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Quantitative mapping of global land degradation using Earth observations

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Land degradation is a global issue on a par with climate change and loss of biodiversity, but its extent and severity are only roughly known and there is little detail on the immediate processes – let alone the drivers. Earth-observation methods enable monitoring of land degradation in a consistent, physical way and on global scale by making use of vegetation productivity and/or loss as proxies. Most recent studies indicate a general greening trend but improved datasets and analysis also show a combination of greening and browning trends. Statistically based, linear trends average out these effects. Improved understanding may be expected from data-driven and process-modelling approaches: new models, model-integration, enhanced statistical analysis and modern sensor imagery at medium spatial resolution should substantially improve the assessment of global land degradation.

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1. Introduction

Recent discussions on competition for land resources suggest that claims on fertile land and even on degraded land, have never been higher (Tilman *et al.* 2009, Rathmann *et al.* 2010). In the context of ever-growing human population, the global area under food crops has peaked at the end of the last century and there is a growing requirement for land for production of bio-fuels. This puts land degradation on the global agenda as an economic, security and environmental issue (Dent *et al.* 2007) and a strong focus is land use change science (Turner *et al.* 2007). The IPCC argues that climate change will drive certain types of land degradation by more extreme weather events and a likely increase in total area affected by drought (Trenberth *et al.* 2007). At the same time, land degradation interacts with atmospheric processes (Cracknell and Varotsos 2007) and may drive climatic change through increasing greenhouse gas emissions and reducing carbon fixation in soils and biomass (Schlesinger *et al.* 1990). Mitigation and adaptation require the ability to predict and monitor land degradation; UNEP's GEO4 report urges governments to respond with 'effective early warning, assessment and monitoring – combine remote sensing with field surveys of key indicators; measure indicators consistently at different scales over the long-term.'

This poses scientific and technical challenges. The distribution and intensity of land degradation are only roughly known; assessments have been local, or based on expert opinion and qualitative classifications (Oldeman *et al.* 1990, Dregne 2002). Satellite remote sensing using time-series imagery with a regular acquisition interval is the only viable option to provide quantitative estimates of degradation at global scale. Quantitative and physically-based models can then be applied, independently of the scale or expert knowledge used in the assessment. In reviewing the currently available datasets and findings of recent, broad-scale research on land degradation, we aim to indentify knowledge gaps, key ecological indicators and successful methods that have not yet been exploited to their full potential. Several disciplines are involved but our focus is on satellite remote sensing data and methods for monitoring land surface dynamics at a global scale.

1.1 Definitions

Land degradation is defined by different schools according to their interests. *Land* is shorthand for the system made up of soil, water, the biota and, also, the man-made landscape and their biophysical processes (Dalal-Clayton and Dent 2001). Loss of its 'usefulness for human beings' (Wasson 1987) is considered as *degradation*. This is generally considered to be synonymous with *soil degradation* (Lal *et al.* 1989). FAO (1979) defined land degradation as 'a process which lowers the current and/or potential capacity of soils to produce'; the Millennium Ecosystem Assessment (MEA 2005) defined it as 'the reduction in the capacity of the land to perform ecosystem goods, functions and services that support society and development'. The term *desertification* has been adopted as a synonym of land degradation in dry lands (UNCCD 1994, Reynolds *et al.* 2007), but common usage implies desert encroachment into adjacent regions (Lamprey 1988).

Both economic loss and ecological degradation may be considered and measured against the capacity to satisfy human needs (Kassas 1995) and this is a common viewpoint of agriculture-oriented research (FAO 1979, Dent and Young 1981). Standing apart from human interest, land degradation has also been defined as deterioration in the physical and chemical properties of the soil as result of environmental change (Imeson and Emmer 1992) and, embracing both viewpoints, as 'a long-term reduction in ecosystem function and productivity from which the system cannot recover unaided' (UNEP 2007).

Despite the lack of a common definition, there is consensus that land degradation is widespread, has severe financial and social consequences and may sometimes be irrecoverable on a human time scale at manageable cost (Okin *et al.* 2001). Also, it can be self-accelerating so the cost of rehabilitation rises exponentially as it advances (Glantz and Orlovsky 1983) and, in some forms, it has a reciprocal relationship with climatic systems (Schlesinger *et al.* 1990, Prospero and Lamb 2003), causing significant changes in global biogeochemical cycles.

1.2 Processes and drivers

The most common perspective on land degradation is what farmers see happening to their land – symptoms such as soil erosion and salinity. That something bad is happening might be obvious but links with the driving processes may not be. These processes may be categorized as biological, physical or chemical (Lal *et al.* 1989)

– though rarely political (Blaikie 1985) – and each may have natural or man-induced causes, also called factors, that are agents or catalysts of the mentioned processes (Lal *et al.* 1989). Figure 1 shows examples of these categories.

FIGURE 1 about here

Whether land degradation is mainly man-induced, natural, or both, is a moot point (Evans and Geerken 2004). Early researchers focused on human-induced land (or soil) degradation (Aubreville 1949, Dregne 1986). Emphasising the impact of man on geology and ecology, Vitousek *et al.* (1997) state that we live on a human-dominated planet and Crutzen (2002) proposed the name *Anthropocene* for the current geological epoch. More recently, fluctuating climatic conditions have been considered a significant cause (UNCCD 1994, Puigdefábregas 1998, Nicholson 2000, El Hassan 2004, IPCC 2007); a change of view brought about by the Sahelian droughts of the 1970s and 80s (Glantz and Orlovsky 1983) and drying of the Aral Sea (Micklin 1988, Small *et al.* 2001) and Lake Chad (Haas *et al.* 2009). Climatic variations are believed to be a greater factor in, for instance, biodiversity in arctic and boreal areas, whereas land use change is considered a greater factor in other biomes (Chapin III *et al.* 2000). Most authors agree that various human and environmental processes interact along complex pathways and that both biophysical and socio-economic indicators should be considered jointly (Lambin *et al.* 2001, Baartman *et al.* 2007). Despite this, biophysical variables other than climatic change have received relatively little attention as causal factors of land degradation (Turner *et al.* 2007). The interaction of the human and the biophysical sub-systems on the land system and the schematic positioning of land degradation within the latter is depicted in Figure 2. The biophysical sub-system interacts with the human sub-system by delivering environmental goods and services (Turner *et al.* 2007) that might be diminished by land degradation as defined by UNEP (2007).

FIGURE 2 about here

Land degradation, in this sense, is an issue beyond the field scale and has become part of the emerging land change sciences (LCS). Research is undertaken by various disciplines including remote sensing, resource economics, landscape ecology and biogeography. It is a challenge to capture the whole system with its interrelationships between acting processes and to scale-up understandings gleaned from field studies to regional, biome and global perspectives.

