At any given place on Earth, complex human-environment interactions are at play, which include differing rates and magnitudes of drivers (e.g. overgrazing, climate change, agricultural practices) and consequences (e.g. soil erosion, changes in productivity, loss of biodiversity). Because these are tied to specific places on the ground with their own intertwined biophysical, social, economic and political environments, land degradation is not a phenomenon that can be modelled or mapped at a global scale.

WAD3 builds on a systematic framework of providing a convergence of reliable, global evidence of human-environment interactions to identify local or regional areas of concern where land degradation processes may be underway. Concerns can be validated or dismissed only by evaluating them within local biophysical, social, economic and political contexts. Local context provides an understanding of causes and consequences of degradation, but also offers guidance for efforts to control or reverse it.

Sources:
- Akca, E.
- Brink, A.
- Cherlet, A.
- Cherlet, M.
- Liniger, H.
- Providoli, I.
Convergence of Global Change Issues

Convergence of evidence: Where the evidence leads

Limitations of global assessments

The assessment and mapping of land degradation at different spatial scales (global, local) is highly desirable. However, numerous limitations make it all but impossible to directly apply, and scale, global assessments to local conditions. For example, (i) some data simply do not exist for all places on Earth (e.g. household income); (ii) while specific data may be widely available, it is often collected and reported using different methods, diverse standards, and/or using incompatible scales; and (iii) some data are wholly site-specific and thus not amenable to global assessments. Limitations such as these encumbered past attempts to produce global maps of desertification\textsuperscript{3,8}, including previous editions of the World Atlas of Desertification (WAD1-3).\textsuperscript{3-5}

Desertification maps were controversial for a variety of interrelated reasons. First, their scientific value was circumscript because of the multifaceted nature of land degradation and the inability to unambiguously define what was actually being mapped. Second, the use of global maps to represent a dynamic, complex issue like land degradation created false equivalences. For example, red zones on a map – used to indicate severe land degradation – cannot capture the nuances, and different manifestations, of land degradation in any two areas (e.g. soil erosion, decreased production, loss of vegetation cover, salinity, water scarcity, pollution, disruption of chemical cycles, loss of biodiversity), its underlying causes (e.g. overgrazing, poor land management, population growth, climate change), and its consequences of interest to humans (e.g. loss of livelihoods, loss of ecosystem services, economic impacts, dust production). Such false equivalences hindered organisations and institutions who attempted to use these maps to prescribe specific types of interventions to ameliorate problem areas.\textsuperscript{6,8}

Third, desertification maps suffer from a lack of “context”, that is, the ability to understand and portray actual conditions on the ground (as exemplified by the red zones described above). Only local context can provide insight into why a particular land degradation issue came to be, how significant it might be, what the range of potential solutions might be available, and whether the potential social, cultural, economic, environmental costs and benefits might warrant intervention (see Case Studies).

New data, new opportunities

Since the publication of WAD in 1992\textsuperscript{4}, there have been a host of scientific and technical advancements that have contributed to the development of a new framework to study environmental problems. These advancements include the emergence of new, comprehensive global data, improved understanding of underlying processes, and technological innovations in analytical tools. As a result, global change issues (e.g. spread of urbanisation, deforestation, ground water depletion) are more readily characterised with increased spatial accuracy, which has led to novel insights of global-scale dynamics, as well as the ability to rapidly disseminate these products to a worldwide audience.

Earlier global mapping attempts relied solely on data obtained from a few satellites that often could not be processed systematically, had few corroborating data, and lacked ample ground observations. Today, the monitoring of the state of the Earth is multi-sourced: the number of Earth-observing satellite systems has increased from about 20 (in 1992) to more than 90 (in 2013)\textsuperscript{4}. There are global networks of long- and short-term land and sea based observations gathered by ground stations and aircraft;\textsuperscript{11} and basic geo-referenced data provide social and economic conditions not directly observable but essential to understanding local context. This multi-sourced theme is illustrated by the Global Earth Observing System of Systems, which is a set of coordinated, independent Earth observation and processing systems that provide information to a broad range of public and private users\textsuperscript{14,15}.

In addition, open access, innovative analytical tools, and significant advancements in information technology (e.g. cloud computing, the Internet of Things, social networking) have facilitated an era of “big data” where new avenues of research (both within and outside the traditional Earth observation community) are flourishing\textsuperscript{16}. This mixture of disciplinary expertise has led to the realisation that a consideration of social and economic processes is necessary to quantify environmental change that matters to humans\textsuperscript{16}.\textsuperscript{17} Moreover, there are economic and political contexts in which all local conditions are bounded, and these complex relationships help better explain previously underappreciated telecoupling between environmental, economic and social drivers in one place, and their sometimes surprising outcomes elsewhere, often far-removed\textsuperscript{18-20} (see Environmental Globalisation, page 40).

The occurrence of multiple global change issues (GCIs) at a location suggests a potential for land degradation (at least in some form).

<table>
<thead>
<tr>
<th>Number of GCIs</th>
<th>% of Global mapped area (1.16 million km\textsuperscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
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</tr>
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<td>4</td>
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<td>5</td>
<td>1</td>
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<tr>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
</tr>
</tbody>
</table>

The six most frequent combinations of 9 coinciding GCIs. There are 1,527 different combinations of the 14 GCIs behind the map above. Some cover large areas, other just a few pixels. The table presents the 8 most frequent combinations of 9 GCIs. Source: WAD3-JRC, 2018.

Constructing convergence of evidence maps

The map illustrates the concept of convergence of evidence. It depicts where global change issues (GCIs) relevant to land degradation coincide at a global scale. The map is constructed using two basic kinds of global data: land cover/land use and global change issues (GCIs). First, land cover/land use data. Total global land mass is stratified into broad classes based on their share of cropland\textsuperscript{21}, rangeland\textsuperscript{22}, and forest\textsuperscript{23} (the term ‘forest’ is used to indicate the ‘tree cover extent’ mapped in the dataset). Depending on specific interests, the availability of data, region and scale of investigation, other stratifications, e.g. climate, soil, and ecosystem services, could be used.

Second, global change issues: 14 global change issues (GCIs) were selected. These GCIs are a mixture of biophysical and socio-economic drivers, and were selected because of their availability as global data and their usefulness as factors associated with land degradation\textsuperscript{24}. Based on whether its value at a particular spatial location is above or below a certain threshold, each GCI is classified as being either a concern for land degradation (e.g. declining productivity) or not (e.g. stable productivity). A GCI threshold is calculated based on the per class distribution of the dataset within each of the broad land classes. At this global scale, for most GCIs the median value is considered (except for agriculture input and land productivity – see table on GCIs for details).

The global map shown here does not represent land degradation. Rather, it illustrates the convergence of evidence of GCIs relevant to land degradation. As noted previously, the correct interpretation of the map must consider contextual information on regional and local conditions, as per individual user’s knowledge. See text for details and following pages for theme maps that illustrate possible stakeholder’s interests.
Opportunity to Explore: Web Access to Global Data

WAD1 and WAD2 were limited by their reliance on the printed page. Once compiled and printed, the information contained in assessment maps could not be probed more deeply. For example, there was no obvious way to examine the data or model that went into designating the Cholistan desert in Pakistan as having severely-degraded soils. This limited the ability of users to understand how land degradation processes at local sites related to other locations or regions. Furthermore, there was no opportunity for systematic feedback, which would permit users to share their knowledge of local conditions. To overcome this, this atlas provides access to the global data that have been assembled at the Joint Research Centre of the European Commission (http://WAD.jrc.ec.europa.eu). The intent is to allow users who have interest in a particular thematic topic (e.g. irrigation, overgrazing, land use change) or specific geographic location to visit the website to explore the occurrence of two or more of the global change issues presented here and, utilising contextual knowledge of a particular location, perhaps combine these data with other global data to explore various drivers and consequences of land degradation processes.

Convergence of evidence approach

Heeding the lessons learned regarding "limitations of global assessments" and benefiting from "new opportunities, new data" (described above), this atlas explicitly decouples global and local assessments and employs a scale-independent approach. This is accomplished by using a convergence of evidence mapping approach, which facilitates the exploration of land degradation – in its various forms and complexities – in lieu of global "maps of desertification". Convergence of evidence refers to the existence of multiple, independent sources of evidence that, when taken together, point towards the same conclusion, inference and/or decision. For these reasons, convergence of evidence analyses are suggestive rather than diagnostic. Importantly, the conclusion can be very strong even if each of the individual sources of evidence by themselves are not sufficient to reach this conclusion. For example, the scientific consensus that the Earth is warming stems from a convergence of evidence of multiple lines of inquiry, such as pollen records, tree rings, ice cores, glacial ice-cap melt, sea-level rise, ecological data, atmospheric carbon dioxide increases, and annual rates of temperature increase. When combined, this evidence converges to a singular, irrefutable conclusion that the globe is warming.

Global change issues (GCIs) used in convergence maps (see also box on ‘Constructing convergence of evidence maps’)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Reference to atlas page reference year and dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aridity</td>
<td>see page 72 GRASS v15 Global Aridity&lt;sup&gt;1&lt;/sup&gt;,&lt;sup&gt;2&lt;/sup&gt; 1993–2014</td>
</tr>
<tr>
<td>Water stress</td>
<td>see page 64 GRNIP year 2010 Aquiduct 2.1&lt;sup&gt;7&lt;/sup&gt;</td>
</tr>
<tr>
<td>Decreasing land productivity</td>
<td>see page 114 period 1999–2013 Ceniaus Global Land 1km SPOT VGT derived LPD&lt;sup&gt;23&lt;/sup&gt;</td>
</tr>
<tr>
<td>Climate-vegetation trends</td>
<td>see page 122 period 1981 and 2010 NARRFUS (1981–2010) and SPE (1901–2010)&lt;sup&gt;22&lt;/sup&gt;</td>
</tr>
<tr>
<td>Fires</td>
<td>see page 124 period 2000-2013 MODIS burned area product&lt;sup&gt;26&lt;/sup&gt;</td>
</tr>
<tr>
<td>Tree loss</td>
<td>see page 125 period 2000-2014 ULP v1.2&lt;sup&gt;27&lt;/sup&gt;</td>
</tr>
<tr>
<td>Population density</td>
<td>see page 26 2015 Gridded Population of the World, Version 4, CIESIN&lt;sup&gt;28&lt;/sup&gt;</td>
</tr>
<tr>
<td>Income level</td>
<td>see page 27 Difference between 2000 and 2015 Gridded Population of the World, Version 4, CIESIN&lt;sup&gt;28&lt;/sup&gt;</td>
</tr>
<tr>
<td>Built-up area change</td>
<td>see page 64 2015 World Bank&lt;sup&gt;29&lt;/sup&gt;</td>
</tr>
<tr>
<td>Low-input agriculture</td>
<td>see page 54 period pre-2014&lt;sup&gt;30&lt;/sup&gt;</td>
</tr>
<tr>
<td>High-input agriculture</td>
<td>see page 54 period pre-2014&lt;sup&gt;30&lt;/sup&gt;</td>
</tr>
<tr>
<td>Irrigation</td>
<td>see page 56 period 2005 Global map of irrigation areas (Version 5)&lt;sup&gt;31&lt;/sup&gt;,&lt;sup&gt;32&lt;/sup&gt;</td>
</tr>
<tr>
<td>Livestock density</td>
<td>see page 60 2014 Global distribution of livestock&lt;sup&gt;33&lt;/sup&gt;,&lt;sup&gt;34&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Condition</th>
<th>Reference to atlas page reference year and dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global distribution of livestock&lt;sup&gt;33&lt;/sup&gt;,&lt;sup&gt;34&lt;/sup&gt;</td>
<td>see page 60 2014 Global distribution of livestock&lt;sup&gt;33&lt;/sup&gt;,&lt;sup&gt;34&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Convergence of Global Change Issues (cont’d)

Interpreting maps

The goal of convergence of evidence mapping (see box ‘Constructing convergence of evidence maps on previous page) is to pinpoint areas on the globe where GCIs coincide. The weight of this evidence (kind and/or number of GCIs) can lead to conclusions on where land degradation may exist. Contextual knowledge and additional information will strengthen such conclusions and warrant further investigation.

A convergence of evidence map does not signify land degradation; rather, as per the convergence of evidence principle described above, no GCI by itself is sufficient to infer land degradation. While the occurrence of multiple GCIs at any location suggests the potential for land degradation (at least in some form), the correct interpretation ultimately must consider contextual information (regarding regional and/or local biophysical and socio-economic conditions). For example, the co-occurrence of high livestock density, water stress and population change in the smallholder coffee region of Kilimanjaro (Tanzania) will most probably have a very different connotation than their co-occurrence in the Panhandle region of Oklahoma (United States). Similarly, the total number of coincident GCIs (e.g. two versus six) per se can only be interpreted with context; that is, a single GCI in one location may have serious consequences in terms of land degradation while six coincident GCIs in another location may have little or no consequences (see following pages).

How to read the maps

Accompanying each convergence of evidence map are summaries of the coinciding global change issues (GCIs). The GCIs are classified as occurring in either dryland or non-dryland (based on Aridity, see Table of GCIs). The GCIs are shown in relation to the land productivity dynamics map (LPD) (for details, see page 114). LPD is global in scope, derived from multi-temporal and long-term time series of remotely-sensed land productivity measures equivalent to NPP, at medium spatial resolution (3 km or better). Briefly, land productivity reflects the overall quality of land and soil, so persistent decreases in land productivity dynamics (LPD) is evidence of a long-term alteration of the health and productive capacity of the land. The LPD map depicts the persistent trajectory of land productivity dynamics during 15 years, from 1999 to 2013, which are summarised by five qualitative classes (see Table below). These five classes represent the intensity and persistence of negative or positive trends and changes of vegetation cover. Note that the first three classes (severe decline, moderate decline and stressed) are used to define the GCI “Decreasing land productivity” (see table of GCIs).

Lithifications of maps

As with all methodologies, there are some limitations:

The thresholds used to classify the GCIs (as being either a concern for land degradation or not) are statistically defined, but the choice for e.g. the ‘median’ is subjective. They can, however, be fine-tuned to fit empirical data and expert knowledge if available;

In some parts of the world, specific land cover types – such as rainforests in South America and cropland in North America – encompass vast and largely continuous areas. Nevertheless, they are rarely homogeneous, often containing a mixture of information such as open versus closed canopies (the former supporting livestock grazing) and are interspersed with fallow fields, roads, remnant woodlands, and human settlements;

While the 14 GCIs are important, they are only a representative subset of potentially-relevant issues. There is currently a lack of global data for many important aspects of land degradation, but as more global data becomes available, other GCIs will be identified, which will strengthen the approach;

Maps of a single theme and coinciding GCIs poses some limits. For example, a map of high livestock density will have a different meaning if it occurs in a high-input cropping system versus a rangeland, which illustrates the necessity of context; and

Global data for many important aspects of land degradation are not available. This includes both biophysical data (e.g. biomass loss, biodiversity, soil organic carbon dynamics, soil erosion, plant encroachment) and socio-economic data (household income, literacy rates, gender mix, etc.). Such joint data are necessary to elucidate and interpret the complexity of factors that govern land degradation in dynamic human-environmental systems. This is illustrated in a number of case studies (see page 188, onward).

Thematic maps

To guide the reader, convergence of evidence maps are presented on the following pages for 13 themes or topics (see Table on this page). The various themes – high density cropland, smallholders, protected areas, etc. – are examples of subject matter selected by a stakeholder who has that particular interest. A theme provides a broad context in which to weigh the evidence of coinciding GCIs and, hence, each map, and accompanying statistics, are limited to the specific area of the globe and continents that are specific for the theme.

Hypothetically, if the spatial occurrence of drought conditions (see “Climate and vegetation trends”, page 122), decreasing land productivity, decreasing population density, and decreasing livestock density were to coincide in rangelands of central Botswana, the collective weight of these GCIs – that is, a convergence of evidence – would strongly suggest that land degradation may exist in this area, or at least that the conditions and current dynamics are present to be potentially susceptible to land degradation. Ultimately, the level of concern and subsequent action (social, cultural, economic, environmental) must be determined by stakeholders who have local context and knowledge.

