands

As part of our methodology, we first of all downscaled the GLASOD database to assess global degraded lands. Land that is currently classified as forest, cropland, area or pastoral land was excluded using geographically explicit land use databases from HYDE, IGBP DISCover and GLC 2000. Important limitations for this methodology are:

- Naturally degraded lands were not included
- Land areas degraded as a result of non-soil degradation were not included
- Salinized lands were not included
- No assumptions were established on the accessibility of degraded lands

Naturally degraded lands may be interesting for bioenergy production, although these can include higher species richness and, therefore, an increased risk on biodiversity losses during conversion to bioenergy production. Further, non-soil degradation, such as lowering of water tables and loss of vegetation, which was not included, is expected to be of limited importance to bioenergy potentials, since during these types of degradation, the soil is generally also affected (Lal, 1997). Further, one may argue that lands that are unaffected by soil degradation are less attractive for bioenergy production, as these are still feasible for food production. Salinized lands, excluded as GLASOD data provided no information on the actual degree, comprises 4% of total degraded area. Ongoing research of the BIOSAFOR consortium may provide more information on the bioenergy potentials of lands affected by natural and human-induced salinization (BIOSAFOR consortium, 2009). Up-to-date, this study estimated 1293 Mha of salt-affected soils (including human-induced and natural). The biomass production on these soils will be assessed in later stages.

Present cropland, pastoral land, urban area or forest were not included in the assessment, as abandoning the present land use of these is often undesirable and practically problematic. The remaining lands, characterized as other land use , comprised 21% of global degraded lands and included 16% of global bioenergy potentials. Also this land may be limited in accessibility; it may be in use for purposes not specified in this study, infrastructure may be inconvenient for bioenergy production or landowners may not support conversion to bioenergy production. This accessibility is highly uncertain as it depends on complex and unpredictable factors such as economy, politics and issues with local landowners. Therefore, we did not include assumptions on the accessibility of the degraded lands that were characterized by other land use. Hence, results should be interpreted as an upper limit of bioenergy potentials.

2.2 Yield estimates

In our research, we have assed the yields for woody species and several perennial grasses (elephant grass and switch grass).The potential yields derived from the IMAGE model were decreased with yield reduction percentages, specific for types and degree of degradation, to account for the limiting effects of degradation. This procedure included the following limitations:

- Generalizations required as a result of the global scope of the study
- Assessments were based on rain-fed productivity, irrigation was not included
- *Jatropha Curcas* was not included, although claims are being made that this species would have promising results on degraded soils

Important generalizations made in our yield assessment include the aggregation of energy species into the generic types woody or grass, general assumptions on management level and production system and the fact that the effects of soil type were not species-specific. Further, site-specific factors other than climate, the soil type, the type of degradation and the degree of degradation were not included explicitly. Choices regarding these factors were based on general expectations. Therefore, effects of these generalizations are expected to be limited.

The yields used in this study are based on rain-fed circumstances – and we have not considered irrigation. We believe that this is in accordance with the relatively extensive management systems which we find likely to be consistent with bio-energy cultivation on degraded lands.

Finally, there are many claims that *Jatropha Curcas* would be promising for cultivation on degraded lands. However, this specie was not included in our assessment, as available data was insufficient for sound yield predictions. Therefore, it was not clear if accounting for this species would affect results

2.3 Uncertainty

Our estimate of bioenergy potentials included several sources of data uncertainty. These sources and their significance are discussed.

Yield reduction and allocation procedure
The significance of several assumptions of the allocation procedure and estimates of yield reduction, which were required due to lacking or inadequate data, was examined in the sensitivity analysis, as described in chapter 6. The sensitivity was found to be highest for the assumed general yield reduction percentages, which were derived from Oldeman (1998). The effect of the two optional sets of percentages was presented as the possible range of global bioenergy potentials. The sensitivity of other assumptions was limited to a maximum of 3 percentages, except for the interpretation of GLASOD ranges of percentages, of which the examined extreme values seemed highly unlikely. The probability that average actual percentages deviated from the average of indicated range classes is thought to be in accordance with a normal distribution. Therefore, the probability that average actual percentages equalled the more extreme values of indicated percentage ranges is severely limited. Accounting for this, the interpretation of percentage ranges is expected to relate to an uncertainty of several percentages.

GLASOD
Degradation data included several sources of uncertainty. The most significant source comprised the subjectivity attached to expert judgment, which was used to develop the GLASOD database. Sonneveld and Dent (2007) performed research on the significance of this problem and concluded a moderate consistency of experts. Also, GLASOD data were relatively old (1990) and, therefore, developments in degraded area of the last two centuries were not included. Further, the examination of land use was hindered by significant uncertainty, as the processed GLASOD data as well as the HYDE land use data were based on a downscaling procedure.

IMAGE
The assessment of yields on degraded lands was complicated by a lack of quantitative data. Yield reductions were based on estimated general yield reduction percentages and, to adjust these for perennial energy crops, calibrated qualitative data. Further, IMAGE potential yield maps were

based on global modelling and were limited in level of detail, indicating yields on a scale of a half by a half degree (Leemans and van der Born, 1994).

Land use
The method to examine current land use was based on an overlay of the degradation data and HYDE, IGBP and GLC land use data. As both the degradation data as well as the HYDE land use data were based on a downscaling procedure, information on land use included significant uncertainty.

4. A sustainability perspective on using degraded lands for bioenergy production

The cultivation of bio-energy on degraded lands might be an attractive way to mitigate climate change without negative impacts on food supply or biodiversity. However, when aiming for sustainability, several other considerations need to be taken into account. Several potential problematic and promising features of bioenergy production on degraded soils are examined, to place the bioenergy potentials in a broader sustainability perspective. Table 7.4 presents an overview of different factors related to the overall sustainability of bioenergy production on degraded lands.