1.3 Classification methods

Land degradation may be assessed qualitatively or quantitatively. The first approach, using expert opinion, may be able to embrace several processes in a single assessment that usually considers the consequences or symptoms of degradation – such as decline of land quality, biomass or vegetation health. The quantitative approach uses proxy measures like spectral reflectance. Remote sensing methods are most frequently employed and depend on establishing relationships between the proxy and the real thing. Most land degradation processes affect the vegetation cover, for which reason vegetation dynamics, which is relatively easy to quantify using earth observation, has been widely adopted as an indicator of land degradation at regional to global scales; this approach has the strength of being repeatable and transferable between scales and regions.

In the beginning, qualitative research included systematic and detailed soil survey. Two approaches emerged (Bergkamp 1996, Boer 1999): one focusing on the sensitivity of *land mapping units* to external changes which imposes limitations to the farmers' freedom of action; the other focusing on the actual change induced by external factors. The first is represented by the well-known Land Capability Classification (Hockensmith and Steele 1949, Klingebiel and Montgomery 1961) which defines land capability classes, each having a defined degree of limitation or conservation problems. This is a rules-based approach, depending on expert judgment. Similarly, the FAO Land Quality Classification relates risk of degradation to crop yields and management factors like germination conditions (FAO 1976). The second approach is represented by the Global Assessment of Human-induced Soil Degradation (Oldeman and van Lynden 1997), an expert assessment of land degradation by classes applied to a common base of landform units depending on the degree (light-severe) and the frequency (percentage occurrence within the mapping unit) of degradation by soil erosion, nutrient depletion, salinity and chemical contamination. Experts are comfortable with both of these approaches; they deliver a familiar perspective of land degradation but they are time-bound and not reproducible.

Air photo interpretation was employed extensively from the 1960s and, later, satellite imagery. In the beginning these were used in a qualitative way. Later, more quantitative methods emerged which often employ several indicators in combination with modelling (Kirkby *et al.* 2004) or statistical methods, like fuzzy inference, to define the contribution of various processes (Feoli *et al.* 2002, Riedler and Jandl 2002, Stroppiana *et al.* 2009). For instance, Vargas *et al.* (2007) used a fuzzy clustering algorithm to calculate classes combining loss of vegetation, soil chemical degradation and soil physical degradation and employed a decision tree to derive a land degradation map.

Various criteria for monitoring ecological status have been proposed respecting scalability, reproducibility, consistency, cost-effectiveness, transferability and statistical rigor (Boer 1999); remote sensing meets many of these criteria.

2. Earth observation datasets and methods

2.1 Time-series datasets of global vegetation status

Land degradation is often linked to a decline in biomass or vegetation cover, which may be measured in terms of biomass productivity, or undesirable changes in composition (Bertiller *et al.* 2002, Hanafi and Jauffret 2007, Wessels *et al.* 2007, Salvati and Zitti 2009, Zika and Erb 2009). Green vegetation has a characteristically high reflectance in the near-infrared (NIR) and a low reflectance in the red part of the electromagnetic spectrum. Many broadband vegetation indices (VI) using this characteristic have been developed. They may be categorized as ratio indices, orthogonal indices or a combination of both, hybrid indices (Dorigo *et al.* 2007). Ratio indices are usually based on the NIR and red reflectance, whereas orthogonal indices were introduced to reduce background effects like soil reflectance and include other wavelengths for this purpose.

The most common ratio VI is the normalized difference vegetation index (NDVI), which is a normalized ratio between NIR and red reflectance (Tucker 1979). It is sensitive to the amount of photosynthetically active vegetation and, therefore, is useful for monitoring biomass (Tucker *et al.* 1985, Prince and Tucker 1986). Correlation with biomass is highest in the mid-range of NDVI values (Asner *et al.* 2004, Phillips *et al.* 2008). In areas of dense vegetation, the NDVI signal saturates and other, orthogonal or hybrid, indices, like EVI (Enhanced Vegetation Index) and SAVI (Soil-adjusted Vegetation Index) or hyperspectral measures perform better (Huete *et al.* 2002a, Asner *et al.* 2004). NDVI has also been used as a proxy for vegetation water content and drought stress but its reliability decreases with mixed vegetation types (Ceccato 2001).

Frequently-acquired imagery from the advanced very high resolution radiometer (AVHRR) has yielded unprecedented insights into our changing planet, by analyses of land cover dynamics, biomass and primary production (Tatem *et al.* 2008). The availability of a long time-series of consistent global NDVI data and detailed studies of its relationship with leaf area index (LAI) and net primary productivity (NPP) have prompted the use of NDVI trends as a proxy for land degradation. It has already been used extensively to study vegetation change and its interactions with climate (Townshend 1994, Loveland *et al.* 2000), global primary production (Prince and Goward 1995), land cover (DeFries *et al.* 1995) and yield prediction and crop modelling (Chen *et al.* 2008, Stöckli *et al.* 2008, Boschetti *et al.* 2009). An 8-km spatial resolution – a characteristic of many AVHRR datasets – is considered to be suitable for global vegetation monitoring (Justice *et al.* 1985, Moulin *et al.* 1997, Pinzon *et al.* 2004, Tucker *et al.* 2005) and constrains the spatial variability between different NDVI products (Tarnavsky *et al.* 2008). The problem for land degradation studies is to discount false alarms raised by other factors, notably fluctuations in rainfall, rising temperatures, atmospheric CO_2 and nitrate precipitation and land use change – which may not be accompanied by land degradation as commonly understood (Bai *et al.* 2008).

Global VI time-series datasets are available from several sensors; Table 1 lists the most commonly used examples. The longest run consists of AVHRR NDVI maximum-value composites (Holben 1986). The Global Inventory Modelling and Mapping Studies (GIMMS) dataset has been compiled from daily AHVRR 4-km Global Area Coverage (GAC) data, geometrically and radiometrically corrected to produce fortnightly 8-km resolution NDVI data from 1981 through 2006 (Tucker *et al.* 2005). These NDVI values are comparable to NDVI products from other sensors such as MODIS, SPOT Vegetation, SeaWiFs and Landsat ETM+ (Brown *et al.* 2006). Other AVHRR NDVI datasets include Fourier-Adjusted, Sensor and solar zenith angle corrected Interpolated and Reconstructed monthly time-series (FASIR - Los *et al.* 2000), Pathfinder AVHRR Land (PAL - James and Kalluri 1994) and Global Vegetation Index (GVI - Goward *et al.* 1993). Although the various datasets started with nearly identical composited AVHRR measurements, different processing has produced absolute NDVI values that can differ substantially, especially in the tropics and northern high latitudes (Hall *et al.* 2006). Also, compared with new-generation time-series data like the MODerate resolution Imaging Spectrometer (MODIS), there are limitations including orbital drift, atmospheric interference, wide spectral bands and discontinuities due to platform changes (de Beurs and Henebry 2004, Fensholt *et al.* 2009, Nagol *et al.* 2009).