1 Continental distributions of coincident global change issues (GCIs)

- Y-axis: number of coinciding GCIs (from 1 to 13, the GCIs high or low fertilizer use are mutually exclusive)
- X-axis: % of area occupied per number of GCIs the area always refers to the specific area of the globe and continents that are specific for the theme – e.g. High density cropland, (in brackets the total area per continent of this theme is given)

Example illustrating the distribution of the number of coinciding global change issues (GCIs) in High Density cropland in South America. The most common number of coinciding GCIs is 3 (most of which are in non dryland regions)

2 Continental distribution of predominant global change issues (GCIs) according to percent area occupied specific for the presented theme top of the map – e.g. High density cropland

Example illustrating the percent occurrence of each of the global change issues (GCIs) in High Density cropland in South America.

3 Land productivity dynamics (in five classes – Y-axis) according to the number of coinciding GCIs (in three groups – few (<4) in blue, several (4-7) in yellow, many (>7) in red) expressed as absolute area occupied (in km²) within the theme

Example showing the number of coinciding global change issues (GCIs) in relation to LPD (in absolute area) in High Density cropland in South America

4 Land productivity dynamics (in five classes – Y-axis) according to the number of coincident issues (in three groups – few (<4) in blue, several (4-7) in yellow, many (>7) in red) expressed as relative area occupied within the theme (which represent 100%)

Example showing the number of coinciding global change issues (GCIs) in relation to LPD (in relative area) in High Density cropland in South America

<table>
<thead>
<tr>
<th>Class (exclusive)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Persistent severe decline in productivity</td>
<td></td>
</tr>
<tr>
<td>Persistent moderate decline in productivity</td>
<td></td>
</tr>
<tr>
<td>Table that determined strong inter annual productivity variations</td>
<td></td>
</tr>
<tr>
<td>Stable productivity</td>
<td></td>
</tr>
<tr>
<td>Persistent increase in productivity</td>
<td></td>
</tr>
</tbody>
</table>
The convergence of evidence principle states that no global change issue (GCI) by itself is sufficient to infer land degradation but if multiple GCIs were to occur at any location, this would suggest the potential for land degradation (at least in some form).

Examples of coincident global change issues at one specific 1 km² grid cell. The examples on each map represent some key situations. Similar information queries are possible for all grid cells on the interactive web site (see BOX ‘Opportunity to Explore: Web Access to Global Data’ on page 145).
Convergence of Evidence: High Density Cropland

High density cropland are areas where >50% of each grid cell (1 km²) is under cultivation

Distributions of predominant issues in NORTH AMERICA

Distributions of predominant issues in WORLD

Distributions of predominant issues in SOUTH AMERICA

Distributions of predominant issues in AFRICA
Examples of global regions where high density cropland are affected by global change issues (GCIs; see Table, page 145) include:

- **Africa**: Sub-Saharan, including Burkina Faso, northern Nigeria, eastern Sudan, south Kenya, Malawi, and Zimbabwe.
- **North Africa**: northern Morocco, Egyptian Nile area, and Tigris-Euphrates region.
- **Asia**: India, Pakistan cropland, agricultural expansion areas in northwest China.
- **Central Asia**: Aral Sea area; eastern Kazakhstan, Uzbekistan, Kyrgyzstan, and Tajikistan.
- **Latin America and the Caribbean**: northeast Brazilian drylands, agricultural expansion areas in the Argentinean Chaco, central Chile, southern Mexican cropland, and parts of Cuba and Haiti; and Australia: Southeast and southwest areas.
- **Europe**: Intense agricultural areas in the Mediterranean and central Europe; cropland.
- **United States**: Irrigated areas in the west.

Global change issues (GCIs) associated with transformations (including land degradation) in high-density cropland include: high population density, high livestock densities, and high fertiliser inputs. These GCIs are found in more than 50% of high-density cropland areas of the globe (see inset).

Analysis shows that in high density cropland:

- Approximately 9% (1.3 million km²) of the high density cropland area experiences potential pressure from 8 to 13 GCIs, most of it in drylands. Signs of land productivity decline are observed in 23% of this area (0.3 million km²).
- Approximately 60% (8.9 million km²) of the high density cropland area experiences potential pressure from 4–7 GCIs, evenly distributed between drylands and non-dryland areas. On 20% of this area (1.8 million km²), they coincide with trends in declining land productivity.
- Approximately 29% (4.35 million km²) of the high density cropland area experiences potential pressure from 1–3 GCIs. Approximately 11.5% (0.5 million km²) of this area shows signs of declining land productivity.
- Only 2% of high density cropland, all non-drylands, are not associated with any of the GCIs.

High density cropland in Asia and Africa, the majority of which is found in drylands, stand out as areas of potential concern, but for different reasons. Both have high population densities, high population growth rates, high livestock density and low income. Where they diverge is total irrigated area (>50% in Asia, <10% in Africa) and high-input agriculture (high fertiliser use: 75% Asia, 35% Africa). While there are undoubtedly hotspots on every continent that can be explored, Asia and Africa show that there are large areas potentially undergoing transformations.

At a continental scale, some patterns with regard to high density cropland and global change issues (GCIs) emerge:

- **Africa**: More GCIs are present here than in most other continents. More than 80% of the high density cropland area has high population densities and population increase, more than 75% is arid, has low per capita income, and almost 75% has high livestock density.
- **Asia**: More than 58% of high density cropland area has 6 or more GCIs. 75% have high population densities, livestock densities and fertiliser use. More than 50% is arid, with high water stress, irrigation, high population growth and low incomes.
- **South America**: High density cropland have comparatively few GCIs. More than 75% of the area has high livestock densities, and more than 60% has high population increases (with half occurring in drylands). Less than 30% has high population densities and most of these are non-drylands.
- **Europe**: GCIs found in more than 25% of the area include population density, livestock density, high input agriculture, and water stress (in the southern parts). Larger numbers of coinciding GCIs are generally found in the southern part of the continent. Change in built-up area is the largest of any continent and occurs on 16.3% of the area.
- **North America**: About 30% of the high density croplands has high population growth and 25% high population densities. More than 75% has high fertiliser inputs, 50% high livestock density and 20% is equipped for irrigation.
- **Oceania**: More than 75% of the high density cropland area is arid, with high fertiliser use. About 50% has high livestock density, 25% has water stress, and comparatively low population increases. Overall, there are fewer GCIs at play and, given lower population pressures and higher income, the potential for land transformations (e.g. degradation) would appear to be lower than in either Asia or Africa.

In 14% of high density cropland of the globe, multiple global change issues negatively impact land productivity; this is more pronounced in drylands and especially in Africa and Asia.
Convergence of Evidence: Low Density Cropland

Examples of global regions where low density cropland are affected by global change issues (GCIs; see Table, page 145) include:

- **Africa**: most of the Sahel and coastal zones along the Gulf of Guinea, cultivated areas of Somalia, southern Democratic Republic of Congo, Zimbabwe, Tanzania, and the coast of Madagascar;
- **Asia**: north China plain and large areas of southeast China, the river basins in Bangladesh Padma and Myanmar Irrawaddy, northern Sri Lanka and hotspots in the Philippines and Java;
- **Central Asia**: northern Kazakhstan, Kyrgyzstan and Tajikistan;
- **South America**: Western Andean slopes, the Amazon delta, drylands of northeast Brazil, and agriculture expansion areas in southern Brazil, Argentina, Uruguay, Paraguay and Bolivia;
- **Europe**: Belarus, and;
- **North America**: Large areas in several Central American countries and Haiti.

Global change issues (GCIs) associated with transformations (including land degradation) in low density cropland areas include:

- Tree loss, high population densities and low input agriculture. With regard to the latter, the intensity of fertiliser use ranges from low use (around 33% of the area) to high use (24% of the area) (contrast this to high density cropland where the figures for low and high fertiliser use are about 21% and 31%, respectively). Tree loss occurs over 36% of the low density cropland area which is significantly higher than in the high density croplands, where tree loss occurs over about 10% of the area.
- Analysis shows that in low density cropland:
  - About 4% (or 0.56 million km²) of the low density cropland area experiences potential pressure from 8 to 13 GCIs, which is significantly less than high density cropland. Signs of land productivity decline are observed in 51% of this area (0.3 million km²).
  - Approximately 68% (1.17 million km²) of the low density cropland area experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 21% of this area (0.24 million km²).

At a continental scale, some patterns with regard to low density cropland and global change issues (GCIs) emerge:

- **Africa**: More GCIs are at play than any other continent. Fully 76% (i.e. 2.7 million km²) have between 5 - 7 GCIs. Population density and population change, along with low income levels, occur in around 90% of this area. Fires affect about 25% of the total area, the largest extent in any continent. About 60% has high livestock densities and 33% has fertiliser deficiencies. The GCIs are found more or less equally in dryland and non-drylands.
- **Asia**: Fully 65% of the low density cropland area has between 4 to 6 GCIs, with population density (80% of the area) and population changes (62% of the area) the most common GCIs, followed by high livestock densities (62% of area). Two important GCIs are low income level (53% of the area) and water stress (30%). The agricultural plains of Bangladesh and Myanmar are experiencing population increase and growing built-up areas, combined with expanding irrigation schemes and high livestock densities. High input cultivation is prevalent in Bangladesh while low input cultivation is prevalent in Myanmar.
- **South America**: There are relatively few GCIs in low density cropland areas of South America, where an average of 4 coincide on nearly 20% of the area. However, there are high livestock densities (over 85% of the area), tree loss (concerns half the area) and declining land productivity (26% of the area), all three occur on more area than on any other continent - but not necessarily coincide. Central American countries (Guatemala, Honduras, El Salvador, Haiti), and small areas on the Pacific side of Costa Rica have a relatively high number of GCIs (5-6) at play.
- **Europe**: Has the lowest number of GCIs of all continents, with 3 - 4 potential GCIs occurring on 24 and 25% of the area, respectively. Only between 6 - 7% of low density cropland is subject to 6 or more GCIs, which are mostly concentrated in Portugal, Greece and Belgium. Livestock density, low nitrogen balance, and high population density are found in around 50% of the area. Tree loss (27% of area) and water stress (17% of area) are the most common biophysical GCIs. Also in low density cropland, the change in built-up area is the largest of any continent (13% of the area). The expanding infrastructure comes largely at the expense of productive land, which is a common feature around towns; this phenomenon is widespread in northern parts of Europe, including large parts of Belarus, where this is associated with forest loss and population changes.
- **North America**: High livestock densities (70% of the area) and tree loss (39%) are the most widespread GCIs. In the dryland portions of North America, water stress (36% of the total area) and drought conditions (i.e. climate-vegetation trends GCI, see table) (28%) are important GCIs.
- **Oceania**: A large extent of dryland has experienced drought conditions (i.e. climate-vegetation trends GCI, see GCI table), which has led to declining land productivity in about 26% of the area. Higher than average livestock densities (51%) of the area and low nitrogen balance (36%) contribute to stress in areas with 3 to 4 GCIs.

Africa stands out with more than 6 coinciding GCIs concerning more than half the low density cropland area.

**Fertiliser use is deficient in about one third of low density cropland.**

- Approximately 26% (4.59 million km²) of the low density cropland area experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 11% of this area (0.51 million km²).
- Around 2% have no GCIs.

**Low density cropland extends over a larger area than high density cropland; less land is subject to many (more than 7) coincident global change issues, but more land is subject to pressure from 4 to 5 GCIs – this is more pronounced in Africa.**
Low density cropland are areas where between 10 - 50% of each grid cell (1 km²) is under cultivation.
### Distributions of Predominant Issues in Europe

<table>
<thead>
<tr>
<th>Region</th>
<th>Aridity</th>
<th>Early Signs of Decline</th>
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<th>Stable, But Stressed</th>
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<th>High-Input Agriculture</th>
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<td>Europe</td>
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<td>0.501 million km²</td>
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### Distributions of Predominant Issues in Asia

| Region         | Aridity       | Early Signs of Decline | Stable, Not Stressed | Stable, But Stressed | Decreasing Land Productivity | Water Stress | Livestock Density | Population Change | Income Level | Fire | Climate-Vegetation Trends | Low-Input Agriculture | High-Input Agriculture | Built-Up Area Change |
|----------------|---------------|------------------------|---------------------|---------------------|----------------------------|-------------|------------------|-------------------|--------------|------|--------------------------|                      |                       |                      |
| Asia           |               |                        |                     |                     |                            |             |                  |                   |              |      |                         |                      |                       |                      |
| % of Area with 10-50% Cropland |               |                        |                     |                     |                            |             |                  |                   |              |      |                         |                      |                       |                      |
| 0.501 million km² |               |                        |                     |                     |                            |             |                  |                   |              |      |                         |                      |                       |                      |

### Distributions of Predominant Issues in Oceania

| Region         | Aridity       | Early Signs of Decline | Stable, Not Stressed | Stable, But Stressed | Decreasing Land Productivity | Water Stress | Livestock Density | Population Change | Income Level | Fire | Climate-Vegetation Trends | Low-Input Agriculture | High-Input Agriculture | Built-Up Area Change |
|----------------|---------------|------------------------|---------------------|---------------------|----------------------------|-------------|------------------|-------------------|--------------|------|--------------------------|                      |                       |                      |
| Oceania        |               |                        |                     |                     |                            |             |                  |                   |              |      |                         |                      |                       |                      |
| % of Area with 10-50% Cropland |               |                        |                     |                     |                            |             |                  |                   |              |      |                         |                      |                       |                      |
| 0.501 million km² |               |                        |                     |                     |                            |             |                  |                   |              |      |                         |                      |                       |                      |
Convergence of Evidence: High Density – High Input Cropland

High density – high input cropland are areas where >50% of each grid cell (1 km²) is under cultivation and where there
is a high rate of nitrogen fertiliser application
Examples of global regions where high density – high input cropland are affected by global change issues (GCIs; see Table, page 145) include:

- **Africa**: Nile delta of Egypt, east Sudan, Kenya and Tanzania (around Lake Victoria), Malawi, Zimbabwe, and west Senegal;
- **Middle East**: cropland in Syria, Iraq and Iran;
- **Asia**: large areas in east China and scattered zones in western China; southern Vietnam, and areas in Pakistan and India; Central Asia: Kyrgyzstan and Uzbekistan;
- **Europe**: central Spain, southern Italy, Turkey.

Global change issues (GCIs) associated with transformations (including land degradation) in high density – high input cropland include high livestock numbers (in about 85% of the area), irrigation, and water stress (about 50% of the area).

Analysis shows that in high density – high input cropland:

- About 20% (or 0.9 million km²) of the high density – high input cropland area experiences potential pressure from 8 to 13 GCIs. Signs of land productivity decline are observed in 19% of this area (0.17 million km²).
- Approximately 62% (2.9 million km²) of the high density – high input cropland area experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 13% of this area (0.37 million km²).
- Approximately 17% (0.8 million km²) of the high density – high input cropland area experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 9% of this area (0.07 million km²).
- Less than 1% have no GCIs.

The global distribution of high density-high input cropland is equally distributed between drylands (49%) and non-drylands (51%).

- Along with high population density and change, elevated livestock densities is an important GCI in these systems (ranging from 60% in North America to 90% in Asia).
- More coinciding issues show more land productivity decline.

In areas of high density – high input agriculture, fewer global change issues coincide where income levels are low. Notable exceptions are in China (particularly in drylands) and low income areas in Africa and India.

**South America**: Only 2.3% of the total area of South America is made-up of high density-high input cropland. However, in the Argentinian Chaco there is evidence that these new cropping areas require further study as to their susceptibility to land degradation.

**Europe**: Increasing population and loss of land due to built-up areas are pressing issues, while expanding irrigation combined with water stress is of concern in southern Europe.

**North America**: While this region has the fewest coincident GCIs, the ones of interest here are water stress, livestock densities, fire, population, and decreasing land productivity.