Sustainability domain	Argument	Impact
Environmental	Mitigating degradation	+
	Biodiversity	+/–
	Ground water depletion	–
	Serving as buffer or to process waste	(+)
	Invasiveness of energy species	(–)
	Pollution	(–)
Social	Increasing local energy security	+
	Job opportunities in rural areas	(+)
	Neglected alternative uses of degraded lands: forage for dairy and meet production, biodiversity	(–)
Economic	Cost-effectiveness to counteract climate change	?

Table 7.4 Sustainability concerns related to bioenergy production on degraded soils. Positive effects are indicated by +, while negative effects are indicated by –. Brackets indicate effects that may occur, but strongly depend on site-specific characteristics, management choices or politics

Environmental

- If cultivated with a relatively extensive production system, as we proposed, perennial energy crops can serve to prevent further soil degradation and to restore the soil by improving chemical, structural and biological characteristics (as explained in chapter 5), which is confirmed by experience in the Conservation Reserve Program of the US (Laughlin & Walsh, 1998, Mann & Tolbert, 2000, Ranney & Mann,1994 and Graham & Downing, 1995). This argument is of major importance, since soil degradation leads to the depletion of a valuable natural resource (Hall, 1995). Furthermore, restoration efforts in the short term are critical to mitigate soil degradation as the process is self exacerbating, as only some stages of restoration can be accelerated by human intervention and as required restoration efforts increase as severity worsens (Daily, 1995).
- Biodiversity effects can be either positive or negative depending on the landscape setting and the species richness of replaced vegetation. Generally positive effects can be expected due to improvements in soil quality, which result in a more healthy environment and lead to a more suitable habitat. Compared to annual food production, cultivation of perennial energy crops resulted in increased occurrence of soil fauna, small mammals and birds (Borjesson,

1999, Semere & Slater 2007, Jordan et al., 2007, Heaton et al 2004, Zhou et al., 2009 and Cook & Beyea 2000).

- The risk of depletion of water resources poses a significant constraint for bioenergy production on degraded lands. Although energy crops are efficient in water use, their high biomass production results in a considerable water requirement (Monclus et al.,, 2009, 2006 and CBD, 2008).
- Other environmental considerations strongly depend on the way bioenergy production is implemented. Perennial energy systems can serve as environmental buffers, absorbing discharged chemicals (e.g. during food production) before reaching water reservoirs (Parrish and Fike, 2005 and Ranney & Mann 1994). Further, pollution from fertilizer and pesticides can increase, although requirements of these are limited and perennial energy species increase the retention capacity of the soil to hold these chemicals (Parrish & Fike, 2005, Mann & Tolbert, 2000). Last, perennial energy species can become invasive due to specific qualities, related to high biomass production, but the significance of this risk is uncertain (Raghu et al., 2006)

Social

- Producing biofuels on degraded lands can increase national energy security, as domestic energy production may decrease dependence on oil exporting countries.
- Bioenergy potentials were found to be located for 31% in Africa, South America, Indonesia and South East Asia. In these developing regions bioenergy production on degraded lands may serve to facilitate the development of poor rural areas, by increasing the efficiency of land use and by providing job opportunities in these areas. However, in contrast presently biofuel production seems to exacerbate inequalities in developing regions, such as Brazil (Van Wey, 2009). Adequate policy intervention may serve to reverse this trend in the future.
- Several alternative uses of degraded lands cannot be realized when producing bioenergy. Low quality soils are also suitable to be used as pastures or to produce forages, needed for dairy and meet production (Ceotto, 2007). Further, they may be rehabilitated for food production or biodiversity purposes, although degraded lands seem less suitable for these land uses (Daily, 1995 and Field, 2008).

Economic

- Bioenergy production on degraded soils might be economically viable, as the reduced benefits of lower yields may be compensated by reduced land rent costs and reduced (labour) inputs, although these factors strongly depend on regional economics (Patwardhan and Anand, 2005). However, also if economic incentives needs to be provided by subsidies, bioenergy production on degraded soil may be economically attractive. Critical for economic interests is the cost-effectiveness of bioenergy production on degraded soils to mitigate climate change and to restore degraded soil. However, this cost-effectiveness is hard to predict as it depends on highly uncertain factors such as the cost-effectiveness of other solutions, adaptation costs and economic developments (Fischer, 2001).

5. Conclusions

We assessed the potential, i.e. the upper limit, of global bioenergy production on degraded lands that were not classified as forest, cropland, pastoral land or urban area. We used geographically explicit information downscaled to a 5 minute grid, we included the limiting effects of degradation on yields and we applied yield reductions based on perennial energy crops, specific for different types and degrees of degradation. The study leads to the following conclusions:

- ➢ The estimated potential equals 32-42 EJ/yr. This equals 7-9% of world energy consumption in 2006 (Energy information administration, 2009). This numbers seems to be consistent with some studies that were published earlier. Compared to these studies, the degraded area included here is relatively low. Practical considerations, such as economic viability and accessibility of degraded lands, were not included and pose significant additional constraints. Yields were relatively high, compared to earlier studies, in accordance with the limited amount of field studies on energy production on degraded lands.

- Promising regions for bioenergy production on degraded lands were Russia, South East Asia, India, Brazil, East Africa and West Africa, which were high in total potentials and the Rest of Central America, Central Europe, Turkey, Indonesia and Mexico, which were high in potentials relatively to total land area. A significant share of global potentials (31%) was located in developing regions, in which bioenergy production on degraded lands may serve to provide developing opportunities for the rural poor.
- Based on literature review, we conclude that bioenergy production on degraded lands can be efficient in reducing GHG emissions, as a limited amount of fossil fuel inputs is required during production, GHG emissions related to these may be offset by sequestration of carbon in the soil and risks on carbon debts are limited as the included degraded lands generally contain little standing biomass (Tillman, 2006, Pineiro et al., 2009 and WI, 2006).
- Although some risks need to be accounted for, bioenergy production on degraded lands that are not in use as forest, cropland, pastoral land or urban area, comprises a promising option in the light of sustainable development, since it combines the restoration of degraded soils with efficient mitigation of climate change.