TABLE 1 about here

Shorter time-series of about 10 years are available from MODIS, SPOT and SeaWiFs. MODIS imagery is acquired every three days, providing aggregated products every 3-16 days. MOD13 is an NDVI dataset with a spatial resolution of 250-1000m and appears to be more accurate than NOAA AVHRR, especially in areas with high atmospheric water vapour content (Huete *et al.* 2002a). MODIS also provides a continuous NPP dataset (Running *et al.* 2004) derived from the fraction of absorbed photosynthetically active radiation (fPAR), which is a more direct physical measurement than NDVI (Phillips *et al.* 2008). The spectral bands used are narrower than for the AVHRR NDVI product so there is less interference with (water) absorption features; importantly, the derived NPP is less sensitive to saturation by dense vegetation. On the other hand, fPAR is generally overestimated in semi-arid areas (Fensholt *et al.* 2004, Turner *et al.* 2006). The French Satellite Pour l'Observation de la Terre provides global vegetation datasets (SPOT VGT) of 1 km resolution. Replacement of SPOT VGT1 by VGT2 in 2003 involved a change in the spectral response functions of channels 1 and 2 (Figure 3*b*) but, after correction, the NDVI products of AVHRR and SPOT are comparable, except for regions with high biomass (Swinnen and Veroustraete 2008). In semi-arid areas, however, Fensholt *et al.* (2009) show that GIMMS and MODIS NDVI agree better than SPOT VGT, as a result of the SPOT discontinuity (Figure 3*a*). The OrbView-2/SeaWiFs (Sea-viewing Wide Field-of-view Sensor) was originally designed to monitor the colour of the oceans, but thanks to convenient spectral bands and a detector and amplifier that does not saturate over land, it also allows monitoring of the land surface (Gobron *et al.* 2001). Differences between SeaWiFs and AVHRR NDVI data can be neglected for land degradation studies, especially in drylands (Laneve and Castronuovo 2005).

FIGURE 3 about here

Many other remotely sensed datasets have been used for regional land degradation studies. It is beyond the scope of this review to list them all and, therefore, we restrict ourselves to radar remote sensing and satellite based imaging spectroscopy which we expect to be useful to global land degradation research in the near future. For other sensors, the reader is referred to a recent review by

Metternicht *et al.* (2010) of remote sensing for land degradation assessments, including local to regional scales.

2.2 Space-borne radar and imaging spectroscopy

Radar was brought into space in the 1980s and has the advantage over optical remote sensing that it can sense through cloud cover and without daylight. Synthetic Aperture Radar (SAR) interferometry has been investigated for identification of potential degradation sites (Liu *et al.* 2004), for monitoring of wind erosion (Del Valle *et al.* 2010), for measurements of soil water (Walker *et al.* 2004) and carbon stock (Goetz *et al.* 2009), for crop monitoring (Baghdadi *et al.* 2009) and to study ecological processes (Kasischke *et al.* 1997). The latter include vegetation mapping and above-ground biomass estimation which, in combination with change detection methods, can provide information on land degradation. For instance, SAR using multiple frequencies and polarizations is better for estimating woody biomass in tropical forest than optical remote sensing (Wang and Qi 2008). There are more and more radar instruments in orbit, especially in C and X bands, with recent launches of TerraSAR-X and COSMO-SkyMed and forthcoming launches of TanDEM-X and SAOCOM. However, consistent time-series needed for land degradation assessment are not yet available.

Methods have been proposed for broad-scale degradation assessment by space-borne imaging spectroscopy. At the moment, Hyperion (on board NASA EO-1 launched in 2000) has been successfully tested for land degradation research (Huete *et al.* 2002b, Asner and Heidebrecht 2003). The Spectral Analyses for Dryland Degradation (SAND) mission was proposed to specifically target dryland degradation (Mueller *et al.* 2001, Kaufmann *et al.* 2002) but not realized; it was followed up by the German Environmental Mapping and Analysis Program (EnMAP) to be launched in 2013 (Kaufmann *et al.* 2006). The lauch of the Italian counterpart PRecursore IperSpettrale della Missione Applicativa (PRISMA) is planned for 2010. All these sensors have a spatial resolution of about 30m which currently limits global applications by the welter of data that attend high resolution. Preliminary results from plant physiological studies, however, indicate the potential power of using imaging spectroscopy for monitoring chlorophyll fluorescence emission as a measure for heat or drought stress (Krumov *et al.* 2008, Soukupova *et al.* 2008). Recently, ESA published plans for the FLEX (Fluorescence Explorer) mission, which will comprise weekly global mapping of fluorescence at 300m spatial resolution (Rascher *et al.* 2008). Potential pigment shifts as indicators for plant stress and plant community composition change are also available at leaf and canopy level (Kokaly *et al.* 2009) from imaging spectrometer data. Data assimilation techniques (Dorigo *et al.* 2007) and angular sampling (Schaepman 2007, Verrelst 2010) will further improve the use of imaging spectrometer data in process modelling for land degradation.

2.3 Climatic and land use / land cover data

Various complementary global datasets may be used in concert with satellite imagery to constrain index-based assessment of land degradation. Global or near-global climatological datasets are available from satellites, including tropical rainfall measuring mission (TRMM) and the AVHRR-based PATMOS-x project and also from long-term, station-based observations (Beck *et al.* 2004, Mitchell and Jones 2005). From these, rain-use efficiency RUE (ratio of NPP to rainfall), light-use efficiency and energy-use efficiency can be calculated (Le Houérou 1984, Goetz *et al.* 1999, Bai *et al.* 2008). If productivity is limited by rainfall, RUE accounts for variability of rainfall and, to some extent, local site characteristics. The combination of NDVI and rainfall or RUE has been widely applied (Hein and de Ridder 2006) but direct use of RUE has its critics (Holm *et al.* 2003, Prince *et al.* 2007).

Soil characteristics and variability are important variables in land degradation studies (Nicholson and Farrar 1994), but the available datasets such as the *Soil map of the World* (FAO-UNESCO 1988), the *Harmonized World Soil Database* (Nachtergaele *et al.* 2008) and SOTER (Van Engelen and Wen 1995) are hardly compatible with earth observation data; the only rigorous application at a regional scale has been in China under the *Global Assessment of Land Degradation and Improvement* (Bai and Dent 2009). Improved global soil and terrain datasets are being developed in the eSOTER project (e-SOTER website 2010) and the GlobalSoilMap.net project (Sanchez *et al.* 2009).

Land use and management have a big influence on land degradation and certain land use changes make land degradation more or less likely (Vacca *et al.* 2000); information about land use and land cover change is therefore essential for studying land degradation. Global land cover maps have been derived from several remotely-sensed datasets including AVHRR (IGBP-DIS), SPOT-VGT (GLC2000), ENVISAT MERIS (Glob-Cover) and MODIS (Herold *et al.* 2008). At finer resolution, Landsat-based land cover datasets include NLCD2001 (USA), CORINE (Europe) and AfriCover (Africa). However, each is specific to its own date and data; they are not mutually comparable. In China, a SPOT VGT-based land cover classification has been used to detect areas at risk of desertification (Huang and Siegert 2006) and is claimed to be superior to GLC2000 and MODIS Land Cover products but, for establishing the causes, the use of higher resolution, Landsat or ASTER, imagery was recommended. The same SPOT data were used to monitor land cover changes in West-Africa by NDVI and SAVI (Lupo *et al.* 2001). Several climate-driven processes of land-cover change were detected but it was also concluded that the data suffered from an incomplete cloud mask and sensor noise. There have been efforts to derive dynamic land cover maps from AVHRR or MODIS time-series (Julien and Sobrino 2009) and there is need for reliable, readily-available products.