**Oceania**: In west and southeast Australia, coincident GCIs include frequent drought conditions, high livestock densities and irrigation. In 38% of these high density-high input areas, land productivity is decreasing or stressed.

### Statistics

- Theme layer derived from FAO GLC-SHARE v1.0™, 2014 and nitrogen balance on landscape: ‘West P. 2014’ (see page 54).
- This map has grid cells of 1 km².
- 39
- 39
- Statistics - in total area (km²) or percentage of total area - are given for both global and/or continental scales.
- Refer to global change issues (GCIs) in the table on page 145.
- Refer to 'how to read the maps' on page 146.

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**Convergence of Evidence: High Density – High Input Cropland**

Globally, 31% of croplands are high density – high input systems, half of which are experiencing 6 or more global change issues.
High density – low input cropland are rather limited globally. Input is considered low when the nitrogen balance remains in the first quartile, i.e. where a deficiency is reported (see table on page 145). Examples of global regions where high density-low input cropland are affected by global change issues (GCIs; see Table, page 145) include:

- Africa: Central and north-western Nigeria, east-central Sudan and some areas in Ethiopia, Uganda, Tanzania, Zimbabwe, and South Africa.
- Myanmar: Part of the Irrawaddy River basin;
- South America: Soy-producing areas of Central Argentina, Bolivia;
- Eastern European, southern Russian and north-central Asia;
- North America: Northwest Yucatan in Mexico, and throughout the United States and Canada.
- Australia: Various locales in southeast Australia.

Global change issues (GCIs) associated with transformations (including land degradation) in high density-low input cropland include livestock density, population and income level as the most important socio-economic GCIs, while decreases in land productivity (in 22% of the area or about 700 000 km²), water stress, and drought conditions (i.e. climate-vegetation trends GCI, see table) are the most important biophysical GCIs. The graph on area distribution of GCIs illustrates that these cropping systems have fewer coincident GCIs as compared to high density - high input cropping systems.

Analysis shows that in high density – low input cropland:

- About 4% (or 0.13 million km²) of the high density – high input cropland area experiences potential pressure from 8 to 13 GCIs. Signs of land productivity decline are observed in 51% of this area (0.07 million km²).
- Approximately 60% (1.9 million km²) of the high density – high input cropland area experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 30% of this area (0.59 million km²).
- Approximately 35% (1.1 million km²) of the high density – high input cropland area experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 12% of this area (0.13 million km²).
- Less than 1% have no GCIs.
- In the limited area where 7 or more GCIs coincide, there is a higher proportion of declining land productivity.

At a continental scale, some patterns with regard to high density – low input cropland and global change issues (GCIs) emerge:

- Africa. There are more coincident GCIs in Africa than anywhere else (more that 75% of the high density-low input cropland areas have >6 GCIs). Tree loss, land productivity decline (in about 24% of the area), drought conditions, population issues, and low income tend to coincide.
- Asia. In Asia, 70% of this cropping system is found in drylands. The most important GCIs are water stress, fire, and to a certain extent, land productivity decline.
- South America. The area of high density – low input cropland is limited, but more than 50% of it (about 601 000 km²) has declining land productivity, most of it in soybean producing areas where also drought conditions probably impacted on the land productivity dynamics.

- Europe. About of 24% of the area (about 300 000 km²) exhibiting declines in land productivity is found in eastern Europe. Water stress and drought conditions are important GCIs, especially in western Russia.
- North America. In about 38% of this area, tree loss is an issue. Other GCIs of note are decreasing land productivity and livestock densities. A specific region of emerging concern is in the agriculture region of northwest Yucatan peninsula in Mexico.
- Oceania. Most high density – low input cropland in Oceania are found in drylands where drought conditions and land productivity decline are important GCIs. Land productivity decline occurs in one third of the non-dryland high density-low input cropland area.

Low input cultivation coinciding with a persistent decline of land productivity dynamics raises concern for potential land degradation.

About 22% of global high density–low input cropland show a decline of land productivity over the last 15 years. This ranges from about 12% in North America and Asia, over 24% in Europe and 17% in Oceania to more that 50% of the high density–low input cropland in South America.
Convergence of Evidence: High Density – Low Input cropland

High density – low input cropland are areas where >50% of each grid cell (1 km²) is under cultivation and where there...
High density – low input cropland are areas where >50% of each grid cell (1 km²) is under cultivation and where there is a low rate of nitrogen fertiliser application.

Distributions of predominant issues in EUROPE

Distributions of predominant issues in ASIA

Distributions of predominant issues in OCEANIA

is a low rate of nitrogen fertiliser application
Convergence of Evidence: Low Density – Low Input cropland

Distributions of predominant issues in NORTH AMERICA

Distributions of predominant issues in WORLD

Distributions of predominant issues in SOUTH AMERICA

Distributions of predominant issues in AFRICA

Low density – low input cropland are areas where between 10 - 50% of each grid cell (1 km²) is under cultivation and...
where there is a low rate of nitrogen fertiliser application

Distributions of predominant issues in EUROPE

Distributions of predominant issues in ASIA

Distributions of predominant issues in OCEANIA

PART V – CONVERGENCE OF EVIDENCE | World Atlas of Desertification 161
Examples of global regions where low density – low input cropland are affected by global change issues (GCIs; see Table, page 145) include:

- **Africa**: Western Sahel, coastal zones of Gulf of Guinea, coastal areas of Somali and Tanzania, coastal and inland areas in the Democratic Republic of Congo; and some areas in Vietnam.
- **Asia**: South-East Asia, the lower part of the Irrawaddy Basin (Myanmar), and some areas in Vietnam.
- **Central Asia**: Some of the “revived” agriculture land in southern Russia, Kazakhstan and Kyrgyzstan.
- **Latin America**: Brazil (southwest of Brasilia, Rondonia and the Amazonia delta areas), Chaco region of Belivia and Argentina, southern Ecuador, Maracaibo region in Venezuela, and smaller areas in central America (such as the Flores region in Guatemala).
- **United States and Europe**: Limited areas, which are usually scattered within high density – low input cropping areas.

Global change issues (GCIs) associated with transformations (including land degradation) in low density-low input cropland include tree loss (which involves all continents, totalling about 35% or nearly 2 million km²) and low income. As compared to high density-low input cropland, income level is the most important GI, and occurs in about 51% of the low density-low input cropland area.

- **Analysis shows that in low density-low input cropland**:
  - About 4% (or 0.22 million km²) of the high density – high input cropland area experiences potential pressure from 8 to 13 GCIs. Signs of land productivity decline are observed in 54% of this area (0.12 million km²).
  - Approximately 74% (4.17 million km²) of the high density – high input cropland area experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 22% of this area (0.91 million km²).
  - Approximately 21% (1.19 million km²) of the high density – high input cropland area experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 8% of this area (0.09 million km²).

- **Low income is a main issue in low density – low input cropland and might constrain land management options.**

At a continental scale, some patterns with regard to low density-low input cropland and global change issues (GCIs) emerge:

- **Africa**: Neatly all the low density-low input cropping area in Africa has high population density and low income. This is a reflection of the prevalence of smallholder farms (see page 64). Tree loss (about 48% of area) and fire (about 26% of area) are the main biophysical issues. Land degradation is a potential concern in about 17% of the area where land productivity is decreasing. More GCIs are coinciding in Africa than the global average.
- **Asia**: Tree loss (about 30%) and water stress (about 26%) are the main biophysical issues in Asia. Next to population density (67% area), income level (about 48% area) is the more frequent coincident GI.
- **South America**: Tree loss (about 52% of area) is the most important biophysical issue. Maps on the forest loss (see page 36) and expanding agriculture (page 50) illustrate that, in many cases, low density – low input agriculture follows a transition from forest to cultivation. Over the total area, GCIs population change occurs in about 70% and low income in 40%.
- **Europe**: Fewer coincident GCIs occur in Europe where tree loss is the main biophysical issue. Drought conditions, fire and decreasing land productivity all occur over less than 10% of the area. Below average income level is an issue over about 23% of the area and increase in built-up space occurs in about 8% of the area, the second highest after North America.

- **North America**: Tree loss occurs over 50% and built-up area in 10% of the total area of low density – low input agriculture, the highest globally. Water stress is found over about 20% of the area.

- **Oceania**: Mostly, 3 - 4 GCIs coincide with drought conditions and decreasing land productivity. Population change is an issue in about 75% of the area. Most of the area has stable land productivity.

- **Less than 1% have no GCIs.**
- **Around 45% of these cropland systems have 5 - 6 coincident GCIs, of which tree loss is primary, followed by decrease in land productivity (about 16%), water stress, drought conditions (i.e. climate-vegetation trends GCI, see table), and fires (each over about 13%).**
- **Biophysical GCIs (e.g. water stress, drought conditions, fire) are less common in these cropping systems than in high density – low input systems.**

Global regions are given for both global and/or continental scales.

- **Theme layer derived from FAO GLC-SHARE v1.0M, 2014 and nitrogen balance on landscape: West P. 2014**
- **This map has grid cells of 1 km².**
- **Statistics - in total area (km²) or percentage of total area - are given for both global and/or continental scales.**
- **Refer to global change issues (GCIs) in the table on page 145.**
- **Refer to ‘how to read the maps’ on page 146.**
Examples of global regions where High Density-Rainfed Cropland are affected by global change issues (GCIs; see Table, page 145) include:

- **Africa**: Northern Morocco, west Senegal, vast areas in central-north Nigeria, Sudan, areas around Lake Victoria, Zimbabwe, and the main agricultural areas in central-east South Africa;
- **Asia**: Northeast China, Myanmar, India and northern Afghanistan;
- **South America**: Central Argentina, small areas in Brazil and Bolivia;
- **Europe**: Limited areas.
- **North America**: Some areas in western Mexico, the United States, and Canada;
- **Australia**: southwest and eastern Australia.

Global change issues (GCIs) associated with transformations (including land degradation) in High density-rainfed cropland include water stress (27% of the area), drought conditions (23% of the area) (i.e. climate-vegetation trends GCI, see table) and decreasing land productivity, low income, and higher than average livestock densities. There are slightly more of these cropping systems with low (26%) versus high agriculture inputs (21%). High input agriculture and livestock densities are the most widespread combination in this rainfed cropland, mostly in North America and Europe.

Analysis shows that in high density-rainfed cropland:

- About 2% (or 0.22 million km²) of the high density-rainfed cropland area experiences potential pressure from 8 to 13 GCIs. Signs of land productivity decline are observed in 54% of this area (0.12 million km²).
- Approximately 56% (6.1 million km²) of the high density-rainfed cropland area experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 24% of this area (1.5 million km²).
- Approximately 41% (4.4 million km²) of the high density-rainfed cropland area experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 0.5% of this area (11 million km²).
- Around 2% have no GCIs.
- About 10% of the global area has more than 7 coincident GCIs, which are associated with decreases in land productivity.
- These cropland are nearly equally distributed between dryland and non-drylands (51 vs. 49%, respectively).

At a continental scale, some patterns with regard to high density-rainfed cropland and global change issues (GCIs) emerge:

- **Africa**: More than 75% of high density-rainfed agriculture occurs in drylands (the most of any continent). Important GCIs are drought conditions, decreasing land productivity, high population densities, population growth, and low income. Nearly 60% of high density-rainfed agriculture in Africa has more than 6 coincident GCIs.
- **Asia**: In Asia, 60% of the area is considered drylands. Hence, water stress is a common GCI, especially in regions of rapid agricultural expansion, such as northeast China. Although low income occurs in about 45% of the area, high-input agricultural is an important GCI in about 30% of the area. In northern Afghanistan, water stress and drought conditions are key biophysical GCIs.
- **South America**: Drought conditions (45% of the area) and decreasing land productivity (43% of the area) are widespread biophysical GCIs. These coincide with high livestock densities (80% of the area) and population change (64% of the area).
- **Europe**: In southern European drylands, drought conditions (i.e. climate-vegetation trends GCI, see table) and water stress are important GCIs, while elsewhere, livestock density and agriculture inputs (both high and low) are concerns.
- **North America**: Very few GCIs, mostly 2 or 3, coincide in high density-rainfed cropland. Water stress and drought conditions (i.e. climate-vegetation trends GCI, see table) are important GCIs in some areas. High livestock numbers exist over 59% of the area and high inputs are found in about 30% of the area.
- **Oceania**: Drought conditions (i.e. climate-vegetation trends GCI, see table) and decreasing land productivity are important GCIs in Australia.

Drought conditions occurred in 23% of global high density-rainfed cropland during the past 3 decades.
Convergence of Evidence: High Density-Rainfed Cropland

High density-rainfed cropland are areas where >50% of each grid cell (1 km²) is under cultivation and the only source of...
High density-rainfed cropland are areas where >50% of each grid cell (1 km²) is under cultivation and the only source of water is rainfall.
Convergence of Evidence: Low Density-Rainfed Cropland

Low density-rainfed cropland are areas where between 10 - 50% of each grid cell (1 km²) is under cultivation and the

Distributions of predominant issues in NORTH AMERICA

Distributions of predominant issues in WORLD

Distributions of predominant issues in SOUTH AMERICA

Distributions of predominant issues in AFRICA
Distributions of predominant issues in EUROPE

Distributions of predominant issues in ASIA

Distributions of predominant issues in OCEANIA


Only source of water is rainfall
Convergence of Evidence: Low Density-Rainfed Cropland

Rather than being remote, most low density rainfed cropland are closer or mixed with populated areas and thus tend to have more issues than high density agriculture areas.

At a continental scale, some patterns with regard to low density-rainfed cropland and global change issues (GCIs) emerge:

- **Africa.** Low density-rainfed agriculture is widespread and associated with areas that have high population density and low income. About 58% occurs in drylands, twice the global average. Important GCIs are tree loss (40% of the area), low agricultural input (40%) and fire (25%). Fire is an important issue in Senegal, Mali, Burkina Faso, Chad and parts of Eritrea, as well as in the southern fringes of the Gulf of Guinea countries. Declines in land productivity are observed on the coastal areas of Somali.

- **Asia.** In this region, 4-5 coincident GCIs predominate, which is slightly above the global average. Population tends to be high (75% of the area) and income levels lower (60% of the area) than median global income. Land productivity has decreased in about 10%, as exemplified in Central Myanmar, parts of Rajasthan (India), and the Philippine islands of Luzon and Mindoro.

- **South America.** High population and livestock densities are common GCIs in low density-rainfed cropland in South America, although vast areas of Brazil and Argentina have few coincident GCIs. Higher than median livestock numbers is an issue in over 80% of the area and tree loss (50% of the area) is above the global average. In areas of agricultural expansion, such as the Argentina soybean and Chaco areas, high input agriculture occurs in 30% of the area. In the Ecuadorian coastal areas, tree loss, drought conditions and land productivity declines coincide with population density and livestock numbers.

- **Europe.** In Europe, which has a highly concentrated population and extensive land use, low density-rainfed cropland are dispersed throughout the landscape. Convergence of GCIs is lower than the global average. Livestock numbers and low inputs are key GCIs in over 50% of the area. Tree loss is in more than 25% of the area while decreasing land productivity affects less than 10% of the area.

- **North America.** Spread over the central and eastern United States and Canada, low density agriculture areas have relatively few GCIs beyond livestock numbers and tree loss (in nearly 40% of the area). Built-up area is higher than the global average in similar areas (10% of the area).

- **Oceania.** A relatively small area of Oceania (0.46 M Km²) is low density-rainfed cropland. More than 60% of it is dryland. Half has been affected by droughts conditions, mainly in eastern Australia. Decreasing land productivity occurs in just over 25% of the area.

Global change issues (GCIs) associated with transformations (including land degradation) in low density-rainfed cropland include tree loss, which is the most important biophysical GCI (31% of the area, most of which occur in non-drylands). Other GCIs include declining land productivity (over 17% of the area) and income level (an issue in nearly 50% of the area).