Above, we concluded that there seems to be potential for bio-energy production on degraded lands. However, further information is required. We revealed several gaps in knowledge, which need further research efforts to provide an adequate scientific foundation for making decisions. This involves in particular the following topics:

- Identifying and mapping degraded lands, indicating on a regional or local scale the location, amount, degree, expected yield reductions and current land use.
- Determining bioenergy yields and required inputs on degraded lands, with different types and degrees, based on quantitative field experiments designed for commercial energy cultivation.
- Assessing the economic viability of bioenergy production on degraded lands and policy options to provide economic incentives in a sustainable manner, serving to benefit the rural poor.
- Assessing the risks related to depletion of water resources, pollution and invasiveness of energy species.
- Identifying the possibility of using degraded lands, currently in use as cropland or pastoral land, for bioenergy production and the consequences of such land use change.

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Annex I: degradation datasets

1. GLASOD

GLASOD was the first uniform source of global land degradation data. The GLASOD project aimed to “strengthen the awareness of decision makers and policy makers on the dangers resulting from inappropriate land and soil management to the global well-being, leading to a basis for the establishment of priorities for action programs” (Oldeman, 1988).

Methods

The world was divided in 21 regions, which were supervised by a correlator. The correlator guided the assessment and divided his region into different units, using remote sensing data from the 1980s and his expert judgment. Units were delineated so that they had equal soil and terrain characteristics, but this was complicated by their minimum size of 5625 km^2. In total more than 250 experts were consulted to estimate: 1) the types of degradation that occurred in the different units, 2) the degree or severity of these degradation processes, 3) the extend to which a unit was affected by degradation, 4) the rate at which degradation occurred and 5) the human practices that caused degradation (Oldeman, 1988). Uniform guidelines were used, which functioned as an instruction manual for the experts. The guidelines directed the experts to choose one of several options for the different pieces of information that were required. They could choose from 20 subtypes of degradation, 5 degrees of degradation, 5 classes of percentages for the extent of degradation, 2 different rates of degradation, and 5 human practices as possible causes (Oldeman, 1988). The final data included only 12 of the 20 subtypes that were originally presented in the guidelines. Three off-site subtypes were not identified by the correlators and therefore excluded. No transparency was given on the motivation to exclude the other 8 subtypes. The extent to which experts were guided by the instructions varied between different subtypes of degradation. For seven subtypes the guidelines included semi-quantitative criteria to assess the different levels of degradation; 5 subtypes were assessed using a definition for identification and general criteria for the level of degradation.

Definitions

The main definition of degradation used in the GLASOD project is “a region where the balance between the attacking forces of climate and the natural resistance of the terrain against these forces has been broken by human intervention, resulting in a decreased current and/or future capacity of the soil to support human life” (Oldeman, 1988). This definition excludes areas with natural degradation that is not caused by humans, while these areas can be feasible for bio-energy production. Other important definitions in the GLASOD project are those which directed the experts in their assessment. As has been stated before, experts assessed the type, the degree, the extent, the rate and the cause of degradation. The guidelines clarify their meaning (Oldeman, 1988):

Type of soil degradation refers to the process that causes degradation
Degree of soil degradation refers to the present state of degradation
The extent of degradation refers to the percentage of the land affected
Rate of soil degradation refers to the apparent rapidity of the process
The cause of degradation refers to the causative factor of human-induced soil degradation

Definitions of the different categories which could by chosen by experts, assessing these aspects, can be found in the GLASDOD guidelines (Oldeman, 1988).

Indicator for degradation

The degree of degradation expresses the severity of the degradation process. Varying from none to extreme, it indicates degradation in the GLASOD project.

For 5 of the 12 subtypes, the degree of degradation is assessed using general descriptions, which are applicable for all types of degradation (Oldeman, 1988). These descriptions refer to the productivity, the agricultural suitability, the efforts needed for restoration and the state of biotic functions.

Hence, several important features of degradation were taken into account for the assessment. On the other hand, general descriptions leave room for interpretation differences between experts.

For 7 of the 12 subtypes, type-specific semi-quantitative criteria were used to assess the degree of degradation (Oldeman, 1988). Experts are guided more strictly reducing chances on differences in interpretation. The criteria refer to physical characteristics of the soil, that relate to degradation. No information is given on the strength of this relation or the way these criteria are developed.

Output

The global assessment was presented on a map with an average scale of 1:10 million (M), ranging from 1:7.5M at the poles to 1:15M at the equator (Oldeman, 1988). The scale varied slightly between the poles and the equator, because a flattened mercator projection was used. The type(s), the degree, the extent, the rate and the cause(s) of degradation were shown for every mapped unit using abbreviations and numbers. Additionally, specific shadings on the GLASOD map indicated the seriousness of the situation, which was determined by a combination of the degree and the extent of degradation. After development of the map, information was transferred to a digital GIS-database.

Usefulness of data

From the GLASOD project, the *degree of degradation* combined with *the extent of degradation* can be used to identify degraded areas and their level of degradation. The calculation of the area surface that is affected by degradation is complicated by the low level of detail of the extent of degradation. The extent is not expressed as a single percentage, but experts needed to choose one of five classes of percentages (0-5%, 6-10%, 11-25%, 26-50% or 50-100%). Therefore, assumptions are needed to calculate the surface area that is affected, for example, using the average percentage of a class. Further, no information is given on the exact location of the affected part. This complicates overlays with other maps.