3. Broad-scale land degradation studies

Global assessments of land quality and dynamics became feasible with the first AVHRR images (Justice *et al.* 1985). Since then, studies using time-series of satellite imagery have mainly focussed on the areas generally considered to be prone to degradation. The Sahel attracted attention because of a succession of severe droughts since the 1960s, with driest years in the early 1980s (Nicholson 2000, Anyamba and Tucker 2005, Govaerts and Lattanzio 2008). It is an important validation site for general circulation models because of the uncertainty about the system's reaction (Cook 2008) and of human-environment models because of the disputes about human influences on land degradation in the Sahel (Helldén 2008). It has often been asserted that the Sahara is encroaching as a result of human activities (Cloudsley-Thompson 1974, Lamprey 1988) but assessment of time-series imagery in the Sudan showed no systematic advance of the desert or reduction in vegetation cover (Hellden 1984). This was confirmed by Tucker *et al.* (1991) and Schlesinger and Gramenopoulos (1996) who found that vegetation density on the margins of the Sahara varies with rainfall, by Seaquist *et al.* (2008) who found no relation between demographics and model-based vegetation dynamics and by Prince *et al.* (1998) on the basis of rain-use efficiency (RUE). Still, Hein and de Ridder (2006) argue for human-induced vegetation degradation over the last two decades based on temporal RUE variability – an interpretation disputed by Prince *et al.* (2007). A systematic increase in vegetation productivity around the Sahara has been measured using satellite imagery (Anyamba and Tucker 2005, Herrmann *et al.* 2005, Olsson *et al.* 2005, Heumann *et al.* 2007, Karlsen *et al.* 2007). Probably, much of what has been identified as human-induced land degradation is a response to climatic fluctuations (Nicholson 2000).

There is also controversy about land degradation in South Africa, both about the existence of severe degradation and about the causes. Several studies identified land degradation, mainly in rangelands (Ross 1963, Adler 1985, Hoffman and Simon 2000), but Dean *et al.* (1995) found no evidence for increasing degradation and other studies in South Africa and surrounding countries concluded that vegetation change could be attributed to natural conditions such as drought and restrictive soil conditions (Dahlberg 2001). In Zimbabwe, Prince *et al.* (2009) recently concluded that locations of degradation were unrelated to natural conditions and thus caused by human land use. Wessels *et al.* (2007), in South-Africa, used the trends of the residuals of NDVI trends (RESTREND) to distinguish human-induced land degradation. They concluded that observed changes could have resulted from several processes, including natural ecological processes and land use changes. Not explicitly assigning causes, Bai and Dent (2007) found that almost half of the cultivated land experienced a decline in productivity over the last quarter century and one third of the whole country, mostly rangeland, showed increasing productivity.

Broad-scale assessments using NDVI in several other parts of the world show a general greening trend (Table 2), but also regions of decline. Like the Sahel, the northern hemisphere has become greener during recent decades (Myneni *et al.* 1997, Slayback *et al.* 2003, Hüttich *et al.* 2007), although a browning trend was found between 1994 and 2002 (Angert *et al.* 2005). Pouliot *et al.* (2009), in Canada, found that AVHRR NDVI data compared well with Landsat data and show an overall positive trend since 1985. Alcaraz-Segura *et al.* (2009), also in Canada, confirm this but remark that AVHRR NDVI exhibit other greening and browning trends than the CCRS (Canadian Centre for Remote Sensing) NDVI dataset. In Australia, an increase in vegetation cover, especially in winter, recorded by fPAR derived from AVHRR PAL has been attributed to an increase in available moisture (Donohue *et al.* 2009).

TABLE 2 about here

NDVI has proved capable of assessing vegetation dynamics and relations to land degradation. However, assessment of land degradation at global scale remains a challenge. One of the first attempts was Dregne's 1977 map of the status of desertification for the UN Conference on Desertification which was based on expert opinion and restricted to dry lands; the later Global Assessment of Human-Induced Soil Degradation (GLASOD - Oldeman *et al.* 1990) provided full global coverage, also based on expert opinion. The situation has been revolutionised by the availability of more than 25 years of consistent Earth-observation data. These are the basis of the first quantitative assessment of global land degradation and land improvement (GLADA) which applies trends analysis to the GIMMS dataset and corrects for trends in rainfall using rain-use efficiency and temperature using energy-use efficiency (Bai *et al.* 2008). The GLADA map detects potential degradation hotspots (Figure 4) and yields quantitative estimates of lost productivity in terms of NPP. However, much potential information in the dataset is not revealed by the linear regression of yearly aggregated values.

FIGURE 4 about here

Assessments of land degradation using NDVI focused mainly on areas where the NDVI signal does not saturate, such as semi-arid and temperate regions with relatively low LAI. But land degradation is not confined to these areas and also occurs in humid tropical and sub-tropical areas with dense vegetation. Deforestation is one of the most common kinds of human-induced land degradation but there are many other facets that may be referred to as forest degradation (Köhl *et al.* 2009) – monitoring of which is technically more challenging than monitoring deforestation (DeFries *et al.* 2007). The estimated extent of deforestation in humid tropic forests is 1.4% of the total area (2000-2005) and another 20% is affected by some kind of logging (Asner *et al.* 2009). Accurate broad-scale estimations are difficult because clearing mostly occurs at a fine scale but MODIS data have been used to create indicator maps (Hansen *et al.* 2008). The impact of natural factors like droughts has also been assessed using MODIS. For instance in the Amazon there has been debate about whether the 2005 drought caused greening (Saleska *et al.* 2007, Samanta *et al.* 2010). Both studies used EVI but the latter concluded that the data were corrupted by atmospheric factors that explained the apparent greening effect. At global scale, FAO undertakes a decennial forest resource assessment but there is no global forest degradation inventory.