Analysis shows that in low density-rainfed cropland:
- About 2% (or 0.32 million km²) of the low density-rainfed cropland area experiences potential pressure from 8 to 13 GCIs. Signs of land productivity decline are observed in 61% of this area (0.19 million km²).
- Approximately 67% (10.2 million km²) of the low density-rainfed cropland area experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 22% of this area (2.2 million km²).
- Approximately 29% (4.48 million km²) of the low density-rainfed cropland area experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 11% of this area (0.49 million km²).
- Around 2% have no GCIs.

Much of the African low density rainfed cropland is associated with low income levels and nutrient deficiency occurs over a vast part of it (40% of the area). Population density and population change affects more the 60% of the area, hence these areas are susceptible to infrastructure and urban expansion, which encroaches into agricultural lands.

Globally, higher than average livestock numbers are common.
Examples of global regions where smallholder cropland are affected by global change issues (GCIs; see Table, page 145) include:

- **Africa**: Nile River basin, Sahel, eastern Africa (regions on the Somali southeast coast, Kenya and northern Tanzania), and Zimbabwe.
- **Asia**: Indus River basin of India, Yellow River basin in northeast China, Java (Indonesia).
- **Central Asia**: Some parts of Uzbekistan, Kyrgyzstan and Tajikistan.
- **North America**: Central Mexico.

At a continental scale, some patterns with regard to smallholder cropping systems and global change issues (GCIs) emerge:

- **Africa**: Africa has the second largest area of smallholder cropland (after Asia), of which about 60% is located in drylands. In more than 60% of the area more than 6 GCIs are found. Higher than average population densities and population changes, and lower than average income is affecting more than 90% of the total smallholder area in Africa. Unlike Asia, in 37% of the area smallholders have low input agriculture, potentially compromising long-term land quality. Land productivity is declining in about 20% of the area. Combinations of 7 or more coincident GCIs occur in stressed or declining land productivity classes.

- **Asia**: A vast area of 8.73 M Km² is managed by smallholders. They must deal with 6 and more convergent GCIs. Water stress (about 40% of the area), as well as population densities, high livestock numbers and below average income (60% of the area) pose significant challenges. Irrigation is practiced in more than 40% of the area and corresponds with high input agriculture that potentially threatens water quality. The Indus basin in Pakistan, most of India, the Yellow river area and coastal areas in eastern China and the Irrawaddy river basin in Myanmar are regions of concern.

- **South America**: Limited areas in north and northeast Brazil, the Ecuadorean coastal area, smaller zones in central Chile and central Mexico show more than 6 coincident GCIs. Tree loss, high livestock densities and high input agriculture are the continent’s main global change issues.

- **Europe**: Key GCIs include higher than average livestock numbers, population densities, and water stress. Smallholder cropping areas have fewer than 4 coincident GCIs. Surprisingly, 26% of smallholder cropping areas have increases in built up areas.

- **North America**: Smallholder areas are very limited and there are few coincident GCIs.

- **Oceania**: There is very limited smallholder cropland in Australia, New Zealand and the rest of Oceania. There are no important issues, aside from high livestock numbers and high agricultural inputs.

Global change issues (GCIs) associated with transformations (including land degradation) in smallholder cropland include tree loss and water stress (both occur in about 27% of the total area). About 40% of smallholder cropland occur in drylands, and most have 6 or more coincident GCIs where non-dryland areas have 5 or less.

Analysis shows that in smallholder cropping systems:

- About 5% (or 1.47 million km²) of the smallholder cropland area experiences potential pressure from 8 to 13 GCIs. Signs of land productivity decline are observed in 26% of this area (0.39 million km²).
- Approximately 77% (12.5 million km²) of the smallholder cropland area experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 15% of this area (2 million km²).
- Approximately 13% (2.2 million km²) of the smallholder cropland area experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 8% of this area (0.18 million km²).
- Less than 1% have no GCIs.
- Key GCIs are high population density and population change (86% and 76% of the land area, respectively), which coincide with low income levels (67% of the area).
- Smallholders in poorer rural areas (about 67% of the area, mostly in Africa and Asia) support many people (68% of the area has higher than average population densities) and must deal with water stress (27%), tree loss (27%) and fire (9%).

Vast areas of smallholder cropland in Africa and Asia must cope with a large number of divergent global change issues. In Asia, overuse of agricultural inputs (e.g., fertilisers) is an environmental issue while in Africa, the opposite (lack of inputs) prevails. There are serious long-term consequences in both instances.
Convergence of Evidence: Smallholder Cropland

Smallholder cropland are areas where >10% of each grid cell (1 km²) is occupied by farms, the medium-size of which...
Distributions of predominant issues in EUROPE

- **Number of coincident issues**: 0 1 2 3 4 5 6 7 8 9 10 11 12 13
- **Aridity**: Dryland, Non-Dryland
- **Coinciding GCIs**: Few (1-4), Several (5-7), Many (>7)

Distributions of predominant issues in ASIA

- **Number of coincident issues**: 0 1 2 3 4 5 6 7 8 9 10 11 12 13
- **Aridity**: Dryland, Non-Dryland
- **Coinciding GCIs**: Few (1-4), Several (5-7), Many (>7)

Distributions of predominant issues in OCEANIA

- **Number of coincident issues**: 0 1 2 3 4 5 6 7 8 9 10 11 12 13
- **Aridity**: Dryland, Non-Dryland
- **Coinciding GCIs**: Few (1-4), Several (5-7), Many (>7)
Convergence of Evidence: Irrigated Cropland

Irrigated cropland are areas where each grid cell (1 km²) has >50% under cultivation, of which >10% is equipped for irrigation.

**Distributions of predominant issues in NORTH AMERICA**

- **Arizona**: Drought dryland with low nitrogen balance and early signs of decline.
- **California**: High nitrogen balance, stable, not stressed.
- **Texas**: Built-up area change, income level, population change.

**Distributions of predominant issues in WORLD**

- **North America**: Dominantly covered by high nitrogen balance, stable, not stressed.
- **Europe**: Various issues including population change, water stress, climate-vegetation trends.
- **Asia**: Several issues such as livestock density, income level, population change.

**Distributions of predominant issues in SOUTH AMERICA**

- **Brazil**: Drought dryland with high nitrogen balance and early signs of decline.
- **Peru**: Population density, tree loss, climate-vegetation trends.
- **Argentina**: Income level, population change, climate-vegetation trends.

**Distributions of predominant issues in AFRICA**

- **South Africa**: High nitrogen balance, stable, not stressed.
- **Nigeria**: Population change, water stress, climate-vegetation trends.
- **Morocco**: Built-up area change, income level, tree loss.

**Graphs and Data**

- Proportion of vegetated continent area.
- % of North American area with >50% cropland and >10% equipped for irrigation.
- % of South American area with >50% cropland and >10% equipped for irrigation.
- % of African area with >50% cropland and >10% equipped for irrigation.

**Key Terms**

- **Drought dryland**: Areas with low nitrogen balance and early signs of decline.
- **Stable, not stressed**: Areas with stable conditions and low stress on the environment.
- **High nitrogen balance**: Areas with high nitrogen levels, often indicating intensive agriculture.
- **Population change**: Changes in population density affecting land use.
- **Water stress**: Areas experiencing water scarcity.
- **Aridity**: Measurement of aridity, indicating dryness.
- **Built-up area change**: Expansion of urban areas.
- **Income level**: Economic status of the region.
- **Tree loss**: Reduction in forest cover.
- **Fires**: Frequency and intensity of wildfires.
- **High-input agriculture**: Intensive farming methods.
- **Low-input agriculture**: Less intensive farming methods.

**Data Points**

- **North America**: % of area with >50% cropland.
- **South America**: % of area with >50% cropland.
- **African continent**: % of area with >50% cropland.

**Graphs**

- **Percentage of area with >50% cropland**.
- **Coinciding GCIs**.
- **Population density**.
- **Income level (GNI/capita)**.
- **Water stress**.
- **Climate-vegetation trends**.
- **Aridity**.

- **Proportion of vegetated continent area**.
- **North American area with >50% cropland and >10% equipped for irrigation**.
- **South American area with >50% cropland and >10% equipped for irrigation**.
- **African area with >50% cropland and >10% equipped for irrigation**.

**Locations**

- **North America**: Chicago, Los Angeles, New York, Las Vegas, Mexico City, Sono, Rio de Janeiro, São Paulo, Buenos Aires.
- **South America**: Rio de Janeiro, São Paulo, Buenos Aires, Lima, Bogota, Lima, Santiago.
Distributions of predominant issues in EUROPE

Distributions of predominant issues in ASIA

Distributions of predominant issues in OCEANIA

PART V – CONVERGENCE OF EVIDENCE
Examples of global regions where irrigated cropland are affected by global change issues (GCIs; see Table, page 145) include:

- Asia: Areas in west and north-east China, Pakistan (Indus River), northern India (Ganges River), western India, and Kyrgyzstan, Uzbekistan in central Asia;
- Middle East: Iran and Nile delta;
- Others: Mediterranean (Europe), western United States, and southern Australia.

( Global change issues (GCIs) associated with transformations (including land degradation) in irrigated cropland include high fertiliser input, water stress, high population densities, high population growth rates, low income and high livestock density. Globally, irrigated cropland occupy 4.2 M km² of land (*), of which 70% occurs in drylands (a primary reason for irrigation). High population density occurs in over 80% of the area, population growth in 75% and low income in 50%.

Analysis shows that in irrigated cropland:
- About 26% (or 1.08 million km²) of the irrigated cropland area experiences potential pressure from 8 to 13 GCIs. Signs of land productivity decline are observed in 17% of this area (0.18 million km²).
- Approximately 66% (2.75 million km²) of the irrigated cropland area experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 15% of this area (0.37 million km²).
- Approximately 7% (0.3 million km²) of the irrigated cropland area experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 10% of this area (0.03 million km²).
- Less than 1% have no GCIs.

About 60% of the area is characterised by high water stress. In about 55% of the area there is an excess use of fertilisers.

In most irrigated cropland, water quality and availability will be an important global change issue.

At a continental scale, some patterns with regard to irrigated cropland and global change issues (GCIs) emerge:

- **Africa.** About 0.14 M km² (*) is classified as irrigated cropland, with 60% of it occurring in drylands, and most of it in the Nile delta. The number of coincident issues is comparatively high. High population growth is found in 90% of the area, population density in almost 100%, low income in 75%, increase in built-up in 25%, high water stress in 30%, high livestock densities in 75%, and high input agriculture in 60%.

- **Asia.** About 3.0 M km² (*) is classified as irrigated cropland, with 60% in drylands. The number of coincident GCIs is comparatively high. There is high population growth in more than 80% of the area, high population density in 90%, low income in 60%, over 80% in both high livestock density and high input agriculture, and 60% shows water stress (corresponding to the dryland portions).

- **South America.** About 0.01 M km² (*) is classified as irrigated cropland, with 60% in drylands. About 60% of the area has high population density and 75% has high population growth, all mostly in drylands. Low income levels occur in about 10% of the area, high livestock density in 70%, high input agriculture in 70%, and both decreasing land productivity and tree loss in 30% of the area.

- **Europe.** About 0.4 M km² (*) is classified as irrigated cropland, split evenly between dryland and non-dryland. The number of coincident GCIs is comparatively low. Each of the following GCIs occur in 50% of the area: population density, high population growth, high livestock density, and high input agriculture.

- **North America.** About 0.5 M km² (*) is classified as irrigated cropland, with 65% in drylands. High population density is found in about 30% of the area, high population growth in 30%, low income levels in <10%, high input agriculture in 80%, and high densities of livestock in 70%.

- **Oceania.** About 0.06 M km² (*) is classified as irrigated cropland, with 80% in drylands. The number of coincident issues is comparatively low. More than 40% of the area has increasing population, 20% has high population density, 80% high livestock density, 75% high input agriculture and 60% high water stress.

More than half of the world’s irrigated cropland are in water stressed areas and possible nitrogen excess due to high fertiliser input occurs in 55% of the irrigated cropland.

- Theme layer derived from: FAO GLC-SHARE v1.0™, 2014 and Siebert S. 2014: GMIA™, 36, 37 (see page 56).
- This map has grid cells of 1 km².
- (*) Statistics - in total area (km²) or percentage of total area - are given for both global and/or continental scales.
- Refer to global change issues (GCIs) in the table on page 145.
- Refer to ‘how to read the maps’ on page 146.
Examples of global regions where cropland with yield gaps are affected by global change issues (GCIs; see Table, page 145 and see Closing Yield Gaps, page 52) include:

- Africa: Morocco, Tunisia, Nile delta in Egypt; Gedaref area in Sudan, Ethiopia, Kenya, Tanzania, Malawi, Zimbabwe and coastal Senegal;
- Asia: northern Turkey, Yellow River Basin (China); Indus valley (Pakistan), various areas in India;
- Europe: Mediterranean dryland areas, including southern Italy, Spain; Moldovan Dniester valley and northern Belgium.

At a continental scale, some patterns with regard to cropland with yield gaps and global change issues (GCIs) emerge:

- **Africa.** Coinciding GCIs in most of African cropland with yield gaps are low input agriculture (26% of the area), land productivity decline (21% of the area), high population density with low income (both in 90% of the area) and less than 4% of this cropland is under irrigation. Stress on the land resource is likely due to low intensity cropping, low input technology and low land productivity, especially when combined with a dense, poor and growing populations. The Maghreb area in northern Africa deviates from this pattern because irrigation is more widespread, and combines with other issues associated with drought conditions and urban growth along coastal areas associated with a decline in land productivity in some areas.

- **Asia.** Irrigation (27% of the area), high input agriculture (30% of the area), and stable or increasing land productivity all coincide with current yield gaps. This suggests that agriculture in this area has been intensified in order to close yield gaps to meet the demands of a growing population. However, 40% of the area is under water stress and this agriculture developments potentially place pressure on both land and water resources, such as in Pakistan’s Indus valley and northeast China. Large areas in eastern Europe, south Russia and north-central Asia stand out due to their recent historic trajectory from abandonment after the collapse of the former Soviet Union followed by the recent “revival” of low input agriculture in some areas (see page 187).

- **South America.** The Argentine Chaco experienced tree loss (40% of the area), drought conditions, and declining land productivity as a result of land use change from the dry forest to agriculture.

- **Europe.** There are very few coincident GCIs. In 60% of the area, mostly in eastern Europe, there is low input agriculture. Tree loss is found in 20% of the area, including Portugal, northwest Spain, Poland, and Latvia, Lithuania and other areas scattered throughout eastern Europe. High population densities and rapid expansion of built-up areas add to pressures on cropland in Belgium. Areas of concern are the mid-west United States, Mexico and Cuba. Coinciding GCIs are tree loss (over nearly 40% of the area), water stress, some fire, and high livestock numbers (in 75% of the area). In north-central Mexico also drought conditions coincided.

- **Oceania.** Water stress, irrigation and high livestock density (65% of the area) and high input agriculture (over 38% of the area) are part of a dynamic agriculture.

Global change issues (GCIs) associated with transformations (including land degradation) in cropland with yield gaps include: various biophysical GCIs (water stress, drought conditions (i.e. climate-vegetation trends GCI, see table), decreasing land productivity) and socio-economic GCIs (low income, high population densities, high input agriculture, low input agriculture). Cropland with yield gaps tend to occur in poorer regions of the world, such as in Africa and India, where low income and water stress are especially important GCIs.

Analysis shows that in cropland with yield gaps:

- About 10% (or 0.82 million km²) of the cropland with yield gaps area experiences potential pressure from 8 to 13 GCIs, which is significantly less than high density cropland. Signs of land productivity decline are observed in 26% of this area (0.22 million km²).
- Approximately 62% (8.1 million km²) of the cropland with yield gaps area experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 20% of this area (1.67 million km²).
- Approximately 26% (4.47 million km²) of the cropland with yield gaps area experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 11% of this area (0.48 million km²).
- Around 2% have no GCIs.
- In 15% of the area with yield gaps, there is a decrease of land productivity that typically coincides with numerous GCIs, such as low input agriculture (28% of the area), and low income (52%).
- Where yield gaps coincide with irrigation, water stress (35% of the area), high input agriculture (27%) and land productivity increase there is the potential for degradation of water resources, as e.g. in northeast China.