Information on the type of degradation can possibly be used to determine which areas are particularly interesting for bioenergy production, because some types of degradation may cause bioenergy crops to have a significant advantage over food crops. The applicability of this idea depends on the availability of specific information in literature.

The rate of degradation and the human practices which caused degradation are thought to be irrelevant for the assessment of the global potential of degraded lands to produce bioenergy.

Present state of degradation

Although the guidelines suggest that the present state of degradation is assessed for all types of degradation, the instructions for salinization lead to the assessment of the change in degradation during the last 50 years (Oldeman, 1988). This inconsistency is not further explained in the report. Information on the present state of salinization seems to be lacking. For the other subtypes, the present state of degradation is assessed.

Level of detail

The level of detail of the data is very low. The base map has a scale of 1:10M and, furthermore, the data is aggregated due to cartographic restrictions. The most detailed level of degradation information can be derived from the size of mapped units, which were permitted to have a minimum size of 5625 km^2, according to the guidelines (Oldeman, 1988).

Up-to-date & inclusion of all types of degradation

The data is outdated since the assessment is performed in 1989-1990, supported by data from 1980-1990. Further, only human-induced degradation is considered, while naturally degraded lands are also attractive for bio-energy production. Last, the unmotivated exclusion of 8 subtypes of degradation raises doubts on the extent to which human-induced degradation is covered.

Reliability of data

Subjectivity due to expert judgment

The use of expert judgment during the preparation of GLASOD inherently generates a high level of uncertainty. Experts may interpret the guidelines differently, due to a, for example, difference in expertise, culture or reference situations. Therefore, it is of high importance that guidelines are clear and straightforward. However, only 7 of the 12 subtypes of degradation were guided by semi-quantitative criteria. The remaining 5 needed to be assessed using a definition for identification and general criteria for the degree of degradation, leaving much room for the

experts' own interpretations. Probably, another source of differences in interpretation is that information on the way to deal with overlapping degradation types was lacking in the guidelines. However, no clarification is given on this subject, leading to unknown significance of this problem.
Sonneveld & Dent (2007) checked the consistency of GLASOD data by comparing sites with identical biophysical and land use characteristics on their GLASOD results. They concluded a moderate consistency of the judgments. GLASOD has been criticized for its exaggeration of the severity of degradation (Safriel, 2007). However, this criticism is based on the severity-shadings on the map and is not referring to data uncertainty.

Remote sensing data
Besides expert judgment, some remote sensing data were incorporated in the assessment. However, this data was often patchy and it was of uncertain quality (Oldeman, 1991).

Arbitrary decisions
Due to the scale of 1:10M, many arbitrary decisions had to be made by correlators during compilation of the data, leading to uncertainty (van Lynden & Oldeman, 1995). Further, the report lacks transparency on the motives to exclude 8 of the 20 subtypes of degradation that were presented in the guidelines from the final data.

Cartographic restrictions
A maximum of two degradation types was assigned per mapped unit, because of space restrictions. Information on more types was excluded (Oldeman, 1991).

2. ASSOD

As a sequel of the GLASOD project, ASSOD covered 17 countries in South and South-East Asia, aiming at a more detailed assessment of this area to increase the awareness on soil degradation problems among policy- and decision makers as well as the general public in the region. Compared to GLASOD, more emphasis was put on the rate of degradation and the impact of soil degradation on soil productivity.

Methods

Using SOTER methodology, areas with a homogeneous set of soil and terrain characteristics were delineated in a structured uniform manner on a map with a scale of 1:5M (van Engelen, 1995). National institutes supervised the assessment of degradation in their own country, involving many experts and advising agencies. They were authorized to correct the base map where necessary. After national institutes delivered their final reports, the ISRIC-institute could ask them to make corrections were needed.
The occurrence and the type of degradation were identified by expert judgment, using adjusted GLASOD guidelines (van Lynden, 1995). Compared to GLASOD, the ASSOD guidelines provided more information to identify degradation, since for all types a description and several possible causes were given. In the final data all types of degradation from GLASOD were included plus 4 extra types (Oldeman, 1995).
In ASSOD the impact of degradation on productivity is used as a proxy for the degree of degradation, This impact is assessed by examining the change in productivity, corrected for the level of management, over the last 25 years, since human-induced degradation occurred mainly during this period in the region. The extent of degradation was assessed as a percentage rounded of to the nearest 5%. The rate and human causes were identified in a way similar to GLASOD (except that 3 possible rates were added and 2 possible causes). Further, national institutes were asked to give information on the overlap between different types of degradation. However, the guidelines did not specify which information was needed. Therefore, during compilation of the data assumptions were needed to assess the overlap (van Lynden and Oldeman, 1997).

