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The global loss of net primary production resulting from human-induced soil degradation in drylands

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Verfasser:	Michael Zika
Matrikel-Nummer:	9605376
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Betreuer:	Ao. Univ.-Prof. Dr. Helmut Haberl

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Vorwort und Danksagung

Die Idee zu dieser Arbeit ist durch meine Zusammenarbeit mit dem Institut für Sozial Ökologie, IFF Wien, der Universität Klagenfurt entstanden. Unter der Leitung von Helmut Haberl wurde damals das Projekt „Global HANPP“ bearbeitet, in welchem die weltweite menschliche Aneignung von Primärproduktion (‘Human Appropriation of Net Primary Production’, kurz HANPP) berechnet wurde. Ich erstellte für dieses Projekt einen internen Bericht über Auslöser und Auswirkungen von Degradation und Desertifikation und präsentierte bestehende Datenbanken, wichtige Publikationen und Zusammenhänge von Degradation auf natürliche Produktivität. Aus diesem Bericht wurde gemeinsam mit Karlheinz Erb und Helmut Haberl das Thema der vorliegenden Arbeit entwickelt. Die Arbeit hat im Endeffekt weit länger gedauert als erwartet, jedoch hat sie mir umfassende Einblicke in menschliche Interaktion mit Ökosystemen geliefert. Degradation bzw. Desertifikation sind wohl zwei der interessantesten und herausforderndsten Forschungsgebiete der nächsten Jahre, die eng mit anderen globalen Umweltveränderungen verknüpft sind und somit einen wesentlichen Teil der humanökologischen Forschungsfelder betreffen.

Die Arbeit ist auf Englisch verfasst und soll als Basis für eine Publikation in einem Fachjournal dienen, welche unmittelbar nach Beendigung der Diplomarbeit angestrebt wird. Um einen detaillierteren Einblick in die Methodik und einen genaueren Überblick über die erhaltenen Ergebnisse zu ermöglichen, liegt der Arbeit ein ANNEX bei, der den Rahmen einer wissenschaftlichen Publikation sprengen würde. Der letzte Teil des Annexes ist ein Poster, welches ich vor einem Jahr auf zwei wissenschaftlichen Kongressen präsentiert habe.

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Inhaltsverzeichnis

Vorwort und Danksagung ... i
Inhaltsverzeichnis ... iii
Abbildungsverzeichnis ... v
Tabellenverzeichnis ... vi
Abstract ... 1
Deutsche Kurzfassung ... 2
1 Introduction ... 9
2 Data and Methods ... 12
2.1 Desertification extent ... 13
2.2 Modeling NPP losses ... 14
3 Results ... 17
3.1 Extent of soil degradation in drylands ... 17
3.2 Net Primary Production losses on desertified areas ... 21
4 Discussion and Conclusion ... 24
References ... 32
Annex A – Methods and Databases ... 43
A.1 Defining desertification ... 43
A.2 Desertification and HANPP ... 46
A.3 Degradation datasets ... 47
A.3.1 GLASOD ... 48
A.3.2 ASSOD ... 49
A.3.3 SOVEUR ... 51
A.3.4 Soil degradation in Russia ... 52
A.3.5 Human-induced soil degradation in Mexico ... 53
A.3.6 Land degradation in South Africa ... 53
A.3.7 Desertification Map of the Drylands of Asia ... 55
A.4 Modeling Net Primary Production losses ... 56
A.4.1 Minimum and maximum estimates ... 56
A.4.2 The “Best guess” estimate ... 57
Annex B – Results ... 62
B.1 Additional Tables ... 62

B.2 Additional Figures 76
Annex C – Poster 80
References 81
Curriculum Vitae 89

Abbildungsverzeichnis

Figure 1. Extent of degraded areas of COMSAD in percent per gridcell 19
Figure 2. Global net primary production loss due to soil degradation in drylands. 22

Figure B 1. Desertification datasets used to update GLASOD map to form ....
COMSAD map 76
Figure B 2. Desertification extent per gridcell of the four degrees in COMSAD: ....
light degree (a), moderate degree (b), strong degree (c) and extreme degree (d) 77
Figure B 3. Desertification extent of COMSAD-LU (COMSAD map ....
with land-use datasets) used for the 'best guess' estimate 77
Figure B 4. Maps of NPP losses of the minimum-maximum estimates. 78
Figure B 5. Map of NPP losses of the 'best guess' ....
expressed in carbon flows with a high value of 525 g C/m²/yr 78
Figure B 6. Maps of NPP losses of the 'best guess' estimate ....
separated by land-use classes. 79

Tabellenverzeichnis

Table 1. Productivity losses according to literature surveys and ....
own assumptions used in this study. 15
Table 2. Comparison of the soil degradation maps GLASOD, ...
COMSAD and COMSAD-LU 18
Table 3. Extent of dryland degradation within COMSAD classes ....
of degradation degrees 20
Table 4. Detailed breakdown of absolute net primary production ....
calculations with regard to climate zones 21
Table 5. Net primary production losses per dryland area, regional breakdown....................... 23
Table 6. Area related NPP losses ('best guess') on grazing land ....
and on cropland, regional breakdown 24
Table 7. Regional breakdown of NPP losses due to desertification ....
in relation to NPP_0 and HANPP 25

Table A 1. Classification of the Humidity Index 45
Table A 2. Matrix of the parameter "Impact" used in ASSOD... 50
Table A 3. Modifications of ASSOD database. 51
Table A 4. Classification of degradation extent after Hoffman *et al.* (1999). 54
Table A 5. Productivity losses estimated by Dregne and Chou (1992) ....
and the modified values used in this study.. 57
Table A 6. Comparison of literature-based productivity losses ....
and NPP losses used in this study 59
Table A 7. Datasets used in this assessment 60
Table A 8. Countries including dryland regions and the definition ....
of regions used in this assessment... 61

Table B 1. National calculations of degraded areas in COMSAD ....
and in COMSAD-LU 62
Table B 2. National calculations of NPP losses expressed as ....
carbon flows and as percentage of potential NPP 67
Table B 3. National calculations of land-use related 'best guess' estimates............................ 71

Abstract

This study presents a global estimate of net primary production (NPP) losses due to human-induced desertification. Only few quantitative data on NPP losses resulting from desertification are available so far, and quantifying them is not facilitated by the fact that there are large discrepancies in the scientific literature on the extent and impact of desertification, suggesting the existence of considerable uncertainties. As a first step, I compiled the best available geographical information system (GIS) datasets on the extent and severity of degradation to obtain a desertification map that was then used for all further calculations. Desertification-induced NPP losses were calculated by applying a set of factors depending on the extent and severity of desertification in each grid cell. The NPP loss factors were derived from a literature survey and from own calculations. In order to consider uncertainties I derived minimum and maximum estimates reflecting possible errors in the available input data. The results of the minimum and maximum estimates were compared with a ’best guess’ estimate, which was refined with recent socio-economic data. My ‘best guess’ is that desertification results in an overall loss of 965 Tg C/yr with a possible range of 799-1936 Tg C/yr. This means that between 4% and 10% of potential productivity (NPP_0) in drylands is lost due to human activities like overgrazing and agricultural mismanagement. However, results are varying considerably within land-use classes (5% in grazing areas, 14% in croplands) and regions (up to 19% of NPP_0 in Eastern and South-Eastern Europe). I give detailed information on the human overuse on limited agricultural areas in drylands and discuss future implications for food-security and land-use change scenarios. All datasets are available in 5 arc minutes gridcells and can be downloaded at http://www.uni-klu.ac.at/inhalt/1088.html.

Deutsche Kurzfassung

Die vorliegende Arbeit präsentiert eine weltweite Abschätzung von Verlusten an Nettoprimärproduktion (NPP) durch menschlich verursachte Desertifikation. Desertifikation wird hier gemäß der UNCCD (United Nations Convention to Combat Desertification) definiert, welche Desertifikation als Degradation in Trockengebieten, und somit in ariden, semi-ariden und trocken sub-humiden Gebieten festlegt. Gemäß dieser Konvention ist Degradation ein permanenter Verlust der natürlichen Produktivität resultierend aus menschlichem Einfluss oder klimatischen Bedingungen.

Um den menschlichen Einfluss auf den Produktivitätsverlust durch Desertifikation zu quantifizieren, wird in dieser Arbeit das Konzept der „menschlichen Aneignung von Nettoprimärproduktion“ (HANPP) verwendet. Nettoprimärproduktion (NPP) ist die jährlich produzierte Nettoenergie, die von Pflanzen durch Photosynthese produziert wird und als Nahrungsgrundlage für Organismen höherer Trophieebenen zur Verfügung steht. Der Mensch verändert diese Energieflüsse durch Biomasseentnahme (NPP_h) oder Landnutzungsänderungen (ΔNPP_{LC}). Während frühere Studien den Produktivitätsverlust von Bodendegradation meist durch Ernteverluste oder durch ökonomische Verluste quantifizierten, stellt diese Studie den Verlust an potentieller NPP als zentralen Teil der ΔNPP_{LC} dar und berechnet somit den direkten menschlichen Eingriff in Ökosysteme.

Um den Fokus dieser Arbeit auf die Auswirkung des Menschen zu legen wurde Desertifikation hier als Bodendegradation festgelegt. Bodendegradation hat einen direkten Effekt auf bestimmte Basisfunktionen in Ökosystemen wie die Nährstoffverteilung und die Wasserversorgung und kann somit direkt die NPP verringern. Im Gegensatz dazu ist Vegetationsdegradation in Trockengebieten oftmals ein Resultat aus kurzfristigen klimatischen Änderungen. Die hohe Dynamik in trockenen Ökosystemen zeigt unmittelbare Auswirkungen bezüglich des wichtigsten Faktors in Trockengebieten, dem Niederschlag. So kann es während Trockenzeiten zu einer raschen Abnahme der NPP kommen, die vielfach als menschliche Misswirtschaft ausgelegt wird. In darauffolgenden Niederschlagsperioden kann sich die Vegetation dann oftmals rasch wieder erholen, wenn der Boden nicht schwerwiegend degradiert ist. Ein weiterer Grund, warum Vegetationsdegradation hier nicht berücksichtigt wird, ist der Fakt, dass sie häufig durch eine veränderte Biodiversität definiert wird, wie etwa

durch Verbuschung in Grasländern. Diese veränderten Pflanzengesellschaften können den ökonomischen und den ökologischen Wert in Ökosystemen mindern, müssen jedoch nicht die Gesamtproduktivität ändern.

Als Grundlage für diese Berechnung des NPP-Verlustes wird eine GIS-Karte über Ausmaß und Ausdehnung von Bodendegradation in Trockengebieten erstellt. Der Basisdatensatz dieser GIS-Karte ist GLASOD (Global Assessment of Soil Degradation), der einzige global verfügbare Datensatz von Bodendegradation. Um der häufigen Kritik an GLASOD bezüglich Subjektivität, Überschätzung und Ungenauigkeit entgegenzuwirken und um die Aktualität der Daten zu erhöhen (GLASOD wurde vor etwa 20 Jahren erhoben), wurden aktuellere, regional verfügbare Datensätze für folgende Regionen und Länder in GLASOD integriert:

- Süd- und Südostasien
- Ost- und Südost-Europa
- Zentral- und Ost-Asien und die Arabische Halbinsel
- Russland
- Südafrika
- Mexiko

Die neu zusammengesetzte GIS-Karte wurde mit einem etablierten Klima-Index („Humidity Index“ oder auch „Aridity Index“) verschnitten, um den Fokus auf aride, semi-aride und trocken sub-humide Gebiete legen zu können. Dieser neu arrangierte Desertifikations-datensatz wird in Folge als COMSAD („Compiled Map of Soil Degradation Assessments in Drylands“) bezeichnet. Um die Verluste von NPP durch Desertifikation zu berechnen wurden die Informationen von Degradationsgrad und Degradationsfläche der COMSAD Karte mit potentiellen NPP-Daten (NPP_0) des Lund-Potsdam-Jena Modells, einem dynamischen globalen Vegetationsmodell, kombiniert. Die Unsicherheiten bezüglich der Datengrundlagen sollen mittels einer Minimum- und einer Maximum-Berechnung abgeschätzt werden. Für beide Berechnungen wurden verschiedene Produktivitätseinbußen von NPP_0 durch Degradationsprozesse angenommen. Um die wahrscheinlichste Abschätzung an NPP-Verlusten innerhalb dieser Minimum-Maximum-Spanne einschätzen zu können, wurde eine sogenannte ‘best guess’ Berechnung durchgeführt. In dieser bestmöglichen Abschätzung werden die Berechnungen ausschließlich auf Acker- und Weideflächen durchgeführt. Die Ausdehnung dieser landwirtschaftlichen Flächen wird durch einen jüngst publizierten Landnutzungsdatensatz ermittelt und durch statistische Informationen bezüglich der aktuellen

Produktivität ergänzt. Alle GIS-Karten wurden in 5x5 Minuten Rasterzellen (ca. 10 km am Äquator) umgewandelt, um eine räumlich explizite Karte an NPP-Verlusten zu erhalten.

Die Ergebnisse der Datenaggregation zeigen, dass sich die Desertifikationsflächen um 15% gegenüber der Basiskarte GLASOD erhöht haben und somit eine Fläche von 11,8 Mio. km² umfassen. Dies entspricht 23% der globalen Trockengebiete. In manchen Regionen wie Ost- und Südost-Asien erhöhte sich die Fläche durch die aktuelleren Datensätze um über 50% gegenüber dem Basisdatensatz GLASOD. Die meisten degradierten Flächen sind in der semi-ariden Zone zu finden, welche auch den größten Anteil an weltweiten Trockengebieten hat (44% der Gesamtfläche). Es ist nicht nur eine klimatische Variabilität, sondern speziell eine regionale und lokale Variabilität von Desertifikation festzustellen. Ost- und Südost-Europa und Südost-Asien sind jene Regionen, die die größten Flächen an Desertifikation im Verhältnis zu ihren Trockengebieten aufweisen (55% und 45%), während die größten absoluten degradierten Flächen in Afrika südlich der Sahara und in Zentralasien inklusive Russland zu finden sind. Auffallend ist, dass das weltweite Ausmaß der Degradierung hauptsächlich durch die qualitativen Kriterien „leicht degradiert“ und „mäßig degradiert“ beschrieben werden kann. Beide Kriterien zusammen umfassen etwa 80% der gesamten degradierten Fläche, während die Kriterien „stark degradiert“ und „äußerst stark degradiert“ nur in Zentralasien und Russland dominant sind.

Bei der Einbeziehung von Landnutzungsdatensätzen in der ‘best guess’ Berechnung kommt es zu einer signifikanten Reduktion der Desertifikationsflächen von 2,3 Mio. km², der Hauptanteil davon in den ariden Gebieten. Ein Großteil der Flächen geht durch die Berücksichtigung von Wildnisgebieten verloren, die keinen menschlichen Einfluss aufweisen, und Flächen, deren natürliche Produktion unter einem Schwellenwert von menschlich nutzbarer Produktivität liegt. Bei der Verschneidung der degradierten Flächen mit landwirtschaftlich genutzten Flächen wird eine mögliche Inkonsistenz der COMSAD mit den Acker- und Weideländern des Landnutzungsdatensatzes sichtbar. In Rasterzellen, die eine höhere Desertifikation als Agrarfläche auswiesen, wurde die Desertifikation auf die maximal vorhandene landwirtschaftliche Fläche reduziert. Diese Unregelmäßigkeiten entsprechen etwa 4% der COMSAD.

Die Ergebnisse der NPP-Verluste zeigen, dass weltweit etwa 965 Tg C pro Jahr durch Desertifikation verloren gehen, mit einer möglichen Breite von 799 Tg C bis 1973 Tg C pro

Jahr. Das entspricht einem Verlust von rund 5% der potentiell natürlichen NPP in Trockengebieten. Deutlich zu sehen sind auch hier die regionalen Unterschiede. Während einzelne Gebiete in Zentralasien und Russland Verluste von bis zu 85% der NPP_0 aufweisen, zeigen die Abschätzungen, dass in den meisten Gebieten die Verluste zwischen 0% und 5% liegen. Der Asiatische Kontinent ist mit über 50% des globalen NPP Verlustes besonders betroffen. Die Regionen im östlichen und südöstlichen Europa und auch im südöstlichen Asien zeigen den größten Verlust in Trockengebieten mit 103 g C/m²/a bzw. 94 g C/m²/a bei der bestmöglichen Abschätzung (‘best guess’). Im Vergleich dazu scheinen die Verluste in Nordamerika und Australien mit ihren weitläufigen Flächen an Trockengebieten mit unter 10 g C/m²/a eher gering.

Bei der bestmöglichen Abschätzung ist durch die separate Berechnung der NPP-Verluste in Agrarflächen und Weideländern ein deutlicher Unterschied der NPP-Verringerung in verschiedenen Landnutzungsklassen sichtbar. Obwohl beide landwirtschaftlichen Nutzungen fast eine idente Menge an absolutem NPP-Verlust aufweisen, muss berücksichtigt werden, dass die degradierten Ackerflächen nur etwa 26% der degradierten Gebiete ausmachen. Daraus folgt ein NPP-Verlust von 14% der NPP_0 in Ackerländern und ein Verlust von etwa 5% der NPP_0 in Weideflächen. Den höchsten Verlust in Ackerländern pro Fläche weist Süd-Asien mit 197 g C/m²/a auf, während diese Landnutzungsklasse in Ostasien (China und Mongolei) mit einer Reduktion von etwa 2 g C/m²/a oder 1% der NPP_0 kaum betroffen ist. In beiden Landnutzungsklassen zeigen sich die höchsten prozentuellen Verluste in Südost-Europa mit 29% auf Ackerflächen und 11% der potentiellen Primärproduktion auf Weideflächen.

Vergleicht man diese Ergebnisse mit früheren globalen Abschätzungen, zeigt sich ein deutlich geringerer Verlust als in anderen Untersuchungen angenommen. Ein Verlust von 5% der potentiellen NPP in Trockengebieten bedeutet einen eher moderaten Einfluss des Menschen in trockenen Ökosystemen, jedoch muss man die starke regionale und sub-regionale Variabilität berücksichtigen. Die resultierende GIS-Karte und auch eine makrogeographische Analyse zeigen deutlich, dass in verschiedenen Gebieten beträchtliche Mengen an natürlicher Produktivität durch Übernutzung und Überbeanspruchung von landwirtschaftlichen Flächen verloren gehen. Im Vergleich mit regionalen HANPP-Berechnungen wird augenscheinlich, dass der Mensch mit unterschiedlicher Effizienz in Ökosysteme eingreift. In Zentralasien und Russland geht beispielsweise ein mäßiger bis hoher Anteil an natürlicher Produktivität verloren. Betrachtet man den relativ geringen HANPP-Wert in dieser Region, zeigt sich, dass bei dieser ohnehin gering genutzten natürlichen Produktivität etwa ¼ durch menschlich verursachte Desertifikationsprozesse verloren geht. Ähnliche Bilder ergeben sich für Nordafrika, Subsahara-Afrika und für die Arabische Halbinsel, wenngleich die NPP-Verluste durch Desertifikation einen etwas geringeren Anteil an HANPP aufweisen. Ost- und Südost-Europa, die Region mit den höchsten Verlusten an potentieller NPP und den höchsten Verlusten pro Fläche, weist ebenfalls einen deutlichen Anteil der Desertifikation an der gesamten HANPP mit über 10% auf. Im Gegensatz dazu sieht man bei den hoch industrialisierten Regionen wie Nordamerika, Australien und Westeuropa einen deutlichen geringeren Anteil der NPP-Verluste durch Desertifikation an HANPP. In Westeuropa ist der Verlust der potentiellen Produktion in Trockengebieten, der mehr als das weltweite Mittel beträgt, vor allem ein regionales Problem, das sich in erster Linie auf die iberische Halbinsel konzentriert. Auch in asiatischen Regionen ist ein geringer Anteil der NPP-Auswirkungen aufgrund von Desertifikation im Verhältnis zu HANPP sichtbar. Jedoch zeigt etwa Südost-Asien, dass NPP-Verluste durch Desertifikation zwar nur etwa 1% der HANPP betragen, aber die Trockengebiete deutlich beeinträchtigen, da diese nur einen äußerst geringen Flächenanteil von 2% haben. Südost-Asien weist sowohl bei Verlust pro Fläche als auch bei prozentuellem Verlust der natürlichen Produktivität den zweitgrößten Wert nach Ost- und Südost-Europa auf. Das zeigt die regionale Problematik von Desertifikation. Obwohl HANPP in dieser Region offensichtlich durch Ernte (NPP_h) oder durch Landnutzungsänderungen in humideren Gebieten geprägt ist, führen Desertifikationsprozesse zu einer deutlichen Verringerung (etwa 12%) der natürlichen Produktion in Trockengebieten.

Den regionalen Unterschieden des NPP-Verlustes liegen verschiedene Ursachen und Belastungen zugrunde. Als Hauptursache gilt die Landwirtschaft. Durch unterschiedliche Verfügbarkeiten und Beschaffenheiten von natürlichen Ressourcen wie Boden und Wasser und durch unterschiedliche Belastungen zeigen sich verschiedene Desertifikationsprozesse. Diese Prozesse können wie folgt gruppiert werden: Wind- und Wassererosionen, chemische Beeinträchtigungen wie etwa Versalzungsprozesse und auch physikalische Beeinträchtigungen, wie z.B. Bodenverdichtungen. In Südost-Europa und auch im europäischen Teil Russlands wurden während der kommunistischen Ära im 20. Jahrhundert große Mengen an chemischem Dünger und schwere Maschinen zur Bewirtschaftung eingesetzt. Daraufhin kam es zu Bodenverdichtungen und Kontaminationen. Durch diese Degradationsprozesse wurde die Bewirtschaftung teilweise eingestellt, woraufhin sich die

Produktivität weiter reduzierte. In anderen Gebieten, wie z.B. in Nordafrika und West-Asien, kam es durch intensive Bewässerung zu Versalzungsprozessen und Erosionen durch Wind und Wasser. In Ostasien wiederum ist Überweidung die Hauptursache für Bodendegradation und den daraus resultierenden NPP-Verlust. Aber auch hier wurden Agrarflächen aufgrund von Erosionsprozessen aufgelassen, die durch Überbeanspruchung und ungenügenden Ausgleich durch Düngemittel entstanden sind. Im Wesentlichen können die Ursachen auf die starke Ausbreitung von landwirtschaftlich genutzten Flächen zurückgeführt werden, die dann von Übernutzung, mangelndem Einsatz von Düngemitteln als Nährstoffersatz und nicht nachhaltiger Biomasseentnahme geprägt sind.