Yield gaps exist in about 45% of all cropland area and are more pronounced in low income countries.
Convergence of Evidence: Cropland with Yield Gaps

Cropland with yield gaps are areas where >10% of each grid cell (1 km²) has yields less than the median values for 17 major crops. The World Atlas of Desertification identifies these areas globally, with a focus on South America, North America, and the world as a whole. The atlas highlights the extent of areas with >10% cropland and below median yield attainment, showing early signs of decline and stable, but stressed conditions. The data is presented in maps and graphs, detailing areas with low-input and high-input agriculture, along with various drivers of desertification such as population change, water stress, and aridity. The atlas also notes the coincidence of various global classification indicators (GCIs) across different regions, emphasizing the convergence of evidence in understanding land degradation and its drivers.
Convergence of Evidence: Rangeland

Rangeland are areas with natural or semi-natural vegetation that provides a habitat suitable for wild or domestic ungulates.

Distributions of predominant issues in NORTH AMERICA

Distributions of predominant issues in WORLD

Distributions of predominant issues in SOUTH AMERICA

Distributions of predominant issues in AFRICA

Distributions of predominant issues in EUROPE

- **Livestock density**
- **Irrigation**
- **High-input agriculture**
- **Low-input agriculture**
- **Income level**
- **Population density**
- **Tree loss**
- **Fires**
- **Climate-vegetation trends**
- **Water stress**
- **Aridity**

Distributions of predominant issues in ASIA

- **Livestock density**
- **Irrigation**
- **High-input agriculture**
- **Low-input agriculture**
- **Income level**
- **Population density**
- **Tree loss**
- **Fires**
- **Climate-vegetation trends**
- **Water stress**
- **Aridity**

Distributions of predominant issues in OCEANIA

- **Livestock density**
- **Irrigation**
- **High-input agriculture**
- **Low-input agriculture**
- **Income level**
- **Population density**
- **Tree loss**
- **Fires**
- **Climate-vegetation trends**
- **Water stress**
- **Aridity**

See next page for explanatory text.
Examples of global regions where rangelands are affected by global change issues (GCIs; see Table, page 145) include:

- Africa: Sahel, southern Somalia, southern Madagascar, South Africa, and Lesotho;
- Asia: scattered areas in Iran, vast areas in Afghanistan, eastern Turkmenistan, central Kyrgyzstan, India (including the Thar Desert), Inner Mongolia (China), and scattered areas in South-East Asia;
- South America: Central Argentina, coastal areas of northern Peru, northeast Brazil;
- North America: Central United States, northern Mexico;
- Oceania: Australia (New South Wales, Queensland).

Global change issues (GCIs) associated with transformations (including land degradation) in rangeland include several socio-economic (high numbers of livestock, human population density, low income) and biophysical (water stress, decreasing land productivity, fire, drought conditions (i.e. climate-vegetation trends GCI, see table) issues.

Analysis shows that in rangelands:

- About 3% (or 0.49 million km²) of the rangeland area experiences potential pressure from 8 to 13 GCIs. Signs of land productivity decline are observed in 60% of this area.
- Approximately 55% (12.3 million km²) of the rangeland area experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 25% of this area.
- Approximately 37% (8.55 million km²) of the rangeland area experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 14% of this area (1.16 million km²).
- Around 5% (1.5 million km²) have no GCIs.

At a continental scale, some patterns with regard to rangeland and global change issues (GCIs) emerge:

- Africa. Rangeland occupies 9.4 M km², of which 79% is in dryland. High population densities are found in 72% of the area, high population growth in 81%, low income in 74%, high livestock density in 52% and high agriculture inputs in 7%. Fire was found in 38% and tree loss in 16%. Decreasing land productivity occurs in 22% of African rangeland.
- Asia. Rangeland occupies 8.7 M km², of which 59% occurs in drylands. High population densities are found in 63% of the area and high population growth in 51%. Low incomes occur in 25% of the area, high agriculture inputs in 12%, and 30% has high water stress.
- South America. Rangeland occupies 3.75 M km², of which 50% is in dryland. High population density was found in 57% of the area, and high population growth occurred in 52%. Land productivity was decreasing or stressed in 35% of the area. High livestock density was found in 80% of the area, 24% of the area was found to have high inputs.
- Europe. Only 1.3 M km² is classified as rangeland. Compared to other continents, there are few coincident GCIs. Population change and high population densities exist in resp. 28% and 57% of the area. Areas of low income cover less than 3%. High livestock density occurred in 62% of the area. High inputs are found in only 12% of the area.

- North America. Rangeland occupies 6.3 M km², of which 66% is in drylands. High water stress was found in 37% of the area, high population densities in 10%, high population growth in 19%, low incomes in 3%, and high livestock densities in 40%.
- Oceania. Rangeland occupies 483 K km², of which 86% is in drylands. High population growth was experienced in 34% of the area, and only 2.5% had high population density. There were essentially no low-income areas. High livestock densities were found in 21% of the area.

Consistent biomass reduction occurs over 15% of global rangeland. Where this coincides with other global change issues, additional pressures building up can trigger land degradation.

- Total global rangeland area is 29 million km², of which 63% is found in drylands.
- High population density and high population growth occur in about 50% of the area, and income is low in 33%.
- High livestock density is found in 53% and fires on 16% of the area.
- Decreasing land productivity occurs in about 18.5% or about a fifth of global rangeland (14% of which is in drylands).

Shrub encroachment in grasslands – which may result in a change in land productivity – is considered land degradation in some regions of the world. Local contextual information is needed to make such a determination.

- Theme layer derived from FAO GLC-Share v1.0**, 2014 and Robinson T., Livestock distribution** 2008.
- This map has grid cells of 1 km².
- Statistics – in total area (km²) or percentage of total area – are given for both global and/or continental scales.
- Refer to global change issues (GCIs) in the table on page 145.
- Refer to ‘how to read the maps’ on page 146.
Examples of global regions where forest occurs that are affected by global change issues (GCIs; see Table, page 145) include:

- **Africa**: coastal rainforest in Sierra Leone, Liberia, Ivory Coast and Ghana as well as the northern and southern fringes of the central African, with relatively large areas in the Democratic Republic of the Congo;
- **Asia**: Boreal regions; Himalayas, Thailand, Laos, Vietnam, Philippines, Papua New Guinea
- **South America**: western and eastern fringes of Amazon rainforest; Coastal areas in Brazil and Chaco region in Bolivia and Argentina;
- **Europe**: Boreal regions; and
- **North America**: United States, Mexico (Yucatan, around Acapulco and the Sinaloa and Sonoran coastal areas), Guatemala, Honduras, Nicaragua and the Dominican Republic.

Global changes (GCIs) associated with transformations (including land degradation) in forest include population density, population change, low income and high livestock numbers. Tree loss is a main issue (36% of the area) while declining land productivity (12% of the area) are relatively frequent GCIs.

Forest occurs predominantly in non-drylands. Dryland forest is about 10% of the total area. New data suggest this to be underestimated (see page 37) but could not be integrated here.

Analysis shows that in forest:

- Less than 1% (or 0.19 million km$^2$) of forest experiences potential pressure from 8 to 13 GCIs. Land productivity decline is observed in 62% of this area (0.12 million km$^2$).
- Approximately 43% (15.7 million km$^2$) of forest experiences potential pressure from 4 to 7 GCIs. Land productivity decline is observed in 21% of this area (3.2 million km$^2$).
- Approximately 50% (18.3 million km$^2$) of forest experiences potential pressure from 1-3 GCIs. Land productivity decline is observed in 10% of this area (1.9 million km$^2$).
- Around 7% (2.6 million km$^2$) have no GCIs. These forested regions are mostly in the northern boreal zone and Amazon tropics.

At a continental scale, some patterns with regard to forest cover and global change issues (GCIs) emerge:

- **Africa**: Low per capita income, high population density and population changes are socio-economic GCIs that all occur in about 90% of African forest. Forest loss (38% of the area) and fire (25%) are the main biophysical GCIs. Fires are very common in Central African Republic, southern Democratic Republic of the Congo, Zambia and Tanzania.
- **Asia**: The extent of forest (nearly 11 million km$^2$) in Asia is the highest of all continents. Forest includes the vast boreal zone where few GCIs coincide. Tree loss (30% of the area), low income (45%) and population density (65%) are all coinciding GCIs in the Himalayas, Laos, Vietnam, northern Thailand, Myanmar and southern China. A GCI combination of forest loss, livestock densities and low income occurs in the Philippines (Luzon and Mindanao), Indonesia (Kalimantan and Java) and Papua New Guinea.

- **South America**: The Gran Chaco area in Bolivia and Argentina (see Argentina case study, page 198), where there are intense land use changes occurring, stands out as a region where a high number of GCIs coincide (as compared to the global average). The key GCIs include forest loss, decreasing land productivity, population densities and livestock densities.
- **Europe**: Forest are mixed with other land uses. Nearly 90% of European forests have < 4 coinciding GCIs, including population densities, livestock densities and low input agriculture. Only 2% of the area is subject to a decrease of land productivity.
- **North America**: GCIs include tree loss, increasing population, increasing livestock densities, and low agriculture inputs. Forest in the southeast United States experience water stress and drought conditions.
- **Oceania**: GCIs on Vanuatu and Fiji include high population and livestock densities and low agricultural inputs, while on the Solomon Islands forest loss and water stress occur.

Tree loss occurs in about 36% of global forested regions.

- Themes layer derived from GFC v1.2 Hansen M.\textsuperscript{e9} 2013 (see page 36).
- This map has grid cells of 1 km$^2$.
- Statistics – in total area (km$^2$) or percentage of total area – are given for both global and/or continental scales.
- Refer to global change issues (GCIs) in the table on page 145.
- Refer to ‘how to read the maps’ on page 146.

Low input - nitrogen deficient - cultivation is a concerning global change issue in 33% of the global forest area.
Convergence of Evidence: Forests

Forests are areas where more than 40% of each grid cell (1 km²) is covered with trees.

Distributions of predominant issues in NORTH AMERICA

Distributions of predominant issues in WORLD

Distributions of predominant issues in SOUTH AMERICA

Distributions of predominant issues in AFRICA
Convergence of Evidence: Protected Areas

Protected areas are those mapped by the World Database on Protected Areas (2018)
Convergence of Evidence: Protected Areas

PART V – CONVERGENCE OF EVIDENCE

Distributions of predominant issues in EUROPE

Distributions of predominant issues in ASIA

Distributions of predominant issues in OCEANIA

See next page for explanatory text.
Examples of global regions where protected areas are affected by global change issues (GCIs; see Table, page 137) include:

- **Africa**: Senegal, Ivory Coast, Ghana, Nigeria, Chad, Kenya, Zambia, Zimbabwe;
- **Asia**: Pakistan;
- **South America**: North east Brazil;
- **North America**: Mexico.

Globally, 20 million km² are designated as protected areas (UN Environment-World Conservation Monitoring Centre). The map depicts 17.3 million km² of protected areas (based on the 2018 update of the World Database on Protected Areas – WDPA), which excludes polar regions and smaller areas.

Global change issues (GCIs) associated with transformations (including land degradation) in protected areas are mainly socio-economic ones, such as population densities (50% of the area), low income (45% of the area), high livestock densities (35%) and low input agriculture (25%); less frequently occurring (all in about 15% of the area) are biophysical GCIs, e.g. decreasing land productivity dynamics, fire and tree loss.

Analysis shows that in protected areas:

- About 1% (or 0.18 million km²) of the protected areas experiences potential pressure from 8 to 13 GCIs. Signs of land productivity decline are observed in 49% of this area (0.85 million km²).
- Approximately 36% (6.2 million km²) of the protected areas experiences potential pressure from 4 to 7 GCIs. Signs of land productivity decline are observed in 24% of this area (1.5 million km²).
- Approximately 58% (10 million km²) of the protected areas experiences potential pressure from 1-3 GCIs. Signs of land productivity decline are observed in 15% of this area (1.5 million km²).
- Around 5% (0.9 million km²) have no GCIs.

At a continental scale, some patterns with regard to protected areas and global change issues (GCIs) emerge:

- **Africa**: Protected areas are present in about 17% of the continental land area, of which 70% occur in drylands. All have noticeably more coinciding GCIs than in other continents. Population densities (75% of the area), low income (60%), low input agriculture (35%) and fire (60%) are the main GCIs. Decreasing land productivity and tree loss occur in around 15% of the area. Further analyses (not included on this map) indicate that various issues, associated with land degradation, are increasing around the outer peripheries of protected areas (http://dopa.jrc.ec.europa.eu/en).
- **Asia**: Protected areas in the Boreal region have less coinciding GCIs (population and livestock densities) than in south Asia. In central Asia, China and southern Asia, population and livestock densities, low input agriculture, water stress and tree loss are main GCIs in protected areas.
- **South America**: Few GCIs occur in the Amazonian protected areas. Other areas on the continent have GCIs, including livestock density and decreasing land productivity (10% of the area).
- **Europe**: Nearly 19% of the European land area contain protected areas (WDPA). The majority are rather small size, often ‘embedded’ in populated anthromes of the continent. Important GCIs include population densities and livestock densities (both about 50% of the area), low input agriculture (38%) and tree loss (25%). Built-up change occurs in 10% of the protected areas. In central Europe, 3-5 issues are common, while in northern Europe less than 3 issues are usually observed.
- **North America**: The main GCIs in Central American protected areas include livestock densities, low input agriculture and decreasing land productivity.
- **Oceania**: Nearly 80% of protected areas are in drylands. In Australia, aridity, Fire and decreasing land productivity are common GCIs. In New Zealand (specifically, the northern coast on the South Island) forest loss, population changes and decreasing land productivity occur.

Protected areas in Africa are more under pressure from coinciding biophysical and socio-economic global change issues than anywhere else.
Convergence of evidence: Zimbabwe

A number of factors that may lead to land degradation are found in the southern African region, but it is in Zimbabwe where these appear to converge. Zimbabwe shares a similar climate and the same climate and vegetation anomalies as its neighbours. It is positioned between the arid Botswana to the east, a relatively arid South Africa to the south and moister Mozambique and Zambia to the north and west. It shares the poverty and population growth problems of its northern and eastern neighbours. It has high livestock densities, similar to Zambia and parts of South Africa and Botswana. High deforestation is driven by agricultural land expansion and harvesting of fuelwood for both tobacco curing and domestic use. This deforestation problem is shared with its northern and eastern neighbours, though the drivers might differ. Though there is high fertiliser use, this is mostly linked to the production of commercial crops such as tobacco, with staple food crops showing a high yield gap and seldom meeting national demand. Land tenure and poverty has resulted in a high proportion of land being opened for cropping and this, combined with the convergence of global change processes, results in Zimbabwe standing out in the region as a country with a high probability of land degradation. This is confirmed by an extensive literature highlighting degradation problems in Zimbabwe that date far back into its colonial past, and were often associated with its regions of communal tenure. Prince et al. (2009) pointed out that degradation in Zimbabwe is observable from continental satellite imagery.

Convergence of evidence: southern Russia

Vast stretches of land developed under Soviet Rule (1917-1991) were abandoned after the breakup of the Soviet Union in the 1990s: Thirty-one million hectares in European Russia, Ukraine and Belarus. Kazakhstan was more affected still, losing more than half of its croplands, almost 20 Mha. Governments and farms have not, however, reverted to the Soviet praxis of extensive development in rain-fed steppe regions of the former SU has retain many of its extensive features: very large farms, low fertiliser usage, low yields, high percentage of fallow lands in crop rotations, low population density and lack of transportation infrastructure. These factors contribute to explain the apparently limited environmental impact of steppe farming. Re-cultivation seems to have occurred until now at low environmental costs.

Notwithstanding privatisation and the tremendous changes in land use and state policy, grain agriculture in rain-fed steppe regions of the former SU has retain many of its extensive features: very large farms, low fertiliser usage, low yields, high percentage of fallow lands in crop rotations, low population density and lack of transportation infrastructure. These factors contribute to explain the apparently limited environmental impact of steppe farming. Re-cultivation seems to have occurred until now at low environmental costs.