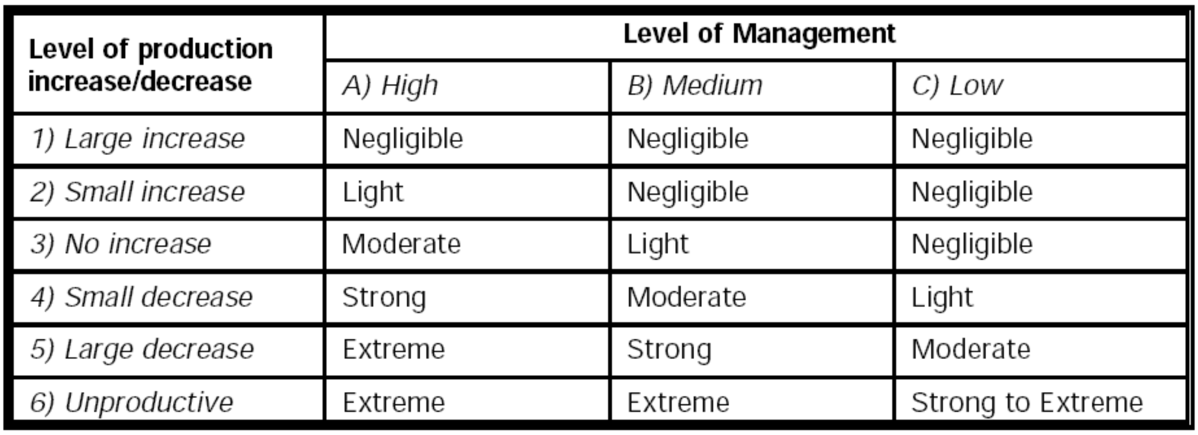
Definitions

The ASSOD guidelines state that the GLASOD definition of degradation is very broad and needs some further refinement (van Lynden & Oldeman, 1995). Degradation is defined as "the partial or entire loss of one or more functions of the soil". The guidelines add to this that the ASSOD report will concentrate on the productivity function of the soil. Definitions of the type, degree, extent, rate and causes are consistent with GLASOD definitions. Two additional concepts were included to determine the degree, i.e. the impact of degradation on productivity and the management level.

- **The impact of degradation on productivity** refers to the current (average) productivity as a percentage of the average productivity in the non-degraded (or non-improved were applicable) situation and in relation to inputs.
- **The management level** refers to the amounts of inputs.

Indicator for degradation

The main indicator for degradation is the degree, which is determined by the change in productivity over the last 25 years, corrected for the level of management (Van Lynden & Oldeman, 1995). To determine the change in productivity quantitative data was used and, if this was lacking, expert judgment. However, the guidelines (van Lynden & Oldeman 1995) give no instructions how to translate quantitative impacts into the qualitative options. It is not known which translation criteria were used and if these were consistent among experts. Further, data was corrected for the management level, because mitigation measures camouflage the genuine impact of degradation (Van Lynden & Oldeman, 1995). This correction was applied using table 2, resulting in a degree of degradation ranging from none to extreme. Other external processes that influenced the productivity were to be excluded by national institutes using their expert judgment.
This indicator focuses on the productivity function of the soil while the GLASOD indicator says also something about agricultural suitability, efforts needed for restoration and other biotic functions. These lacking concepts in the ASSOD criteria are indirectly included because they tend to coincide with changes in productivity (Safriel, 2007). However, a difference in judgment of a situation is possible, e.g. if an area is less suitable for agriculture due to pollution, while the productivity is unaffected. Although attractive for bioenergy according to the level of degradation, the ASSOD indicator will identify this area as non-degraded.



Level of production increase/decrease	**Level of Management**		
	A) High	*B) Medium*	*C) Low*
1) Large increase	Negligible	Negligible	Negligible
2) Small increase	Light	Negligible	Negligible
3) No increase	Moderate	Light	Negligible
4) Small decrease	Strong	Moderate	Light
5) Large decrease	Extreme	Strong	Moderate
6) Unproductive	Extreme	Extreme	Strong to Extreme

Table 2. combining the change in productivity and the level of management to determine the degree of degradation in ASSOD (van Lynden & Oldeman, 1995).

Output

Differing from GLASOD, ASSOD data was directly digitized into a GIS-based database. The extent, type, rate and causes of degradation resembled GLASOD, except for a few differences such as the addition of several subtypes of degradation and a more sophisticated assessment of the rate and extent of degradation. Data on the degree differed significantly due to the use of a different method, taking the impact on productivity as a criterion for the degree of degradation. The level of productivity decrease/increase as well as the level of management are specified in the GIS-database. However it seems that no data is available on the variables which determined the change in productivity, i.e. the present productivity and the productivity 25 years ago.

Usefulness of data

Similar to GLASOD, the extent of degradation can be used to identify degraded areas and the types of degradation may help to select areas which are particularly interesting for bio-energy production. Again, it is not known which part of the mapped unit is affected and the percentage is not known exactly, although the accuracy is improved (20 classes of 5%) compared to GLASOD.

The degree of degradation, which is needed to determine the level of degradation, differs between both projects. ASSOD uses the impact of degradation on productivity as a criterion for the degree of degradation, while in GLASOD general and type-specific physical criteria were used to indicate the present state of degradation.

Present state of degradation

The impact on productivity is defined as the *change* in productivity due to the degradation in the last 25 years. Therefore, this indicator gives no information on the current state of degradation, which is needed to asses the global potential of bioenergy production on degraded lands. Information on the current state of productivity was needed to determine the change, but this information is not included in the GIS database.

Level of detail

ASSOD has a higher level of detail than GLASOD, although it is still moderate. The improved scale (1:5M) and the lack of cartographic restrictions (data was directly saved in a digital database) result in a higher level of detail than in GLASOD. For example, India was divided into 50 units for GLASOD and contains more than 600 in ASSOD (van Lynden & Oldeman, 1997)

Up-to-date & inclusion of all types of degradation

The expert judgments were performed during 1995 and 1996 and quantitative data from 1980-1995 was used. so the data is relatively old, although it is more recent than GLASOD data. Similar to GLASOD, only human-induced degradation is included. This human-induced degradation is covered more extensively than in GLASOD, since more types of degradation are included. The possibility remains that some degradation types are not included, although I think that the most important types are assessed. Further, the final report states that due to missing data and different interpretations some types of degradation were underrepresented (van Lynden & Oldeman, 1997). Last, the productivity indicator may cause some bioenergy attractive areas to be excluded because degradation affected other biotic functions.

Reliability of data

Subjectivity due to expert judgment

The reliability of ASSOD is, similar to GLASOD, limited due to subjectivity of expert judgment, which is the main method used to assess degradation. However, several adjustments in the methods decreased this subjectivity. First, the base map is produced using uniform SOTER guidelines, instead of expert judgment. Second, instead of more than 250 experts, 17 national institutes performed the assessment and they implemented corrections suggested by ISRIC, limiting space for differences in interpretations. Third, the guidelines gave a more clear description of types of degradation, facilitating consistency during identification. Last, quantitative data (if available) was used to assess the change in productivity.