Um in Zukunft die wachsende Bevölkerung ausreichend mit Nahrung zu versorgen, ist es notwendig, zusätzliche landwirtschaftlich nutzbare Flächen zu erschließen oder die Effizienz bestehender Flächen zu erhöhen. Um die Erschließung neuer Agrarflächen auf Kosten von anderen Ökosystemen einzudämmen, sollte der Schwerpunkt in der Effizienzerhöhung liegen. Diese kann einerseits durch eine bessere Verwertung von bisher ungenutzter, aber entnommener Biomasse oder durch eine adäquate Zufuhr von Nährstoffen erfolgen. Zusätzlich könnten bereits degradierte Flächen rehabilitiert werden um die Produktivität, die verloren gegangen ist, wieder für den Menschen nutzbar zu machen. Diese Verluste können durch die durchgeführte Berechnung der NPP sichtbar gemacht werden und geben in Zusammenhang mit dem Indikator HANPP eine wertvolle Einschätzung über mögliche zukünftige Landnutzungsentwicklungen.

Hierbei ist jedoch wichtig, in Zukunft neuere regionale Datensätze über Ausmaß und Konsequenzen von Desertifikation zu entwickeln, um sie mit globalen NPP-Datensätzen aus Modellierungen oder Fernerkundung zu kombinieren. Mittels globaler, GIS-basierter Studien wie dieser können regionale Unterschiede verglichen werden und Erfahrungen von negativen Entwicklungen bestehender Bodendegradationen in noch nicht betroffenen Regionen eingebracht werden. Jedoch ist regionales und lokales Wissen über biophysikalische und sozio-ökonomische Faktoren unerlässlich, um gewisse Trends in globalen Modellen zu interpretieren. Dies trifft speziell auf Afrika zu, wo in Zukunft ein enormer Zuwachs an landwirtschaftlichen Flächen prognostiziert wird. Durch die Aneignung von entsprechendem Know-how und Zugang zu Ressourcen kann eine positive Entwicklung gefördert werden, um eine entsprechende Nahrungssicherheit zu gewährleisten.

1 Introduction

Land-use and land-cover change strongly affect patterns and processes in global ecosystems. Humans dominate, transform and modify ecosystems in order to obtain ecosystem services and goods (Turner II *et al.*, 1990; Vitousek *et al.*, 1997). While these human activities support human well-being and economic development, they also alter biogeochemical cycles and ecosystem functions, and result in biodiversity loss (DeFries *et al.*, 2004; Gitay *et al.*, 2002; Millennium Ecosystem Assessment, 2005a). The ongoing land-cover changes resulting from the conversion of natural land to agricultural areas and intensification of croplands ensure the growing demand for food, feed, fiber and recently the supply of biofuel. However, these increasing needs, ensuing from the growing population and world economy, often result in degradation and desertification due to agricultural intensification on croplands and overgrazing on pasture lands (Foley *et al.*, 2005; Le Houérou, 2002).

Desertification has been identified as a major symptom of land-use and land-cover processes (Asner *et al.*, 2004; Lepers *et al.*, 2005) taking place in drylands all over the world that cover about 41% of terrestrial land area (Millennium Ecosystem Assessment, 2005b). Desertification and its definition are highly debated in the scientific community (Reynolds and Stafford-Smith, 2002; Thomas, 1997). I here follow the well-established definition of the United Nations Convention to Combat Desertification (UNCCD), which defines desertification as *"land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities"* (United Nations, 1994, p.4). Furthermore in regard to the convention, land degradation means a temporary or permanent reduction of the biological productivity of ecosystems including human-induced alteration of soil and vegetation structure.

Desertification has a variety of socioeconomic and biophysical consequences, ranging from local to global scales (Reynolds *et al.*, 2007). Previous global studies share serious concern about the effects of desertification on sustainability, by giving estimates on the extent and dynamics of this phenomenon (Dregne, 1983; Dregne and Chou, 1992; Mabbutt, 1984). However, all these assessments vary greatly in definition, and are frequently not based on measured data but rather on local experience, guesses, personal opinions and anecdotal evidence (Thomas and Middleton, 1994). The most comprehensive assessment of the extent, degree, severity, causes and rates of global degradation is the GLASOD database (Oldeman *et al.*, 1991), referring to the year 1988 and based on a plethora of expert knowledge. GLASOD estimated that about 20% of global drylands are degraded, whereas the other assessments estimated that up to 70% of the global drylands are subjected to desertification. A desktop study in the context of the Millennium Ecosystem Assessment (MA) estimated an overall desertification extent of 10% of the assessed dryland area including hyper-arid areas (Lepers *et al.*, 2005). In the review by Safriel *et al.* (2005), the most likely global desertification extent is estimated to be within the range of 10-20% of the global terrestrial surface. It becomes evident that these discrepancies in the extent of desertification hamper systematic analyses of the consequences of desertification for ecosystem functioning or for the ability of ecosystems to provide services to human society. Both are urgent challenges in current land use research (Foley *et al.*, 2005; Millennium Ecosystem Assessment, 2005a).

This study aims to provide a spatially explicit estimate of the human impact on net primary production (NPP) resulting from soil degradation in global dryland ecosystems. NPP is determined by the supply of nutrients and water provided by soils; thus, soil degradation has detrimental effects on these functions and thus lowers the NPP of ecosystems (Blum, 1998; Lal and Stewart, 1990; Nabhan *et al.*, 1999; Safriel, 2007). According to the UN definition, desertification also encompasses changes in vegetation structure. However, such alterations are often short-term dynamics depending on fluctuations of precipitation, in particular in the semiarid zone (Cao and Woodward, 1998; Herrmann *et al.*, 2005; Le Houérou *et al.*, 1988; Prince *et al.*, 1998; Ramankutty *et al.*, 2006; Reynolds and Stafford-Smith, 2002; Sala *et al.*, 1988; Wessels *et al.*, 2007). In areas where soil degradation is not serious, vegetation can recover soon after precipitation (Ayoub, 1998), thus desertification can only be defined as a persistent reduction of biological productivity within a given ecosystem (Prince, 2002; Safriel, 2007). Furthermore, vegetation degradation affects mainly plant composition (Hoffman *et al.*, 1999; Kharin, 2002). For example, shrub encroachment in grasslands may deteriorate the economic and nutritional value of grassland ecosystems (Asner *et al.*, 2004), but does not necessarily result in reductions of NPP, as previous studies showed (Huenneke *et al.*, 2002; Jobbágy and Sala, 2000; Schlesinger *et al.*, 1990). Therefore, the focus of this research was set on soil degradation in drylands, which is also termed hereafter as desertification.

Soil degradation can significantly alter terrestrial NPP. NPP is a central parameter of ecosystem functioning and a fundamental supporting ecosystem service (Daily *et al.*, 1997; Ito and Oikawa, 2004; Millennium Ecosystem Assessment, 2005a; National Research Council, 2000). It is defined as the net energy produced by green plants through photosynthesis available each year for transfer to other trophic levels. NPP plays an important role in the global carbon cycle (IGBP Terrestrial Carbon Working Group, 1998) and is an essential resource for society, providing food, feed and fiber (Haberl *et al.*, 2001; 2007; Imhoff *et al.*, 2004; Krausmann *et al.*, 2008).

A well-established measure of human impact on net primary production is HANPP, an abbreviation for “human appropriation of net primary production” (Haberl, 1997; Haberl *et al.*, 2004; 2007; Vitousek *et al.*, 1986; Wright, 1990). HANPP is the sum of harvested biomass (NPP_h) and land–used induced productivity changes including soil degradation (ΔNPP_{LC}) (Haberl *et al.*, 2004; 2007). ΔNPP_{LC} is calculated as the difference of potential net primary production (NPP_0) and the actual prevailing vegetation (NPP_{act}). In their pioneer work, Vitousek *et al.* (1986) estimated the contribution of desertification to HANPP at 2.25 Pg C/yr, a major component of ΔNPP_{LC} and therefore of HANPP. The aim of this study is to derive the most likely current magnitude and pattern of ΔNPP_{LC} stemming from desertification, along with an estimate of the uncertainty range, using best available Geographical Information System (GIS) datasets and, where appropriate, statistical land use datasets.

In order to calculate NPP losses caused by desertification in a spatially explicit manner, I carried out a GIS analysis at 5 minutes geographical resolution (approximately 10x10 km at the equator). I used existing maps to derive a world map of the extent and degree of desertification, combining this information with model results on global potential productivity (Haberl *et al.*, 2007), using the Lund-Potsdam-Jena dynamic global vegetation model (LPJ-DGVM) (Gerten *et al.*, 2004; Sitch *et al.*, 2003). In order to consider uncertainties, I derived minimum and maximum estimates, based on different assumptions about degradation effects on NPP, and compared these calculations with an estimate using statistical information on the current productivity of croplands (Haberl *et al.*, 2007) and spatially explicit land-use datasets (Erb *et al.*, 2007).

The findings of the present study were compared to the results of NPP loss due to desertification by Vitousek *et al.* (1986) and to the results of HANPP calculated by Haberl *et al.* (2007). I further analyzed the map of NPP losses regarding regional variations and different land-use and land cover changes. Further developments of agricultural systems in drylands and the ongoing debate on food security in developing countries are discussed in connection with productivity losses.

2 Data and Methods

In my attempt to calculate the effect of soil degradation on NPP in dryland ecosystems in a spatially explicit manner, I created a new gridded map of global desertification on the basis of a global dataset and publicly available regional databases on degradation. In order to derive this desertification map used for all further calculations (in the following referred to as COMSAD, abbreviated for "COmpiled Map of Soil degradation Assessments in Drylands") I followed the definition by Middleton and Thomas (1997) for dryland zones as discussed below in more detail. The COMSAD dataset contains information about the extent and the degree of desertification. Extent refers to the area subjected to desertification within each gridcell (percent of the total area). Degree gives information on the grade of desertification, thus, four degree levels of desertification (light, moderate, strong, extreme) were distiguished. The calculations of NPP losses due to desertification were based on assumptions on the effect of desertification on NPP according to these four degree levels. Two sets of assumptions were used in order to get a minimum and maximum estimate. Using spatially explicit datasets on the current global productivity of cropland (Haberl *et al.* 2007), a "best-guess" calculation was performed in order to reflect data uncertainties in input data.

All calculations were performed on a global 5 arc min grid. The analyses were carried out on macrogeographical (continental) regions and geographical sub-regions as defined by UNSD (2006) (Table A8).

2.1 Desertification extent

The basis of the calculations is the generation of the COMSAD map. This map was generated by using information of the GLASOD database (Oldeman *et al.*, 1991) and refining it with newly available, spatially explicit information on soil degradation. Despite some criticisms concerning overestimation and subjectivity (e.g. Warren and Olsson, 2004) I relied on GLASOD, because it is currently the only comprehensive dataset on soil degradation with global coverage (Dregne, 2002). In order to overcome at least some of the potential problems of GLASOD (Oldeman and van Lynden, 1998; Olsson, 1993; Sonneveld and Dent, in press), I used it as a base map and updated it with the following more recent regional maps (Table A7):

- South and Southeast Asia: *"ASSOD - Assessment of the Status of Human-Induced Soil Degradation in South and Southeast Asia" (van Lynden and Oldeman, 1997)*
- Central and Eastern Europe: *"SOVEUR - Soil Vulnerability Assessment in Central and Eastern Europe" (van Lynden, 2000)*
- Central Asia and Arabian Peninsula: *"Desertification map of Asia" (Kharin et al., 1999b)*
- Mexico: *"Evaluation of human-induced soil degradation in México" (Secretaria de Medio Ambiente y Recursos Naturales, 2002)*
- Russia: *"Land Degradation in Russia" (Stolbovoi and Fischer, 1998)*
- South Africa: *"Land Degradation in South Africa" (Hoffman et al., 1999)*

All soil degradation GIS maps are based on polygons or image files and contain semiquantitative information about extent, degree and type of degradation (e.g. erosion, chemical deterioration). Most assessments used different definitions of the impact of desertification (degree, impact, level); in consequence, this information was harmonized with "degree" in this study. Four degree classes defining the scale of degradation effects (see Annex A) are discerned throughout COMSAD. The map by Kharin and colleagues (1999a) contains only three degree classes, with an aggregate level "strong and extreme". This class was defined as "strong" in the COMSAD dataset, in order to obtain a rather conservative estimate. Furthermore, COMSAD contains information on the extent of the individual degree within each mapping unit, i.e. polygon.

The datasets, containing information in polygons, were converted to a gridded map with 5 minutes geographic resolution. However, the South African dataset (Hoffman *et al.*, 1999) provides only extent classes, i.e. ranges of extent per degree level. In order to integrate this dataset into COMSAD, the mean value of each range was used to derive the extent of the according degree level with each gridcell.

For two datasets (van Lynden and Oldeman, 1997), the sum of all extents per degree in a gridcell can exceed 100%, due to the basic approach of these datasets which quantifies the extent of degradation according to the type of degradation. Areas which are subjected to more than one type are thus also counted more than once (Stolbovoi and Fischer, 1998). As it is not possible to identify the location of these overlaps, gridcells with the sum of extents >100% have been rearranged in order to match 100% by capping the extent of the lowest degree level. (ANNEX A.3.2). The resulting map, COMSAD, shows the total extent of all degradation types.

The newly compiled datasets on soil degradation were overlaid with the Humidity Index to cut out dryland areas. Dryland areas were spatially defined using the well-established UEA/CRU Global Humidity Index (Deichmann and Eklundh, 1991), calculated as the ratio of annual precipitation and potential evapotranspiration (P/PET) (Middleton and Thomas, 1997; Safriel *et al.*, 2005). According to the definition of desertification in the World Atlas of Desertification (Middleton and Thomas, 1997), the areas included in this investigation are arid, semi-arid and dry sub-humid climate zones with a P/PET ratio between 0.05 and 0.65. Cold, humid and hyperarid climatic zones are excluded. Hyperarid environments (P/PET < 0.05) are true deserts that are hardly affected by human activities due to their low biological productivity (Dregne, 2002; Middleton and Thomas, 1997).

2.2 Modeling NPP losses

This study aims to estimate the NPP losses due to desertification in order to quantify the human impact on energy and carbon flows in drylands. Therefore, it is necessary to quantify desertification effects on NPP in ecosystems. COMSAD contains information on the degree of desertification in each gridcell. This information was used to derive an estimate of NPP effects of degradation.

NPP losses were calculated by combining the information on extent and degree of COMSAD with assumptions on NPP losses according to degree levels derived from literature surveys (Table 1), and potential net primary production (NPP_0). As a basis map, the NPP_0 estimate for the year 2000 by Haberl *et al.* (2007) based on model runs of the Lund-Potsdam-Jena dynamic global vegetation model (LPJ-DGVM) (Sitch *et al.*, 2003) with improved hydrological data (Gerten *et al.*, 2004) was used. These data are provided in a global grid with 5 minutes geographic resolution.

The degradation degree levels were interpreted as percentage losses of NPP in comparison to NPP_0, in line with Prince (2002). This is not straightforward, as most studies on productivity losses due to desertification refer to agricultural losses in a broad sense, like yield reductions or economic decreases (Pimentel *et al.*, 1995). Moreover, the above-described databases remain vague and give only semi-quantitative information about the definitions of the individual degree classes. Only few authors give quantitative information on the effects of degree which can be used to derive factors in terms of NPP losses. Table 1 summarizes assumptions by Dregne and Chou (1992), Crosson (1995) and Oldeman (1998) on agricultural losses, separately for cropland and rangelands. Table 1 also displays the assumptions followed in this study on how NPP gets lost according to degree levels. As in the minimum-maximum calculation no information on land use, e.g. cropland or grazing, is used, the factors refer to overall reduction in NPP, regardless of the specific land use.

Table 1. Productivity losses according to literature surveys and own assumptions used in this study.

Degree	Description	Productivity losses [%] (Dregne & Chou, 1992)		Productivity losses [%] (Crosson, 1995 & Oldeman, 1998)		NPP losses [%] (This study)	
		Cropland	Rangeland	Cropland	Rangeland	Minimum estimate	Maximum estimate
1	light / slight	0-10	0-25	15	5	5	25
2	moderate	10-25	25-50	35	18	18	50
3	strong / severe	25-50	50-75	75	50	38	75
4	extreme / very severe	50-100	75-100	Not defined		63*	100

*The percentage loss for extreme degree in this study is not derived by mean value of croplands, but by the mean value of the lower range of croplands and the lower range of rangelands. I assume that 75% may be too high for a minimum estimate.

In order to validate the minimum-maximum estimate of NPP losses due to desertification, I calculated a ‘best guess’ estimate, taking spatially explicit data on land use and NPP on cropland into account. From a global assessment of HANPP (Haberl *et al.*, 2007), a spatially explicit dataset on NPP on cropland, which is consistent with national census statistics on land use and harvest (Krausmann *et al.*, 2008), is available. This dataset was used to quantify degradation effects on NPP on croplands.

Starting point of this assessment is the intersection of the degradation extent in COMSAD with a global land use dataset on cropland and grazing land (Erb *et al.*, 2007). This dataset is consistent with FAO census cropland statistics (FAO, 2004) on the country level and contains, besides information on cropland and grazing land, consistent information on built-up areas, forestry, and untouched areas. Using this dataset, the proportion of agricultural land subjected to desertification in each gridcell was calculated. In some gridcells, the extent of degradation exceeds the extent of agricultural areas (sum of cropland and grazing land), an indication of degradation effects in forests or untouched areas. As the basis approach of this study is to quantify human-induced soil degradation effects, and neither climate-induced nor vegetation degradation effects, this discrepancy was eliminated by capping the extent of degradation at the extent of agricultural areas in each gridcell. This resulted in a significant reduction of the degradation extent in comparison to COMSAD, in particular in arid regions (see below). The extent of degraded agricultural area in each gridcell was allocated uniformly to cropland and grazing land according to their relative weight in each gridcell.

By calculating the difference of the potential NPP (NPP_0) and current NPP (NPP_{act}) on croplands situated in drylands, I assessed desertification effects on croplands. Estimating NPP losses due to this difference is, of course, a rough proxy, as NPP_0 is not equivalent to the production potential of cropland ecosystems, and effects such as the shortening of the vegetation period, which are not directly related to degradation, are subsequently subsumed under degrading effects. Nevertheless, due to the lack of more suitable data on production potentials, and because this approach is in line with the suggestions by Prince (2002), I used NPP_0 as a proxy of the production potentials on cropland. Furthermore, this approach allows the usage of statistical data and thus of an independent dataset. Areas where NPP_{act} exceeds NPP_0, i.e. areas of intensive agriculture (Haberl *et al.*, 2007), were excluded from the assessment, as on these gridcells no degradation effects on NPP are apparent. The difference between NPP_0 and NPP_{act} in each gridcell was multiplied by the area covered with degraded cropland in each gridcell in order to estimate the NPP losses due to desertification on croplands.

In contrast to cropland, no statistical data are available for the calculation of NPP losses due to desertification on grazing land. Therefore, a similar approach as for the calculation of the minimum-maximum estimate was followed. In a first step, NPP_{act} on natural grazing land was taken from Haberl *et al.* (2007), based on the potential NPP run of LPJ-DGVM. For artificial grasslands, i.e. grasslands which are a result of land conversions and are thus situated in potential forest biomes (Ramankutty and Foley, 1999), the LPJ result was reduced by 22%. This factor was derived from a comparison of measured site data on NPP of grasslands located in forest biomes (for details see: Haberl *et al.*, 2007). Assuming NPP loss factors of 5%, 18%, 50% and 80% for the degrees 1 to 4, respectively, I calculated NPP losses for each gridcell per degree-layer of COMSAD. These NPP losses are then multiplied by the area covered by degraded grazing land in each gridcell.

3 Results

3.1 Extent of soil degradation in drylands

According to COMSAD the global extent of desertification is 11.8 million km² of desertified areas (Table 2). The amendment of the GLASOD database increased the global desertification extent by 15%. About 23% of the world's drylands are at least to some extent affected by soil degradation. The semi-arid zone shows the highest extent with 4.8 million km², while desertified areas in the arid and dry sub-humid zones amount to 4.5 and 2.5 million km², respectively. In some regions like Eastern Asia and South-Eastern Asia the desertified area even increased by more than 50% as a result of the integration of new datasets (not shown).

Table 2. Comparison of the soil degradation maps GLASOD, COMSAD and COMSAD-LU
All figures are in million km².

	Total dryland area	desertified area (GLASOD)	desertified area (COMSAD)	desertified area (COMSAD-LU)
Dry sub-humid	12.8	2.2	2.5	2.3
Semi-arid	22.5	4.1	4.8	4.3
Arid	15.5	3.9	4.5	2.9
World	50.8	10.3	11.8	9.5

The intersection of COMSAD with the global land use dataset by Erb *et al.* 2007 (COMSAD-LU) leads to a significant reduction in desertification extent, in particular in the arid zone. Desertification extent in COMSAD-LU is 20% or 2.3 million km² smaller than in COMSAD. The main reason for this discrepancy is due to the fact that COMSAD identifies large areas (1.7 million km²) as desertified in zones which are classified as wilderness and non-productive areas in Erb *et al.* 2007, the lion share of which are situated in the arid zones. The remaining mismatch of 0.5 million km² (4%) is associated with the intersecting procedure which caps the extent of degradation at the extent of agricultural areas in each gridcell (see above).

The final map of COMSAD (Figure 1) shows the desertification extent in percent per gridcell. Large parts of the Sahel Zone, the Middle East, the western part of Russia and Mexico as well as some parts in India, Pakistan and China indicate desertification extents between 80% and 100%. China shows the largest extent of soil degradation in drylands with more than 1.7 million km². This amounts to almost 90% of the total degraded area in Eastern Asia or 30% of the whole Asian continent.

