Mapping global ecosystem degradation and its impacts

A cooperation of PBL, ISRIC, WUR, UU, Deltares, WRI, SOW-VU and PIK

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0. Abstract

The awareness that ecosystem degradation has detrimental implications for livelihoods, biodiversity and climate change has resulted in the renewed call by policymakers for quantitative information on degradation and the implication on ecosystem functioning as a basis for food, water and energy security, and the cost of rehabilitation. Progress towards agreed policy targets, including restoration of 15% of degraded ecosystems (CBD) or for a zero net degradation (UNCCD) cannot be measured without quantified information.

Much research on land degradation over the past decades has given partial views on various components only. We elaborate a methodology to integrate knowledge from various disciplines for quantitative estimates of global land degradation and loss of ecosystem functioning in the past, present and future. Advances in information technology and remote sensing facilitate analysis of massive amounts of remotely sensed and legacy data and the integration with complex quantitative crop, soil and climate modelling into global assessment methods.

Changes in net primary production world-wide over the past three decades and geographically specified information on climatic variations, soil and land use provide the basis for identification and mapping of ongoing ecosystem degradation. For identifying and mapping and historical degradation, pristine soil conditions of soil depth, top soil depth, soil organic matter and sand, silt and clay content, are reconstructed through back casting from knowledge about the impact of land use and other soil forming factors on soil characteristics and productivity. Subsequently, the loss -and consequently- restoration potential of ecosystem functions such as water retention, biodiversity maintenance, food and fibre production, and floods, drought and climate regulation, can be assessed by using the global models IMAGE, GLOBIO, LPJmL and PC-GLOB-WB. Costs and benefits of restoration can be estimated based on the global WOCAT database that contains over 450 case studies of location specific conservation measures and their impact on productivity and other ecosystem services.

1. Current status of global land degradation assessments

Soil degradation hampers ecosystem functioning which in turn causes a threat to future food security, maintenance of biodiversity and mitigation of climate change. Yet, global soil degradation assessments are based on qualitative expert judgments or remotely sensed quantitative proxy values that suffice to raise awareness but are too coarse to identify appropriate sustainable land management interventions or to provide quantitative and spatial information on the extent of the problem (Bindraban et al., 2012). For the same reason ongoing land degradation hasn’t been taken into account in scenarios of integrated global environmental assessments, nor hasn’t restoration been taken into account as most promising policy option (PBL, 2010; UNEP, 2011; OECD, 2012). A serious omission given the severity of the problem and the increasing competing claims for land and renewable natural resources (PBL, 2010).

The Global Assessment of Soil Degradation (GLASOD) developed by Oldeman et al (1991) has for long been the single global assessment of land degradation based on expert judgement. More recently Bai et al (2008) developed the GLADA (Global LAnd Degradation Assessment) approach based on consistent remotely sensed changes in NDVI (Normalized Differentiated Vegetation Index) over the period 1981–2006 to identify areas of land degradation and improvement. NDVI or greenness serves well as a proxy for biomass and with that as an integral measure of land quality (Bindraban et al., 2000), but depends on factors like climate (especially fluctuations in rainfall, temperature, sunshine and length of the growing season), land use and management (land clearing, afforestation or exclusion zones), large-scale ecosystem disturbances such as fires; and increase in nitrate deposition (Dentener, 2006) or atmospheric carbon dioxide (Nowak, et al., 2004). Hence, the impact of these factors on land degradation should be disentangled in human and natural induced causes in order to identify measures for intervention.

Accurate assessment of degradation is essential for estimating (potential) loss of ecosystem functioning and future consequences for humankind. Ye and Van Ranst (2009) for instance assessed loss of crop yield in China based on the GLASOD degradation assessment for Asia ASSOD (Van Lynden and Oldeman, 1997). Such assessments have inherent weaknesses, because they are derived from yield reduction factors based on expert judgements, on partial insight of adverse soil conditions on yield, and on statistical procedures that do not allow extrapolation over time nor in space.