Although these improvements reduced the subjectivity of expert judgment significantly, it still remains an important source of uncertainty. The management level, the occurrence of degradation types, the rate of degradation and the causes of degradation were assessed using only expert judgment. Further, experts needed to use their judgment to exclude processes that influenced the productivity other than degradation. This seems a complicated task, which probably involves a high level of subjectivity. Also, the guidelines lacked instructions on how to translate quantitative productivity data into qualitative possibilities. It is not clear in literature if, eventually, these instructions were handed to the institutes, to prevent different interpretations.

The final report (van Lynden & Oldeman, 1997) gives some examples of interpretation problems, that the significance of these problems. For example, Indonesia calculated the productivity instead of the impact of productivity on degradation and there was some vagueness on the interpretation of ‘human-induced’. This latter was caused by a lack of instructions in the guidelines on areas that were degraded due to human-induced as well as natural influences.

Arbitrary decisions & missing data

During compilation of the data many arbitrary decision were made (van Lynden & Oldeman, 1997). Also some of the proposed corrections were not realized. Further, missing data was a considerable problem. For example, management data was missing for some areas and pollution was only identified by China. The final report (van Lynden & Oldeman, 1997) comments by stating that these problems are inherent to the compilation and correlation of so manifold data. Last, specifications of the data on overlap between degradation types was not clear in the guidelines. Therefore, assumptions were needed to estimate this overlap.

3. SOVEUR

The SOVEUR project aimed to develop a detailed assessment of 13 countries in central and eastern Europe, succeeding the GLASOD and the ASSOD project. With a focus on pollution, SOVEUR aimed to facilitate policy formulation at the regional and national level and to strengthen the capabilities of national environmental organizations in central and eastern Europe (van Lynden, 2000a).

Methods

National institutes were asked to delineate units with equal soil and terrain characteristics on a base map with a scale of 1:2.5M, using SOTER methodology. National institutes performed the assessment using expert judgment and quantitative data from a variety of sources.

The occurrence and type of degradation were assessed by expert judgment using slightly adjusted ASSOD guidelines. The same types and descriptions were included, with an exception for the degradation type pollution, which was split up into 6 subtypes (Van Lynden, 2000a).

After identification of the type of degradation, the degree was assessed using methodology based on both the GLASOD and the ASSOD project. The severity of the process as well as the impact of degradation on productivity were indicated. Additionally for pollution, the impact on several other soil functions was assessed.

The extent to which a mapped unit was affected by degradation was expressed as a percentage of the area (rounded to the nearest 5%). Further, information on the overlap between different types of degradation was supplied by the national institutes, since instructions for this were presented conveniently in the guidelines in contrast to GLASOD and ASSOD (van Lynden, 2000a)

Indicators for degradation

In the SOVEUR project 2 indicators for degradation were integrated. First resembling GLASOD, the severity of the degradation process was assessed with general criteria, including 5 levels, ranging from none to extreme degradation (van Lynden, 2000a). The general criteria referred only to the amount of efforts needed for restoration. Compared with GLASOD, the agricultural suitability, productivity and the state of biotic functions were left out. I think that the effort needed for restoration is a convenient proxy for these other concepts, and therefore this imposes no limits on the data.

A second indicator, the impact of degradation on soil functions, was assessed with an ASSOD-based methodology. For the degradation type pollution, the impact of degradation on 6 different soil functions was assessed, using quantitative criteria. The most relevant one for this research, the biomass production function, includes the capacity to provide food. Therefore, all relevant features of degradation were covered.

For other types of degradation, the impact on the productivity was assessed using the ASSOD method, improved with quantitative-based management levels (Van Lynden, 2000a). If possible, the management level was determined as the part of farmers expenses spend on mitigation measures. This indicator, holds the same constraint as in ASSOD. Situations are possible where degradation occurs while the productivity remains unaffected.

Definitions

Definitions resembled those used for ASSOD. Degradation is defined as “the partial or entire loss of functions of the soil” (2000a). Although ASSOD integrates only the productivity function of the soil, SOVEUR assesses for the pollution type the impact on several soil functions, to account for the various consequences of pollution. Of these functions, the **biomass production function** is most relevant for this research and it is defined as: providing food, (renewable) energy and natural features (e.g. forest provides an important natural habitat). Although formulated

Output

A digital GIS-database was developed, containing information on the type, extent, rate and causes of degradation. All these aspects were expressed in the same manner as for ASSOD. The same degradation types were assessed as in ASSOD, although the options for pollution were more specified. As an indicator for the degree, the severity of degradation (5 options) and the impact on productivity (5 options) were included for all degradation types. For pollution, additionally, the impact on 6 soil functions was assessed; It is not known if the present productivity, which was determined in the process, is available in the data.

Usefulness of the data

The extent of degradation can be used to identify degraded areas and the type of degradation may be used to assess in which areas bio-energy production has an advantage over food production, making them particularly attractive for bioenergy production. The degree, which is needed to select areas that are attractive for bioenergy production, is expressed by two indicators, the impact on productivity and the intensity of the process, of which the most feasible one should be chosen.

Present state of degradation

Using general criteria, the severity of the process is assessed as the present state of degradation. The impact on productivity is measured as the change in productivity during the last 25 years, compensated for the management level. Hence, the present state of degradation is not assessed directly, although it is needed in the process. The usefulness of the impact-indicator depends largely on the availability of this information.

Level of detail

The level of detail of the SOVEUR project is moderate. The scale of 1:2.5M provides a more detailed base- map compared to GLASOD and ASSOD. SOTER methodology was applied by national institutes, which are generally well-informed about the different soil and terrain types in their country.