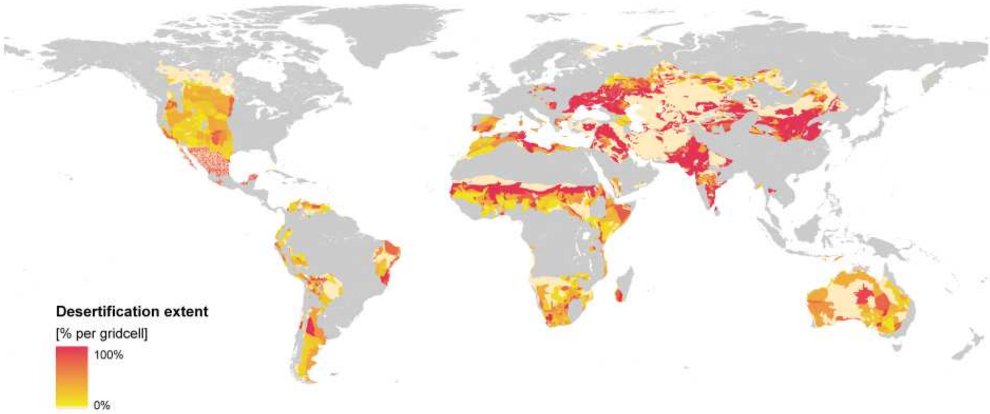

Figure 1. Extent of degraded areas of COMSAD in percent per gridcell

23% of the global drylands are subjected to desertification, with significant regional variation. Among the most affected regions are Eastern & South Eastern Europe and South-Eastern Asia, with 55% and 45% of their dryland area affected by desertification. Nevertheless, the absolute extent of drylands in these regions is comparatively small (700.000 km² and 111.000 km², respectively). Sub-Saharan Africa, for example, comprises over 11 million km² drylands, 2.6 million km² (23%) of which are affected by desertification. In the other regions (Northern America, Latin America & the Caribbean and Oceania, including Australia) the extent of desertification is below the world average with 11%, 19% and 13%, respectively (Table 3).

The degree levels "light" and "moderate" are the dominant classes and sum up to 80% of the total degraded area in drylands. In Oceania, Australia and Northern America these two categories account for almost all (98%) desertification areas, and with the exception of Central Asia and the Russian Federation, at least 75% of the desertification area is comprised by these degradation degrees. In the latter case, a considerable area of desertification is affected within the degree classes "strong" and "extreme" (61% of total desertified area in this region).

Table 3. Extent of dryland degradation within COMSAD classes of degradation degrees

	Dryland area	Degradation degree				Total	
		light	moderate	strong	extreme		
	[1000 km²]	[1000 km²]	[1000 km²]	[1000 km²]	[1000 km²]	[1000 km²]	[% of drylands]
Northern America	5 375.07	126.03	468.59	12.16	-	606.78	11
Latin America & the Caribbean	6 426.15	529.35	589.31	79.91	7.24	1 205.82	19
Western Europe	517.84	49.26	66.03	12.77	-	128.06	25
Eastern & South-Eastern Europe	704.75	81.24	270.23	36.53	3.04	391.03	55
Sub-Saharan Africa	11 384.25	1 052.56	1 128.17	354.01	62.36	2 597.09	23
Northern Africa and Western Asia	3 573.01	241.05	665.40	300.06	-	1 206.51	34
Central Asia and Russian Federation	7 330.31	184.31	372.70	329.95	544.70	1 431.66	20
Eastern Asia	4 169.24	1 185.99	238.67	445.51	16.99	1 887.16	45
South-Eastern Asia	111.72	8.85	31.31	4.43	0.59	45.18	40
Southern Asia	4 650.98	590.13	616.48	171.38	59.25	1 437.24	31
Oceania and Australia	6 568.21	828.66	22.07	11.04	4.17	865.95	13
World	50 811.53	4 877.43	4 468.95	1 757.77	698.33	11 802.49	23

3.2 Net Primary Production losses on desertified areas

According to my minimum and maximum estimates, potential NPP losses due to human-induced desertification amount to between 799 Tg C/yr and 1973 Tg C/yr (Table 4). This means that at least 1.22% of global terrestrial NPP_0 or about 4% of the potential net primary production in drylands is lost due to desertification. The maximum estimate represents a significant impact on dryland ecosystems with more than twice the NPP loss of the minimum calculation. Both calculations indicate that the highest absolute amount of NPP is lost in the semi-arid zone. More than 50% of the total loss occurs in this climate zone. The 'best guess' estimate is that 965 Tg C/yr or 4.91% of NPP_0 on dryland areas are lost due to desertification. It is notable that the minimum estimate has higher NPP losses in arid areas than my 'best guess' estimate, which results from the exclusion of large wilderness and non-productive areas in the 'best guess' calculation.

Table 4. Detailed breakdown of absolute net primary production calculations with regard to climate zones

	Units	Arid	Semi-arid	Dry sub-humid	Total
Area	[million km²]	15.5	22.5	12.8	50.8
NPP_0 in drylands	[Tg C/yr]	2 053	9 691	7 886	19 630
Minimum estimate					
NPP losses	[Tg C/yr]	89	413	297	799
NPP losses	(% of total NPP_0 in drylands)	4.34	4.26	3.77	4.07
Maximum estimate					
NPP losses	[Tg C/yr]	251	1 005	716	1 973
NPP losses	(% of total NPP_0 in drylands)	12.24	10.37	9.08	10.05
'Best guess' estimate					
NPP losses	[Tg C/yr]	86	515	364	965
NPP losses	(% of total NPP_0 in drylands)	4.17	5.31	4.62	4.91

Sources: Haberl *et al.* (2007); own calculations

The map presented in Figure 2 shows the worldwide desertification-induced NPP loss in drylands of the 'best guess' analysis as percentage of NPP_0. My findings show reductions up to 85% of NPP_0, especially in the Central Asian region and the Russian Federation. About 2.5% of all degraded areas in the COMSAD map show an NPP loss of over 50%. Despite these extreme values, most regions only indicate a productivity loss of about 0-5% of NPP_0. The largest reductions of potential productivity occur on the Asian continent. More than 50% of all degraded areas and almost 50% of total NPP losses are localized in Asia.

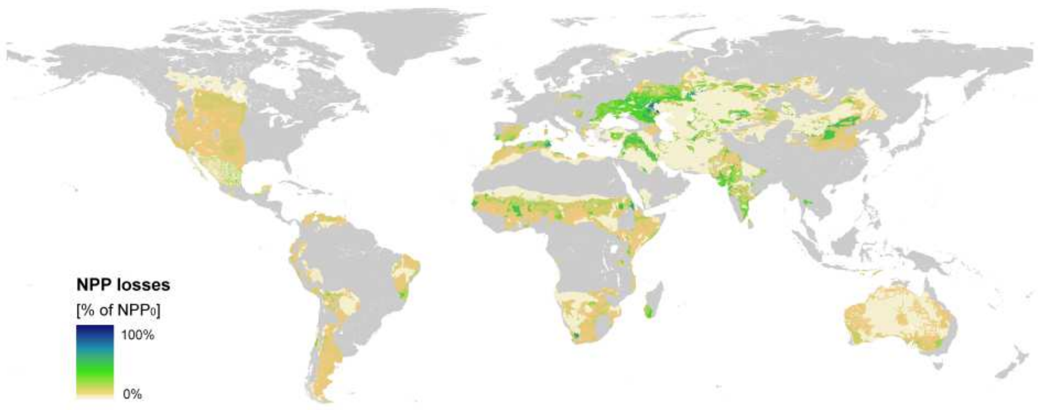

Figure 2. Global net primary production loss due to soil degradation in drylands.
The gridcells show NPP losses as percentage of NPP0 of the 'best guess' estimate with a high value of 85%.

A regional breakdown (Table 5) gives information on regional variations of productivity reductions. The maximum estimate shows that highly affected areas in South-Eastern Asia and Eastern & South-Eastern Europe reveal losses of 150 g $C/m^2/yr$ and 141 g $C/m^2/yr$ respectively, with regard to the overall dryland area in these regions. In contrast, in Northern America, Oceania and Australia the prevailing human-induced productivity reductions only account for 11-21 g $C/m^2/yr$ on drylands. The minimum approach results for all regions in considerably lower losses per dryland area and year. Most of the regions have losses below 20 g $C/m^2/yr$. The situation in the 'best guess' calculation is similarly low, but here drylands in South-Eastern Europe appear to be the heavily affected with 103g $C/m^2/yr$, as well as drylands in South-Eastern Asia with 94g $C/m^2/yr$.

Table 5. Net primary production losses per dryland area, regional breakdown

	Dryland area [% affected by degradation]	Minimum estimate [g C/m²/yr]	'Best guess' estimate [g C/m²/yr]	Maximum estimate [g C/m²/yr]
Northern America	16%	7	9	21
Latin America & the Caribbean	30%	15	15	45
Western Europe	34%	19	35	54
Eastern & South-Eastern Europe	68%	52	103	141
Sub-Saharan Africa	31%	15	19	38
Northern Africa and Western Asia	62%	13	20	34
Central Asia and Russian Federation	27%	34	34	60
Southern Asia	39%	17	23	43
South-Eastern Asia	52%	56	94	150
Eastern Asia	66%	13	12	40
Oceania and Australia	27%	3	4	11
World	35%	16	19	39

Table 6 shows a detailed analysis of area-related NPP losses on cropland and on grazing land, according to the 'best guess' estimate. Overall productivity loss in croplands with 468 Tg C/yr almost equals the NPP loss in grazing lands with 496 Tg C/yr, though croplands only occupy 2.5 million km² or about 26% of the total degraded land. Significant differences in productivity reductions are found between grazing land and croplands. Croplands lose on average about 14% of their potential NPP, while the reductions on grazing lands average approximately 5%. The annual net primary production change per cropland area ranges from 28 g C/m²/yr in Northern America to 197 g C/m²/yr in Southern Asia. Croplands of Eastern Asia seem to be rather unaffected by desertification, with about 1% reduction within the land-use class. On grazing lands, approximately 18 g C/m²/yr are lost due to desertification with regional variations from 3 g C/m²/yr in Oceania to 58 g C/m²/yr in Eastern and South-Eastern Europe. In both land-use categories the highest percentage losses appear in Eastern and South-Eastern Europe with 29% on croplands and 11% of potential primary production on grazing lands.

Table 6. Area related NPP losses ('best guess') on grazing land and on cropland, regional breakdown

	Grazing land				Cropland			
	Area [1000 km²]	NPP_0 [g C/m²/yr]	NPPloss [g C/m²/yr]	NPPloss [%]	Area [1000 km²]	NPP_0 [g C/m²/yr]	NPPloss [g C/m²/yr]	NPPloss [%]
Northern America	2 774	339	8	3	971	517	28	5
Latin America & the Caribbean	3 544	535	17	3	499	630	77	12
Western Europe	175	495	25	5	207	503	65	13
Eastern & South-Eastern Europe	183	542	58	11	392	540	158	29
Sub-Saharan Africa	7 411	415	20	5	867	561	75	13
Northern Africa and Western Asia	1 366	228	20	9	592	371	71	19
Central Asia and Russian Federation	4 095	307	34	11	1 136	486	99	20
Southern Asia	2 067	220	11	5	1 619	407	51	13
South-Eastern Asia	47	805	54	7	40	781	197	25
Eastern Asia	2 433	277	20	7	409	457	2	1
Oceania and Australia	2 848	336	3	1	375	439	40	9
World	26 943	363	18	5	7 110	483	66	14

4 Discussion and Conclusion

This study was carried out to obtain a spatially explicit dataset on net primary production losses due to human-induced desertification. In order to perform a detailed analysis of the effects of human-induced desertification on the NPP of dryland ecosystems, I combined biophysical parameters of desertification and net primary production with socio-economic datasets of land use in the ‘best guess’ estimation. The results of 965 Tg C/yr with a possible range of 799–1973 Tg C/yr give evidence for a noteworthy human impact on potential productivity. This means that about 5% (4–10%) of the potential productivity in drylands is lost every year due to human-induced desertification. These findings are significantly lower than previous estimates by Vitousek *et al.* (1986) with 2250 Tg C/yr, especially the minimum and the ‘best guess’ estimates. Considering the amount of NPP lost due to desertification in the light of a recent global HANPP assessment (Haberl *et al.*, 2007), the ‘best guess’ calculation contributes about 6.7% to the total NPP appropriated by humans (Table 7). This is slightly lower than the estimate by Vitousek *et al.* (1986) (7.7%), but considerably lower than the maximum estimate which contributes about 13.6% to HANPP. These differences can be explained by more recent databases on NPP and desertification extent used in this study, and by a generalized assumption of Vitousek *et al.* (1986) on productivity losses, regardless of degradation levels.

Table 7. Regional breakdown of NPP losses due to desertification in relation to NPP_0 and HANPP

	Global area	Dryland area	NPP_0 worldwide	NPP_0 in drylands	HANPP worldwide*	NPP losses (range)	NPP losses (range)
	[million km²]	[million km²]	[g C/m²/yr]	[g C/m²/yr]	[g C/m²/yr]	[% of NPP_0 in drylands]	[% of HANPP]
Northern America	18.5	5.4	432	408	95	2.3 (1.8-5.1)	2.9 (2.2-6.4)
Latin America & the Caribbean	20.3	6.4	811	623	126	2.4 (2.5-7.2)	3.8 (3.9-11.2)
Western Europe	3.7	0.5	551	499	222	7.0 (3.7-10.7)	2.2 (1.2-3.4)
Eastern & South-Eastern Europe	2.2	0.7	597	543	311	19.0 (9.5-25.9)	10.6 (5.3-14.5)
Sub-Saharan Africa	24	11.4	562	399	104	4.7 (3.7-9.4)	8.6 (6.7-17.1)
Northern Africa and Western Asia	10.3	3.6	83	180	35	10.8 (7.1-18.8)	19.3 (12.8-33.6)
Central Asia and Russian Federation	20.5	7.3	405	393	47	8.7 (8.6-15.4)	26.0 (25.7-46)
Southern Asia	6.7	4.7	382	279	240	8.2 (6.1-15.5)	6.6 (4.9-12.5)
South-Eastern Asia	4.5	0.1	1022	804	305	11.7 (7-18.7)	0.8 (0.5-1.2)
Eastern Asia	11.5	4.2	363	249	126	4.8 (5.1-16)	3.4 (3.7-11.5)
Oceania and Australia	8.4	6.6	455	351	51	1.0 (0.7-3.1)	5.6 (3.9-16.5)
World	130.4	50.8	502	386	111	4.9 (4.1-10.1)	6.7 (5.5-13.6)

Sources: Haberl *et al.* (2007); own calculations

*excluding human-induced fires

As shown in Figure 2, NPP losses due to human-induced desertification are distributed in geographical patterns, especially on the regional and sub-regional level (e.g. the European part of Russia, the Inner Mongolia Autonomous Region or the Iberian Peninsula, which are highly affected regions within their macrogeographical division). A macrogeographical comparison (Haberl *et al.*, 2007; UNSD, 2006) of potential productivity losses and regional HANPP calculations (Haberl *et al.*, 2007) shows the varying efficiencies of human land-use activities and the magnitude of desertification within the total appropriated NPP (Table 7).

In Central Asia and the Russian Federation potential productivity losses due to desertification have a moderate to high impact on NPP_0 in drylands (9%), and contribute strongly to total HANPP (with over 25%). While HANPP is relatively low in the whole region (12% of NPP_0), a significant amount of productivity losses results from desertification. A similar situation can be found in Northern Africa and Western Asia. Eastern and South-Eastern Europe has the highest reductions of potential NPP in dryland areas with 19%, as well as the highest amount of NPP losses per area (Table 5). Considering that this region shows a high ΔNPP_{LC} value and a high HANPP value, and a noticeable share of NPP losses of regional HANPP, it becomes obvious that this region has large productivity alterations which are lost through human mismanagement. In contrast, in industrialized regions like Northern America and Australia NPP losses are rather small with 2% and 1% of potential NPP, respectively. In both regions NPP losses as a share of HANPP remain below the global average (6% and 3%, respectively). The situation in South-Eastern Asia should be evaluated carefully. Although the contribution of NPP losses to HANPP is almost negligible (0.8%), it has to be noted that this region only has about 2% dryland area. Thus, losses due to desertification appear to be a local, but not a regional problem, which reduces potential productivity in drylands by 12%. In Eastern Asia and Sub-Saharan Africa reductions of potential NPP are remarkably smaller than in South-Eastern Asia. In both regions the NPP losses account for 5%, which equals the global average. However, land-use activities differ significantly. While land-use induced productivity losses (ΔNPP_{LC}) in Eastern Asia are small (Haberl *et al.*, 2007), as are NPP losses due to desertification (3% of HANPP), Sub-Saharan Africa is characterized by large reductions of NPP (11% of HANPP) due to desertification and a large share of ΔNPP_{LC} in total HANPP (Haberl *et al.*, 2007). The results of NPP losses due to desertification, interlinked with the findings of regional HANPP, provide a good basis for evaluating the efficiencies and mismanagements of agricultural areas in drylands. Even if some areas appear only slightly affected in their potential productivity, there can be a great potential to increase agricultural production.

These regional variations of NPP losses due to desertification and the multiple effects on the environment and society are driven by multiple factors and underlying causes (Geist, 2005). The dominant cause is agricultural activity with a 95% probability, including grazing and cropping, but desertification can be best explained by a combination of several variables rather than by a single one (Geist and Lambin, 2004). The findings in this study underline the regional and local agricultural pressure resulting in desertification. Various human activities trigger different desertification processes. While an overuse of chemical fertilizers and heavy machinery in the former communist era highly affected Eastern- and South-Eastern Europe as well as the western part of Russia by soil compaction, erosion and soil pollution (Bouma *et al.*, 1998; van Lynden, 2000), regions in Eastern Asia suffered from insufficient use of fertilizers during intensification periods (Jiong, 1999). In both regions, desertified land was abandoned which has led to a per capita decrease of agricultural production (Ramankutty *et al.*, 2008). In regions where agricultural areas showed an impressive growth in drylands during the last decades (e.g. Northern Africa and Western Asia, Rosegrant *et al.*, 2001), desertification processes like salinization, water and wind erosion occurred due to the depletion of water resources caused by intensive irrigation (Abahussain *et al.*, 2002; El-Beltagy, 1999; Ma and Ju, 2007; Saiko, 1998; Young, 1994). Human-induced desertification effects on grazing land can be mainly identified by large expansions of livestock sectors resulting in overgrazing, which may trigger soil compaction and erosion effects (Collado, 2001; Huber-Sannwald *et al.*, 2006; Ma and Ju, 2007; Ojima *et al.*, 2004).[1]

All the above-mentioned land-use practices and the resulting desertification effects can significantly alter potential productivity. While intensively used croplands, optimized by fertilizers and well-managed grazing areas, can enhance aboveground and belowground NPP (Haberl *et al.*, 2007; McNaughton, 1985; Pandey and Singh, 1992; Trujillo *et al.*, 2006), various land-use activities and landscape modifications have detrimental effects on potential NPP (DeFries, 2002; Foley *et al.*, 2005; Haberl *et al.*, 2007). The steady growth of population and the increasing demand for food and fiber will put further pressure on terrestrial ecosystems, especially in drylands. This pressure, resulting from human land-use activities, can lead to desertification processes and therefore to a permanent decline of potential productivity (Prince, 2004). This amount of NPP is lost for further land-use practices which sustain human needs.

These needs are likely to increase on a global scale, most likely in highly populated dryland areas in developing countries and countries at the stage of economic take-off. It is projected by IFPRI's IMPACT model that the food and feed demand for cereals will increase by over 100% in developing countries in the period from 1993 to 2020. The largest increases in cereals, meat and tubers are expected in Sub-Saharan Africa with about 120% for cereals and 140% for meat (Pinstrup-Andersen *et al.*, 1997). On a global scale, including also non-dryland areas, a net increase of 120 million ha agricultural area is projected until 2030 (FAO, 2003), mainly in areas of Latin America and Sub-Saharan Africa (Alexandratos, 1999). In comparison, some Asian regions, like Southern and South-Eastern Asia, already showed great expansions of croplands during the twentieth century (Lepers *et al.*, 2005; Ramankutty *et al.*, 2008) and have barely spare land left for further agricultural expansion (FAO, 2003). Other studies estimated that approximately 900 million ha of croplands and pasture lands are necessary to fulfill the needs of the world population until 2050 (Tilman *et al.*, 2001). Recent calculations show that 1.8 billion ha could provide at least a minimum level of cultivation (FAO, 2003), although spare land, currently uncultivated, may be overestimated (Young, 1999).

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[1] More detailed information about regional variations of desertification causes and processes can be found in Barrow (1991), Mainguet (1991), Dregne (2002) or Geist (2005).

To fulfill the ongoing demand for ecosystem services and goods in drylands, there is an urgent need to improve the agricultural output and the efficiencies of HANPP. NPP, a key parameter of ecosystem functioning, is essential in providing ecosystem services. As shown by Haberl *et al.* (2007), efficiencies can be seen by the ratio of harvested NPP and total HANPP. A decrease of land-use induced productivity changes would enhance this ratio. Improvements can be achieved by enhancing restoration of desertified areas, by reducing land-cover conversion of prime agricultural land to infrastructure areas and by increasing agricultural efficiencies and the usage of unused extracted biomass (Krausmann *et al.*, 2008; Lal *et al.*, 1989; Lal and Stewart, 1990). Furthermore, additional measures to increase harvests are suggested. Some croplands in Sub-Saharan Africa only show an NPP of about 10-30% of potential NPP due to insufficient amounts of fertilizers (Vlek, 1995). Considering that local small-scale farmers often have good local knowledge and techniques to manage resources like water and soil fertility, the use of adequate amounts of fertilizers is frequently determined by world market prices (Tiffen and Mortimore, 2002). Improved grazing land management may control desertification effects, enhance livestock productivity and ameliorate the ecosystem productivity which provides social security during climate impacts like droughts (IPCC, 2007). Taking into account that this study shows regional productivity losses of up to 19% of potential NPP and that there are regional NPP losses which amount to 26% of the total HANPP, there seems to be great potential to improve desertified areas.

The world map presented in Figure 2 presents an overview of regional and local distributions of productivity reductions due to desertification. Although these results correspond to regional assessments of NPP alterations and desertification processes, the estimates have to be evaluated carefully. This study presents a first step to interlink a ground-based study of desertification with a global model of net primary production, an important parameter for ecosystem performance, but the quality of the results mainly depends on the quality of input data. By harmonizing soil degradation datasets, a possible deviation of 7% of the desertification extent occurs in Southern and South-Eastern Asia (cf. Middleton and Thomas, 1997). The combination of land-use datasets (Erb *et al.*, 2007) and the COMSAD map to COMSAD-LU resulted in an area reduction of about 20% compared to COMSAD, which can be explained by exclusions of wilderness and non-productive areas. The remaining mismatch is considered to result from inconsistencies between land-use data and the desertification extent of COMSAD. Although the resulting area of COMSAD-LU falls well within the range of the global desertified area suggested by Safriel *et al.* (2005), there remains the possibility of some weaknesses, either of soil degradation datasets or of the global wilderness map (Sanderson *et al.*, 2002). Furthermore, the inconsistencies can be explained by different years of assessment. While the land-use maps refer to the year 2000, the data on desertification extent were assessed in different years (Table A8), most of them before the year 2000.