Number of coincident issues

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Underlying Concepts of Land Degradation

Case studies on land degradation processes

Even when there are similar causal agents, manifestations of land degradation at the local scale is a function of local biophysical and socio-economic factors. Nevertheless, at a very broad scale, the ‘syndrome’ approach has been used to model and describe bundles of interactive processes and symptoms of land degradation that appear repeatedly and in many places in typical combinations and patterns. A syndrome of land change thus constitutes the particular combination of specific causal conditions, involving both approximate and underlying factors, and rates of change, i.e., slow and fast causative variables. This implies that, for any given human-environment system, a limited number of causes are essential to predict the general trend in land use.

Five syndromes have been linked to dryland/land degradation processes: the Sahel, Overexploitation, Rural Exodus, Dust Bowl, and Aral Sea. Syndrome analysis relies on a specific semi-qualitative modelling methodology, which brings together elements from complex systems theory, fuzzy logic and expert-judgement evaluations to design maps of the global extension of these syndromes. Similarly, more than 30 high-resolution datasets on land-use intensity, environmental conditions and socio-economic indicators have been used to identify and map twelve archetypes of land systems.

Convergence of Evidence

The “convergence of evidence” mapping in this atlas (see page 144) builds on the same principles. The global change issues (GCI) address the intricate linkage of natural factors (the biophysical GCI) and human action (socio-economic GCI) needed to understand land degradation dynamics. Without being based on modelled prior assumptions, it thus illustrates how and where important GCI currently coincide and exert pressure on land resources, which may in fact lead to land degradation. However, definite conclusions about actual states and processes require contextual knowledge and additional information on local or regional scales.

Hence, global maps describe the disposition of a region towards specific syndromes or archetypes, or they provide suggestions rather than diagnostic conclusions. Only a few studies have demonstrated how conceptual models may be used to produce geographically-explicit assessments of land condition on regional scale.

Trade-Offs in Land Use Change

While there is agreement that land degradation is intrinsically linked to land use practices, the approaches how to adequately measure and evaluate their impact on ecosystem level are diverse. The concept of ecosystem goods and services, first used in the late 1960s, was of central importance to the Millennium Ecosystem Assessment and its treatment of desertification and land degradation. Goods and services consist of flows of materials, energy, and information from natural capital stocks, which combine with manufactured and human capital services to produce human welfare, while ecosystem functions refer to the...
habitat, biological or system properties or processes. Land use practices have not only affected global and regional climate due to the emission of relevant greenhouse gases, but also by altering energy fluxes and water balance. Hence, land use and land change directly impact ecosystem services. Land use and land change and their associated alterations of habitat structure -- as well as release of substances like fertilisers, pesticides, and air pollutants -- impact ecosystems goods and services, amongst them biodiversity, substance flows, water and air quality, soil properties and disease vectors, and ultimately human well-being.

Management decisions always involve trade-offs among ecosystem services, which must be balanced with respect to societal objectives, i.e. to reduce negative environmental impacts of land use while maintaining economic and social benefits. Although quantifying the levels and values of these services has proven difficult, a scientifically based assessment of these trade-offs is an essential prerequisite for decision-making.

Ecosystem stewardship has been proposed as an action-oriented framework to foster the social-ecological sustainability under rapidly changing conditions. Three strategies underlying ecosystem stewardship are: (i) reducing the magnitude of, and exposure and sensitivity to, known stresses; (ii) focusing on proactive policies that shape change; and (iii) avoiding or escaping unsustainable social-ecological traps. All social-ecological systems are vulnerable to change but have the ability to adapt and are resilient, all of which can sustain ecosystem services and human well-being via ecosystem stewardship. Convergence of evidence mapping of GCIs is solution oriented as it provides information on coinciding land stress factors that should be addressed to alleviate stress.

Earth Observation from Space

In conceptualising key aspects of land degradation and desertification as pathological processes of multi-annual land-cover dynamics it is almost mandatory to consider time spans on the scale of decades and to discern changes on the long run from the impact of short-term fluctuations driven by seasonal pulses or single events. Precise and unbiased information on drivers of land degradation, the extent of affected areas and their characteristics over extended periods of time, are important local aspects that are needed for designing mitigation strategies and for monitoring the efficiency of their implementation. However, access to relevant and continuous data is difficult and often limited. The availability of pertinent Earth observation (EO) data, collected since the 1970s by a multitude of satellite missions, has become increasingly important in compensating for such information gaps. Some of the available satellite data archives cover time spans of more than 30 years and provide open access. Importantly, several of the most relevant satellite missions are already projected into the next decades (e.g. the EU Copernicus EO programme), such that continuity of high-quality Earth observation data is assured. This continuity is an important prerequisite for tracing the high inter-annual variability of ecosystems and for distinguishing between the role of human actions and climate variability.

The reliability of EO derived indicators for changing land surface properties relevant to land degradation processes can be substantially improved when integrating remote sensing, ground-based observation and supportive geospatial data. Inferring type and magnitude of changes in conditions on the ground exclusively from the analysis of satellite datasets might be difficult, as it has been shown with respect to the observed “greening” of the Sahel region of Africa since 1990.

Selected Cases

The case studies presented here demonstrate that human interaction and inadequate management of scarce resources especially in drylands are central components of the land degradation problem. Furthermore, they provide guidance into how best to harness the competence of humans to successfully mitigate the consequences and design pathways towards a more sustainable future.
Case study: Monitoring population pressure in low resilience areas

The Sahel, Africa - a complex human-environment system

**Background**

In the past 50 years, anthropogenic influence and climatic variability have caused major environmental changes in the semi-arid Sahelian zone, and the desertification/degradation of arable lands has been of major concern for livelihoods and food security. In the wake of the major droughts in the early 1970s and 1980s, there was a significant increase in scientific efforts to provide an empirically supported understanding of both the climatic and anthropogenic factors involved.

Over decades of intensive research on human-environmental systems in the Sahel, there is no overall consensus about the severity of land degradation. A range of conflicting observations and interpretations of the environmental conditions in the region and the direction of changes can be found in the literature.

**Drivers of change**

The example from Burkina Faso, shown below, illustrates the main drivers of environmental change. The most important drivers are population growth and land tenure. The most common global change issues (see page 190) over the whole of the Sahel, shown at the bottom of the page, are indeed population change and low income levels.

Examples of causal relationships are displayed using connecting arrows. The interrelationship between drivers and their implications are complex, and all impacts of these drivers have feedbacks on the drivers themselves. Each of the drivers could be considered an opportunity for land restoration and livelihood improvement.

**Characterising changes over recent decades**

Analyzes of Earth-observation (EO) data over the Sahel area show positive trends in rainfall and in vegetation greenness (obtained by using Normalized Difference Vegetation Index (NDVI) time series) over recent decades. This phenomenon occurs over the majority of the Sahel region and is known as the ‘regreening’ of the Sahel — see top map on the next page. This has been interpreted as an increase in vegetation productivity and contradicts prevailing narratives of a vicious cycle of widespread degradation caused by human overuse as a function of a rapidly increasing population and climate change. The regreening is widely accepted to be driven by an increase in rainfall. However, areas of decreasing NDVI, for example in Niger and Sudan, indicate that the regreening is not uniform across the entire Sahel.

Whereas the increase in NDVI, as observed from EO data, can be confirmed by ground observations of vegetation productivity, long-term assessments of biodiversity at finer spatial scales highlight a negative trend in species diversity. New research also suggests that a considerable part of the observed greening in areas of low population density stems from an increase in woody vegetation rather than the herbaceous vegetation that traditionally supports livestock foraging. Overall it remains unclear whether the observed positive NDVI trends are associated with environmental improvements with positive effects on people’s livelihoods.

**Convergence of evidence**

Throughout the Sahel region smallholder cropland is prevalent and cultivation is mostly done on fields smaller than 2 ha.

Maps on the following pages show the coincident global change issues (GCIs) in the Sahel region and the graphs show the occurrence of GCIs within the smallholder cropland (see page 144 and after).

Over the larger part of the smallholder cropland (82%), all in dryland, five to seven GCIs coincide. All these smallholder communities are characterised by low per capita income. In 50% of this area, population change is high as are population densities. Being mostly small subsistence based farms, livestock densities are also high in 70% of the area. 30% of this smallholder cropland is nutrient deficient and only 5% is irrigated. Drought conditions have impacted on 20% of the area, and land productivity has seen a persistent decline in 18% of the area. This is probably lower than expected, but is still slightly higher than the average of 14% of global cropland (see pages 148 and 152). Places where six or seven GCIs coincide and a decline in land productivity is observed may be of concern.

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**Table:**

<table>
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<th>Number of variables</th>
<th>% of Sahel area with &gt;10 % cropland and below median field size (0.705 million km²)</th>
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</tbody>
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**Graph:**

- **Woody cover change 2000-2014**
- **Sparingly populated**
- **Densely populated**

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**Footnotes:**

1. Source: Daniel Tiveau/CIFOR. Flickr.com
2. Landscape of Sahel
3. Source: derived from Ouedraogo, I. et al., 2015
5. Drivers of land change in Cassou, Southern Burkina Faso.
6. Source: derived from Ouedraogo, I. et al., 2015
7. Landscape of Sahel
8. Source: Ouedraogo, I. et al., 2015
9. Source: Ouedraogo, I. et al., 2015
10. Source: Ouedraogo, I. et al., 2015
11. Source: Ouedraogo, I. et al., 2015
12. Source: Ouedraogo, I. et al., 2015
13. Source: Ouedraogo, I. et al., 2015
15. Source: Ouedraogo, I. et al., 2015
16. Source: Ouedraogo, I. et al., 2015
17. Source: Ouedraogo, I. et al., 2015
18. Source: Ouedraogo, I. et al., 2015
19. Source: Ouedraogo, I. et al., 2015
20. Source: Ouedraogo, I. et al., 2015
21. Source: Ouedraogo, I. et al., 2015
22. Source: Ouedraogo, I. et al., 2015
23. Source: Ouedraogo, I. et al., 2015
24. Source: Ouedraogo, I. et al., 2015
PART V – CONVERGENCE OF EVIDENCE

**Trend in Sahelian vegetation 1981-2014 (wet season NDVI per year)**

**Population change 1990-2000 (people per km²)**

**Woody cover change 2000-2014 (% woody cover)**

**Convergence of global-change issues**

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**Loss in biodiversity**

Local population perception suggests a general loss in woody species diversity in Mali.
Human- and climate-induced desertification in the Sahel has been a major concern during recent decades. Conflicting findings are found in the literature as regards whether or not desertification has been a general feature of the Sahel. Partly, this relates to differences and inconsistencies in the definition of concepts and to disciplinary, strategic, methodological and sampling differences. It is therefore of great importance to monitor land dynamics in a transparent way by combining long-term information from EO data of different levels of spatial detail with ground observations. Currently, EO time series show a positive trend in vegetation greenness across the Sahel without indications of widespread desertification. However, an improved understanding of the changes in ecosystem composition and functioning behind this greening is needed. Recent studies suggest that the trend can at least partially be attributed to the expansion of agricultural areas, a considerable proportion of which is irrigated. How much of the increasing productivity is sustainable, or will be absorbed by rapid population growth, is difficult to decide. However, it is clear that the pressure on available land, but also on protected areas will continue to increase. Currently, the relationships between changes in ecosystem services (including livestock forage, fuelwood and biodiversity) and livelihoods/land use remain unclear in the Sahel, making conclusions on the environmental and societal benefit premature.

**Changes in vegetation composition**

**Drought-induced tree and shrub dying**
Several years of low rainfall have caused a recent mass dying of shrubs in Senegal.

**Spreading of robust species**
*Balanites aegyptiaca* and *Combretum glutinosum* spread in the sparsely populated rangelands of Senegal.

**Agroforestry**
The increasing amount of woody cover in agricultural fields in northern Nigeria reflects the protective management of parkland trees by farmers.

**Importance of spatial scale in land degradation monitoring**
Comparison of trend analysis results derived from medium resolution (250 m left) and low resolution (8 km right) products in northern Burkina Faso. The 25 m resolution product reveals that land degradation was limited to plateau areas (in red), whereas valley areas show improved conditions (in blue), thereby providing additional insights into mechanisms and drivers of change.
The mapping and understanding of environmental change is a difficult endeavour in the highly complex human-environment system of the Sahel. More than any place else in the world, local drivers of changes (e.g. shifting cultivation, fires, soil erosion, misuse of natural resources) are superimposed upon global drivers (e.g. climate change, drought), which in turn may lead to gradual and/or abrupt change in ecosystem functioning. All these result, when looking at the entire Sahel, in a patchwork of diverse change scenarios.

A map of ecosystem-change types that highlights the possible occurrence of an abrupt change in ecosystem functioning (method based on 7) shows categories of change in the functioning of the Sahel’s ecosystem. The map shows changes and abrupt shifts in ecosystem functioning using rain-use efficiency (RUE, i.e. the ratio between the above ground biomass and total rainfall). The map captures a number of details regarding the environmental changes that have occurred over the period from 1981 to 2011, ranging from monotonic change (positive or negative) over interrupted trends (two periods of similar trends separated by an abrupt shift) to reverse trends in ecosystem functioning (two periods of distinct different trends separated by an abrupt shift).

The diverse nature of the changes in the Sahelian ecosystems is illustrated by photo pairs, high-resolution satellite images, interview results and a drought diagram. The approximate location of the illustrated cases is reported on the Sahel scale change map.

**Land degradation**

Livestock caused soil degradation in Senegal’s pastoral zone

1994

Livestock caused soil degradation in Senegal’s pastoral zone

2015

Land and soil degradation

Extensive removal of trees in Mali’s rangelands, causing soil erosion (Case A). Whereas trees in farmer’s fields are protected (Case B), the surrounding rangeland is highly degraded, and dense tiger bush from 1967 is transformed into stony desert in 20119.

**History of drought**

There has been an alleviation of the drought constraint in Sudan since the 1980s and early 1990s. However, recurrent droughts remain a threat for the environment and the population, notably due to the unstable political situation11.

Overuse of woody resources leads to soil degradation

Jan 2003

Oct 2012

**Source:** Tappan, G. and Brandt, M. 2017.
Designing and implementing sustainable land-management strategies is intrinsically tied to the availability of objective, repeatable and spatially distributed information on the state of ecosystems. The development of assessment strategies is also in the interest of the United Nations Convention to Combat Desertification and its stakeholders. The related sustainable development goal Target 15.3 to achieve land degradation neutrality by 2030 requires indicator information on the amount of degrading or degraded land expressed as a percentage of the total land area. The 2dRUE approach addresses such requirements in its assessment and monitoring components that produce data on the state and trend of the land. Furthermore, 2dRUE reports on a full scale of land states other than, but related to, degradation.

From the perspective that land degradation implies a loss or reduction of ecosystem functions (i.e. the ability to provide goods and services), the dynamics and interactions of coinciding socioeconomic and biophysical issues need to be understood at all scales. However, the physical condition of the land is a requisite biophysical aspect. Spatially explicit approaches are needed that aim at characterising ecosystem health, for example in relation to changes of net primary productivity. The condition of a piece of land is defined both by its current state and by its associated trend, best addressed by separate assessment and monitoring procedures.

In this sense, ‘land condition’ is an expression of the ecological maturity of ecosystems, which struggle for equilibrium between the opposing forces of human exploitation and ecological self-organisation. Land-change and ecosystem-adaptation processes can include land degradation. Building on this concept, the 2dRUE approach contains separate assessment and monitoring procedures, the results of which are ultimately combined to express the ‘land condition’.

Earth-observation satellites play an important role in assessing vegetation status and changes over time. The characterisation of vegetation productivity alone, however, is rarely enough to produce unbiased assessments on whether an ecosystem is performing at the level of expectation. An option to overcome this conceptual bottleneck is to design assessment frameworks that combine satellite observations of plant productivity with additional spatially explicit data fields. This was the basis of the development of the 2dRUE surveillance approach.