The complexity of factors affecting land degradation calls for location-specific interventions to prevent or mitigate degradation or to rehabilitate degraded areas. The World Overview of Conservation Approaches and Technologies database (WOCAT, 2012) contains more than 450 soil and land management technologies and their corresponding implementation strategies based on field investigations in over 50 countries. It offers a unique standardized set for interventions for dissemination of best practices to field practitioners, decision-makers and policy-makers. Yet, the disconnection between the different levels of assessments and interventions remains to be overcome.

2. Methodology to link data sources and approaches to arrive at global assessments

Based on a review of degradation research Bindraban et al (2012) find that the methodologies that have been used over the past decades to assess degradation and the associated impact on ecosystem productivity reveal little consistency. Different methods leading to divergent outcomes can hardly be verified. We feel that it should be feasible to develop a comprehensive approach to better assess both extent and impact of soil degradation interlinking various scales. The increasing computational power, along with the availability of consistent long term remotely sensed information and increasing insights in production ecological processes provide a means to integrate and verify process-based approaches at ever higher spatial scale and resolution to more accurately assess both degradation and impact interlinking different scale levels. Interlinked with existing model-based environmental impact assessment models, such as IMAGE (Bouwman *et al.*, 2006) and GLOBIO (Alkemade et al., 2009), this approach could result in powerful tools to assess: 1) ecosystem degradation *per se* and its direct *in situ* impacts, and 2) associated off-site and indirect impacts, for example on water basin hydrology. The integrated nature of the IMAGE modelling suite allows to assess these impacts in isolation, as well as in a context of other processes in global change.

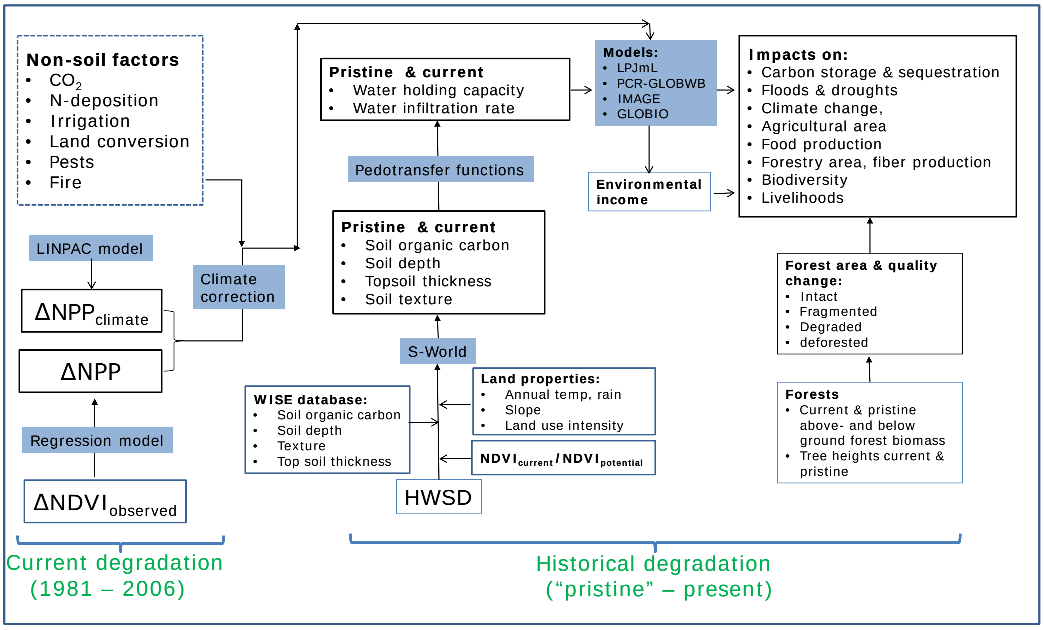

Figure 1. Flow diagram to interlink a range of methodologies to arrive at a comprehensive assessment of land degradation and impact on ecosystem functioning; 1) the current degradation assessments linking NDVI analyses and crop-soil modelling, 2) assessment of pristine and current soil properties, 3) assessment of forest cover and 4) integration in comprehensive models.