Another uncertainty concerns the global extent of soil degradation. I updated the base map GLASOD with regional, more recent datasets due to the criticisms of possible limitations, overestimations and subjectivity (Helldén, 1991; Sonneveld and Dent, in press; Warren and Olsson, 2004). While Eurasia (except Western Europe) was completely replaced by more recent maps, it was not possible to derive appropriate maps for Northern America, Australia, Latin America and the Caribbean (except Mexico), Northern Africa and Sub-Saharan Africa (except South Africa). Therefore, GLASOD data were used for these regions, considering the possibility of inaccuracy, especially in the highly debated Sahel Zone (Helldén, 1991). While GLASOD indicated large areas to be affected by human-induced desertification, several studies based on remote sensing technology (Herrmann *et al.*, 2005; Nicholson *et al.*, 1998; Oba *et al.*, 2001; Prince *et al.*, 1998; 2007) did not find evidence for widespread human-induced desertification effects. They explained the vegetation changes by climate variability in the highly dynamic drylands in the Sahel. A grid-based comparison of NPP reductions (remote sensing data) and GLASOD soil degradation data proved high spatial correlation in the Sahel Zone (Prince *et al.*, 1998). Weak correlations with GLASOD pixels only occurred by using aggregated output data on extent and severity. These aggregated classes give an excellent overview for policy makers, but it is a simplification of degradation information (Oldeman, 1994) and may explain the weakness in the statistical tests (Prince *et al.*, 1998). Following these conclusions, the present study only used the exact extent and the defined degree in each gridcell rather than categories or aggregated classes, which would probably raise reliability of GLASOD. This was confirmed by my analysis of NPP losses in the "Sahelian Acacia savanna" (Olson *et al.* 2001) which shows NPP losses of about 6.5% of the potential NPP. This is only slightly above the worldwide average, but below the NPP losses in Europe, Northern Africa and most regions in Asia (Table 7). These results conform to the above-mentioned remote sensing studies in the Sahel Zone and demonstrate that, high extents of soil degradation did not necessarily lead to high amounts of NPP losses in cases of low degradation degrees. This is in line with DeFries *et al.* (1999) who calculated only a small amount of carbon loss on grasslands and shrubland, although large areas were affected by degradation. Results from other recent studies on productivity reductions in Southern Africa

(Prince, 2004; Wessels *et al.*, 2007) showed that their remote sensing data were quite compatible with the expert assessment by Hoffman *et al.* (1999) and with GLASOD (Safriel, 2007).

These discrepancies in quality of input data show that there is an evident need for more accurate global data on desertification. Forthcoming assessments should combine global satellite-derived studies (e.g. Evans and Geerken, 2004; Wessels *et al.*, 2007) or productivity models, like LPJ-DGVM, with recent local and regional ground studies linking biophysical and socio-economic attributes to achieve advancement in this multidimensional issue (Reynolds *et al.*, 2007). Alterations of global NPP data may lead to misinterpretations of human activities without an evaluation of landscape data. Short-term climate variations, land abandonment for rehabilitation, intensification of cultural areas or well-managed grazing areas can increase or decrease potential net primary production, even if no desertification processes occur (Evans and Geerken, 2004; Haberl *et al.*, 2007; Trujillo *et al.*, 2006). The prevailing study combines ground data of soil degradation and modeled NPP datasets from the LPJ dynamic global vegetation model refined with socio-economic statistical data. Therefore, this assessment provides a first step towards a comprehensive quantitative evaluation of human-induced desertification processes. I believe that losses of potential NPP give a good evaluation of the effects of desertification on human well-being. A gridded world map of desertification gives a spatially explicit overview of regional variations and can be best compared to other GIS maps concerning ecosystem deterioration, human impact or land-use systems (e.g. Erb *et al.*, 2007; Haberl *et al.*, 2007).

Making progress in assessing and monitoring desertification will provide a useful basis for further decisions in landscape modifications and efficiency improvements, most likely in Africa. Lessons about hampered ecosystem services can be learned from regions where human overuse and mismanagement have already deteriorated NPP. Although desertification is interlinked with global change problems and socio-economic issues and causes environmental feedback loops and off-site effects, desertification is not only a global concern (Puigdefábregas, 1998). Due to regional variations of degradation drivers and biophysical consequences (Reynolds *et al.*, 2007), desertification is mainly a local problem which needs local solutions (Gisladottir and Stocking, 2005). Farmers in dryland areas have great experience in coping with their environmental situation (Mazzucato and Niemeijer, 2001; Stocking, 2003), but often they only need more support on world markets and better prices for agricultural products to develop new strategies and handle overexploitation (Koning and Smaling, 2005). Global and local decisions on combating desertification can improve the situation of global food security and means an important step towards sustainable development.

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Annex A – Methods and Databases

This Annex describes the methods that have been used to modify, analyze and compile several databases calculated in geographical information systems (GIS) in order to quantify net primary production (NPP) losses due to desertification. Carrying out such a spatial explicit analysis of productivity alteration implies a well-established dataset on desertification extent and degree. For this reason, the starting point of this assessment was the GLASOD (Global Assessment of Soil Degradation) dataset (Oldeman *et al.*, 1991) which provides the only global available information on soil degradation. However, GLASOD is criticized by its over-generalization and lack of data reliability (e.g. Warren and Olsson, 2004). Considering this fact, it was inevitable to update this map with best available recent datasets to obtain a more accurate database for further calculations. The newly compiled map was combined with estimates on productivity losses and potential NPP, calculated with the Lund-Potsdam-Jena dynamic global vegetation model (LPJ-DGVM) in a global grid with 5 min geographic resolution (approximately 10x10 km at the equator). Desertification-induced NPP losses were calculated by applying a set of factors depending on the extent and severity of desertification in each grid cell according to the above-mentioned desertification map. In order to consider uncertainties I derived minimum and maximum estimates reflecting possible errors in available input data. The results of the minimum and maximum estimates were crosschecked by a "best estimate", which was refined with socio-economic data for the year 2000.

A.1 Defining desertification

The definition of desertification has developed throughout the last decades and regarding to the research issue which was focused on. Reynolds and Stafford-Smith (2002) did an excellent review on the variety of definitions of desertification. The most common definition of desertification was determined by the United Nations Convention to Combat Desertification (UNCCD) as *"land degradation in arid, semi-arid, and dry subhumid areas resulting from various factors, including climatic variations and human activities"* (United Nations, 1994, p.4). Furthermore the CCD defined land degradation as a *"reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process* *or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical and biological or economic properties of soil; and (iii) long-term loss of natural vegetation".*

The aim of this study is to quantify the human impact on net primary production due to soil degradation in dryland ecosystems, not considering climatic variations. Productivity losses in consequence of degradation are closely coupled to alterations of soil resources (Nabhan *et al.*, 1999). One of the main soil functions is biomass production, needed for food, fodder and renewable energy. Therefore a transformation of this function is closely linked to human activities like agricultural production (Blum, 1998). Vegetation degradation is excluded is this assessment taking into account that alterations of vegetation production in drylands are often short term dynamics (Ramankutty *et al.*, 2006) and therefore climate variability often underlies desertification (Reynolds and Stafford-Smith, 2002). Dryland ecosystems are highly dynamic with strong, interannual rainfall variations (e.g. Le Houérou *et al.*, 1988) and vegetation productivity mainly depends on precipitation (Cao and Woodward, 1998; Sala *et al.*, 1988), especially in the semiarid zone (Herrmann *et al.*, 2005; Wessels *et al.*, 2007). In areas where soil degradation is not serious, vegetation can recover soon after precipitation (Ayoub, 1998).

Furthermore several criteria of vegetation degradation like a change in plant composition (Hoffman *et al.*, 1999; Kharin, 2002) do not necessarily result in NPP losses. Shrub encroachment in grasslands and therefore spatial alterations of nutrient distribution indicate an increase of desertification processes like soil erosion, but this vegetation shift does not actually result in a significant change of net primary production (Huenneke *et al.*, 2002; Schlesinger *et al.*, 1990). Analyzing shrublands and grasslands in previous studies showed no significant difference in the mean annual productivity, but high interannual variations in aboveground primary productivity (Jobbágy and Sala, 2000). Considering land-cover changes to croplands a recent assessment showed that intensively used agricultural areas can show a higher productivity than the potential vegetation before land cover change (Haberl *et al.*, 2007). In this context and in the focus of my research, soil degradation in drylands is termed in this assessment also as desertification or solely as degradation.

Following the definition by CCD that desertification occurs in arid, semi-arid and dry sub-humid zones, these three climate zones had to be localized within the selected degradation datasets. Although some authors defined these climate zones only by isohyets (e.g. Le Houérou, 2001; Mainguet, 1991), this study used the well-established ratio between annual precipitation and potential evapotranspiration (P/PET), also known as Aridity Index or Global Humidity Index. The ratios of the UEA/CRU Global Humidity Index[2] (Deichmann and Eklundh, 1991) can be seen in Table A1. For the period 1951 to 1980 the monthly values were averaged to draw a map based on mean annual potential moisture. The calculation of PET follows the method of Thornthwaite (1948), though some improvements have been made. The hyper-arid zone boundary shifted from 0.03 to 0.05, because the Thornthwaite method is known to underestimate PET in very dry regions (Middleton and Thomas, 1997).
Although hyper-arid environments formally belong to the drylands, I excluded them from this assessment because they are hardly affected by human activities due their low biological productivity and therefore by human-induced desertification (Dregne, 2002; Middleton and Thomas, 1997). In contrary, recent reports encompassed the hyper-arid zone in their definition of desertification (Lepers *et al.*, 2005; Millennium Ecosystem Assessment, 2005). The cold and the humid zones are not considered in this study.

This dataset was converted to a gridded GIS database with 5x5 minutes geographical resolution to adjust this map to the other datasets as described below.

Table A 1. Classification of the Humidity Index

Climate zone	P/PET ratio
Hyper-Arid	P/PET < 0.05
Arid	0.05 < P/PET < 0.20
Semi-arid	0.20 < P/PET < 0.50
Dry sub-humid	0.50 < P/PET < 0.65
Humid	0.65 < P/PET
Cold	Areas that have more than six months of an average temperature below 0 degrees and not more than three months where the temperatures reach above 6 degrees

Source: Deichmann and Eklundh (1991)

[2] The Global Humidity Index from GRID and UEA is available online at UNEP GRID Data Portal (http://www.grid.unep.ch/data/)

A.2 Desertification and HANPP

HANPP, an abbreviation for “Human Appropriation of Net Primary Production”, is a well established indicator to measure human influence on ecosystem energy flows. Net primary production (NPP), the net amount of biomass provided by plants in a given time through photosynthesis, is appropriated by humans to support their socioeconomic needs. Therefore the energy remaining in ecosystems for further transfer within trophic levels is reduced.

HANPP was introduced by Vitousek *et al.* (1986) and further used in several studies within the last two decades on global scale (Haberl *et al.*, 2007; Imhoff *et al.*, 2004; Rojstaczer *et al.*, 2001; Wright, 1990) as well as on national or local scale (Haberl *et al.*, 2001; 2004b; 2005; O'Neill *et al.*, 2007; Prasad and Badarinth, 2004), though methods and definitions varied in these studies (Haberl *et al.*, 2002). Following the most recent assessment, HANPP is calculated as the difference of potential primary production (NPP_0) and the actual prevailing NPP (NPP_{act}) remaining in ecosystems after harvest (NPP_t). Hence HANPP is the sum of vegetation harvested (NPP_h) and land-use induced productivity changes including soil degradation (ΔNPP_{LC}) (Haberl *et al.*, 2004a; Haberl *et al.*, 2007) and can thus be expressed by the following formulae:

$$HANPP = NPP_0 - NPP_t$$

with

$$NPP_t = NPP_{act} - NPP_h$$

or

$$HANPP = \Delta NPP_{LC} + NPP_h$$

with

$$\Delta NPP_{LC} = NPP_0 - NPP_{act}$$

In their pioneer work Vitousek *et al.* (1986) analyzed desertification as a major component of the net primary production altered by land-use changes (here defined as ΔNPP_{LC}) and therefore of HANPP. This study aims to complement results of a recent comprehensive global HANPP assessment (Haberl *et al.*, 2007), assessed in a Geographical Information System (GIS). Further I wanted to develop a more accurate method to calculate net primary production alterations caused by human impact in dryland ecosystems compared to the rather simplified calculation by Vitousek *et al.* (1986). Though they calculated only an overall estimate, it has to be noticed that they used the best available datasets. Yet there is still room for further improvements which mainly depend on future data developments.

A.3 Degradation datasets

The starting point for this GIS-based analysis of degraded areas in the world drylands was the "World map of the status of human-induced soil degradation" based on GLASOD (Oldeman *et al.*, 1991). With respect to the probable inaccuracy and limitations of this database (Oldeman and van Lynden, 1998; Olsson, 1993; Sonneveld and Dent, in press) I updated the GLASOD map with more specific and more recent regional datasets (Table A7) like the "Assessment of the Status of Human-Induced Soil Degradation in South and Southeast Asia" (ASSOD) (van Lynden and Oldeman, 1997), the "Soil Vulnerability Assessment in Central and Eastern Europe" (SOVEUR) (van Lynden, 2000), a desertification map of Asia (Kharin *et al.*, 1999b) and with national datasets from Mexico (Secretaria de Medio Ambiente y Recursos Naturales, 2002), Russia (Stolbovoi and Fischer, 1998) and South Africa (Hoffman *et al.*, 1999). The newly compiled map on degradation was overlayed with the GIS map of the Humidity index to derive a map for soil degradation in drylands (hereafter referred also as desertification). This map is hereafter denominated as "COMSAD" (COmpiled Map of Soil degradation Assessments in Drylands). The specifications and the modifications of each database to derive COMSAD are discussed below in more detail.

A.3.1 GLASOD

The GLASOD dataset was the first comprehensive soil degradation map at the scale of 1:10 M (average) to *“create awareness of the present status of soil degradation for policy-makers, decision-makers, and the general public at large”* (Oldeman *et al.*, 1991). Over 250 scientists around the world assessed the extent, the degree, the rate, different causes and degradation types of soil degradation. The information on degradation refers to the change of soil condition in the post World War II period. The assessed data were later on transferred to a GIS database. Oldeman *et al.* (1991) set four types of soil degradation including several subtypes: wind erosion, water erosion, chemical deterioration and physical deterioration. Each type was classified by its degree and its extent. The extents of the affected mapping units were aggregated to five classes (0-5%, 6-10%, 11-25%, 26-50%, more than 50%). The degree, which describes the status of the soils to which they are presently degraded, is classified in four categories (light, moderate, strong, extreme). To obtain a rather uniform assessment, Oldeman (1988) provided general guidelines with semi-quantitative criteria for the degrees of each degradation type. The GLASOD data and the final report can be downloaded from http://www.isric.org.

The main output of the GLASOD map contains information about four severity classes (slight, medium, high, very high) of human-induced soil degradation. The parameter “severity” is an index, combined by the degree and the extent categories of degradation (for more information see: Oldeman *et al.*, 1991). Though the severity gives an excellent overview for policy-makers, it is a simplification of degradation information (Oldeman, 1994). For this reason the exact extent and the degrees were derived from the dataset and used for further calculations rather than categories or indices.

To calculate spatial explicit productivity losses on desertified areas, it is crucial to use GIS datasets with spatial allocation of soil degradation. Therefore and regarding the compatibility with NPP datasets and land-use datasets, the GLASOD dataset was rearranged from polygons to a global grid with 5 minutes geographic resolution. Each gridcell located in a certain map unit (polygon) of the original map was assigned the degradation extent in percent per gridcell, based on the proportion of the degraded areas to the total area of this polygon. For further calculations, this map was used to create four sub-maps (also called “layers” in GIS analysis), one for each degradation degree. The extents of all degradation types affected by the same degree were summed up to each layer. These four maps were overlayed with the Humidity Index to obtain the extent in soil degradation in drylands (desertification).

These steps to create a gridded map on soil degradation in drylands were repeated in each other dataset combined with GLASOD as described below, taking into consideration the specific differences of each database.

A.3.2 ASSOD

The ASSOD database (van Lynden and Oldeman, 1997) was created as a follow-up assessment of GLASOD. The main objective was to develop an improvement of GLASOD on a regional scale for South and Southeast Asia (1:5 M). The GLASOD methodology was modified to put emphasis on the impact on agricultural productivity, rather than the state of degradation, but still it is a qualitative classification. As shown in Table A2 the impact on degradation was defined by five categories (negligible, light, moderate, strong, extreme) derived through a matrix of 18 fields combining the level of management (A, B, C) and productivity increases or decreases (1-6) (van Lynden, 1995; van Lynden and Oldeman, 1997). When analyzing ASSOD database the additional value “C7” can be found, so I decided to define C6, here described as “Strong to Extreme”, as “Strong” and additionally introduced “C7 as “Extreme”.

Though “impact” in ASSOD has a different definition than “degree” in GLASOD, both semi-quantitative parameters were denominated as “degree” in this assessment and used equally for the map compilation. Furthermore the study presented here excludes negligible impact on degradation and only includes the impact classes from light to extreme.

Table A 2. Matrix of the parameter "Impact" used in ASSOD

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

Source: van Lynden and Oldeman (1997)

While ASSOD is not limited on the number of degradation types per mapping unit as GLASOD[3], it shows obvious limitations concerning the analysis of their extent. The sum of all degradation extents, stable terrains and wasteland may exceed the total area of 100% per gridcell. This may happen by means of overlaps between degradation (sub)types (van Lynden and Oldeman, 1997) or due to spatial uncertainties of degradation extents. Considering the lack of spatial information of occurring overlaps, the polygons with a total area of more than 100% had to be rearranged to examine the degradation extent for further calculations. For this reason the degradation extent is reduced to a maximum of 100% by emphasizing on the highest impacts, taking into consideration that higher impacts have greater consequences for potential productivity. In a first step the total extent was calculated for extreme impacts. Furthermore, strong, moderate and at least light impacts are added respectively, as long as the total extent of 100% is not exceeded. If two equivalent impact classes occur in one mapping unit, no specific degradation type is pointed out. Emphasis is only put on impact and extent. Table A3 shows an example of the modifications taken on ASSOD.

[3] GLASOD has a maximum of two degradation types per polygon, while ASSOD is not limited and shows up to 10 different types per map unit.

Table A 3. Modifications of ASSOD database.
Polygons with total area more than 100% are modified as shown on the polygon with the code “3511b-TH”. The original data show a total extent of 141%, including all (sub)types. To modify the total extent to a maximum of 100%, the extent of several degradation types were replaced. Main emphasis was placed on higher impact values, so the total extent was reduced using a hierarchical method. Changes in extents of degradation types can be seen in grey squares. Negligible impacts are not considered in this assessment and are always rearranged to Nil.

Polygon 3511b-TH	Type 1 (Wt)		Type 2 (Cn)		Type 3 (Cs)		Type 4 (Pk)		Type 5 (Pw)		Type 6 (Pu)		Total
	Extent [%]	*Impact*	*Extent [%]*	*Impact*	*Extent [%]*	*Impact*	*Extent [%]*	*Impact*	*Extent [%]*	*Impact*	*Extent [%]*	*Impact*	Extent [%]
original data	50	strong	60	moderate	10	extreme	10	moderate	1	negligible	10	negligible	141
output data, rearranged	50	3	40	2	10	4	0	0	0	0	0	0	100

The ASSOD database is available online at ISRIC website (http://www.isric.org)

A.3.3 SOVEUR

The SOVEUR database was developed like ASSOD as a sequel to GLASOD, but on a finer scale (1:2.5 M) and with more emphasis on soil pollution (van Lynden, 1997; van Lynden, 2000). The assessment of soil degradation was one part in a comprehensive assessment considering soils in Central and Eastern Europe (also including soil and terrain information, soil components and soil properties), which was published on a CD-ROM (FAO, 2002).

The SOVEUR dataset incorporates both parameters of soil degradation assessed in GLASOD and ASSOD (degree and impact). This study only considers the impact of soil degradation, again termed as “degree” for the compilation of the final map in order to reconcile the SOVEUR data with more recent datasets like ASSOD and “Land degradation in Russia” and Mexico (see description below). Compared to ASSOD, overlaps cannot exceed 100% of the total area and means therefore a major improvement.

Both parts of SOVEUR, the western part including several countries in Central and Eastern Europe (Table A7) and the eastern part presenting the European part of Russia, are combined and assembled into GLASOD. These region updates on extent and impact followed the methods described above.

The original dataset can be derived from the CD-ROM published by the Food and Agricultural Organization (FAO, 2002) or online at: http://www.isric.org

A.3.4 Soil degradation in Russia

The data on soil degradation in Russia (Stolbovoi and Fischer, 1998; Stolbovoi, 2002) were obtained from the data compilation "Land Resources of Russia" published by IIASA on a CD-ROM and on the World Wide Web (Stolbovoi and McCallum, 2002). Stolbovoi *et al.* (1998) used the guidelines of ASSOD (van Lynden, 1995) to design the attributes of the degradation database in order to improve the limitations of GLASOD concerning Russia.

The database provides several types of soil degradation, also including "desertification", but here, desertification is defined as "expanding areas of deserts as a result of natural (cyclic changes in climate) and anthropogenic causes (wood cutting, removal of herbaceous vegetation due to overgrazing)" (Stolbovoi *et al.*, 1998). Therefore desertification does not follow the definition of the UN (United Nations, 1994) (Zonn and Kapoustin, 2002) and will not be used as the only source to update COMSAD, but as a single degradation type summed up with other soil degradation types provided by Stolbovoi and Fischer (1998).

Following ASSOD, the soil degradation status in Russia is defined by the impact on productivity (Table A2). The matrix on the impact is limited here to the fields A1-A6. As described above in A.3.2, overlaps can occur and the sum of all degradation types in some mapping units can exceed 100% of the total area. To solve this problem, the method specified above (Table A3 and text explanation) was applied. Further, the compilation with GLASOD by using the extent in percentage per gridcell and the impact classes from 1 to 4 was done as described above.