2dRUE diagnostically maps the land condition over large territories for a given time period.

### Aridity Index

The mean UN Food and Agriculture Organisation-UN Environmental Programme aridity index over the analysis period is a by-product of 2dRUE. This index is derived from the ratio of mean annual precipitation to potential evapotranspiration and expresses the portion of atmospheric water demand that is met by precipitation. The United Nations Convention to Combat Desertification considers areas where the aridity index ranges from 0.03 to 0.65 as being susceptible to desertification. The data required to compute the aridity index are part of the climate archive.

### 2dRUE data requirements: raster archives of climate recordings and vegetation properties

The data required for assessment and monitoring concepts such as 2dRUE here include archived time series of satellite observations of vegetation properties and corresponding spatially interpolated climate data. Vegetation indices (derived from the multi-spectral satellite observations) represent an excellent proxy for characterising vegetation in terms of biomass or net primary productivity (the amount of biomass produced per unit of time). The normalised difference vegetation index (NDVI) is a suitable choice because its integral over the course of the year is a proxy for net primary productivity. Archived time series (for example the SPOT Vegetation S10, MODIS/Terra MOD13Q1) are made available through national or international data repositories, but may need to be gridded over a given study area and period based on spatial interpolation algorithms.

### Aridity Index

The monitoring concept aims at estimating the relative performance of each landscape location with respect to its potential optimum conditions. It is thus simultaneously compared to all other locations over the analysis period.

### Assesment

The monitoring concept aims at following the evolution of every landscape location over time, which might be associated with changing climate or its internal ecological dynamics (potentially subject to external forcings such as land-use change).

### Monitoring

The monitoring concept aims at following the evolution of every landscape location over time, which might be associated with changing climate or its internal ecological dynamics (potentially subject to external forcings such as land-use change).
Rain-use efficiency

Land-condition assessment must depend on ecological functions, which change proportionally to prevailing processes of self-organisation or degradation. Rain-use efficiency (RUE) is an efficiency ratio that describes output net primary productivity in relation to input rainfall. Large values represent well-developed soil-plant systems that support vegetation functions over a time span greater than intervals between rainfall events. High RUE also implies that most of the water leaves the ecosystem through evapotranspiration rather than through run-off.

Climate correction of rain-use efficiency

Observed RUE needs adjustments to enable comparisons between all locations across climates. This correction builds on combining the observed RUE for each landscape location with their respective aridity index values (below). The relative performance of a location is then derived from comparing its individual RUE respective aridity index values (below). The relative performance combines the observed RUE for each landscape location with their respective aridity index values (below).

Understanding land states

Both biomass and productivity are expected to decrease as land degradation proceeds, but peak turnover rate (i.e. the ratio of productivity to biomass) is found at intermediate stages of exploitation. The states legend follows such a rationale. First, the long-term RUE-AI scatterplot boundary functions and their confidence intervals are used to detect reference and baseline performances, along with their respective anomalies (bottom left). Second, the range central class is further subdivided according to empirical thresholds of both biomass (long-term RUE) and turnover rate (the ratio of short-term RUE to long-term RUE) to yield a sequence of increasing exploitation intensity: mature, submature, productive with high biomass, productive with low biomass, degraded and very degraded (below).

Monitoring

Monitoring aims to track trends of change. It is a flow-type variable, which complements the state determination made by the assessment component. The rate of change of biomass per year is an accepted indicator of ecosystem change trends, and NDVI is used as a surrogate. In simplified terms, biomass changes can be attributed either to interannual climate oscillations or to intrinsic ecological dynamics. Whilst the former are useful to evaluate climate effects (including climate change), the latter suggest gradual ecosystem changes in terms of land degradation (negative trends) or ecological succession (positive trends).

Several techniques are available to discriminate climate from human effects, most of them involving regression-based statistical analysis. In 2dRUE, a stepwise regression is applied, which uses annual values of mean NDVI as the dependent variable, and time and aridity index as predictors. Because these predictors are intercorrelated, a procedure is implemented such that the second predictor is incorporated to the regression model only if it makes a significant contribution to the determination fixed by the first predictor alone. The result is a robust, albeit conservative estimation, which frames any combination of climate and human effects.

Temporal scales

Two temporal aspects of RUE are implemented in 2dRUE. A long-term performance score builds on using the average annual RUE over a multi-year observation period, it represents a suitable proxy to biomass. The short-term RUE is computed for a specific 6-month period during which the maximum vegetation index (e.g. NDVI) of the time-series is detected; it is considered a suitable proxy for productivity.
Desertification and land uses

Changing conditions within land-use systems are an expression of ecosystem functions and performance, and therefore provide a proxy for land degradation. In the Iberian peninsula, statistical analysis of land-condition trends and changes based on the 2dRUE approach reveals two opposing dynamics.

On the one hand, biomass production in large areas of agriculture remained static or has fluctuated with the climate, but has never increased over time. This could suggest a sustainable exploitation of net primary production in both rainfed and irrigated agricultural systems. However, some agricultural ecosystems exhibit clear signs of active degradation processes, which could drive them towards terminal stages in which exhausted and unproductive systems are ultimately abandoned. What will remain are simplified (degraded) ecosystems with low productivity and poor vegetation cover. Areas of increasing intensification, particularly where marginal lands are under irrigation, appear as prominent hotspots.

On the other hand, in comparison, there are large regions of higher ecosystem maturity that reveal increasing productivity. These regions mostly consist of natural and semi-natural vegetation under ecological succession after phases of economically triggered land abandonment, such as the rural exodus in the middle of the 20th century, or the accession of Spain and Portugal to the European Union.

An important question is whether these dynamics are connected. In the past, usable lands went through alternating cycles of production and fallow. Marginal lands served as an important buffer by being brought into production ‘as needed’ (less so in Portugal, where maintaining overall land condition is a priority). Exploitation and self-organisation were thus sequentially linked in this scenario. Nowadays, increasingly driven by global policies and market mechanisms, the traditional system seems to fail into separate development pathways for agricultural and marginal land, the former being intensified until exhaustion and the latter left to succession beyond practical recovery. The associated risk is that pathways of interconversion become irreversible, therefore risk pressure on degrading ecosystems can no longer be buffered by reactivating reserves in marginal lands.

Validation

Validation of land condition assessments is difficult, owing to the limited availability of ecological functional data (e.g. subsamples or biomass for the climate potential) suitable for describing complex problems such as land degradation. Most of existing assessments of degradation are expert-based, thus largely subjective. They may be useful at the interpretation stage, but not for proper validation where the objective is to accept or reject an assessment product. It is therefore necessary to fall back on spatial data which describe key elements of ecosystems. One option is to compare land indices derived with 2dRUE to the percentage of Total Organic Carbon (TOC), available through the Map of Organic Carbon in Topsoils in Europe [16]. We found that the TOC distributions change proportionally to states of increasing ecosystem maturity. Moreover, the threshold of 2% TOC discriminates states where a change of management or direct out of organic matter seems appropriate.

NORTHERN CONTINENTAL IRRIGATED AGRICULTURE

The northern margin of the semi-arid Ebro basin is characterised by rocks formed by the evaporation of water (evaporites, such as gypsum, anhydrite and halite (common salt)). The development of large irrigation schemes that use surface run-off from the Pyrenees has transformed traditional mixed agriculture into alfalfa-maize crop complexes and stock breeding (sheep and beef). A consequence of the unlimited use of water resources is the mobilisation of salts, which triggers soil salinisation, loss of soil structure and erosion of toxic soils, and salt leaching into the drainage network.

SOUTHERN CONTINENTAL IRRIGATED AGRICULTURE

Traditional agriculture in the south-eastern part of the central Iberian uplands combined olive groves, vineyards and grain crops. Over the past 40 years, this system has evolved to produce forage crops (alfalfa and maize) associated with sheep breeding, together with industrial crops (sunflower) and grapes, most under irrigation with groundwater. However, lower temperatures in the upland areas limit the quality and competitiveness of these crops on the market. Economic gains have thus been moderate, while the over-exploitation of aquifers and subsequent degradation of wetlands pose major environmental problems.

DEHESA AND MONTADO AGROFORESTRY AND STOCKBREEDING

It affects the whole south-west quadrant of Iberia. This land-use system is complex and integrates agroforestry and stock breeding (sheep, beef and pigs). Its survival under current economic trends faces several difficulties. One is the small amount of circulating capital in relation to the fixed one. Landowners are little interested in sustainable management. They usually stock their holdings above carrying capacity by supplying feed from outside. The resulting soil compaction by trampling diminishes infiltration and increases run-off and soil erosion.

OLIVE TREE AGRICULTURE

The central part of the Guadalquivir basin and adjacent rangelands traditionally supported rainfed olive orchards with large, widely spaced trees. These old groves are increasingly replaced by smaller (young) trees, planted at higher densities and supported by drip irrigation, a process driven to a large extent by subsidies and short-term benefits. The encroachment of olive plantations into marginal lands with steep hillslopes increases the risk of soil erosion. In addition, shallow-rooted trees keep the soil under tree canopies almost permanently at field capacity. The consequences of this transformation process are not yet fully understood.

Case study: Land condition surveillance using geospatial data (cont’d)

2dRUE approach over Iberia and north-west Africa (cont’d)
Desertification trends in the Maghreb

The north-western Maghreb covers north-west Africa between the Mediterranean Sea and the Sahara Desert (Morocco, Algeria and Tunisia). The region has experienced major land-use changes since gaining political independence around 1960, and is now undergoing dynamic economic changes. Traditional knowledge, combined with new land-use opportunities, underlies current, specific drivers of land degradation: the movement of population to urban areas of emerging economic activity comes at the expense of the abandonment of rural areas, the extension of arable land into forested areas, soil salinisation and overgrazing. Climate conditions are often harsh, including extreme droughts and rainfall events, and associated floods. New agricultural developments include drilling boreholes, ploughing hillsides and building roads for moving livestock, all of which aim to increase local production in the short-term at the expense of long-term land sustainability.

Land-degradation states

The results of the 2dRUE-based land-condition assessment for the period from 1998 to 2008 demonstrate that moderate land conditions (productive with either low or high biomass) prevail and account for 454 880 km² (41 % of the drylands domain). Good conditions (submature and mature) follow with 331 232 km² (30%), while poor conditions (degraded and very degraded) were less common, with 228 070 km² (21%). In general, better condition states appear to be more common than poorer ones, which is also true for the references: reference performance, representing optimum vegetation cover (in terms of RUE), occupies 37 896 km² (3.45%), whilst baseline performance (which relates to vegetation limited by soil conditions, such as saline areas or rocky outcrops) extends over only 9 130 km² (0.83%).

Land-degradation trends

The area of land undergoing active degradation (degrading trend) is only 0.7% of the total. In contrast, much more land (24.1%) is found to be increasing in productivity. Land where productivity is fluctuating only in correspondence to interannual climate oscillations extends over 10.8% of the territory. Finally, there is a vast proportion of static land (64.4%) that shows no trend at all.

Panorama from the hills south of Marrakesh, Morocco.
Source: Del Barrio, G.

Marabout* burial site
Sepulchre sites have been respected through the history of the Maghreb; nowadays they serve as permanent reminders of the original landscape. Here, an isolated juniper (*Juniperus oxycedrus*) with exposed roots shows the extent of recent landscape transformation and soil loss in the Plateau of Rekkham, Northern Morocco.

* "a Muslim holy man or hermit, especially in North Africa" (OED Online. Oxford University Press, March 2018. Web. 23 April 2018)

Source: Del Barrio, G. (based on Del Barrio, G. et al., 2010) (AP).
Horqin sandy lands, Inner Mongolia, China

The unprecedented combination of population growth and economic development in China has caused a range of land-transformation processes across the nation. The Horqin sandy lands (map on the right) is located in the agro-pastoral zone between the Inner Mongolian Plateau and the Northeast Plains in China (42°41’ – 45°45’ N, 118°35’ – 123°30’ E). The Horqin Sandy Lands is one of the extended sand areas in northern China and includes a significant part of the Inner Mongolian grasslands. The vegetation consists predominantly of shrubs and perennial grasses; trees occur only in protected patches where water conditions are favourable. Winds from the north-west blow on average 230 days per year and may exceed force 8 on the Beaufort Scale (a speed of 17 ms⁻¹) for more than 40 days; the region is thus an important source for sandstorms occurring in northern China, especially in the Beijing–Tianjin–Tangshan Region. Climatically, the region is part of the continental drylands, with hot and short summers and very cold winters. The mean annual temperature minima and maxima range from –8.8 °C in January to 30.4 °C in July; the mean annual precipitation is 375 mm, with nearly 80% concentrated in the months from June to September. However, an important characteristic is rainfall irregularity: annual precipitation, for example, varied from 205 to 679 mm per year in the 2000-2008 period. These physiographic characteristics, including easily erodible loess soils and mobile sand dunes, render the area sensitive to pronounced land-degradation processes. Recent climate-change studies have identified trends of warmer and drier conditions in Inner Mongolia.¹

The Horqin Sandy Lands is a typical example of the sand-dominated ecosystems in Inner Mongolia, which supported a traditional and sustainable nomadic production system: extensive areas of sandy dunes and plains covered by drought-resistant shrubs and grass species provided top-quality pasture for sheep grazing. Still today, isolated forest patches provide additional evidence of a performant ecosystem in the forest-steppe transition zone with high capacities for regulating and supporting ecosystem services, such as carbon sequestration, air-quality regulation (suppression of dust movements through dune stabilisation) and the preservation of habitats and biodiversity. The widespread sandy soils with exceptionally high infiltration rates are the prime reason for the development of abundant groundwater reserves, sometimes accessible within only a few meters below ground.²

Traditionally home to Mongolian nomads, the Horqin Sandy Lands became increasingly influenced by Chinese culture. From the 1920s onwards Chinese immigrants started to migrate towards the northern regions and brought with them a cultural tradition that is rooted in farming, a practice further promoted by the socialist regime after 1949, when pastoralists were forced to give up their nomadic way of life and to settle in small villages, hamlets or individual farms.

In recent decades, three peaks of land reclamation from grassland to cropland occurred in 1955-1956, 1958-1962 and 1971-1973 under new policies such as ‘giving prominence to food production’. In particular, the Great Leap Forward policy in 1958-1962, including the introduction of a long-lasting mandatory process of agricultural collectivisation, aggravated the intensifying pressure on the sandy lands. During the Great Reclamation policy in 1960-1962, large areas of grassland were cultivated in Inner Mongolia. ‘Produce high yields on dune fields’ was a modern slogan in the 1960s.³

In the wake of these policies, the total population in the Horqin Sandy Lands increased from about 950 000 in 1947 to approximately 3.5 million in 1996. Population density increased during this period from 10.4 (1947) to almost 40 people per square kilometre.⁴

The intense and rapid cultivation of extended rangeland areas and the growth in livestock numbers has increased grazing pressure around newly established settlements and brought large-scale pastoral movements between seasonal pastures to an end.⁵ This policy took place at the expense of important ecosystem services, since the continued degradation of the natural grass and shrub vegetation triggered the acceleration of wind erosion, the formation of blowouts and the widespread mobilisation of dunes and laminar sand flows (‘sandification’). Not surprisingly, most of the new fields lost their already-limited productivity and were abandoned after 2 or 3 years of cultivation. Specialists have concluded that the degradation of more than a third of Inner Mongolia has had significant impact on ecosystem services over the last century (e.g. its carbon sequestration), the local economy and the regional climate.⁶⁷

It may have been national policies, such as the reforms during the first period of new policy formulation (1979-1985) and decisions and regulations issued by regional governments, that encouraged new and intensified agricultural land-use practices (increasing mechanisation, use of fertilisers, expansive groundwater-based irrigation). With respect to the links between poverty and the marginal agricultural-production system under environmental pressure, it appeared justified to prioritise agricultural production over environmental health. However, in response to environmental concerns, a large number of restoration and protection measures have been implemented (enclosures of pastureland, grazing regulations, tree-planting campaigns).⁸ Yet the question arises as to whether and how the impact of these political incentives can be objectively assessed on landscape level.
Satellite observations provide valuable surrogates linked to land-use changes, and can reveal conversions and modifications that connect to the condition of ecosystem services. Since 1972 the Landsat series of Earth-observation satellites has been collecting images of the Earth, resulting in the longest continuously acquired collection of space-based terrestrial observations. The spatial resolution ($30 \times 30$ m$^2$) and length of observation of the imagery has made the Landsat archives an invaluable information source for science, management and policy development.