Biogeochemical models can assess changes in vegetation productivity with and without human activity: a decline in productivity that cannot be explained by climatic variations might be attributed to human influences (Seaquist *et al.* 2008). At global scale, Nemani *et al.* (2003) applied a biome-specific production efficiency model and two AVHRR datasets (GIMMS and PAL) and found that global climatic and atmospheric changes have eased several constraints on NPP, which had increased by 6 per cent over the period 1982-1999 (Figure 5). Similarly, Cao *et al.* (2003), in China, used AVHRR data and two biogeochemical models to estimate inter-annual variations of NPP. One of the models, the global production efficiency model (GLO-PEM) uses only remotely-sensed input data and, thus, delivers independent estimates of NPP (Goetz *et al.* 2000). They concluded that, in contrast with the global trend, the net ecosystem production in China decreased in the past decades because of stronger warming than the global average. Seaquist *et al.* (2003) built a LUE model for estimation of GPP in the Sahel, which was parameterized with satellite data (PAL). In a follow-up they used the model to disentangle the effects of climate and human influence and concluded that the identified changes could not be correlated to human activity (Seaquist *et al.* 2008). To address human appropriation of NPP (HANPP) at global scale, Haberl *et al.* (2007) used the Lund-Potzdam-Jena (LPJ) dynamic global vegetation model for calculating potential NPP. They concluded that almost 24% of yearly potential NPP was lost due to human activities (based on the year 2000) including harvesting (53%) and land-use change (40%). These data have also been used to focus on human-induced dryland degradation at global scale (Zika and Erb 2009). The extent of degrading areas was taken from a compilation of mainly qualitative land degradation assessments, including GLASOD. They found a loss in NPP of 1.6% with respect to the global terrestrial NPP but emphasized, that results are hard to interpret because of uncertainties in the underlying assumptions. Another model that has been regularly used in combination with earth observations for modelling of NPP is the Carnegie-Ames-Stanford (CASA) biogeochemical (BGC) model (Potter and Klooster 1997, Yu *et al.* 2009).

FIGURE 5 about here

In this review, biomass decline has so far been considered as a gradual process on the human time scale, but it may equally well be considered a catastrophic shift caused by gradual environmental change (Scheffer *et al.* 2001, Rietkerk *et al.* 2004). The latter effect is caused by positive feedback mechanisms like the effect of vegetation on soil erosion and the other way around (Janssen *et al.* 2008). Mid-Holocene desertification in North Africa has been identified as such a catastrophic shift (Dakos *et al.* 2008) but assessment of catastrophic land degradation using remote sensing is yet an unexplored field of research.

4. Broad-scale monitoring of physical and chemical land degradation processes

Soil erosion by runoff water is considered to be the most widespread process of land degradation (Eswaran *et al.* 2001, Vrieling 2007). Most commonly, it is assessed by measuring or modelling the detachment of particles by rain splash and overland flow and up-scaling to the catchment. Vrieling (2006) and Metternicht *et al.* (2010) review the application of satellite remote sensing, which can show the larger erosional features such as rills, gullies and land slips. Smaller features like crusting or soil compaction may be spectrally distinguishable on bare ground (Goldshleger *et al.* 2001) but attempts to quantify them in remotely sensed imagery have been limited to small plots. The same holds for monitoring of gully erosion

(Marzolff and Poesen 2009) and quantification of soil properties (Summers *et al.* 2009), which are mostly done using high-resolution, often airborne, remote sensing. However, a recent modelling approach for soil erosion at continental scale for sub-Saharan Africa by Symeonakis and Drake (2010) found that the estimates are within the same order of magnitude as field measurements. In dry lands, wind is an important agent of erosion and deposition (Ravi *et al.* 2010) but it is hard to quantify at broad scales (Symeonakis and Drake 2004). Radar remote sensing has been tested for mapping of wind-driven land degradation by mapping its primary factors: surface roughness, soil moisture, local incidence angle and vegetation cover (Del Valle *et al.* 2010). The acute processes of chemical land degradation are salinization and chemical contamination. Salt accumulation may arise from groundwater, coastal flooding or irrigation; chemical contamination may be natural, for instance in volcanic areas, or, most often, man-made (Gardner *et al.* 2004). Salinity may be detected with relatively high-resolution imagery like Landsat (Chen and Rao 2008) but comparison with the GLADA assessment at 8km resolution shows some sensitivity at the broader scale as well (Figure 6). However, the coarse resolution of most satellite imagery compared with the variability of salt concentrations in the soil and the interference of other soil properties with the detected signal limit its value for detailed mapping (Mougenot *et al.* 1993, Ben-Dor 2009). At the same time, high-resolution data impose a practical constraint on broad-scale mapping. Metternicht and Zinck (2003, 2009) give an overview.

FIGURE 6 about here

5. Future steps for Earth observations

There is broad agreement that efficient action to arrest land degradation requires 'effective early warning, assessment and monitoring – combining remote sensing with field surveys of key indicators' (UNEP 2007); but it remains a contentious field (Bai *et al.* 2008). Field observations and experiments combined with expert synthesis measure physically different things at a different scale from those measured by remote sensing. Expert judgment of 'the real thing' is local and time-bound and it is hardly possible to validate 25 years of NDVI measurements in the field, after the event, at 8-km resolution. Remote sensing can take us several steps towards accurate and consistent monitoring of land degradation at the global scale, but interpretation of imagery and derived products comes with challenges. Some important steps towards better understanding of time-series of satellite imagery are listed below.

5.1 Advanced time-series analysis

The value of a 25-year + time-series of AVHRR can hardly be over-stated. Land degradation nearly always affects vegetation and NDVI is one of the few, consistent indicators available at global scale over the long term. In spite of the limitations of AVHRR data already discussed, data-driven approaches can derive several biophysical variables (Goetz *et al.* 2000). Since 2000, MODIS, SPOT VEG and SeaWiFS provide improved datasets in terms of accuracy or spatial resolution. Each dataset contains information on inter- and intra-annual variability, phenological cycles, frequency and shift of growing seasons and distinction between gradual and abrupt changes (Azzali and Menenti 1999, Jönsson and Eklundh 2002, Zhang *et al.* 2003, Verbesselt *et al.* 2010) which might be linked to climatic changes, changes in land use and management and/or land degradation. Current assessments eliminate intra-annual information by reducing the temporal resolution, while existing methods can account for phenological variation without averaging to yearly values, for instance by harmonic analysis of NDVI time-series (Jakubauskas *et al.* 2001, Hird and McDermid 2009). For this purpose, the HANTS algorithm (Verhoef *et al.* 1996, Roerink *et al.* 2000, Jun *et al.* 2004) performs well in comparison with several others (White *et al.* 2009). If more measurements are maintained in the analysis, it is also possible to capture trend breaks or shifts. For instance, certain regions exhibit combined greening and browning trends (Angert *et al.* 2005), which are averaged out by simple linear trends analysis.

When using vegetation dynamics as indicator for land degradation, it is essential to account for phenological variation and, when using regression to quantify trend slopes, it is essential to deal with trend shifts and breaks. The analysis of the full temporal domain of AVHRR and other datasets is needed to achieve these goals.