Up-to-date and inclusion of all types of degradation

Collected during 1998 and 1999 (with data used from 1973-1998), the results of the SOVEUR project are one decennium old. Although improved compared to GLASOD and ASSOD, this is still a time span in which degraded lands can change significantly.

The SOVEUR project assesses human-induced degradation. Similar to ASSOD it could be that important degradation types were not included in the guidelines. However, in my opinion all relevant types are assessed.

Reliability

Subjectivity due to expert judgment

In the SOVEUR project, expert judgment was used to identify degraded areas (except for pollution), to assess the severity of the degradation process and to assess the impact of productivity if data was not available. Compared to ASSOD, the use of expert judgment was decreased because the management level was assessed quantitatively instead of qualitatively. Despite this improvement, expert judgment is still applied for essential components of the assessment such as the identification of degradation and, partly, the assessment of the level of degradation. Therefore differences in interpretation are a significant source of uncertainty. The final report (Van Lynden, 2000b) gives some examples of problems which were encountered due to expert judgment. Some countries assessed the risk of degradation instead of the status, some cross-border problems remain after corrections had been implemented and last, differing results between countries were partly explained by differences in detail of their base map (Van Lynden, 2000b).

Missing data & arbitrary decisions

Similar to ASSOD, arbitrary decisions and missing data caused significant uncertainty during compilation of the national level data (Van Lynden, 2000b). For example, data for pollution, the recent past rate and causes of degradation were incomplete. Further, not all corrections which were proposed during an evaluation workshop, were eventually implemented. The final report confirms this problems by stating that “due to varying data availability and quality the extent of degradation may have been overestimated in some cases, certain types of degradation and land-use system conversion may have been underrepresented” (van Lynden, 2000b).

4. MEA

The Millennium Ecosystem Assessment aims to evaluate the degree to which ecosystem services, on which human societies depend, are sustainable, given the many environmental stresses they face. A synthesis of geo-referenced degradation information for 1981-2000 was included.

Methods

Data of 14 global, regional and sub-regional studies on degraded lands in the dry and hyperarid zones of the world were compiled into one map with grid cells of 10x10 km^2. Studies which showed degradation during the period 1980-2000 were examined. Methods, definitions and time-frames varied between studies. The reliability of remote sensing data was checked by evaluating validation research. Extensive consultation within the scientific community was performed to ensure utilization of the most reliable datasets in a correct manner. This lead to more strict data control than for GLASOD and to a coverage of 62% of global drylands (Safriel, 2007). Areas with severe degradation (highest degree of 3-4 or values above a high threshold (Safriel, 2007)) were marked as degraded.

Output

A compilation of 14 studies provided a global GIS-database, in which for 62% of the drylands and hyperarid areas, degraded areas were marked. Further, the amount of studies covering a gridcell was indicated to provide information on the intensity of research.

Definitions

The data, used in this desk study, is based on a variety of definitions, differing depending on the data source.

Usefulness

Only severely degraded areas are indicated in this study. For example, in GLASOD these are described as irreclaimable and beyond restoration. These areas are not useful for bioenergy production and, therefore, the data cannot directly be used for my study.

Present state

The study aimed to indicate the current state of degradation. The precise methods to combine data sets are not found in literature. Therefore it is not known if all data assessed the present state.

Level of detail

The level of detail of the data is good with gridcells of 10x10 km^2, although no information is given on the extent of degradation within a gridcell.

Up-to-date and coverage of degraded areas

The data covers the period from 1980-2000, so some data sources are more recent than others. Only degradation of drylands and hyparid zones is examined, excluding degradation in all other ecosystem types. Further the data covers 62% of these areas. Other limitations depend on the studies which are compiled. For example, it is not known if those studies included natural degradation.

Reliability

The reliability of the data largely depends on the reliability of the compiled studies, which is not discussed in Lepers *et al*. (2005). Research of those studies is not performed because of the low usefulness of the dataset for this study. The strict data control may lead to more reliability than for GLASOD (Safriel, 2007).

Some uncertainties arise from the compilation of the data. First, scales had to be adjusted, resulting in arbitrary decisions. Further, the research intensity differed between regions. This may create bias, because in more intensively studies regions, more degradation processes may be revealed. The map, which shows the study intensity, makes this problem explicit, but the significance remains unknown.

5. GLADA

GLADA is the first global assessment of degradation which is totally based on remote sensing data, excluding subjectivity due to expert judgment. The assessment aims to identify areas that are degrading and areas which are improving. Further research is needed to validate results and provide more specific information.

Methods (Bai *et al*., 2008)
Changes in net primary production were used as an indicator for land degradation and improvement because degrading land is characterized by a decreasing net primary productivity (NPP) of the soil. However, several factors other than degradation may cause a decreasing NPP and they should be excluded from analysis. Net primary productivity is also affected by climatic influences such as fluctuations in net radiation, rainfall and the length of growing season, by changes in land use or management practices, by natural disturbances such as fires or pests and by structural climate change (higher CO^2 concentration and more N-deposition may facilitate plant growth). Although these factors influence the net primary productivity, they do not necessarily coincide with degradation. The GLADA assessment corrects NPP values for rainfall and the length of the growing season, but the other factors are not taken into account.

NDVI as a proxy
The normalized difference vegetation index (NDVI) is used as a proxy for NPP, which is measured by remote sensing as the ratio of red and near-infrared light, reflected by the land. This proxy is widely acknowledged to be accurate in determining NPP on regional scale (Bai *et al*., 2008). A dataset of Global Inventory Modeling and Mapping Studies (GIMMS) is used with NDVI values from every 15 days for the period July 1981 to December 2003 on a global map with 8 km across gridcells. NDVI data are translated to NPP data by correlation with 'moderate-resolution imaging spectroradiometer' (MODIS) NPP data, which were available from 2000. Combining the NDVI and the NPP datasets for the overlapping period, the relation between both variables was calculated and used to translate NDVI values of 1981-2000 to NPP values.