With respect to the assessment of SOVEUR, only the Asian part of Russia was used from the study conducted by Stolbovoi and Fischer (1998). This selection was done because of two reasons. First, the SOVEUR database does not include overlaps which exceed 100% of the total area by summing up all (sub)types. This improves the reliability about the adjusted data on extent and impact. Second, the Russian part of SOVEUR database is already based on the assessment of Stolbovoi and colleagues (1998) and provides additional recent estimates on soil pollution (Batjes, 2000).

The dataset is available online at: http://www.iiasa.ac.at/Research/FOR/russia_cd/index.htm

A.3.5 Human-induced soil degradation in Mexico

The human-induced soil degradation map of Mexico was carried out in a two-year project by the Ministry of Environment and Natural Resources (Secretaria de Medio Ambiente y Recursos Naturales, SEMARNAT) as part of the "National forest and soil inventory" (Sánchez-Colón, 2004; Secretaria de Medio Ambiente y Recursos Naturales, 2002). The aim of the study was to improve past assessment on soil degradation on a finer scale (1:250 000) to strengthen the knowledge about status and risks of soil degradation processes.

The assessment of degradation types and causes is based on ASSOD methodology with slight modifications. The extent of each degradation type is given in percent of the mapping unit (polygon) as a multiple of 5 (Secretaria de Medio Ambiente y Recursos Naturales, 2002). To describe the degradation status, four categories of degradation level (hereafter denominated as degree) were defined (slight, moderate, strong, extreme), which are mainly based on the definition suggested by Oldeman *et al.* (1991). Stable terrains and wasteland were excluded in my study, while the other types were summed up by their extent as described in A.3.1 and adjusted to GLASOD database. As done in all other databases described earlier in this ANNEX, only arid, semi-arid and dry sub-humid areas are included for assessing desertification.

The Mexican study on human-induced soil degradation can be obtained from SEMARNAT through Salvador Sánchez-Colón (ssanchez@semarnat.gob.mx).

A.3.6 Land degradation in South Africa

As a consequence to the UNCCD, the National Botanical Institute (NBI) and the Programme for Land and Agrarian Studies (PLAAS), in the School of Government at the University of the Western Cape carried out a study on land degradation in South Africa, which was completed in 1999 (Hoffman and Todd, 2000; Hoffman *et al.*, 1999). The criteria for assessing extent, degree, rate and severity of soil degradation are based on the GLASOD approach. The severity and the rate were combined with the percentage area of each Land Use Type (LUT) to obtain a soil degradation index. The LUTs include croplands, veld (rangeland), forests, settlement areas, conservation areas and other areas, like mines. This index seems to be a valuable tool for further analysis concerning social-economic parameters (e.g. poverty or unemployment rate) and biophysical parameter (e.g. precipitation)

(Hoffman and Todd, 2000; Hoffman *et al.*, 1999; Meadows and Hoffman, 2002; 2003). For this study I only used the extent and the degree and no aggregated parameters to avoid "over-simplification" (see A.3.1).

To obtain a GIS-based dataset including extent and degree for further calculations, some modification had to be done. While GLASOD also provides the exact extent of soil degradation additionally to the five extent classes, the South African database only gives information about these five categories. In my aim to adjust this database to the newly modified COMSAD map, the averaged values of the each extent class were assigned to the gridcells (Table A4) while converting the polygons to the gridded map. Because of the inaccuracy of this method, the total area of several map units exceeded 100%. For this reason, I used the weighted averages of all extents occurring in these units.

Table A 4. Classification of degradation extent after Hoffman *et al.* (1999).
The mean values were assigned to each gridcell affected by the prevailing class

	Extent [% of soil degradation in each Land Use Type]				
extent classes	1 (0-5%)	2 (6-10%)	3 (11-25%)	4 (26-50%)	5 (>50%)
mean	2.5%	8.0%	18.0%	36.5%	75.0%

It has to be noted that Hoffman *et al.* (1999) also assessed vegetation degradation (or 'veld degradation'), which was defined by six types (e.g. "change of species composition" or "bush encroachment"), but this was neglected in this study for the reasons described above in Annex A.1. Furthermore I excluded extent and degrees of soil degradation in "conservation areas", because I assume that climate-induced degradation is more likely the main driver in these areas than human-induced degradation.
GIS data, the report and additional information about the assessment "Land degradation in South Africa" can be derived from: http://www.sanbi.org/landdeg/

A.3.7 Desertification Map of the Drylands of Asia

The desertification map of Asia (Kharin *et al.*, 1999b) was compiled by combining several assessment from the past (e.g. Kharin *et al.*, 1993) and remote sensing data of NDVI (Normalized Difference Vegetation Data). Kharin *et al.* (1999a) examined different types of desertification, like erosion, salinization, waterlogging or vegetation degradation in five land use types. The desertification status is defined by three degrees (slight, moderate, severe and very severe) which are classified by semi-quantitative criteria. The published desertification map shows categories of land use types and degree. Seven classes are excluded from this assessment like bogs, Solonchaks, bare land, stones, mountains, moving sand and extra-arid lands.

Several modifications were necessary to adjust this map to COMSAD. First, the published map is a Photoshop format image, with 4x4 arc minutes resolution. While transferring this map to a GIS software, some inaccuracies occurred by assigning the correct class to each pixel due to the grey scales. Therefore each pixel was evaluated and corrected accordingly to the original map. Nevertheless I cannot rule out the possibility that some pixels were still classified wrongly. Second, Kharin *et al.* (1999a) did not follow the dryland classification of UNCCD. For this reason I had to overlay this map with the Humidity Index to reclassify the dryland areas. Considering the UNCCD definition, several areas, especially the dry sub-humid areas, are probably not assessed in the study of Kharin *et al.* (1999a). Third, due to the overlapping of this map with other databases, several countries had to be excluded from this assessment, like Pakistan, India, China, Russia and Egypt (Table A7). Forth, the desertification map only gives information of three degree classes, aggregating "severe" and "very severe". In order to avoid an exaggerated overestimation, I adjusted this category to my degree class number 3 (strong). Furthermore Kharin *et al.* (1999a) did not define non-degraded land or stable areas. All areas examined in their assessment are at least slightly desertified or are assigned to one of those classes excluded from assessment. So every map unit is assumed to have 100% extent of its suggested degradation type and degree, except those areas which are explicitly defined by a second type in the printed map included in the report (Kharin *et al.*, 1999a). This fact may contribute to an overestimation in some mapping units. Fifth, as explained in A.1, vegetation degradation will be not considered in this study, so all degradation categories including vegetation degradation are disregarded. After preparing the data of Asia for further calculations, the soil degradation layers were prepared as described above and integrated in COMSAD.

The desertification map[4] (Kharin *et al.*, 1999b) can be downloaded at ftp://dbx.cr.chiba-u.jp/data/DrylandMap/ and the report (Kharin *et al.*, 1999a) can be derived from Ryutaro Tateishi for free (contact information on http://www.cr.chiba-u.jp/~tateishi-lab/).

A.4 Modeling Net Primary Production losses

Previous studies on productivity losses due to desertification are mainly related to agricultural losses, like yield alterations or economic decreases (Bojö, 1996; Crosson, 2003; Dregne and Chou, 1992; Oldeman, 1998; Pimentel *et al.*, 1995; Scherr, 1999). This study aims to estimate the net primary production losses due to desertification to quantify human impact on energy flows in dryland ecosystems relating to the indicator HANPP. For this reason the newly compiled COMSAD was taken as a base map for further calculations as described below. In order to consider uncertainties I derived minimum and maximum estimates reflecting possible errors in available input data. The results of the minimum and maximum estimates were cross-checked by a refined "best guess" calculation.

A.4.1 Minimum and maximum estimates

NPP losses were calculated by combining the extents and degrees of COMSAD with percentage losses derived from modified literature surveys (Table A5), and potential net primary production (NPP_0). NPP_0 was derived from the Lund-Potsdam-Jena dynamic global vegetation model (LPJ-DGVM) (Sitch *et al.*, 2003) with improved hydrological data (Gerten *et al.*, 2004) calculated by Haberl *et al.* (2007) for the year 2000. They ran the LPJ model for the period of 1901 to 2002 and averaged the five year results between 1998 and 2002 to avoid an annual vegetation peak in 2000. These data are provided in a global grid with 5 minutes geographic resolution. The four layers of COMSAD presenting the extent per gridcell of each degree were multiplied with modified percentage losses based on the study of Dregne and Chou (1992). The percentage losses of the minimum estimate was taken from the mean values suggested for croplands, while the productivity losses of the maximum estimate are based on

[4] There are two maps provided for download. The coloured jpg-file gives an excellent overview about the assessment and is the same map as the one included in the report (Kharin et al., 1999a) in a large print-format. The grey-shaded psd-file can be obtained for further GIS analysis. The file "readme.doc" gives geographical information about the psd-file for further GIS-based analysis.

the upper range of the percentage losses suggested for rangelands. The minimum and the maximum estimates did not distinguish between land-use classes and show an overall result on global NPP losses due to desertification.

Table A 5. Productivity losses estimated by Dregne and Chou (1992) and the modified values used in this study

Degree	Productivity losses [%] (Dregne and Chou, 1992)		Productivity losses [%] (this study)	
	croplands	rangelands	minimum estimate	maximum estimate
light / slight	0-10	0-25	5	25
moderate	10-25	25-50	18	50
strong / severe	25-50	50-75	38	75
extreme / very severe	50-100	75-100	63*	100

*The percentage loss for extreme degree in this study is not derived by mean value of croplands, but by the mean value of the lower range of croplands and the lower range of rangelands. I assume, that 75% may be to high for a minimum estimate

A.4.2 The "Best guess" estimate

The minimum and the maximum estimates give a good range of occurring NPP alterations of potential productivity due to desertification. However, in relation to HANPP, a more detailed approach incorporating socioeconomic data is needed. This so called "best guess" is calculated on two different land-use types, croplands and grazing lands, considering the actual net primary production (NPP_{act}) for the year 2000. The land-use datasets were derived from a new comprehensive assessment by Erb *et al.* (2007) with 5 min. geographic resolution. They calculated the global extent of five land-use classes (cropland, forestry, urban and infrastructure area, grazing lands, wilderness and unproductive area) for the year 2000 in a GIS-based analysis. These five layers (each for one land-use class) show the extent in percent per gridcell and sum up to 100% per gridcell.

Due to the lack of spatially explicit information in the source datasets of COMSAD and the missing information about direct links between land use and soil degradation in datasets like GLASOD (Oldeman, 1994), there remain uncertainties about degrees and extents of degraded areas within grazing lands and croplands. Therefore desertified areas in each land-use dataset are used in a weighted proportion to the total agricultural area. I multiplied the extent of each land-use class with a ratio of the total extent of soil degradation divided by the total agricultural area (croplands and grazing lands). All gridcells with a ratio >1 were rearranged to a maximum value of 1 to avoid cases with higher desertification extents than agricultural extents.

NPP_{act} was introduced to the “best guess” to calculate desertification as part of ΔNPP_{LC} following the concept of HANPP as defined by Haberl *et al.* (2007). Though Prince (2002) suggested to calculate NPP losses due to desertification by simply subtracting NPP_{act} from NPP_0, Haberl and colleagues (2007) assume that the amount of NPP, derived through this subtraction, also includes land-use changes and land-cover changes. In this study NPP losses due to desertification in grazing areas are calculated by using the principle of Haberl *et al.* (2007), while productivity losses on croplands are calculated in terms of the concept of Prince (2002) as described below.

NPP losses on grazing lands

To calculate NPP losses on grazing areas, two NPP_{act} datasets were assessed: one shows actual net primary production without desertification (NPP_{act} before degradation, $NPP_{act\text{-}bd}$), and the other one already includes desertification and is denominated as “NPP_{act} after degradation” ($NPP_{act\text{-}ad}$). $NPP_{act\text{-}bd}$ was assessed from the NPP_0 dataset derived from LPJ-DGVM. I used the potential productivity on natural grasslands and combined these data with actual productivity of deforested areas to include land conversion from forests to artificial grasslands. For land cover conversion, a 22% reduction of potential productivity is assumed (for detailed information on conversion factor see: Haberl *et al.*, 2007). To obtain $NPP_{act\text{-}ad}$, NPP_{act} before degradation is multiplied with modified percentage losses suggested by Crosson (1995) and Oldeman (1998) for pasture lands (Table A6) and desertification extents of the four COMSAD layers.

The losses of primary production on grazing lands were calculated by multiplying the difference of $NPP_{act\text{-}bd}$ and $NPP_{act\text{-}ad}$ with the weighted extent of degraded grazing lands. Further the degraded grazing lands were overlayed with a land-use dataset of wilderness and unproductive area calculated by Erb *et al.* (2007) to exclude areas suffering from climate-induced rather than from human-induced desertification. These areas without land use are based on a combination of a global wilderness map (Sanderson *et al.*, 2002) and areas with an aboveground NPP below the threshold of 20 g C/m^2, which are assumed to provide not enough annual productivity for grazing activities (Lamprey, 1983). Further details can be seen in Erb *et al.* (2007).

Table A 6. Comparison of literature-based productivity losses and NPP losses used in this study

Degree	Productivity losses [%] (Crosson, 1995; Oldeman, 1998)		NPP losses [%] (this study)
	croplands	rangelands	grazing lands
light / slight	15	5	5
moderate	35	18	18
strong / severe	75	50	50
extreme / very severe	not defined		85*

*The percentage loss for extreme degree in this study was estimated, neither Crosson (1995) nor Oldeman (1998) did provide data for this degree. Though the extreme degree of soil degradation is defined as unreclaimable, I assume that a minimum of 15% of net primary production still exists.

NPP losses on croplands

Aboveground NPP_{act} on croplands was derived from Haberl *et al.* (2007). They used the LPJ-model and statistical databases to create a grid-based world map on cropland productivity. Belowground NPP_{act} was calculated by using the ratio of belowground NPP to total NPP suggested by Saugier *et al.* (2001). The NPP_{act} dataset already includes soil degradation and is therefore identified here as $NPP_{act\text{-}ad}$. As there remain spatial uncertainties about degrees and extents by recalculating $NPP_{act\text{-}bd}$ with percentage losses assumed by Crosson (1995) and Oldeman (1998) I calculated NPP losses by subtracting NPP_{act} from NPP_0 (derived by LPJ-model run) as suggested by Prince (2002). Irrigated and intensively cultivated areas with a higher actual productivity than NPP_0 were not considered to avoid calculation errors.

The land-use dataset was taken from the assessment of Erb and colleagues (2007). They created the cropland map by combining a base map of Ramankutty and Foley (1998) with recent national FAO cropland statistics (FAO, 2004). The NPP losses due to desertification were calculated by multiplying the difference of NPP_0 and NPP_{act} with the weighted extent of degraded croplands.

Table A 7. Datasets used in this assessment

Database	*Conductor and References*	*Year of data assessment*	*Data output*	*Countries used in this assessment*
Global Assessment of the Status of Human Induced Soil Degradation (GLASOD)	ISRIC/FAO (Oldeman et al 1991)	1988-1990	polygons	Algeria, Angola, Azerbaijan, Argentina, Australia, Armenia, Bolivia, Botswana, Brazil, Burkina Faso, Cameroon, Canada, Cape Verde, Central African Rep., Chad, Chile, Colombia, Congo, Dem. Rep. of Congo, Côte d'Ivoire, Cuba, Cyprus, Benin, Dominican Republic, Ecuador, Egypt, Ethiopia, Eritrea, France, Djibouti, Georgia, Gambia, Germany, Ghana, Greece, Guinea, Guinea-Bissau, Haiti, Italy, Jamaica, Kenya, Libyan Arab Jamah., Madagascar, Mali, Mauritania, T.F. Yug. Rep. Macedonia, Morocco, Mozambique, Namibia, Niger, Nigeria, Papua New Guinea, Paraguay, Peru, Portugal, Sao Tome and Principe, Senegal, Somalia, Spain, Sudan, Swaziland, Togo, Trinidad and Tobago, Tunisia, Turkey (European part), Uganda, United Rep. Tanzania, United States, Venezuela, Western Sahara, Yugoslavia, Zambia, Zimbabwe
Assessment of the Status of Human-Induced Soil Degradation in South and Southeast Asia (ASSOD)	ISRIC/FAO (van Lynden & Oldeman 1997)	1995	polygons	China, East Timor[5], India, Indonesia, Myanmar, Nepal, Pakistan, Sri Lanka, Thailand
Soil Vulnerability Assessment in Central and Eastern Europe (SOVEUR)	ISRIC/FAO (van Lynden 2000)	1998-1999	polygons	Bulgaria, Belarus, Czech Republic, Hungary, Republic of Moldova, Poland, Romania, Russian Federation (European part), Ukraine
Land Degradation in Russia	IIASA/FAO (Stolbovoi & Fischer 1998)	1992-1993	polygons	Russian Federation (Asian part)
Desertification map of Asia	CEReS (Kharin *et al.* 1999)	between the 1970s and 1998	.psd - file	Afghanistan, Iran, Iraq, Israel, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lebanon, Mongolia, Oman, Saudi Arabia, Syrian Arab Republic, Tajikistan, Turkey (Asian part), Turkmenistan, Uzbekistan, Yemen, Palestine Occupied Territory
Land Degradation in South Africa	Hoffman *et al.* (1999)	1997-1998	polygons	South Africa
Evaluación de la degradación del suelo causada por el hombre en la República mexicana. Escala 1:250,000	SEMARNAT (2002)	2001	polygons	Mexico
Humidity Index	CRU/UEA and UNEP/GRID (Deichmann & Eklundh 1991)	1951-1980	polygons	worldwide
Land Use Data (cropland and grazing land)	Erb *et al.* (2007)	2007 for the year 2000	5x5 min grids	worldwide
Wilderness area	Sanderson *et al.* (2002)	2002	5x5 min grids	worldwide
Potential net Primary Production (NPP_0)	Haberl *et al.* (2007) using LPJ (Sitch *et al.* 2003, Gerten *et al.* 2004)	2007 for the year 2000	5x5 min grids	worldwide
Terrestrial Ecoregions of the World	Olson *et al.* (2001)	2001	Polygons	worldwide

[5] In ASSOD database East Timor is not separated from Indonesia

Table A 8. Countries including dryland regions and the definition of regions used in this assessment

Northern Africa and Western Asia	Algeria, Armenia, Azerbaijan, Cyprus, Egypt, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Libyan Arab Jamah., Morocco, Oman, Saudi Arabia, Syrian Arab Republic, Tunisia, Turkey, Western Sahara**, Yemen
Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Cameroon, Cape Verde**, Central African Republic, Chad, Dem. Rep. of Congo, Congo, Côte d'Ivoire, Djibouti, Eritrea, Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Madagascar, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Sao Tome and Principe**, Senegal, Somalia, South Africa, Sudan, Swaziland, United Rep. Tanzania, Togo, Uganda, Zambia, Zimbabwe
Central Asia and Russian Federation	Kazakhstan, Kyrgyzstan, Russian Federation, Tajikistan, Turkmenistan, Uzbekistan
Eastern Asia	China, Republic of Mongolia
Southern Asia	Afghanistan, India, Islamic Republic of Iran, Nepal, Pakistan, Sri Lanka
Northern America	Canada, United States of America
South-Eastern Asia	Indonesia, Myanmar, Thailand, Timor-Leste
Latin America and the Caribbean	Argentina, Bahamas*, Bolivia, Brazil, Chile, Colombia, Cuba, Dominican Republic, Ecuador, Falkland Islands (UK)**, Haiti, Jamaica, Mexico, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela, South Georgia and the South Sandwich Islands (UK)*
Western Europe	France, Germany, Greece, Italy, Norway*, Portugal, Spain
Eastern and South-Eastern Europe	Bulgaria, Czech Republic, Hungary, T.F. Yug. Rep. Macedonia, Republic of Moldova, Poland, Romania, Yugoslavia, Ukraine
Oceania and Australia	Australia, New Caledonia (France)**, Papua New Guinea

113 countries are included in the assessment relating to global dryland areas.
*Dryland areas in these countries did not indicate desertification in the used datasets and were excluded for further calculations.
**These countries were excluded in the 'best guess' calculation due to wilderness and non-productive areas or due to missing croplands and grazing lands. The regions are based on the classification of the macro geographical (continental) regions and geographical subregions suggested by the United Nations Statistical Division (2006).