The methodology that is being developed by a consortium of institutes[1] comprises various analytical pathways to arrive at an objective and quantitative assessment of changes in soil characteristics, that in turn allows to quantify the impact on ecosystem functioning in combination with other environmental factors such as climate.

2.1 Disentangling natural and human induced causes of current degradation

To disentangle human and natural induced causes of land degradation Bai et al. (2012) and Conijn et al. (2012) integrated analytical methods for NDVI and crop-soil modelling. The impact of climatic variability on NDVI was, for instance, at first statistically adjusted (Bai et al., 2008). However, changes in climatic conditions, such as the total amount of rainfall in a seasons or temperature, may not proportionally affect biomass production. The combination of satellite-based estimation of NDVI and calculated total annual biomass based on long-term series of climatic data and constant crop and soil properties is used to disentangle the likely impact of climate from other causes on the observed trends in NDVI.

Consistent remotely senses NDVI, representing the greenness on the earth's surface, corrected for view geometry, volcanic aerosols, and other effects not related to vegetation cover, is available at 8km-spatial resolution for the period 1981-2006 (Bai et al., 2008). Total annual production of biomass is calculated for every year in the period 1981-2006 with the crop model LINPAC (Conijn et al., 2011; Jing et al., 2012) following production ecological principles (van Ittersum and Rabbinge, 1997) and refers to the rain-fed production level, i.e. optimum management but not irrigated, ample nutrient availability and free from pests, diseases and weeds. The model calculates biomass based on crop characteristics, soil and weather data: including soil texture, soil depth, soil water holding capacity, radiation, temperature, precipitation, vapour pressure and wind speed.

Time series of gridded weather data from the Climate Research Unit (CRU, 2011) were used as input with a resolution of 30x30 arc-minutes. Soil characteristics were obtained from the ISRIC-WISE v1.0 database (Batjes, 2006) in combination with the Digital Soil Map of the World from FAO with a resolution

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of 5x5 arc-minutes (FAO, 1996). The land use map of Erb et al. (2007) was used to estimate the crop land fraction with a resolution of 5x5 arc-minutes. The annual crop has been approximated by taking the characteristics of a wheat/maize crop as input (wheat for temperate and maize for tropical regions) and those of Miscanthus to represent perennial vegetation.

The changes in annual NDVI and biomass are compared at 5 by 5 arc-minutes resolution leading to four combinations. First, a positive NDVI and positive biomass change suggests that the improved greenness might be totally or partly explained by improved weather conditions as these are the cause for the increase in biomass. A relatively low positive NDVI change and high positive biomass change could even indicate that deteriorating conditions of e.g. soil and land use have had a negative effect on the vegetation, but have been masked by the larger positive effect of climatic changes. Second, positive NDVI and negative biomass change suggests that worsening climatic conditions decreased biomass but rather than an expected negative effect on NDVI, the greenness has improved. This might have possibly been caused by favourable interventions like irrigation, fertilization, increasing atmospheric CO2 concentrations, deposition of reactive nitrogen, or reforestation. Hence favourable human interventions or natural changes could have caused these combined trends. Third, negative NDVI and positive biomass change suggest that the greenness declines against a trend of expected positive change from climatic conditions. It is likely then that other factors such as deforestation or severe soil degradation have had a larger impact on the productivity. And Forth, negative NDVI and negative biomass change suggest that the decline in greenness may have resulted (partly) from worsening climatic conditions. Here a stronger decline in NDVI over biomass could also indicate a worsening of soil conditions or land use change, like deforestation.

2.2 Assessing pristine and current soil properties

Developing a geo-referenced database of world soil property layers for pristine and current situations (Stoorvogel et al., 2012) is important for our modeling effort. Global soil maps like the Harmonized World Soil Database (HWSD, FAO *et al.* (2009)) and databases with soil profile information like the WISE database (Batjes, 2009) provide an excellent starting point. In the last decades a wide array of additional auxiliary global environmental data on e.g., topography, land use and climate has become available to develop such spatial distribution of soil properties.