Accounting for fluctuations in growing season and rainfall
As explained before, the following step was to correct NDVI values for fluctuations in rainfall and differences in growing season. To account for the latter, the date at which the measuring year started was adjusted so that one whole growing season was included. Hence, for the Southern hemisphere measurements for 1 October to 30 September were included for one year and for Northern the hemisphere measurements for the calendar year were included. Two methods were used to account for the influence of rainfall. First, the yearly amount of rainfall, observed by local stations, and the annual sum of NDVI were used to calculate for every pixel the rain use efficiency (RUE), i.e. the NDVI per unit rainfall. Although RUE is correlated strongly to rainfall variability in the short-run, long-term negative trends may indicate degradation. For areas, where the rainfall and the NDVI had a positive relation, the RUE efficiency has been calculated. If NDVI decreased and RUE increased the area was masked (just as urban areas), because the decrease in NDVI was attributed to the decrease in rainfall instead of degradation. For the other areas, trends in NDVI and RUE were analyzed using linear regression and a T-test. If both indicators showed a negative trend, an area was assumed to be degraded.

In GLADA a second method was applied to account for rainfall variability. The statistical relation of data from 1980-2003 between rainfall and annual sum NDVI (used as a surrogate for total productivity) was calculated for each pixel. With the resulting regression equation, the expected NDVI was predicted for the rainfall values. Subsequently, the difference between the predicted and the observed NDVI was used as an indicator, called RESTREND. Trends of this indicator were analyzed using linear regression and a T-test. If the NDVI as well as the RESTREND were negative, degradation was identified.

To identify an area as improved, increasing trends of NDVI and RUE, and an increasing energy use efficiency were required. After trends were calculated, NDVI data were translated to NPP, to provide meaningful results.

For land degradation as well as land improvement the NPP and a rainfall-adjuster indicator (RUE or RESTREND) were required. The idea for this is that RUE is best appropriate to assess situations where rainfall is limiting productivity and NPP is more convenient for situations where rainfall is not the limiting factor for plant growth (Bai *et al*., 2008). The results were compared with data on land cover, soil and terrain, rural population density and indices of aridity and poverty to explore patterns of degradation.

Definitions

The GLADA project defines degradation as a long-term loss in ecosystem function and productivity that requires progressively greater inputs to repair the situation (Bai *et al*., 2008).

Output

Several yearly NDVI indicators are given for each pixel; the maximum, the minimum, the maximum-minimum, the annual sum, the standard deviation of the measurements and the coefficient of variation (the dispersion relative to the mean value). The annual sum of NDVI is the most meaningful indicator because it is used as a surrogate for the biomass productivity in a year. Further, information on the trends in NPP and RUE are included in the database for every gridcell. It is not known exactly if more information is available. Working with the dataset will reveal this.

Usefulness

The GLADA project identifies hotspots of degradation. These areas can be used to assess the global potential of degraded lands to produce bioenergy. An indication of the level of degradation can be obtained from the strength of the negative trends in RUE and NPP. No information is available on the types of degradation.

Present state

The present situation can be accounted for by the exclusion of areas with high current productivity, although identification of degradation was originally based on trends.

Level of detail

The level of detail of the NDVI data (32 km^2 gridcells) is very high compare to other large scale assessments. However, the level of detail of information on the severity of degradation is problematic, since one 32 km^2 gridcell is examined with one NDVI signal. Consequently 2 km^2 of severe degradation may give the same NDVI value as 8 km^2 light degradation. Hence, the level of detail for the degree of degradation is relatively low. For the expert judgment based projects, this problem was avoided because the level of degradation and the affected percentage of the mapped unit were assessed directly.

Up-to-date and coverage of degraded areas

The assessment is relatively up-to-date, because trends were calculated until 2003 (5 years ago). All historical degradation is excluded, i.e. degradation which occurred before 1981. The final report states that these degraded areas are less important with respect to restoration measures, because they are often stabilized (Bai *et al*., 2008). For this research, however, they are relevant because of their usefulness for bioenergy production.

The GLADA project is not accounting for several factors other than degradation that may affect NDVI values. These include fluctuations in net radiation, changes in land use or management practices, natural disturbances such as fires or pests and structural climate change. Areas may be identified as degraded by remote sensing, while in fact the decline in NDVI had another cause. To account for this problem, the GLADA project will perform ground research to validate results (Bai *et al*., 2008). This research, however, is not finished yet. Therefore, use of the current state of information causes inclusion of non-degraded areas. Further, in an early state of degradation some types may occur without vegetation losses and will not be detected by the NDVI-measurement (Bai & Dent, 2008). Although potentially attractive for bioenergy production, these are excluded.

Reliability

The reliability of GLADA data is high compared to GLASSOD, ASSOD en SOVEUR because no expert judgment is involved and remote sensing data was validated successfully for some areas (Bai *et al*., 2005)

However, Bai *et al*. (2008) mention several reasons for uncertainty of the NDVI method. First, the NDVI signal can be saturated, resulting in less precision for strongly vegetated areas such as forests. Second, clouds obstruct the signal, which may result in an underestimation for cloudy areas, although some measures have been taken to prevent this. Further, the great variability of rainfall in drylands and the scarcity of observation stations make interpolation between different points problematic. Last, the translation of NDVI to NPP is approximate.

Despite using RUE and RESTREND to account for the effect of rainfall variability, results for the Sahel are probably partly due to rainfall recovery from the droughts in the 1980s (Bai *et al*., 2008). The estimate of degradation is conservative because a decreasing trend of RUE and NPP are acquired to identify an area as degraded. If only RUE decreases, this may also indicate degradation, because degradation can lessen the rainfall-induced increase in NPP without changing its sign.