Annex B – Results

B.1 Additional Tables

Table B 1. National calculations of degraded areas in COMSAD and in COMSAD-LU

Country/Region	Total area [km²]	Dryland area [%]	Degraded area of COMSAD per degree: Light [km²]	Moderate [km²]	Strong [km²]	Extreme [km²]	Total [km²]	Degraded area of COMSAD-LU: Total [km²]
Canada	9 330 522.00	15.91	49 676.45	38 860.95	0	0	88 537.40	85 981.77
United States	9 177 302.00	42.39	76 353.07	429 731.69	12 156.93	0	518 241.70	495 537.22
Total Northern America	**18 507 824.00**	**29.04**	**126 029.52**	**468 592.65**	**12 156.93**	**0**	**606 779.10**	**581 518.99**
Argentina	2 759 905.75	53.03	222 886.98	42 566.53	1 345.52	0	266 799.04	261 803.83
Bolivia	1 084 269.88	57.78	10 613.47	66 696.98	20 882.20	0	98 192.66	82 228.91
Brazil	8 455 399.00	15.35	131 248.73	86 215.02	24 492.67	0	241 956.42	226 421.66
Chile	739 917.94	20.98	4 733.03	6 018.51	10 311.34	0	21 062.88	18 858.43
Colombia	1 140 780.75	17.46	15 809.36	5 361.74	0	0	21 171.10	19 950.98
Cuba	104 952.59	11.42	516.42	743.29	0	0	1 259.70	974.00
Dominican Republic	47 194.97	5.51	55.15	182.68	12.21	0	250.04	231.50
Ecuador	256 576.16	63.74	6 081.72	4 504.81	0	0	10 586.53	8 703.65
Haiti	26 150.03	2.80	0	0	677.59	0	677.59	133.54
Jamaica	10 606.82	31.53	250.80	585.20	0.00	0	836.00	741.97
Mexico	1 942 260.25	69.61	118 623.39	284 353.90	15 817.06	7 237.98	426 032.33	270 135.68
Paraguay	396 720.94	55.32	15.87	624.44	0	0	640.32	640.32
Peru	1 288 399.75	36.59	6 734.12	53 845.53	1 971.29	0	62 550.94	41 597.01
Trinidad and Tobago	5 319.12	4.77	6.34	95.07	0	0	101.41	67.60
Venezuela	910 188.63	49.27	9 565.87	37 520.64	4 403.88	0	51 490.38	49 717.68
Total Latin America and the Caribbean	**19 168 642.56**	**33.47**	**527 141.26**	**589 314.33**	**79 913.76**	**7 237.98**	**1 203 607.33**	**982 206.77**

Table B1 (continued)

Country/Region	Total area	Dryland area	Degraded area of COMSAD per degree					Degraded area of COMSAD-LU
			Light	Moderate	Strong	Extreme	Total	Total
	[km²]	[%]	[km²]	[km²]	[km²]	[km²]	[km²]	[km²]
France	547 382.81	0.35	0	332.61	0	0	332.61	279.96
Germany	356 525.72	5.02	6 826.16	0	0	0	6 826.16	6 068.53
Greece	129 976.59	46.14	13 450.53	4 105.64	0	0	17 556.17	17 177.70
Italy	298 219.41	20.46	1 768.22	5 338.46	5 286.24	0	12 392.93	12 056.05
Portugal	91 738.22	29.55	1 634.69	13 752.05	0	0	15 386.75	14 432.31
Spain	506 371.72	69.08	25 580.91	42 498.22	7 487.66	0	75 566.79	74 503.31
Total Western Europe	**1 930 214.47**	**26.82**	**49 260.51**	**66 026.99**	**12 773.90**	**0**	**128 061.41**	**124 517.86**
Bulgaria	110 741.05	53.29	6 143.44	1 821.08	424.98	6.17	8 395.68	7 425.54
Czech Republic	78 345.39	12.96	720.71	1 209.35	622.11	0	2 552.17	2 546.43
Hungary	92 346.27	46.63	5 304.20	13 517.24	409.24	0	19 230.69	18 748.93
Republic of Moldova	33 482.63	100.00	7 574.76	9 197.95	4 007.07	2 297.13	23 076.91	22 195.04
Poland	310 099.09	19.34	2 547.61	21 235.39	0	0	23 783.01	22 676.41
Romania	236 325.58	38.43	11 762.49	58 299.93	6 722.34	713.22	77 497.99	70 833.72
Ukraine	587 786.13	65.38	44 038.18	161 488.27	23 092.34	19.21	228 638.01	223 340.55
T.F.Yug.Rep. Macedonia	25 164.53	37.11	1 085.98	1 693.29	483.08	0	3 262.35	2 935.43
Yugoslavia	101 434.83	14.40	2 060.54	1 764.56	773.11	0	4 598.21	4 598.21
Total Eastern and South-Eastern Europe	**1 575 725.49**	**44.73**	**81 237.92**	**270 227.07**	**36 534.27**	**3 035.74**	**391 035.00**	**375 300.27**
Angola	1 252 364.13	19.30	0	1 365.61	528.69	0	1 894.30	1 854.27
Botswana	579 841.19	100.00	6 322.48	24 068.08	17 718.54	0	48 109.11	43 826.85
Cameroon	465 745.56	12.81	605.24	4 218.58	11 048.06	0	15 871.87	15 216.22
Central African Rep.	620 895.25	20.15	1 331.90	0	209.18	0	1 541.08	1 418.33
Chad	1 274 684.13	68.19	149 825.28	71 876.18	2 338.75	0	224 040.21	178 365.14
Congo	344 758.00	0.15	0	89.84	0	0	89.84	89.84
Dem. Rep. of Congo	2 305 080.75	0.44	0	1 615.41	0	0	1 615.41	1 502.51
Benin	116 518.68	87.06	6 368.90	9 108.82	445.45	0	15 923.17	15 478.04
Ethiopia	1 126 735.88	58.07	66 793.00	38 817.74	20 952.70	15 575.58	142 139.01	142 105.23
Eritrea	120 530.13	83.21	5 361.49	1 680.46	11 638.83	7 771.12	26 451.90	22 566.51
Djibouti	20 931.38	73.94	2 708.53	0	386.93	0	3 095.47	3 095.47
Gambia	10 438.23	97.60	904.19	242.26	0	0	1 146.45	1 101.67

Table B1 (continued)

Country/Region	Total area	Dryland area	Degraded area of COMSAD per degree					Degraded area of COMSAD-LU
			Light	Moderate	Strong	Extreme	Total	Total
	[km²]	[%]	[km²]	[km²]	[km²]	[km²]	[km²]	[km²]
Ghana	232 714.97	65.35	4 466.94	6 728.37	8 740.00	0	19 935.31	18 352.36
Guinea	245 077.44	14.34	1 384.44	0	0	0	1 384.44	1 384.44
Côte d'Ivoire	321 660.66	38.43	6 975.85	12.77	304.17	0	7 292.80	7 292.80
Kenya	571 324.06	71.18	23 637.86	8 068.84	16 958.51	0	48 665.21	45 526.52
Madagascar	593 179.44	23.23	2 399.25	10 148.59	41 620.01	167.25	54 335.10	54 193.45
Mali	1 255 064.50	80.09	115 306.70	155 083.75	8 584.06	0	278 974.51	208 811.42
Mauritania	1 040 036.06	45.58	109 463.97	60 609.25	16 759.32	0	186 832.54	161 986.37
Mozambique	779 010.13	37.77	20 234.11	2 845.07	885.72	0	23 964.90	23 872.55
Namibia	824 220.44	90.79	20 239.34	38 010.58	5 744.23	0	63 994.16	34 430.59
Niger	1 186 041.38	62.09	166 362.09	162 728.39	12 915.42	0	342 005.89	250 510.11
Nigeria	910 915.69	58.02	9 127.69	65 667.59	10 744.86	0	85 540.14	85 101.09
Guinea-Bissau	31 909.12	5.78	10.48	142.46	0.00	0	152.94	152.61
Senegal	196 596.70	94.25	9 322.08	8 206.15	28 560.27	0	46 088.50	45 482.48
Somalia	636 352.06	80.12	72 472.94	7 187.03	7 961.34	9 543.20	97 164.51	86 500.10
South Africa	1 217 843.88	66.40	106 920.99	68 093.60	4 877.48	28 031.08	207 923.15	182 151.72
Zimbabwe	388 127.41	67.07	591.06	20 860.99	1 862.47	0	23 314.52	21 483.41
Sudan	2 495 025.00	67.28	126 015.71	315 435.26	33 538.94	0	474 989.90	440 969.95
Swaziland	17 508.31	49.98	0	0	218.77	0	218.77	218.77
Togo	57 214.39	34.03	110.49	2 382.69	3 978.76	0	6 471.94	5 440.19
Uganda	206 027.31	4.58	81.41	201.43	2 379.25	555.16	3 217.25	2 515.29
United Rep.Tanzania	882 246.56	10.90	1 560.66	11 092.91	3 943.09	717.81	17 314.47	17 093.49
Burkina Faso	273 705.41	100.00	14 649.01	23 845.84	76 796.47	0	115 291.32	104 945.84
Zambia	741 655.31	16.30	960.91	7 730.55	870.16	0	9 561.62	9 561.62
Total Sub-Saharan Africa	**23 341 979.50**	**48.77**	**1 052 514.99**	**1 128 165.08**	**353 510.45**	**62 361.19**	**2 596 551.70**	**2 234 597.25**
Algeria	2 320 661.75	20.90	28 962.81	59 467.33	15 542.89	0	103 973.02	88 469.16
Azerbaijan	85 855.24	83.85	648.58	6 768.85	0	0	7 417.43	7 394.72
Armenia	28 554.48	98.19	244.44	1 849.93	0	0	2 094.37	2 094.37
Cyprus	9 348.59	86.46	0	1 616.49	0	0	1 616.49	1 551.02
Georgia	67 802.08	34.84	307.01	1 384.20	0	0	1 691.21	1 640.83
Iraq	434 925.13	99.88	361.71	108 411.79	128 267.47	0	237 040.96	180 151.80
Israel	20 963.52	68.97	2 844.97	8 191.72	794.88	0	11 831.57	7 834.14

Table B1 (continued)

Country/Region	Total area	Dryland area	Degraded area of COMSAD per degree					Degraded area of COMSAD-LU
			Light	Moderate	Strong	Extreme	Total	Total
	[km^2]	[%]	[km^2]	[km^2]	[km^2]	[km^2]	[km^2]	[km^2]
Jordan	89 319.86	72.85	0	11 619.44	2 870.88	0	14 490.32	9 938.00
Kuwait	18 037.81	88.42	0	843.38	7 170.46	0	8 013.84	2 899.76
Lebanon	10 685.67	56.83	0	5 142.16	0	0	5 142.16	4 763.88
Libyan Arab Jamah.	1 619 363.75	22.72	117 354.72	61 584.51	0	0	178 939.23	86 763.71
Morocco	402 335.19	92.26	14 095.71	21 038.43	2 546.09	0	37 680.24	33 316.43
Oman	312 086.91	13.94	0	492.99	2 445.64	0	2 938.63	574.48
Saudi Arabia	1 937 509.88	23.74	0	44 582.34	78 626.70	0	123 209.03	34 285.55
Syrian Arab Republic	187 940.14	97.97	964.36	96 736.09	26 395.18	0	124 095.63	113 708.38
Tunisia	155 411.66	93.58	68 925.47	15 846.56	0	0	84 772.04	53 517.19
Turkey	775 302.63	76.78	4 584.88	202 648.86	23 736.45	0	230 970.18	206 434.31
Egypt	991 458.19	7.39	1 760.29	7 842.18	0	0	9 602.47	3 605.57
Yemen	457 909.34	28.93	0	5 294.33	11 648.65	0	16 942.97	5 381.89
Total Northern Africa and Western Asia	**9 925 471.79**	**35.52**	**241 054.96**	**661 361.58**	**300 045.27**	**0**	**1 202 461.80**	**844 325.20**
Kazakhstan	2 656 522.75	99.15	115 538.04	225 942.26	35 580.58	0	377 060.88	360 148.26
Kyrgyzstan	192 774.38	57.39	717.25	1 882.52	0	0	2 599.76	2 104.29
Russian Federation	16 578 535.00	21.96	0	13 454.66	263 620.70	544 700.97	821 776.33	704 066.88
Tajikistan	141 788.67	40.00	9 994.71	0	0	0	9 994.71	8 449.26
Turkmenistan	465 802.94	100.00	12 460.67	65 055.94	21 515.64	0	99 032.25	95 442.17
Uzbekistan	426 359.59	99.18	45 598.93	66 366.12	9 234.55	0	121 199.61	107 566.22
Total Central Asia and the Russian Federation	**20 461 783.33**	**35.82**	**184 309.60**	**372 701.49**	**329 951.48**	**544 700.97**	**1 431 663.54**	**1 277 777.08**
Afghanistan	640 950.25	94.01	2 673.52	13 251.77	7 189.71	0	23 115.00	21 544.14
Sri Lanka	65 864.59	23.45	7 444.48	0	0	0	7 444.48	6 440.75
India	3 146 287.50	58.59	319 767.50	340 358.78	92 665.66	59 252.25	812 044.19	747 439.05
Iran(Islamic Rep. of)	1 615 403.88	90.00	34 955.91	84 580.35	369.88	0	119 906.14	111 824.58
Nepal	146 938.05	9.29	4 214.66	0.00	0	0	4 214.66	3 500.37
Pakistan	875 449.94	82.49	221 069.87	178 284.95	71 157.51	0	470 512.33	305 366.86
Total Southern Asia	**6 490 894.20**	**71.65**	**590 125.94**	**616 475.85**	**171 382.76**	**59 252.25**	**1 437 236.80**	**1 196 115.75**

Table B1 (continued)

Country/Region	**Total area**	**Dryland area**	**Degraded area of COMSAD per degree**					**Degraded area of COMSAD-LU**
			Light	**Moderate**	**Strong**	**Extreme**	**Total**	**Total**
	[km²]	**[%]**	**[km²]**	**[km²]**	**[km²]**	**[km²]**	**[km²]**	**[km²]**
Myanmar	670 811.06	3.32	2 191.64	0	0	0	2 191.64	2 191.64
Indonesia	1 913 179.63	2.18	3 519.20	1 770.57	1 474.66	0	6 764.44	6 497.63
East Timor	15 272.30	86.66	330.88	2 316.18	0	0	2 647.06	2 581.14
Thailand	512 654.31	6.75	2 807.76	27 226.68	2 957.56	588.20	33 580.20	30 810.79
Total South-Eastern Asia	**3 111 917.30**	**3.59**	**8 849.48**	**31 313.44**	**4 432.22**	**588.20**	**45 183.34**	**42 081.19**
China	9 350 681.00	33.82	1 097 765.38	164 626.29	434 937.74	16 987.12	1 714 316.53	1 280 170.27
Mongolia	1 548 318.63	65.03	88 224.17	74 039.15	10 576.21	0	172 839.53	87 976.37
Total Eastern Asia	**10 898 999.63**	**38.25**	**1 185 989.55**	**238 665.44**	**445 513.95**	**16 987.12**	**1 887 156.06**	**1 368 146.63**
Australia	7 641 186.50	85.92	828 616.30	22 073.43	11 032.38	4 169.60	865 891.71	517 989.57
Papua New Guinea	471 967.66	0.56	14.84	0	0	0	14.84	12.72
Total Oceania and Australia	**8 113 154.16**	**80.96**	**828 631.14**	**22 073.43**	**11 032.38**	**4 169.60**	**865 906.55**	**518 002.28**
World	**123 526 606.42**	**41.09**	**4 875 144.86**	**4 464 917.36**	**1 757 247.38**	**698 333.05**	**11 795 642.65**	**9 544 589.27**

Sources: own calculations

Table B 2. National calculations of NPP losses expressed as carbon flows and as percentage of potential NPP

	NPP_0			NPP losses					
Country/Region	**Drylands**	**Grazing lands**	**Croplands**	**Minimum estimate**		**Maximum estimate**		**'Best guess' estimate**	
	[Tg C/yr]	**[Tg C/yr]**	**[Tg C/yr]**	**[Tg C/yr]**	**[% of NPP_0 in drylands]**	**[Tg C/yr]**	**[% of NPP_0 in drylands]]**	**[Tg C/yr]**	**[% of NPP_0 in drylands]]**
Canada	815.60	135.51	194.64	5.08	0.62	17.08	2.09	15.67	1.92
United States	1 376.47	804.27	307.62	33.33	2.42	94.68	6.88	35.25	2.56
Total Northern America	**2 192.07**	**939.77**	**502.26**	**38.41**	**1.75**	**111.75**	**5.10**	**50.93**	**2.32**
Argentina	682.41	517.71	53.52	9.49	1.39	37.83	5.54	12.20	1.79
Bolivia	444.55	181.31	13.25	13.85	3.11	33.90	7.63	11.35	2.55
Brazil	1 013.29	472.68	85.00	28.55	2.82	82.43	8.13	31.98	3.16
Chile	53.67	38.18	2.80	2.13	3.96	4.83	8.99	1.98	3.70
Colombia	183.19	122.16	8.40	1.66	0.90	6.22	3.39	1.89	1.03
Cuba	11.30	4.13	3.36	0.15	1.31	0.46	4.11	0.21	1.87
Dominican Republic	2.82	0.72	1.07	0.04	1.57	0.13	4.48	0.12	4.26
Ecuador	148.72	14.43	15.99	0.90	0.60	3.08	2.07	2.43	1.64
Haiti	0.80	0.08	0.06	0.28	35.15	0.55	69.38	0.08	10.48
Jamaica	3.43	0.63	0.89	0.12	3.53	0.36	10.63	0.25	7.20
Mexico	528.74	179.41	89.48	26.38	4.99	76.03	14.38	23.55	4.45
Paraguay	169.04	52.59	14.52	0.12	0.07	0.33	0.19	0.12	0.07
Peru	375.67	97.90	8.31	7.77	2.07	21.74	5.79	4.00	1.07
Trinidad and Tobago	0.26	0.15	0.03	0.02	6.87	0.05	19.37	0.01	5.27
Venezuela	376.35	213.68	17.74	7.09	1.88	19.41	5.16	7.62	2.02
Total Latin America and the Caribbean	**3 994.24**	**1 895.76**	**314.42**	**98.52**	**2.47**	**287.34**	**7.19**	**97.80**	**2.45**
France	1.06	0.28	0.05	0.03	3.15	0.09	8.75	0.02	2.09
Germany	10.74	2.31	4.35	0.20	1.91	1.02	9.53	0.05	0.43
Greece	26.87	8.35	10.60	0.64	2.38	2.44	9.10	0.71	2.64
Italy	27.40	8.75	9.84	1.37	4.99	3.15	11.51	1.51	5.52
Portugal	15.15	4.93	6.17	1.44	9.50	4.10	27.06	3.34	22.01
Spain	177.33	61.98	73.06	5.93	3.35	16.95	9.56	12.40	6.99
Total Western Europe	**258.55**	**86.60**	**104.09**	**9.61**	**3.72**	**27.77**	**10.74**	**18.03**	**6.97**
Bulgaria	30.38	6.84	14.92	0.40	1.31	1.37	4.51	1.18	3.88
Czech Republic	6.26	0.68	3.48	0.30	4.77	0.76	12.20	0.32	5.09
Hungary	25.98	7.03	15.32	1.74	6.69	5.10	19.63	1.54	5.92
Republic of Moldova	17.54	3.12	11.41	2.56	14.61	6.05	34.52	4.74	27.04

Table B2 (continued)

Country/Region	NPP$_0$			NPP losses					
	Drylands	Grazing lands	Croplands	Minimum estimate		Maximum estimate		'Best guess' estimate	
	[Tg C/yr]	[Tg C/yr]	[Tg C/yr]	[Tg C/yr]	[% of NPP$_0$ in drylands]]	[Tg C/yr]	[% of NPP$_0$ in drylands]	[Tg C/yr]	[% of NPP$_0$ in drylands]]
Poland	37.93	8.34	17.25	2.49	6.56	7.09	18.70	4.17	11.00
Romania	43.71	13.56	23.72	6.70	15.32	18.07	41.33	9.05	20.69
Ukraine	207.87	57.12	118.67	21.54	10.36	58.88	28.32	50.50	24.30
T.F.Yug.Rep. Macedonia	4.67	1.40	1.32	0.27	5.88	0.75	15.98	0.40	8.59
Yugoslavia	8.33	1.07	5.90	0.41	4.88	1.13	13.51	0.90	10.80
Total Eastern and South-Eastern Europe	**382.66**	**99.18**	**211.98**	**36.41**	**9.51**	**99.19**	**25.92**	**72.80**	**19.02**
Angola	130.89	100.49	4.91	0.26	0.20	0.63	0.48	0.31	0.24
Botswana	200.75	144.54	1.32	5.07	2.53	11.22	5.59	5.68	2.83
Cameroon	34.47	19.78	7.19	2.90	8.41	6.13	17.79	3.93	11.39
Central African Rep.	83.56	46.33	4.95	0.09	0.11	0.30	0.36	0.13	0.16
Chad	305.92	235.40	18.09	6.25	2.04	20.91	6.83	6.64	2.17
Congo	0.41	0.20	0.01	0.01	3.15	0.04	8.75	0.01	3.43
Dem. Rep. of Congo	8.54	3.66	0.08	0.25	2.90	0.69	8.05	0.21	2.52
Benin	65.53	33.39	12.40	1.46	2.23	4.44	6.78	2.54	3.88
Ethiopia	296.36	267.66	13.91	13.94	4.70	31.61	10.67	17.71	5.97
Eritrea	21.79	14.56	1.95	2.48	11.38	4.65	21.36	2.71	12.43
Djibouti	4.75	4.74	0.00	0.09	1.82	0.30	6.25	0.08	1.78
Gambia	5.89	1.80	1.27	0.05	0.87	0.20	3.42	0.22	3.71
Ghana	104.09	60.54	20.46	3.05	2.93	7.15	6.87	4.18	4.01
Guinea	22.52	17.38	0.38	0.05	0.20	0.23	1.00	0.06	0.24
Côte d'Ivoire	95.67	39.38	21.65	0.35	0.37	1.52	1.59	1.79	1.87
Kenya	203.86	145.05	16.95	5.62	2.76	13.91	6.82	8.27	4.06
Madagascar	115.16	99.17	4.41	16.01	13.90	32.96	28.62	20.92	18.16
Mali	313.20	179.67	26.93	11.87	3.79	34.73	11.09	12.66	4.04
Mauritania	65.36	54.30	1.06	4.68	7.15	14.18	21.69	4.60	7.03
Mozambique	202.57	114.92	12.75	1.24	0.61	4.81	2.38	2.33	1.15
Namibia	164.29	133.39	3.63	1.56	0.95	4.33	2.63	1.51	0.92
Niger	172.03	128.95	19.93	14.28	8.30	40.30	23.43	15.94	9.26
Nigeria	299.05	145.62	108.44	8.66	2.90	22.76	7.61	15.22	5.09
Guinea-Bissau	1.09	0.14	0.09	0.02	1.41	0.04	3.99	0.03	2.77
Senegal	97.40	50.10	12.19	6.15	6.31	13.24	13.59	9.09	9.33

Table B2 (continued)