5.2 Spatial contextual analysis

The spatial contextual approach, which includes the pixel location and interaction with adjacent pixels as source of information, is relatively unexplored. For coarse resolution data, this might include stratification by phenological zones, while at finer resolution changes in land use may be incorporated (Friedl *et al.* 2002, Lupo *et al.* 2007). In any case, the spatial resolution of the imagery should correspond with the scale at which the processes act. In case of climate-driven land cover changes (e.g. warming, change in precipitation) a 1-km resolution will suffice, whereas most human-driven land cover changes (e.g. land transformation, logging, over exploitation) occur at 250m-500m scale (Townshend and Justice 1988). Patchiness, or spatial configuration, of vegetation is often used to study ecosystem health or degradation (Bastin *et al.* 2001, Ludwig *et al.* 2007). In water-limited ecosystems, patchiness might be self-organizing due to a positive feedback relation between vegetation and water availability (Rietkerk *et al.* 2004): dense vegetation allows for high water infiltration into the soil and lower soil evaporation. As a result, vegetation may persist where it is already established but bare soil does not allow for vegetation to establish. The catastrophic shift between vegetated patchy state and bare homogeneous state, e.g. due to overgrazing, might have severe consequences for land degradation in drylands (von Hardenberg *et al.* 2001). It is a challenge and urgent issue to anticipate these changes using earth observation and include these in dryland degradation models (Kéfi *et al.* 2007).

5.3 Modelling

Satellite-based Earth observation methods are confined to physical measurement - in most cases radiances or reflectance factors (Schaepman-Strub *et al.* 2006). Mapping of indicators of land degradation relies on empirical models, mostly using statistical methods, to establish relations between the physical measurement and the degradation process. Models that aim to predict catastrophic shifts need a long time-series of sufficient quality and resolution to capture the dynamics of the system (Dakos *et al.* 2008). Currently available remotely sensed time-series enable trend analysis of some fast-reacting sub-systems but large climatic systems are known to react over centuries (deMenocal 2008). At shorter time-scales, remotely sensed data can be coupled to outputs from vegetation dynamics or light-use efficiency models like Biome-BGC (White *et al.* 1999), LPJ (Bonan *et al.* 2003), CASA (Potter *et al.* 1999) or crop growth simulation models (Jongschaap 2006); differences between observed productivity and simulated productivity without human interference might indicate land degradation. Although many studies have shown the potential of this approach, it remains a challenge to combine these models with others, e.g. soil erosion models (Symeonakis and Drake 2010) and land change models / human-environment models (Turner *et al.* 2007, Helldén 2008) into a generic land degradation model.

5.4 Validation

Validation is crucial for remote sensing studies. We have consistent satellite data of the past 30 years, but no compatible field data. Field validation is hardly feasible for pixels ranging from 1-8 km (Running and Nemani 1988) and, because of heterogeneity on the ground, extrapolation is often problematic. Every study of scalability issues deals with the trade-off between local precision, which is improved by on-the-spot assessment (Baartman *et al.* 2007) and global accuracy which needs a consistent, world-wide overview but which is hard to recognize in the field. The AVHRR dataset captures the typical length of time on which degradation processes occur, whereas the new generation sensors capture the typical spatial scale (Townshend and Justice 1988). If the 1981–2006 AVHRR data were to be processed in a manner quantitatively comparable to that of the new generation of sensors, many advantages of MODIS and SPOT Vegetation data could be realized while retaining historical information (Tucker *et al.* 2005). Many regional and national studies will remain essential to validate broad-scale degradation estimates – either qualitative or quantitative.

6. Conclusions

Land degradation is a global environmental and development issue but there is no consensus on its causes, severity and extent. Many scientific and political fields are involved in research and policy making and there is agreement about the need for up-to-date, quantitative information at national and global scales to support mitigation. This requires consistent monitoring of key indicators at a range of scales. Loss of vegetation productivity or cover has been widely used to quantify land degradation, not least because of the availability of long-term NDVI time-series. Broad-scale studies show a general greening trend over recent decennia but, also, regions of productivity decrease, e.g. in south China. The first quantitative global assessment of land degradation and improvement (GLADA) used yearly averaged linear trends in NDVI, translated in terms of NPP as a proxy measure. However, the results of global studies are disputed because they are different from traditional expert assessments and they are hard to validate in the field. At the same time, local assessments are only snapshots of small areas, generally too detailed for global application. Steps towards improvement of broad-scale assessments include more advanced time-series analysis, integration of state assessments using statistical methods with model based links to processes or drivers, the use of spatial-contextual information and validation using regional assessments. The first might include recognition of intra-annual variation, non-linear trends and breaks or shifts in greening and browning trends. The others might include the use of regional studies at medium spatial resolution, for instance land degradation assessments, but also dynamic land use mapping and other land dynamics or land change studies for validation and identification of driving processes. A truly global assessment, empirical or deterministic, requires more than NDVI measurements which have limited application in humid, densely vegetated (high LAI) regions. Integration with a future global forest degradation assessment is needed.

The long-term AVHRR NDVI record provides an invaluable historical record but there is still a gap in the methodology to couple this dataset to the datasets from the new generation of improved sensors. Using the full potential of all available datasets – in all temporal, spectral and spatial dimensions – will be a significant step towards global-scale assessment of land degradation. Advances in satellite-based remote sensing will improve its measurement, but further development of physically-based process models is needed to establish cause-and-effect relationships. Until then, Earth observation-based mapping of indicators will continue to reveal ambiguities.

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List of Tables

Table 1. Most commonly used time-series of vegetation imagery for broad-scale land degradation studies, limited to datasets with a high temporal resolution and global coverage.

Table 2. Selected studies of broad-scale vegetation trends.

List of Figures

Figure 1. Examples of land degradation. Top: (*a*) Man-induced soil erosion on agricultural fields (Volker Prasuhn, website); (*b*) Secondary (man-induced) salinity in farmland, California (USDA Agricultural Research Service); (*c*) Loss of forest cover through shifting agricuture, Wau district, Sudan (UNEP website). Bottom: (*d*) Soil erosion induced by snowmelt (Volker Prasuhn); (*e*) Acid sulphate scald caused by drainage change (Gardner *et al.* 2004) which may be natural or man-made; (*f*) Drought -induced vegetation decline and soil erosion (WMO).

Figure 2. The positioning of land degradation within the land change science framework. Modified after Turner *et al.* (2007).

Figure 3. Comparison of GIMMS, MODIS NDVI and SPOT VGT for a test site in Senegal. Reproduced from Fensholt *et al.* (2009).

Figure 4. Linear trends in net primary production (NPP) from the global assessment of land degradation and improvement (GLADA). Reproduced from Bai *et al.* (2008).

Figure 5. Linear trends in yearly accumulated net primary production (NPP) from 1982-1999 using a global production efficiency model. Reproduced from Nemani *et al.* (2003).