Four soil properties, important from a perspective of assessing productivity, were studied: organic matter in the topsoil, depth of the topsoil, soil texture of the soil profile, and soil depth. The ranges of the soil properties per soil type were assessed using the soil profile data from WISE. Four auxiliary landscape properties, i.e., slope, annual rainfall, average annual temperature, and land use intensity, were considered to be main driving factors for the variability in soil properties within the soil types. Correlation between the landscape properties and the soil properties were used to assess the global distribution of the soil properties. The methodology, denominated S-world (Soils of the World), resulted in global maps of the four soil properties. The basic formula in this procedure, performed at the grid cell level, is:

$$Soil_{LUI} = Soil_{low} + \Big(\big(Soil_{high} - Soil_{low}\big) * 0.01 * \Big(\big(f_{Temp} \times \omega_{Temp}\big) + \big(f_{Prec} \times \omega_{Prec}\big) + \big(f_{Slope} \times \omega_{Slope}\big) + \big(f_{LUI} \times \omega_{LUI}\big) \Big) \Big)$$

Where:

$Soil_{low}$	is the value of the 1st decile of a specific characteristic (organic C% of topsoil, thickness of topsoil, soil thickness, soil clay content) of this soil type in the WISE database;
$Soil_{high}$	is the value of the 9th decile of the same characteristic of this soil type in the database;
f_{Temp}	is a temperature factor;
f_{Prec}	is a precipitation factor;
f_{Slope}	is a slope factor;
f_{LUI}	is a land use intensity factor;
ω_{xxxx}	is the weight attributed to the effect of each parameter (temperature, precipitation, slope and land use intensity) on the soil characteristic based on expert judgement.

f_{Temp} , f_{Prec} and f_{Slope} are calculated as $(x-x_{low})/(x_{high}-x_{low})$, where x is the prevailing value of f_{Temp} , f_{Prec} or f_{Slope} in the grid cell and x_{low} and x_{high} are the 1st and 9th decile respectively of the same landscape property for this soil type in the WISE database. The land use intensity factor, $f_{LUI,}$ is set to 1.0 for crop land and 0.5 for mosaics of crop land and pasture or natural vegetation. For natural areas and pastures $f_{LUI,}$ is calculated as the ratio between actual and potential NDVI of each grid cell, where the potential NDVI was calculated using a frontier analysis, with temperature and precipitation as regression variables. Current soil properties are modeled by using current land use intensity, pristine conditions are modeled by setting the land use intensity at 0.

In early 2013 the accuracy of resulting maps of historical degradation and ongoing degradation will be tested by comparing them with location-specific data (Sonneveld et al., in development).

2.3 Assessing change in forest cover and carbon storage

Forest degradation was defined as a substantial reduction in tree cover density in comparison with potential density. Four classes of forest degradation were mapped (WRI, 2012):

- Intact forest landscapes (IFL), which show no signs of significant human activity.
- Fragmented forest which contain forest that is fragmented by roads and/or managed for wood production
- Degraded forest which contain forest with a lower tree canopy density than its potential density: Closed forest which have been transformed into open forest or woodland or open forest into woodland.
- Deforested lands – landscapes of forest with different potential density which have been converted into non-forest (canopy cover less than 10 percent).

On the basis of these forest degradation maps the associated loss of carbon has been calculated as the difference between the potential and the current carbon stock on these lands:

*Carbon loss = Area of degraded forest * (Potential carbon stock/ha – Current carbon stock/ha)*

An estimation of the loss of forest productivity in terms of C sequestration, fibre and timber is still in development.