Country/Region	NPP$_0$			NPP losses					
	Drylands	Grazing lands	Croplands	Minimum estimate		Maximum estimate		'Best guess' estimate	
	[Tg C/yr]	[Tg C/yr]	[Tg C/yr]	[Tg C/yr]	[% of NPP$_0$ in drylands]	[Tg C/yr]	[% of NPP$_0$ in drylands]]	[Tg C/yr]	[% of NPP$_0$ in drylands]]
Somalia	76.79	65.39	3.29	2.11	2.75	4.93	6.42	2.57	3.35
South Africa	201.05	150.67	24.23	6.29	3.13	18.23	9.07	8.45	4.20
Zimbabwe	157.10	69.34	13.12	2.50	1.59	6.68	4.25	3.13	1.99
Sudan	750.74	555.44	89.62	24.84	3.31	69.94	9.32	33.18	4.42
Swaziland	5.55	3.40	0.48	0.05	0.95	0.10	1.88	0.06	1.07
Togo	12.73	3.94	4.98	1.23	9.67	2.68	21.02	1.80	14.11
Uganda	8.66	3.12	3.48	0.97	11.20	1.84	21.28	1.13	13.04
United Rep.Tanzania	75.58	48.42	3.68	3.18	4.20	7.61	10.06	3.95	5.22
Burkina Faso	156.77	91.60	22.18	19.10	12.18	40.70	25.96	22.64	14.44
Zambia	83.01	46.18	6.48	1.21	1.45	3.24	3.91	1.47	1.77
Total Sub-Saharan Africa	**4 543.11**	**3 078.66**	**486.49**	**167.85**	**3.69**	**427.23**	**9.40**	**215.12**	**4.74**
Algeria	68.65	35.76	22.16	3.54	5.15	9.83	14.32	7.80	11.37
Azerbaijan	26.23	15.62	5.84	0.44	1.67	1.24	4.73	0.53	2.01
Armenia	10.43	6.01	2.11	0.12	1.16	0.35	3.33	0.15	1.47
Cyprus	3.37	2.18	0.50	0.12	3.60	0.34	10.00	0.13	3.90
Georgia	13.04	4.15	3.13	0.14	1.05	0.40	3.07	0.27	2.04
Iraq	68.42	40.54	20.40	10.58	15.46	25.16	36.77	14.14	20.66
Israel	3.35	1.17	1.36	0.35	10.37	1.05	31.37	0.17	5.15
Jordan	4.14	2.52	0.92	0.40	9.56	1.09	26.40	0.51	12.42
Kuwait	0.79	0.26	-	0.15	18.87	0.30	37.82	0.07	9.00
Lebanon	2.65	1.44	1.02	0.41	15.40	1.13	42.78	0.53	20.14
Libyan Arab Jamah.	27.71	16.55	5.30	0.99	3.58	4.16	15.02	1.63	5.89
Morocco	86.31	41.90	32.33	1.31	1.51	3.80	4.40	3.07	3.56
Oman	1.25	0.75	0.01	0.01	0.87	0.03	2.08	0.01	0.47
Saudi Arabia	6.22	1.10	0.23	0.35	5.69	0.81	13.06	0.08	1.24
Syrian Arab Republic	41.25	19.90	18.73	7.35	17.81	18.54	44.95	10.73	26.02
Tunisia	21.85	2.86	16.14	1.20	5.50	4.40	20.13	6.61	30.24
Turkey	248.17	115.94	88.75	18.10	7.29	47.47	19.13	23.23	9.36
Egypt	2.44	0.62	0.18	0.06	2.58	0.18	7.31	0.02	0.94
Yemen	5.11	2.63	0.68	0.12	2.25	0.25	4.81	0.06	1.11
Total Northern Africa and Western Asia	**641.39**	**311.92**	**219.78**	**45.73**	**7.13**	**120.53**	**18.79**	**69.75**	**10.87**

Table B2 (continued)

Country/Region	NPP$_0$			NPP losses					
	Drylands	Grazing lands	Croplands	Minimum estimate		Maximum estimate		'Best guess' estimate	
	[Tg C/yr]	[Tg C/yr]	[Tg C/yr]	[Tg C/yr]	[% of NPP$_0$ in drylands]	[Tg C/yr]	[% of NPP$_0$ in drylands]	[Tg C/yr]	[% of NPP$_0$ in drylands]]
Kazakhstan	793.73	658.91	88.53	16.30	2.05	46.74	5.89	20.61	2.60
Kyrgyzstan	45.51	36.09	5.02	0.15	0.33	0.44	0.97	0.09	0.20
Russian Federation	1 891.95	447.99	439.85	224.93	11.89	378.83	20.02	223.95	11.84
Tajikistan	19.01	11.98	3.29	0.16	0.85	0.81	4.27	0.25	1.32
Turkmenistan	62.40	58.00	2.83	2.83	4.54	7.23	11.59	2.64	4.22
Uzbekistan	65.97	43.61	12.39	2.78	4.21	8.99	13.63	2.50	3.79
Total Central Asia and the Russian Federation	**2 878.58**	**1 256.58**	**551.91**	**247.16**	**8.59**	**443.05**	**15.39**	**250.04**	**8.69**
Afghanistan	113.60	88.23	19.22	0.83	0.73	1.96	1.72	0.85	0.75
Sri Lanka	11.54	5.00	2.41	0.28	2.41	1.39	12.04	1.12	9.68
India	844.20	139.14	568.34	68.06	8.06	168.49	19.96	95.27	11.29
Iran(Islamic Rep. of)	263.57	198.06	42.42	4.50	1.71	13.51	5.13	4.45	1.69
Nepal	7.78	1.89	2.65	0.11	1.47	0.57	7.34	0.21	2.69
Pakistan	57.23	23.13	24.39	5.31	9.27	15.43	26.97	4.54	7.93
Total Southern Asia	**1 297.92**	**455.45**	**659.42**	**79.09**	**6.09**	**201.35**	**15.51**	**106.44**	**8.20**
Myanmar	17.06	5.83	9.59	0.08	0.49	0.42	2.46	0.53	3.13
Indonesia	36.05	14.42	8.54	0.87	2.40	2.39	6.63	1.75	4.84
East Timor	10.56	6.42	0.58	0.35	3.27	0.99	9.37	0.34	3.18
Thailand	26.13	10.98	12.82	4.97	19.00	12.96	49.61	7.88	30.16
Total South-Eastern Asia	**89.80**	**37.65**	**31.53**	**6.26**	**6.97**	**16.76**	**18.67**	**10.50**	**11.69**
China	915.58	570.28	185.86	52.19	5.70	162.89	17.79	48.90	5.34
Mongolia	121.76	102.92	1.13	1.10	0.90	3.16	2.59	0.61	0.50
Total Eastern Asia	**1 037.34**	**673.20**	**186.99**	**53.29**	**5.14**	**166.04**	**16.01**	**49.51**	**4.77**
Australia	2 299.34	956.39	164.85	16.66	0.72	70.74	3.08	23.90	1.04
Papua New Guinea	3.22	0.61	-	0.00	0.02	0.00	0.11	0.00	0.02
Total Oceania and Australia	**2 302.56**	**957.00**	**164.85**	**16.66**	**0.72**	**70.74**	**3.07**	**23.90**	**1.04**
World	**19 618.22**	**9 791.79**	**3 433.73**	**799.41**	**4.07**	**1 973.00**	**10.06**	**964.80**	**4.92**

Sources: Haberl *et al.* (2007), own calculations

Table B 3. National calculations of land-use related 'best guess' estimates

Country/Region	NPP_0 Drylands [Tg C/yr]	NPP_0 Grazing lands [Tg C/yr]	NPP_0 Croplands [Tg C/yr]	NPP losses Grazing lands [Tg C/yr]	NPP losses Grazing lands [% of NPP_0]	NPP losses Croplands [Tg C/yr]	NPP losses Croplands [% of NPP_0]	NPP losses Total [% of NPP_0 in total agricultural area]
Canada	815.60	135.51	194.64	1.70	1.25	13.98	7.18	4.75
United States	1 376.47	804.27	307.62	21.85	2.72	13.40	4.36	3.17
Total Northern America	**2 192.07**	**939.77**	**502.26**	**23.54**	**2.51**	**27.38**	**5.45**	**3.53**
Argentina	682.41	517.71	53.52	8.23	1.59	3.96	7.41	2.13
Bolivia	444.55	181.31	13.25	9.41	5.19	1.94	14.61	5.83
Brazil	1 013.29	472.68	85.00	19.23	4.07	12.74	14.99	5.73
Chile	53.67	38.18	2.80	1.87	4.89	0.12	4.20	4.84
Colombia	183.19	122.16	8.40	1.19	0.97	0.71	8.41	1.45
Cuba	11.30	4.13	3.36	0.07	1.60	0.15	4.33	2.83
Dominican Republic	2.82	0.72	1.07	0.01	1.77	0.11	10.07	6.74
Ecuador	148.72	14.43	15.99	0.26	1.78	2.17	13.60	7.99
Haiti	0.80	0.08	0.06	0.03	39.00	0.05	81.43	57.13
Jamaica	3.43	0.63	0.89	0.04	6.17	0.21	23.38	16.23
Mexico	528.74	179.41	89.48	9.72	5.42	13.83	15.45	8.76
Paraguay	169.04	52.59	14.52	0.09	0.17	0.03	0.17	0.17
Peru	375.67	97.90	8.31	3.27	3.34	0.73	8.78	3.77
Trinidad and Tobago	0.26	0.15	0.03	0.01	5.42	0.01	20.89	7.98
Venezuela	376.35	213.68	17.74	5.94	2.78	1.68	9.47	3.29
Total Latin America and the Caribbean	**3 994.24**	**1 895.76**	**314.42**	**59.37**	**3.13**	**38.43**	**12.22**	**4.42**
France	1.06	0.28	0.05	0.02	8.01	-	-	6.69
Germany	10.74	2.31	4.35	0.05	2.02	-	-	0.70
Greece	26.87	8.35	10.60	0.21	2.56	0.50	4.68	3.75
Italy	27.40	8.75	9.84	0.87	9.97	0.64	6.49	8.13
Portugal	15.15	4.93	6.17	0.56	11.32	2.78	45.01	30.05
Spain	177.33	61.98	73.06	2.75	4.44	9.65	13.20	9.18
Total Western Europe	**258.55**	**86.60**	**104.09**	**4.47**	**5.16**	**13.56**	**13.03**	**9.45**

Table B3 (continued)

Country/Region	NPP$_0$ Drylands	NPP$_0$ Grazing lands	NPP$_0$ Croplands	NPP losses Grazing lands		NPP losses Croplands		NPP losses Total
	[Tg C/yr]	[Tg C/yr]	[Tg C/yr]	[Tg C/yr]	[% of NPP$_0$]	[Tg C/yr]	[% of NPP$_0$]	[% of NPP$_0$ in total agricultural area]
Bulgaria	30.38	6.84	14.92	0.10	1.43	1.08	7.25	5.42
Czech Republic	6.26	0.68	3.48	0.04	6.50	0.27	7.87	7.64
Hungary	25.98	7.03	15.32	0.49	6.90	1.05	6.88	6.88
Republic of Moldova	17.54	3.12	11.41	0.56	17.97	4.18	36.65	32.63
Poland	37.93	8.34	17.25	0.55	6.55	3.63	21.02	16.30
Romania	43.71	13.56	23.72	2.17	15.98	6.88	29.01	24.27
Ukraine	207.87	57.12	118.67	6.59	11.54	43.91	37.01	28.73
T.F.Yug.Rep. Macedonia	4.67	1.40	1.32	0.11	8.08	0.29	21.74	14.70
Yugoslavia	8.33	1.07	5.90	0.08	7.04	0.82	13.95	12.89
Total Eastern and South-Eastern Europe	**382.66**	**99.18**	**211.98**	**10.68**	**10.77**	**62.12**	**29.30**	**23.40**
Angola	130.89	100.49	4.91	0.26	0.26	0.05	0.94	0.29
Botswana	200.75	144.54	1.32	5.53	3.82	0.15	11.60	3.89
Cameroon	34.47	19.78	7.19	2.54	12.84	1.39	19.30	14.56
Central African Rep.	83.56	46.33	4.95	0.09	0.19	0.05	0.92	0.26
Chad	305.92	235.40	18.09	5.20	2.21	1.43	7.92	2.62
Congo	0.41	0.20	0.01	0.01	5.56	0.00	27.27	6.56
Dem. Rep. of Congo	8.54	3.66	0.08	0.18	5.04	0.03	36.10	5.74
Benin	65.53	33.39	12.40	0.91	2.72	1.64	13.20	5.56
Ethiopia	296.36	267.66	13.91	14.99	5.60	2.72	19.54	6.29
Eritrea	21.79	14.56	1.95	2.29	15.70	0.42	21.71	16.41
Djibouti	4.75	4.74	0.00	0.08	1.78	-	-	1.78
Gambia	5.89	1.80	1.27	0.02	0.99	0.20	15.75	7.11
Ghana	104.09	60.54	20.46	2.30	3.80	1.88	9.18	5.16
Guinea	22.52	17.38	0.38	0.04	0.24	0.01	3.34	0.31
Côte d'Ivoire	95.67	39.38	21.65	0.24	0.60	1.55	7.15	2.93
Kenya	203.86	145.05	16.95	4.96	3.42	3.31	19.56	5.11
Madagascar	115.16	99.17	4.41	19.77	19.93	1.15	26.05	20.19
Mali	313.20	179.67	26.93	10.01	5.57	2.65	9.83	6.13
Mauritania	65.36	54.30	1.06	4.29	7.90	0.30	28.70	8.30

Table B3 (continued)

Country/Region	NPP$_0$ Drylands [Tg C/yr]	NPP$_0$ Grazing lands [Tg C/yr]	NPP$_0$ Croplands [Tg C/yr]	NPP losses Grazing lands [Tg C/yr]	NPP losses Grazing lands [% of NPP$_0$]	NPP losses Croplands [Tg C/yr]	NPP losses Croplands [% of NPP$_0$]	NPP losses Total [% of NPP$_0$ in total agricultural area]
Mozambique	202.57	114.92	12.75	1.14	0.99	1.19	9.35	1.82
Namibia	164.29	133.39	3.63	1.42	1.07	0.09	2.36	1.10
Niger	172.03	128.95	19.93	11.76	9.12	4.18	20.95	10.70
Nigeria	299.05	145.62	108.44	5.05	3.47	10.17	9.38	5.99
Guinea-Bissau	1.09	0.14	0.09	0.01	7.35	0.02	22.01	13.17
Senegal	97.40	50.10	12.19	5.20	10.38	3.89	31.89	14.59
Somalia	76.79	65.39	3.29	2.45	3.75	0.12	3.78	3.75
South Africa	201.05	150.67	24.23	5.71	3.79	2.74	11.29	4.83
Zimbabwe	157.10	69.34	13.12	1.99	2.86	1.14	8.72	3.80
Sudan	750.74	555.44	89.62	20.06	3.61	13.12	14.64	5.14
Swaziland	5.55	3.40	0.48	0.06	1.74	-	-	1.53
Togo	12.73	3.94	4.98	0.42	10.66	1.38	27.63	20.13
Uganda	8.66	3.12	3.48	0.68	21.87	0.45	12.86	17.12
United Rep.Tanzania	75.58	48.42	3.68	3.20	6.62	0.74	20.21	7.58
Burkina Faso	156.77	91.60	22.18	16.06	17.53	6.58	29.68	19.90
Zambia	83.01	46.18	6.48	1.11	2.40	0.36	5.51	2.78
Total Sub-Saharan Africa	**4 543.11**	**3 078.66**	**486.49**	**150.03**	**4.87**	**65.10**	**13.38**	**6.03**
Algeria	68.65	35.76	22.16	2.49	6.97	5.31	23.98	13.48
Azerbaijan	26.23	15.62	5.84	0.30	1.94	0.23	3.87	2.46
Armenia	10.43	6.01	2.11	0.09	1.47	0.06	3.07	1.88
Cyprus	3.37	2.18	0.50	0.07	3.22	0.06	12.24	4.90
Georgia	13.04	4.15	3.13	0.06	1.39	0.21	6.64	3.64
Iraq	68.42	40.54	20.40	8.40	20.72	5.74	28.11	23.20
Israel	3.35	1.17	1.36	0.13	10.70	0.05	3.48	6.81
Jordan	4.14	2.52	0.92	0.24	9.66	0.27	29.55	14.97
Kuwait	0.79	0.26	-	0.07	27.16	-	-	27.16
Lebanon	2.65	1.44	1.02	0.21	14.63	0.32	31.55	21.65
Libyan Arab Jamah.	27.71	16.55	5.30	0.45	2.74	1.18	22.24	7.47
Morocco	86.31	41.90	32.33	0.63	1.50	2.44	7.55	4.13

Table B3 (continued)

Country/Region	NPP$_0$ Drylands [Tg C/yr]	NPP$_0$ Grazing lands [Tg C/yr]	NPP$_0$ Croplands [Tg C/yr]	NPP losses Grazing lands [Tg C/yr]	NPP losses Grazing lands [% of NPP$_0$]	NPP losses Croplands [Tg C/yr]	NPP losses Croplands [% of NPP$_0$]	NPP losses Total [% of NPP$_0$ in total agricultural area]
Oman	1.25	0.75	0.01	0.01	0.77	-	-	0.77
Saudi Arabia	6.22	1.10	0.23	0.08	7.02	-	-	5.81
Syrian Arab Republic	41.25	19.90	18.73	3.62	18.19	7.11	37.97	27.78
Tunisia	21.85	2.86	16.14	0.17	5.83	6.44	39.90	34.77
Turkey	248.17	115.94	88.75	10.42	8.99	12.81	14.44	11.35
Egypt	2.44	0.62	0.18	0.02	3.68	-	-	2.87
Yemen	5.11	2.63	0.68	0.06	2.15	-	-	1.70
Total Northern Africa and Western Asia	**641.39**	**311.92**	**219.78**	**27.51**	**8.82**	**42.24**	**19.22**	**13.12**
Kazakhstan	793.73	658.91	88.53	14.97	2.27	5.64	6.37	2.76
Kyrgyzstan	45.51	36.09	5.02	0.09	0.25	-	-	0.22
Russian Federation	1 891.95	447.99	439.85	117.69	26.27	106.26	24.16	25.22
Tajikistan	19.01	11.98	3.29	0.10	0.87	0.15	4.50	1.65
Turkmenistan	62.40	58.00	2.83	2.57	4.44	0.06	2.18	4.33
Uzbekistan	65.97	43.61	12.39	1.85	4.24	0.65	5.23	4.46
Total Central Asia and the Russian Federation	**2 878.58**	**1 256.58**	**551.91**	**137.28**	**10.92**	**112.76**	**20.43**	**13.83**
Afghanistan	113.60	88.23	19.22	0.77	0.87	0.08	0.43	0.79
Sri Lanka	11.54	5.00	2.41	0.12	2.34	1.00	41.44	15.07
India	844.20	139.14	568.34	16.76	12.04	78.52	13.81	13.47
Iran(Islamic Rep. of)	263.57	198.06	42.42	3.37	1.70	1.08	2.54	1.85
Nepal	7.78	1.89	2.65	0.04	1.93	0.17	6.53	4.62
Pakistan	57.23	23.13	24.39	2.29	9.88	2.25	9.23	9.55
Total Southern Asia	**1 297.92**	**455.45**	**659.42**	**23.34**	**5.12**	**83.10**	**12.60**	**9.55**

Table B3 (continued)

Country/Region	NPP$_0$			NPP losses				
	Drylands	Grazing lands	Croplands	Grazing lands		Croplands		Total
	[Tg C/yr]	[Tg C/yr]	[Tg C/yr]	[Tg C/yr]	[% of NPP$_0$]	[Tg C/yr]	[% of NPP$_0$]	[% of NPP$_0$ in total agricultural area]
Myanmar	17.06	5.83	9.59	0.03	0.45	0.51	5.30	3.47
Indonesia	36.05	14.42	8.54	0.38	2.65	1.36	15.96	7.60
East Timor	10.56	6.42	0.58	0.24	3.72	0.10	16.64	4.80
Thailand	26.13	10.98	12.82	1.88	17.13	6.00	46.80	33.11
Total South-Eastern Asia	**89.80**	**37.65**	**31.53**	**2.53**	**6.71**	**7.97**	**25.27**	**15.17**
Myanmar	17.06	5.83	9.59	0.03	0.45	0.51	5.30	3.47
Indonesia	36.05	14.42	8.54	0.38	2.65	1.36	15.96	7.60
East Timor	10.56	6.42	0.58	0.24	3.72	0.10	16.64	4.80
Thailand	26.13	10.98	12.82	1.88	17.13	6.00	46.80	33.11
Total South-Eastern Asia	**89.80**	**37.65**	**31.53**	**2.53**	**6.71**	**7.97**	**25.27**	**15.17**
China	915.58	570.28	185.86	47.89	8.40	1.01	0.55	6.47
Mongolia	121.76	102.92	1.13	0.60	0.58	0.01	0.71	0.58
Total Eastern Asia	**1 037.34**	**673.20**	**186.99**	**48.48**	**7.20**	**1.02**	**0.55**	**5.76**
Australia	2 299.34	956.39	164.85	8.97	0.94	14.93	9.06	2.13
Papua New Guinea	3.22	0.61	-	0.00	0.10	-	-	0.10
Total Oceania and Australia	**2 302.56**	**957.00**	**164.85**	**8.97**	**0.94**	**14.93**	**9.06**	**2.13**
World	**19 618.22**	**9 791.79**	**3 433.73**	**496.20**	**5.07**	**468.60**	**13.65**	**7.29**

Sources: Haberl *et al.* (2007), own calculations

B.2 Additional Figures

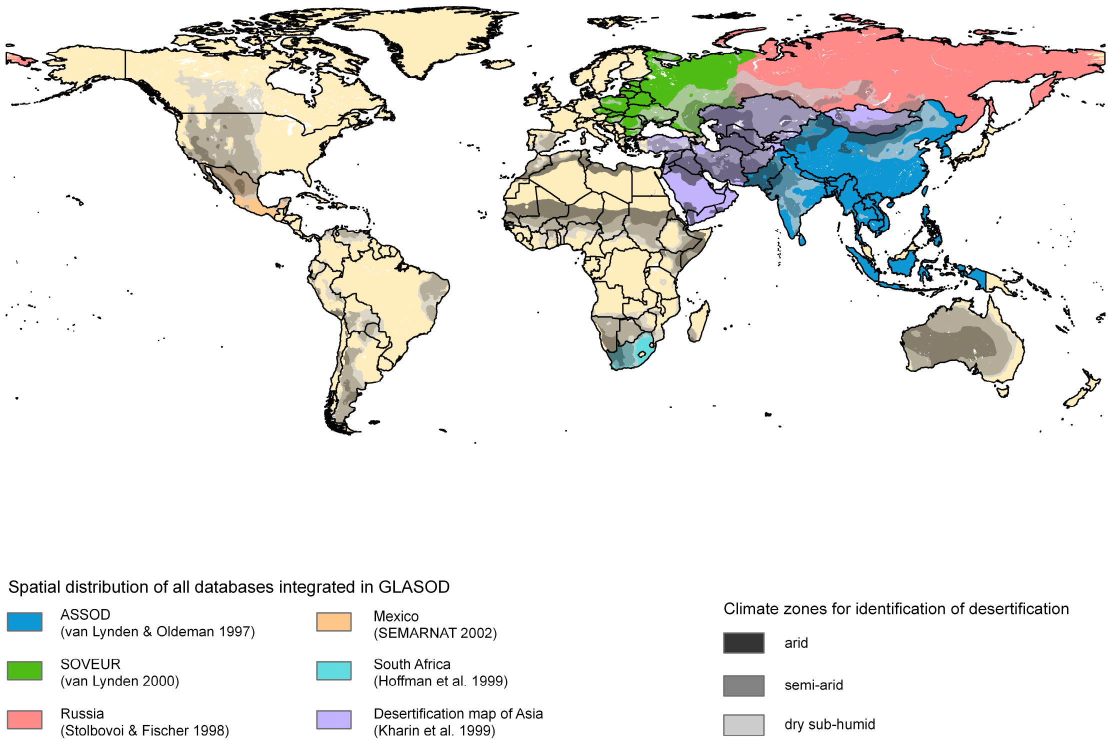

Figure B 1. Desertification datasets used to update GLASOD map to form COMSAD map;
grey shaded areas show the dryland climate zones (arid, semi-arid and dry sub-humid), drylands with yellow background are associated with GLASOD database.