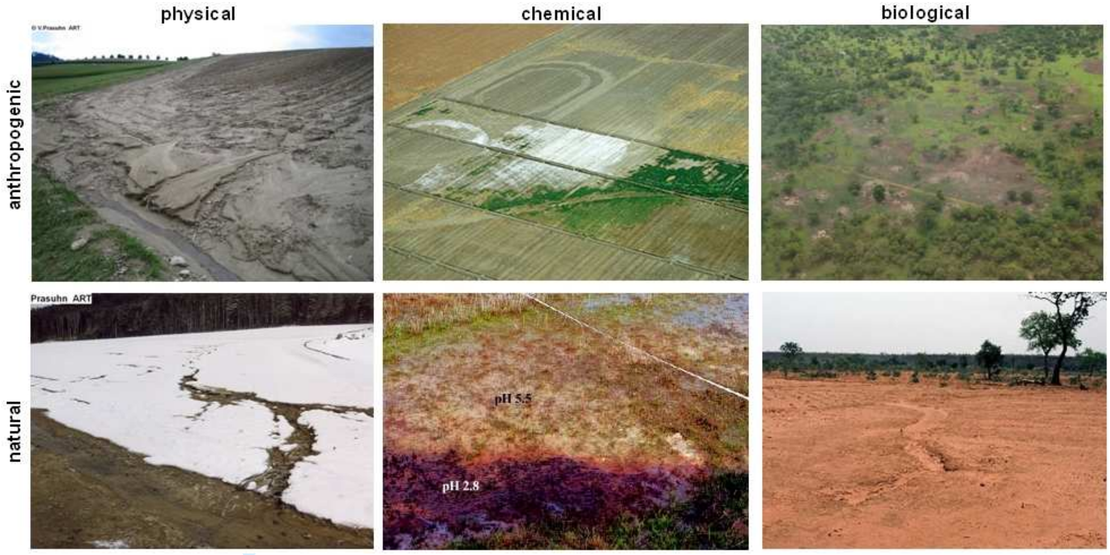
Figure 6. Salinization study in China: middle- Landsat image of study area, overlaid by GLADA NDVI trend (Figure 4); right - red indicates degradation and blue improvement (1988-1996). Modified after Chen and Rao (2008).

Table 1. Most commonly used time-series of vegetation imagery for broad-scale land degradation studies, limited to datasets with a high temporal resolution and global coverage.

Dataset / Product	Sensor	Platform	Time range	Spatial res.	Indicator	Temporal resolution
Pathfinder Land (PAL)	AVHRR	NOAA satellites	1981-2006	8 km (GVI 16km)	NDVI	10-day MVC
Global Vegetation Index (GVI)						Weekly MVC
GIMMS						15-day MVC
FASIR						15-day MVC
MOD13 / MYD13	MODIS	Terra / Aqua	2000-present	250 m – 1 km	NDVI / EVI	8 or 16-day MVC
MOD17A2 / MYD17A2				1 km	GPP	8-day composite
VGT-S10	VGT	SPOT-4	1998-present	1 km	NDVI	10-day synthesis
L3-SMI NDVI	SeaWiFS	OrbView-2	1997-present	4.63 km	NDVI	Weekly MVC

Table 2. Selected studies of broad-scale vegetation trends.

Extent	Indicator	Resolution	Time range	RS data	Conclusion	Reference
Global	NPP (PEM)	0.5 deg	1982-1999	PAL / GIMMS	6% increase in global NPP	Nemani *et al.* (2003)
Global	NPP (CASA)	1 deg	1983-1988	FASIR	Increase in global NPP, 6-month to 1-year offset in timing of anomalies	Potter *et al.* (1999)
Global	NDVI	8 km	1981-2003	GIMMS	Greening and browning trends globally	Bai *et al.* (2008)
Northern hemisphere	NDVI	8 km	1982-1999	GIMMS/FASIR	Significant greening trends (61% of vegetated area)	Slayback *et al.* (2003) Tucker *et al.* (2001) Zhou *et al.* (2001)
Northern hemisphere	NDVI	1 deg	1982-2002	GIMMS	Shifting greening and browning trends, net greening	Angert *et al.* (2005)
Northern Eurasia	NDVI		1998-2005	SPOT VGT	Greening trend	Hüttich *et al.* (2007)
Northern high latitudes	NDVI	8 km	1981-1991	PAL / GIMMS	Photosynthetic activity increased, suggesting increase in plant growth	Myneni *et al.* (1997)
Sahel	NDVI / RUE	8 km	1982-1990	GIMMS	No evidence of desertification	Prince *et al.* (1998)
Sahel	NDVI / rainfall	8 km	1982-2003	GIMMS	Greening trend	Herrmann *et al.* (2005)
Sahel	NDVI	8 km	1982-1999	PAL	Greening trend	Olsson *et al.* (2005)
Sahel	Albedo		1984 v 2003	MeteoSAT	Greening associated with decreasing albedo	Govaerts and Lattanzio (2008)
Australia	fPAR	0.08 deg	1981-2006	PAL	Increase in vegetation cover	Donohue *et al.* (2009)
South America	fPAR / NDVI		1981-2000	AVHRR	Overall increase of 1.3%	Paruelo *et al.* (2004)
China	NPP (PEM)	0.5 deg	1981-2000	AVHRR	Increase in NPP (0.32% / year), decrease in net ecosystem productivity between 80s and 90s due to global warming	Cao *et al.* (2003)



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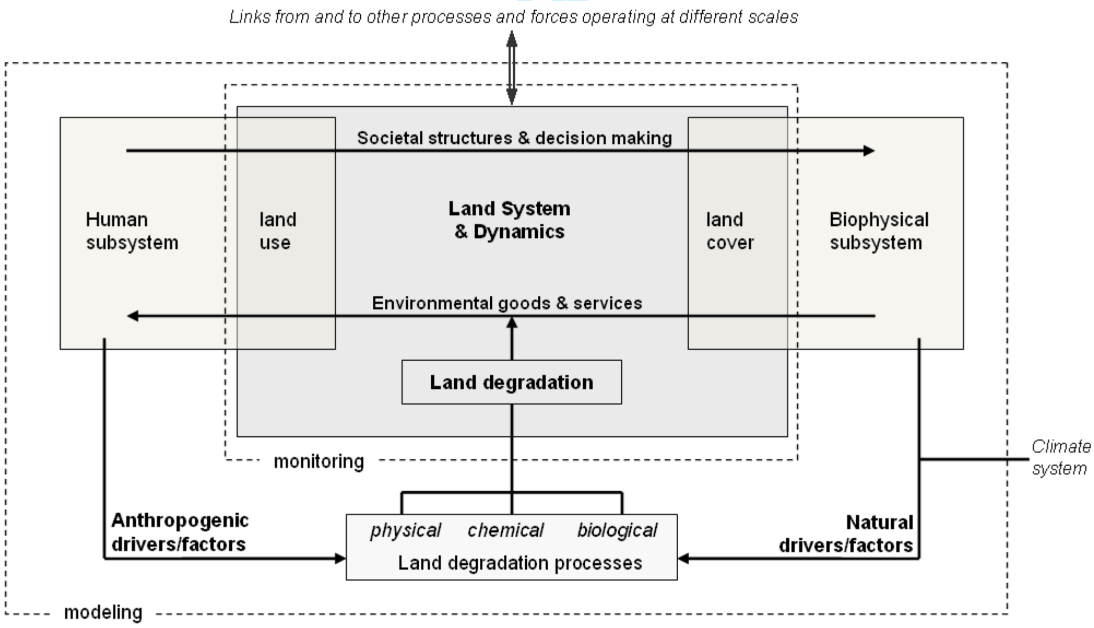