2.4 Aggregated assessment of impact

The information thus generated in the various components can either be used directly in the integrated modelling suit, or after an interpretation via so-called pedo-transfer functions to calculate parameters such as water infiltration rate and plant available soil water holding capacity from basic soil characteristics. For example, changes in soil, land use and land cover induce changes in landscape hydrology which, with a one-day time step are captured by the GLOFRIS module of the PCR-GLOBWB model (Winsemius *et al.*, 2012) to calculate the incidence and risks of river floods. The LPJmL model (Bondeau *et al.*, 2007; Biemans *et al.*, 2011) uses the same information, to calculate crop yields and water use for irrigation. The comparison of NDVI and biomass calculation based on production ecological principles allows identification of location specific drivers for degradation or rehabilitation. IMAGE assesses the effects of CO_2 emissions on climate change and integrates all these results to calculate the required amount and location of different types of agricultural land to satisfy a given demand for food and other agricultural products for different socioeconomic scenarios. Additional coupling with an economic model (not included in Figure 1) such as LEITAP (Van Meijl *et al.*, 2006) could eventually provide an estimate of economic impacts on the prices of land and food, agricultural employment and GDP. The GLOBIO model will assesses the loss of biodiversity due to historical degradation which is only partly taken into accounted in its analyses for UNEP and the CBD, and will assess additional losses in the future due to loss of productive landscapes and consequent additional demand for land.

Furthermore, overlays of the results are being made with geo-referenced data on the proportion of rural incomes from agriculture, livestock or other activities that are directly dependent on ecosystem functioning. This information is being used to identify regions that are particularly vulnerable to ecosystem degradation and where livelihoods are most likely to be affected. Extrapolation of current degradation trends, could eventually be used as an early warning system to identify degradation hotspots, where pressure on the land could even lead to geopolitical insecurity.

3. Closing remarks

The methodology proposed aims to integrate both scientific insight from different disciplines and advance information technological means to arrive at a comprehensive assessment of degradation and its causes for identifying location-specific interventions measures. The results aimed at, especially those on restoration options, might be of direct relevance for the achievement of all three Rio conventions, as well as for achieving the Millennium Development Goals on food, water and energy security. Preliminary results will be orally presented and both the methodology and the results will be openly discussed to advance the approach. The consortium also calls upon interested parties to contribute to this global effort.

References

Alkemade, R., van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M. & ten Brink, B. 2009. GLOBIO3: A Framework to Investigate Options for Reducing Global Terrestrial Biodiversity Loss 2009. Ecosystems 12:3, 374–390.

Bai, Z.G., J.G. Conijn, P.S. Bindraban, B. Rutgers, 2012. Global changes of remotely sensed greenness and simulated biomass production since 1981. Towards mapping global soil degradation. ISRIC – World Soil Information, Wageningen. ISRIC Report 2012/02.

Batjes, N.H., 2009. Harmonized soil profile data for applications at global and continental scales: updates to the WISE database. Soil Use and Management 25, 124-127.

Bai, Z.G., D.L. Dent, L. Olsson, M.E. Schaepman, 2008. Proxy global assessment of land degradation. Soil Use Manage 24:223-234.

Biemans, H., I. Haddeland, P. Kabat, F. Ludwig, R.W.A. Hutjes, J. Heinke, W. von Bloh, D. Gerten, 2011. Impact of reservoirs on river discharge and irrigation water supply during the 20th century. Water Resour. Res. 47, W03509.

Bindraban, P.S., M. van der Velde, L. Ye, M. van den Berg, S. Materechera, D. Innocent Kiba, L. Tamene, K.V. Ragnarsdóttir, R. Jongschaap, M. Hoogmoed, W. Hoogmoed, C. van Beek and G. van Lynden, 2012. Assessing the Impact of Soil Degradation on Food Production. Current Opinion in Environmental Sustainability 4 (5): 478–488.

Bindraban, P.S., J.J. Stoorvogel, D.M. Jansen, J. Vlaming, J.J.R. Groot, 2000. Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance. Agriculture Ecosystem and Environment 81:103-112.

Bondeau, A., P.C. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. MÜLler, M. Reichstein, B. Smith, 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology 13, 679-706.

Bouwman, A.F., T. Kram, K. Klein Goldewijk (Eds.), 2006. Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency, Publication 500110002/2006, Bilthoven.