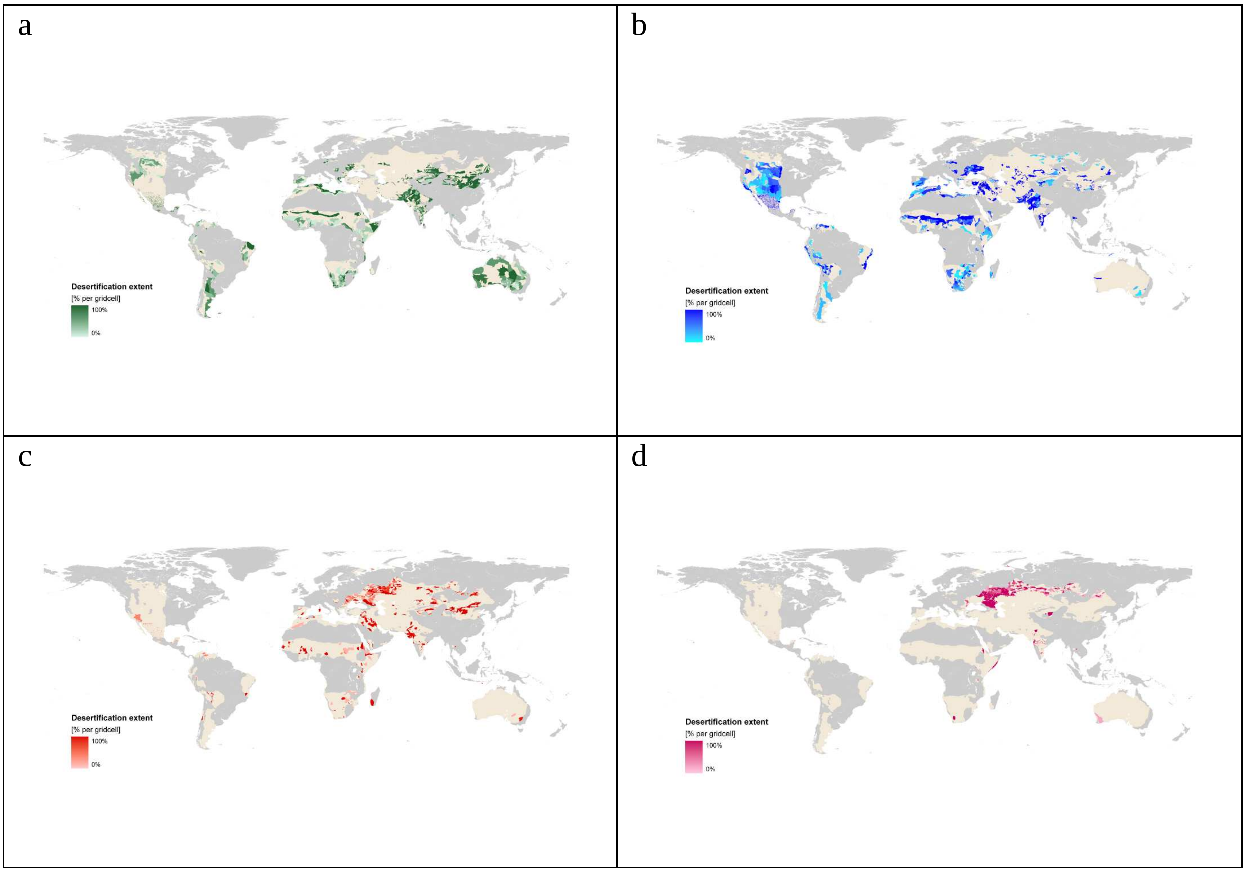

Figure B 2. Desertification extent per gridcell of the four degrees in COMSAD: light degree (a), moderate degree (b), strong degree (c) and extreme degree (d)

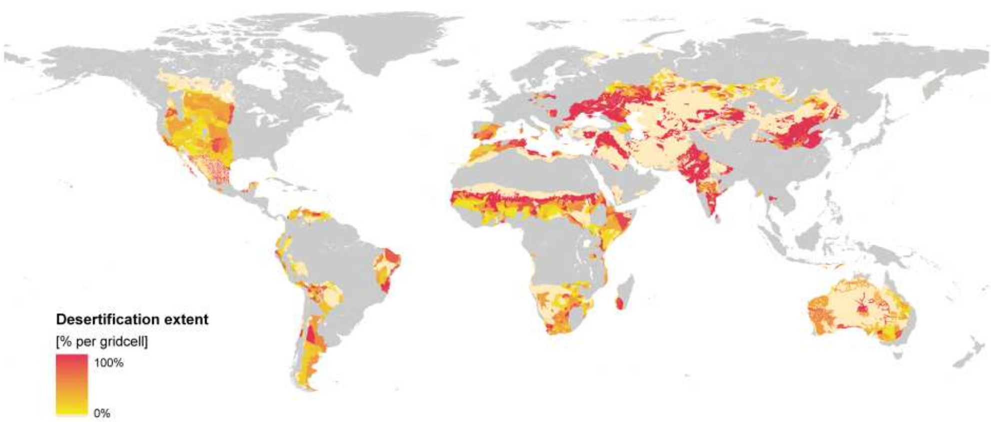

Figure B 3. Desertification extent of COMSAD-LU (COMSAD map with land-use datasets) used for the 'best guess' estimate

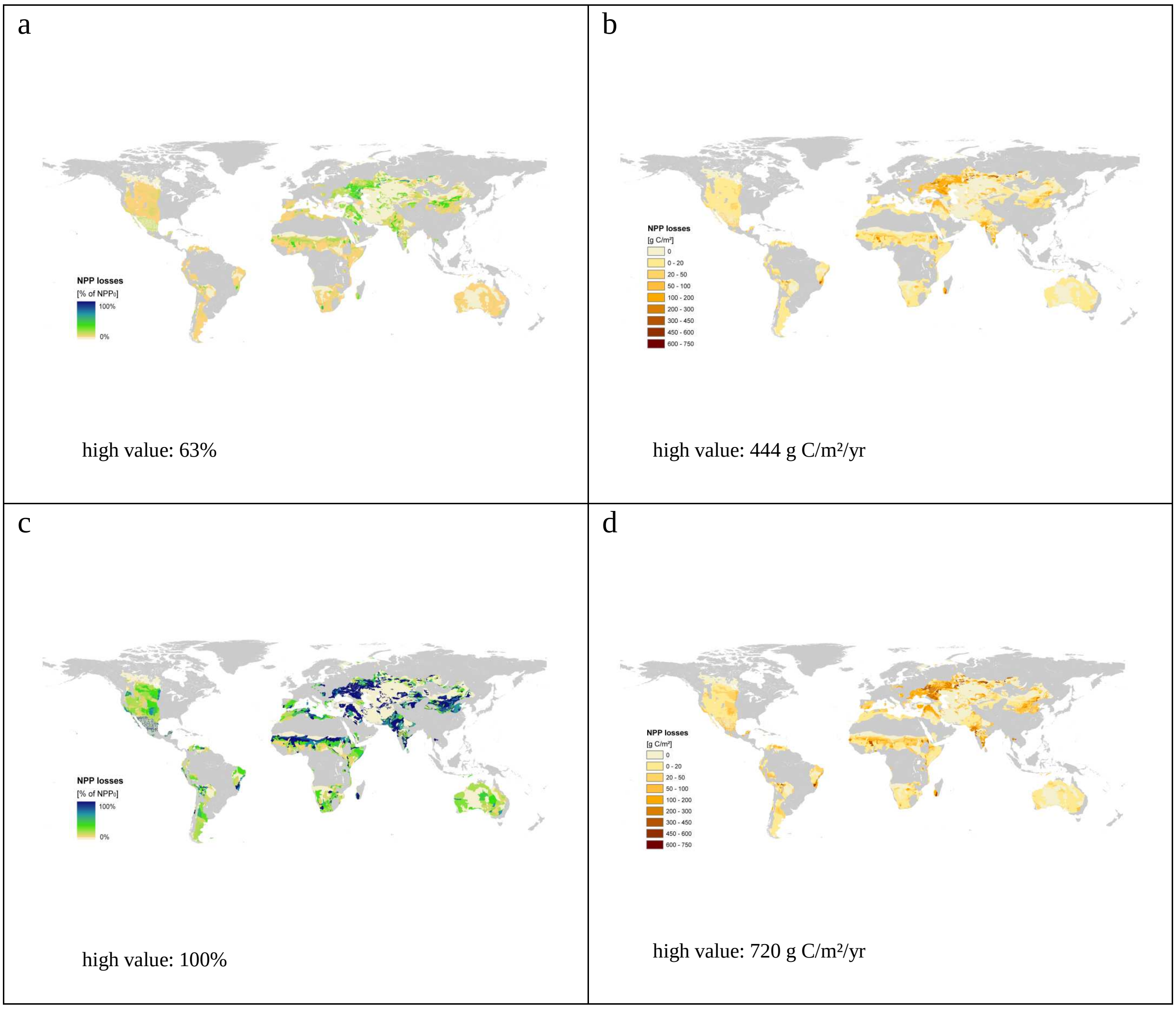

Figure B 4. Maps of NPP losses of the minimum-maximum estimates.
Figures a and b show the reduction calculated in the minimum estimate as percent of NPP_0 and as g C/m²/yr; figures c and d show the results of the maximum calculation; grey areas are non-dryland areas not considered in this study; the light yellow areas are not affected by desertification

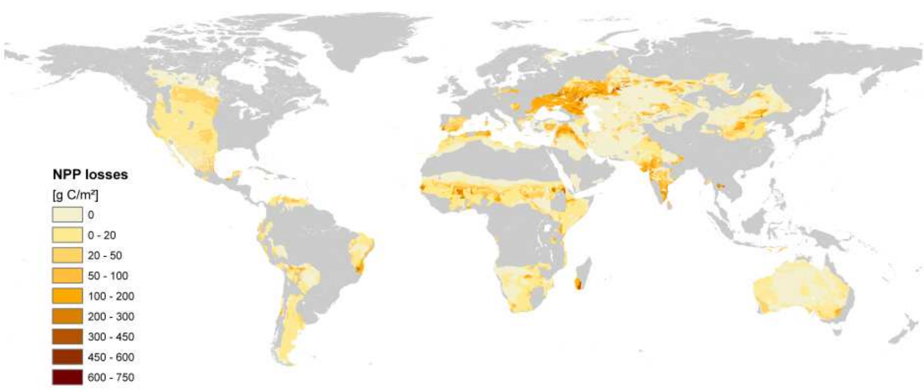

Figure B 5. Map of NPP losses of the 'best guess' expressed in carbon flows with a high value of 525 g C/m²/yr

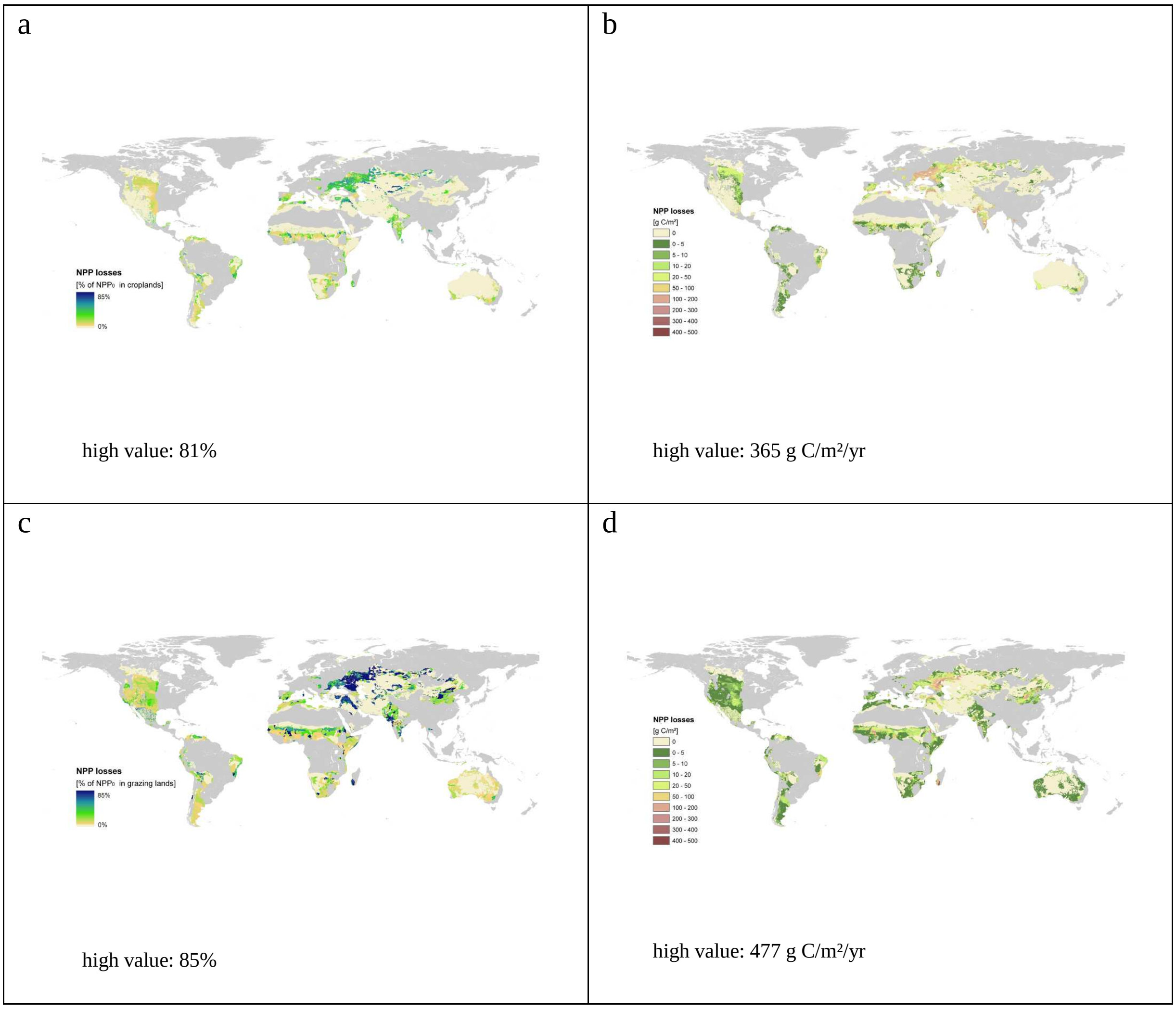

Figure B 6. Maps of NPP losses of the 'best guess' estimate separated by land-use classes.
Figures a and b show the NPP losses in croplands as percentage losses of NPP_0 and as carbon flows per year; NPP losses in grazing lands are shown as % of NPP_0 (figure c) and as carbon flows (figure d)

Annex C – Poster

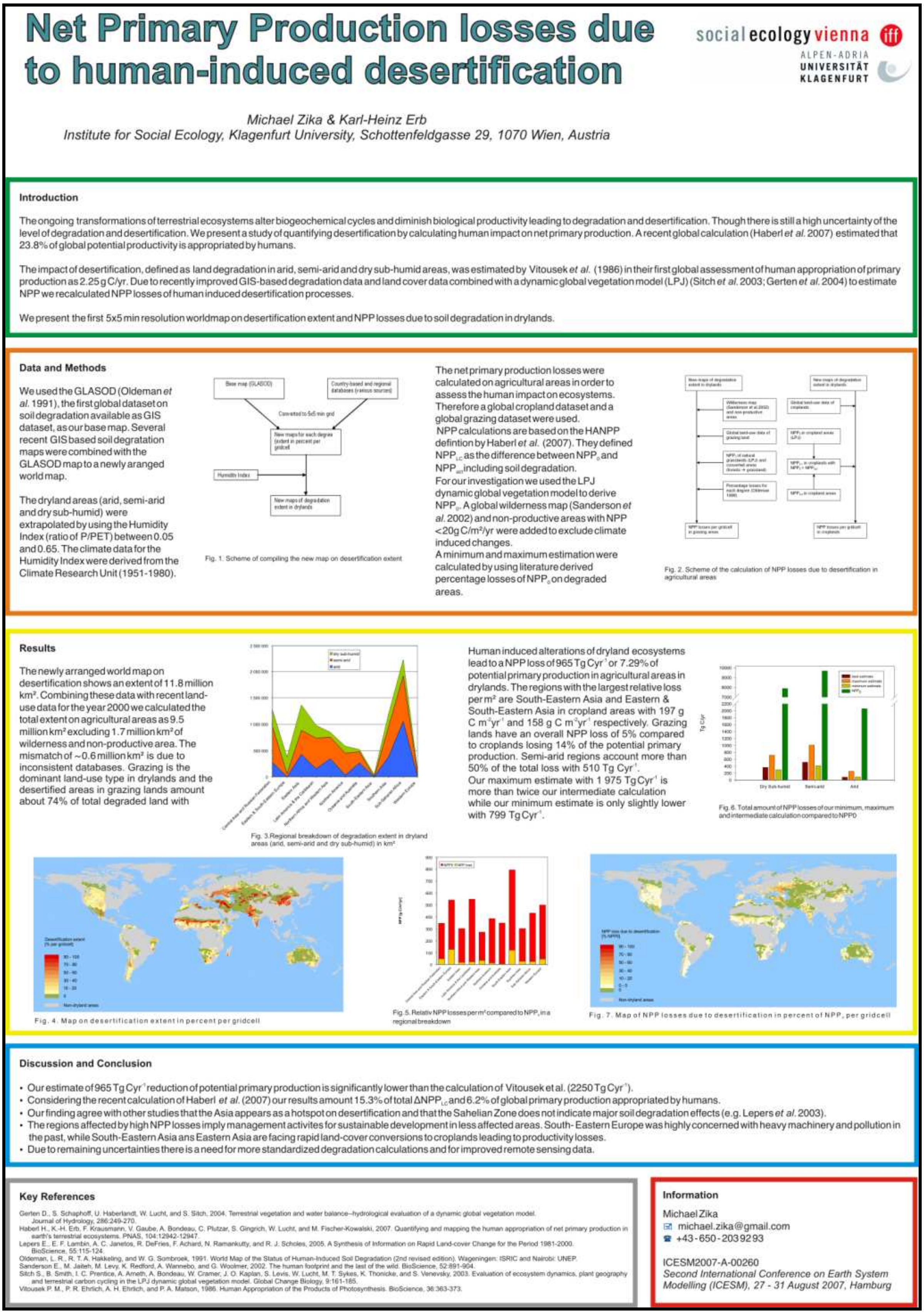

Figure C 1. Poster presented at the "Second International Conference on Earth System Modelling (ICESM), 27 – 31 August 2007, Hamburg, Germany

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Curriculum Vitae

Persönliche Information

Name:	Michael Zika
Geburtsdatum, -ort:	18. August 1976, in Stockerau, Österreich
Adresse:	Anton Jordan-Gasse 14/9, 2100 Korneuburg, Österreich
Telefon:	+43 (0) 650 – 203 92 93
E-mail:	michael.zika@gmail.com

Ausbildung

2007 – 2008	Teilnahme am Lehrgang „Studium Integrale-proVISION (SI-proVI) – Lehrprogramm für eine vorsorgende Gesellschaft“ mit den beiden Kursen „Projektbeobachtungs-Modul“ und „Öffentlichkeits-Modul“.
bis 2008	Studium der Ökologie mit Schwerpunkt Humanökologie, Vienna Ecology Center, Universität Wien und Institut für Soziale Ökologie, Universität Klagenfurt
bis 1996	Realgymnasium Stockerau mit Schwerpunkt auf Naturwissenschaften

Relevante Berufserfahrungen und Auszeichnungen

2007	3. Platz beim Wettbewerb **Prix ATTC 2007** mit dem Projekttitel *„Klimaschutz als Teil einer nachhaltigen Stadtentwicklung –Mistelbach als Modell einer sozio-ökologischen Nahverkehrslösung“*.
2006 – 2007	Tutor für die Freilandtage der „Biologische Einführungsübungen“, Universität Wien, Prof. Helmuth Sieghardt
2006	Technischer Assistent während des **ConAccount meetings** 2006 am Institut für Soziale Ökologie, Universität Klagenfurt, Prof. Helga Weisz
2005	Projekt-Assistenz bei der Erstellung einer Wasserbilanz der Mülldeponie Rautenweg Wien, Universität Wien, Prof. Rudolf Maier
2004 – 2005	Literatursuche, Datensuche und Verfassen eines internen Berichts über „Land degradation and desertification“ für das Projekt „Global human appropriation of NPP 1700-2000“, IFF Wien, Universität Klagenfurt, Prof. Helmut Haberl

Publikationen und Konferenzen

Zika, M. & K.H. Erb. *„Net Primary Production losses due to human-induced desertification”*, **Second International Conference on Earth System Modelling,** Hamburg, Germany (27. August – 31. August 2007), Poster Präsentation

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Kratochvil, R., N. Eisenmenger, F. Krausmann, I. Baart, A. Colard, C. Ehgartner , M. Eichinger, G. Hempel, A. Lehrner, R. Müllauer, R. Nourbakhch-Sabet, M. Paler , B. Patsch, F. Rieder, E. Schembera, W. Schieder, C. Schmiedl, E. Schwarzlmüller, W. Stadler, C. Wirl, S. Zandl, and M. Zika. *„Materialflüsse in den USA, Saudi Arabien und der Schweiz“*. Social Ecology Working Paper 74, Wien. 2005