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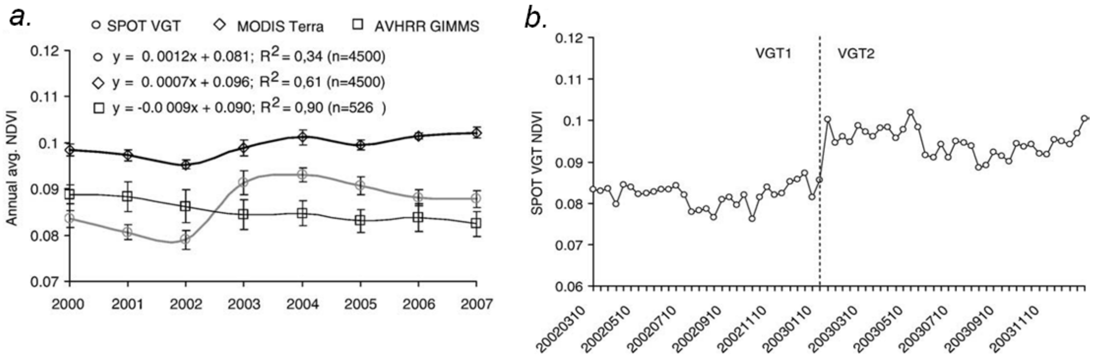

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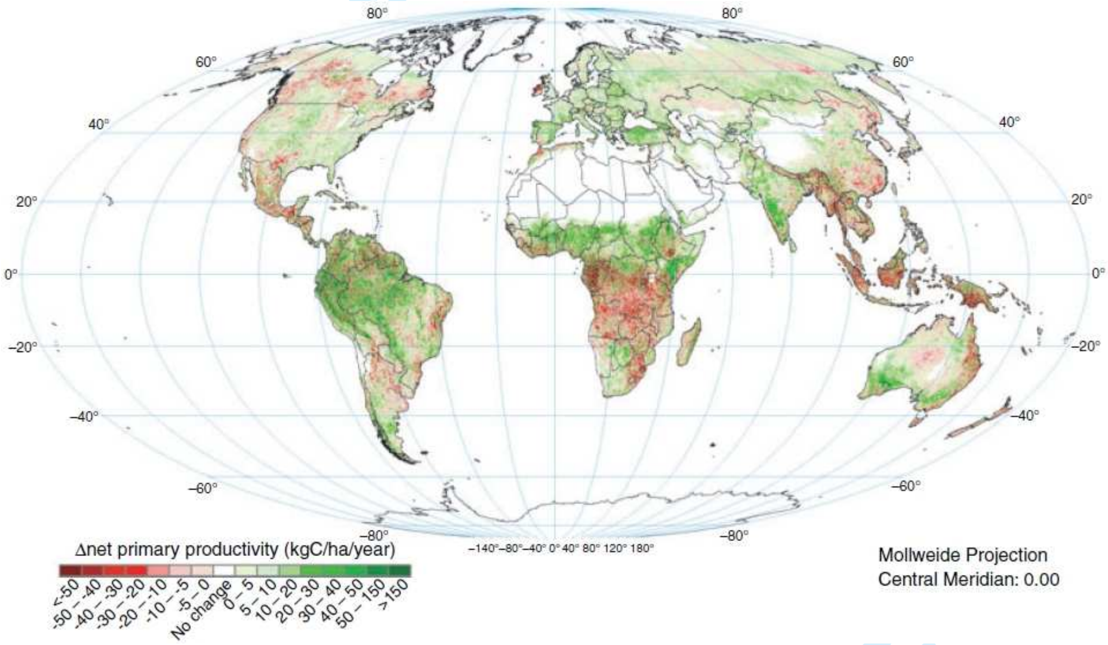

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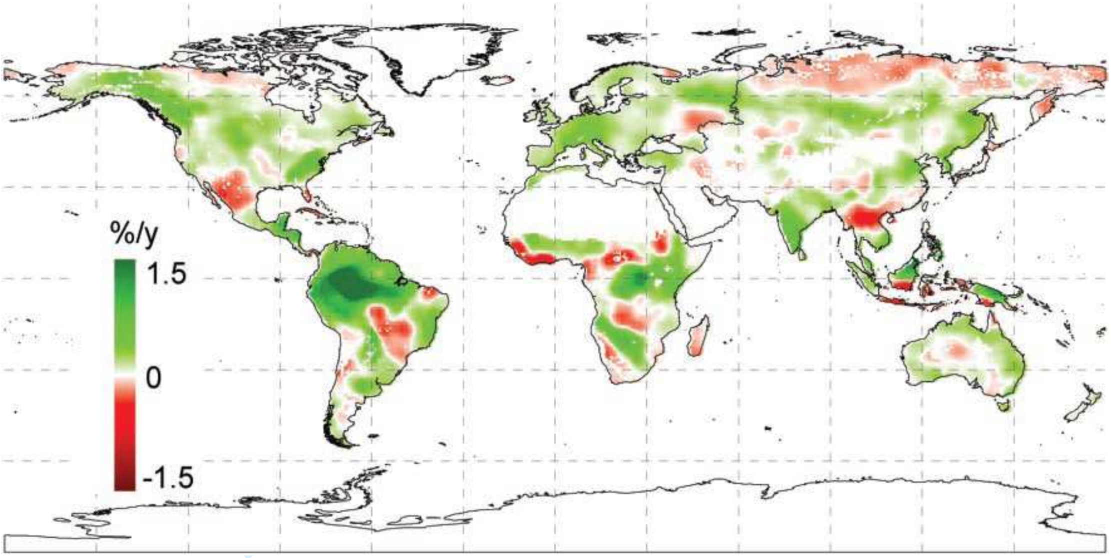

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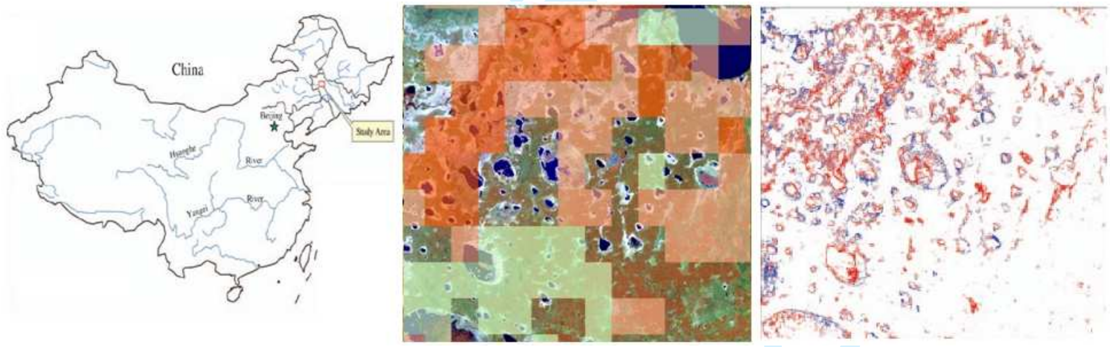

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