Conijn, J.G., Z.G. Bai, P.S. Bindraban, B. Rutgers, 2012. Global changes of net primary productivity, affected by climate effects and sudden changes since 1981. ISRIC Report 2013/xx (in prep.).

Conijn, J.G., E.P. Querner, M.L. Rau, H. Hengsdijk, J.W. Kuhlman, G.W. Meijerink, B. Rutgers, P.S. Bindraban, 2011. Agricultural resource scarcity and distribution. A case study of crop production in Africa. In Report 2011/380. Plant Research International, Wageningen.

CRU [University of East Anglia Climatic Research Unit], 2011. CRU Time Series (TS) high resolution gridded datasets, [Internet]. NCAS British Atmospheric Data Centre. Available from http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276. Accessed November 15, 2011

Dentener, F.J., 2006. Global maps of atmospheric nitrogen deposition, 1860, 1993 and 2050. Data set. Available online (http:// daac.ornl.gov/) from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, TN, 2006.

Erb, K.H., V. Gaube, F. Krausmann, C. Plutzar, A. Bondeau & H. Haberl, 2007. A comprehensive global 5 min resolution land-use dataset for the year 2000 consistent with national census data. Journal of land use science, 2, 191-224.

FAO, IIASA, ISRIC, ISSCAS, JRC, 2009. Harmonized World Soil Database (version 1.1). FAO and IIASA, Rome, Italy and Laxenburg, Austria.

Jing Q., S.G. Conijn, J.E.E. Jongschaap, P.S. Bindraban, 2012. Modeling the productivity of energy crops in different agro-ecological environments. Biomass and Bioenergy 46: 618-633.

Laestadius, L, S. Minnemeyer, A. Leach, (2012). Assessment of Global Forest Degradation. World Resources Institute, Washington.

Nowak, R.S., D.S. Ellsworth, S.D. Smith, 2004. Functional responses of plants to elevated atmospheric CO2—do photosynthetic and productivity data from FACE experiments support early predictions? New Phytol 2004, 162:253-280.

Oldeman, L.R., R.T.A. Hakkeling, W.G. Sombroek, 1991. World map of the status of human induced soil degradation. ISRIC/UNEP report 1991. Wageningen.

OECD, 2012. OECD Environmental Outlook to 2050.

Stoorvogel, J.J. , A.J.A.M Temme, M. Bakkenes, N. Batjes, J. Brandsma, 2012. Global mapping of soil properties and human induced changes: S-World 1.1. Soil Geography and Landscape Group, Wageningen University, Wageningen.

PBL (2010). Rethinking Global Biodiversity Strategies. Bilthoven, Netherlands Environmental Assessment Agency, Publ. no. 500197001.

UNEP, 2011. Global Environment Outlook 5. UNEP, Nairobi.

Van Meijl, H., T. van Rheenen, A. Tabeau, E. Eickhout, 2006. The impact of different policy environments on agricultural land use in Europe. Agriculture, Ecosystems & Environment 114, 21-38.

Van Ittersum, M.K., R. Rabbinge, 1997. Concepts in production ecology for analysis and quantification of agricultural input–output combinations. Field Crops Res. 52:197-208.

Van Lynden, G.W.J. and L.R. Oldeman, 1997. The Assessment of the Status of Human-Induced Soil Degradation in South and Southeast Asia. Wageningen, The Netherlands: United Nations Environment Program (UNEP), Food and Agricultural Organization of the United Nations (FAO), International Soil Reference and Information Centre (ISRIC).

Winsemius, H. C., L.P.H. van Beek, B. Jongman, P.J. Ward, A. Bouwman, 2012. A framework for global river flood risk assessments, Hydrology and Earth System Sciences Discussions, 9(8), 9611–9659, doi:10.5194/hessd-9-9611-2012, 2012.

WOCAT, 2012. World Overview of Conservation Approaches and Technologies. Conservation-approaches-and-technologies-WOCAT. https://www.wocat.net/

Ye L. and E. Van Ranst, 2009. Production scenarios and the effect of soil degradation on long-term food security in China. Global Environ. Change 2009, 19:464-481.