According to satellite-based estimates, claimed to be a magnitude more precise than official statistics, conversion from grasslands to croplands has dominated land transformation in Inner Mongolia.

Earth observation data, such as from Landsat or Sentinel satellites, are in constant use for agricultural management, production forecasting and insurance, for land use and cover change, for forestry, water resource management, study of ecosystem services and functioning, for climate science and climate-change studies, and for studying snow and ice, coastal areas, deserts, geology, soils, urban change and transport, among many other applications.

This map of global-change issues (GCIs, see page 144) clearly reflects the ongoing land-change processes in the Horqin sandy lands. The GCI patterns reveal the case-study area clearly. Mapping the coincidence of global-change issues highlights areas of concern at the global scale. Analysing the patterns at the regional scale aptly shows the areas and dynamics as described in the case study: expansion of cultivation with increase in productivity, spreading of urban areas with high population densities, areas of loss of water resources and pressure on the rangeland expressed in the decline of land productivity. The example here illustrates the relevance of global GCIs across the scales, and the potential and the importance of linking these to local contextual information for the correct interpretation of possible degradation situations. Knowledge of local interactions and the impact of change processes can also cautiously be upscaled to adjacent regional areas. The rectangle is the area as shown on the Landsat imagery at the bottom on the next page.

Source: WAD3 based on GSW (see page 86, 10, GHSL11, GPW v412, LPD (see page 114), Nitrogen balance on landscape13, GMIA v514, Aqueduct 2.115.

Source: Landsat 8.

Source: NASA.

Expanding agriculture creates pressure on the remaining rangelands.

Source: Hill, J.

This map of global-change issues (GCIs, see page 144) clearly reflects the ongoing land-change processes in the Horqin sandy lands. The GCI patterns reveal the case-study area clearly.
Case study: Agriculture expansion calls for trade-offs in ecosystem services (cont’d)

Horqin sandy lands, Inner Mongolia, China (cont’d)

Multispectral satellite imagery, such as the multiannual series of observations by the Landsat or the recent Copernicus Sentinel satellites, can be processed and analysed with mathematical models to identify the spectral contributions of previously specified surface materials. For tracking the environmental changes that occurred after implementing new economic policy, specially designed spectral models produce indicators for important provisioning, supporting and regulating of ecosystem services:

- estimated proportion of photosynthetic Green vegetation (GV) (sensitive to changes in biomass production after agricultural intensification);
- estimated proportion of mobile sand (MS) (sensitive to remobilised and dislocated sandy material, assuming that intensified grazing with excessive stocking rates is a major socio-economic driver behind this process);
- estimated proportion of surface water/wetlands (W) (sensitive to the declining water table, primarily triggered by groundwater extraction, might affect the spatial extension of lakes, ponds, bogs and swamps).

When applied to a long series of observations (in this case Landsat data from 1987 to 2010), the resulting trend maps of physically based estimates of surface conditions provide important information on dynamic changes on the landscape level16.

The linear trend analysis of estimates for MS and GV provides clear evidence for substantial land-cover changes in the study region. When looking at major land-use systems, it can be seen that almost all the complete cropland area (in particular the intensely managed, irrigated areas, such as IA and RA) has increased productivity levels within the observation period (1987-2007). In comparison, most grazing ranges (R1-R3) have experienced substantial productivity losses during this period. Rangelands with interspersed agricultural areas (R/A) exhibit a patchwork of areas with positive and negative changes in GV abundance. The changing presence of water at the land surface is not always a continuous process adequately characterised by linear trends. Lakes, bogs and wetlands tend to shrink and disappear within short periods, and their spatial extension was thus mapped at 5-year observation intervals (1987, 1995, 2001, 2006 and 2010). The extension of lakes, ponds, bogs and swamps within the Landsat coverage has diminished from approximately 62,000 ha (1987) to 22,800 ha in 2010, i.e. a reduction of more than 60% (see graphs at the bottom of this page).

The observed changes in land-surface properties emerge from the consequences of new economic policies in the agricultural sector. Since then, the objective of improving rural livelihoods had been pursued by a combination of incentives aimed at increasing agricultural productivity, combined with enforced regulations.

Increased water pumping for expanding irrigation cultivation in the Horqin sandy lands, China. Source: Hill J.
directed towards protecting rangeland resources at risk. An important issue was to render agricultural production less dependent on climatic risks (e.g. drought), primarily by increasing the proportion of irrigated areas. With the water table sometimes just a few metres below surface, this goal was achieved with simple technologies and moderate investment. The number of power wells in Naiman County, for example, almost continuously increased from approximately 2 000 (1985) to slightly more than 10 000 in 2007 (an increase of +800%).

Additionally, private initiative has been encouraged by modified land leasing concepts and by increased access to investment, agricultural mechanisation and fertilisers. However, the increase in agricultural productivity was followed by an accelerated decline of the water table, where the most rapid change occurred between 1995 and 2001. In addition, one finds additional indicators for increasing environmental risks: the accessibility of groundwater resources also facilitated the expansion of agricultural production into formerly rangeland-dominated ecosystems, along with the reactivation of formerly abandoned agricultural land with marginal productivity. Not only did this increase the exploitation of groundwater resources, but it also caused a reduction of the area available for grazing sheep and cattle. In combination with the legal restrictions in accessing certain parts of rangelands this almost inevitably led to increasing stocking rates on remaining rangelands, where widespread areas with declining productivity prevail.

A synoptic representation of changes in ecosystem services suggests that over the past 20 years the ‘agricultural production’ provisioning service was optimised at the cost of other services, primarily ‘groundwater recharge’ (see circular representation on the right). Cropland has been invading former rangelands, causing a reduction of grazing ranges and increasing stocking rates on remaining rangelands. The ‘dune fixation’ and ‘range production’ ecosystem services are experiencing a notable reduction. Negative impacts include ‘forest production’ trees, traditionally used for cutting firewood, are frequently dying off due to the increasing distance to the water table; the ‘preservation of habitats and biodiversity’ and ‘regional climate and air quality regulation’ (reduced vegetation cover contributes dust storms) have been accelerated. The process which was observed since the 1990s represents a typical example of transforming human-environment systems with limited resource availability into an alternative state that is likely not more sustainable over time. It is representative of large parts of the arid and semi-arid regions in China, such as Inner Mongolia, Gansu and Xinjiang. Driven by the necessity to alleviate poverty in rural communities, innovation and technologies found their way into the agricultural production system. However, the new economic policy, which allowed individuals to profit directly from increased meat or wool production, also fostered the pressure on the land resources and resulted in intensified agricultural land use and large-scale overgrazing.

One of the most important consequences is severe water stress, with increasingly depleted groundwater levels due to the increased irrigation demands. More recent satellite observations confirm that the drying of lakes and ponds has not ceased, while groundwater exploitation and the expansion of high-tech irrigation systems (primarily used for producing alfalfa as fodder crop) into former rangelands is progressing at a speed previously unimaginable.

The background of the recent trends are China’s efforts in securing enough affordable food for a population that is not only growing but also about to change its diet; beef sales to China are rising, and so is the demand for livestock fodder in the country. The semi-arid rangelands in northern China now appear to be land reserves to satisfy the increasing demand. This is, of course, as long as sufficient groundwater resources exist to sustain this type of agricultural production.
The Okavango River system

The Okavango River system in southern Africa is accompanied by diverse and mainly traditional land uses. However, it is an area that is affected by population growth, climate change and the increasing and intensified use of natural resources, and is therefore expected to become a global hot-spot of land-use change. Three neighbouring countries share access to the Okavango system: Angola in the north and Botswana and Namibia in the south. Each of the countries relies on fresh-water provision by the riverine system to different extents and for different purposes. The headwaters of the Okavango River have their source in the central highlands of Angola and can be separated into an eastern (Cuito) and a western (Cubango) catchment. In the western part several tributaries form the Cubango River, which forms the border between Angola and Namibia and, after it is joined by the Cuito River, flows southwards to Botswana as the Okavango River to feed the Okavango Delta. The Okavango Delta is the world’s largest intact inland delta; it is a biodiversity hub of global relevance and provides important services to mankind. The delta and the middle reaches rely on regular, seasonal pulses of fresh water to retain provision of ecosystem functions and services. In these areas, the predominant ecosystem services cover a wide variety, such as fresh-water provision, water purification, crops, fish, wildlife, fuel, timber, fibre and forage.

The Angolan Cubango catchment

In the area of the Cubango catchment, intact forest systems occur along with steadily growing cities, and recently paved roads border and cross the natural woodlands.

The main vegetation unit of the study area is Miombo forest, which is dominated by Brachystegia, Julbernadia and Cryptosepalum species. Miombo forests cover large areas in southern Africa and provide essential products like timber, firewood and charcoal. On the southern African subcontinent the Miombo forests are regarded as one of the tipping points in the Earth system, as summer rainfall and humidity are transported from the Congo rainforest zone via the Miombo belt towards the southern arid savannas. Floral diversity is high, while faunal diversity is relatively low, which may be due to the extensive dry season.

The wet and dry seasons are highly distinct, and the majority of the rainfalls occur during the wet season (November to April). The landscape of the study area is characterised by large floodplains, mainly stretching from north to south, and lateral valleys fragmenting the woodlands that are situated on higher slopes and hilltops. On the floodplains, thick peat layers occur due to the constant interflow from the slopes. Two main paved roads and several minor roads and earth tracks cross the area, connecting the major cities (Menongue, Chitembo and Cuchi) and several smaller villages, as well as agricultural areas.

Dominant land-use and land cover systems of the Okavango basin based on MODIS time series parameters. Source: Stellmes, M. et al., 2013.

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The landscape of the study area is comprised of large areas covered by medium dense to dense Miombo forests, mainly on the hillsides and slopes, grasslands in the valleys and wetlands in the valley bottoms with thick peat layers.

Source: Röder, A., Stellmes, M., Schneibel, A.

Case study: When food security compromises land resources and biodiversity

Quantifying choices for the upper Okavango catchment, Angola

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The Angolan civil war

Rural Angola was severely affected by the civil war, which intermittently lasted for 27 years (1979-2002) and led to the displacement of the rural population and the breakdown of the agricultural sector. After the ceasefire resulted in a fast and extensive expansion of agricultural fields to meet rising food demand. But to this day people rely on ineffective cultivation practices due to a lack of fertilisation and poor agricultural practices. Yet the increase in crop production at the expense of natural resources carries an inherent potential for conflict, since the demand for timber and wood extraction is also expected to rise. The Angolan government spends large amounts on reconstruction and the improvement of infrastructure, along with agricultural development. Nevertheless, this support is slow and insufficient, especially regarding future changes (e.g. climate change, population growth, foreign investments in large-scale agricultural projects). Policies will be challenged to find adaptive pathways to protect natural areas while supporting the provision of sufficient food for a growing population.

Land use in rural Angola

Traditional smallholder agriculture in the region is largely based on a shifting cultivation system with slash-and-burn techniques for field clearing and, after a period of cultivation, long-term fallows of several decades for the regenerations of soil fertility. The main crop in the study area is maize, in addition to secondary crops like beans and manioc and a variety of tertiary crops, mainly vegetables and tubers. Every 5 to 10 years (depending on soil fertility), these areas are abandoned and the household moves deeper into the forest to clear a new patch of forest for the establishment of its next cultivation area. In contrast, in areas where land pressure is increasing, it appears that semi-permanent and permanent forms of smallholder agriculture are becoming or will become increasingly important.

With limited access to markets, and thus mainly relying on subsistence agriculture, the rural population in Angola is heavily dependent on natural resources, which can also provide additional household income (e.g. honey, charcoal or bushmeat). Currently, the rural population adopts a ‘modern’, consumption-driven lifestyle that leads to rising aspirations for cash income. This in turn results in rising levels of charcoal production, which is the best available cash income source for many rural households. However, this leads to deforestation and thus the erosion of the traditional livelihood base. The predominant slash-and-burn agriculture, honey and charcoal production already put a high pressure on natural resources in the study area and challenge land-use sustainability.

Upstream–downstream perspectives

Besides the national perspective, the very nature of this system poses potential conflicts, because any development in upstream Angola may negatively affect downstream neighbours and economic sectors. This includes deforestation for smallholder agriculture or the creation of dams for energy provision, which are expected to disrupt the flood pulse cycle. The increased usage of fertilisers and pesticides is also expected to negatively affect water quality.

Roads are spatial drivers of deforestation

Deforestation patterns are clearly connected to the proximity of settlements and the abundance and quality of roads. Almost half of the new fields were established closer than 1 km to existing roads (46%). More than 70% lie within a 2 km radius and more than 90% are within a distance of 5 km. This indicates that new fields are mainly established within a short walking distance of roads and tracks. Fields are more likely to be established along tar roads than earth roads. These patterns can be explained by better connectivity of agricultural areas and markets and the correction of fields to larger settlements, which are mainly located along tar roads.
Historical legacy in agricultural dynamics

The rate of deforestation in the Cubango catchment has been dynamic and has reflected the relative intensity of historic conflicts. Deforestation for the establishment of fields decreased by more than 70% to 4,000 ha during the active conflict period (1994-1998) and subsequently tripled to 12,000 ha per year after the ceasefire in 2002. The rate of deforestation currently remains at a high level of around 10,000 ha/year. Since under rising land pressure people change to semi-permanent and permanent agriculture, this means that less area returns to fallow, thus providing fewer shrub and forest ecosystems. Regeneration is generally slow, and many fallowed agricultural fields did not reach the pre-disturbance state regarding biomass during the 25 years of observation.

Case study: When food security compromises land resources and biodiversity (cont’d)

Total area of natural land converted to agriculture (in hectares) on an annual basis (dotted line) and fitted with a moving average filter of 3 years.

Source: Data from: Schneibel, A. et al., 2016.

Year of forest clearing for agricultural expansion from 1989-2014, with additional close-up looks at the cities of Chitembo, Cuchi and Menongue. The results are based on time series segmentation with LandTrendr on annual Landsat NBR images.

Source: Schneibel, A. et al., 2016.
The farming system is changing due to land pressure

The farming system and the rate of agricultural expansion are closely connected to spatial and temporal drivers like the location and severity of armed conflicts, the resettlement of people, the reconstruction and location of infrastructure and the availability of forested areas. Fields have turned from shifting to semi-permanent farming systems during the last 25 years, especially around cities that are well connected by infrastructure. Those cities that were strongly affected by the civil war trend is quite recent, starting after the ceasefire in 2002. Cities that were not located close the fighting show higher land pressure and earlier transition to semi-permanent systems, sometimes since the early 1990s (graph below). However, land pressure is rising, and those cities that were affected by the destruction of fields, the mining of arable land and population movements also show a high deforestation rate since the end of the civil war. This rising land pressure is likely to affect biodiversity, the provision of resources and rural livelihoods in a negative way, and is thus a potential source of conflict, especially since the Moombo forests of the region have been identified as being one of the next tipping points[16].

Quantifying the trade-off

Indicator values based on publications and on household surveys can quantify on one hand the amount of maize grains that can be harvested on the new fields, and on the other hand the woody biomass that is lost due to slash-and-burn agriculture. Depending on different soil types, farming techniques and damage from insects or pests, the rate varies greatly between farmers. While the cutting of forest is a once-only action, fields are used for several years, providing a stable basis for food supply.

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The spread of invasive alien trees in South Africa

In South Africa IAPs have long been recognised as having significant impacts on the flow of ecosystem services. Areas of high rainfall, the source areas of major river systems, tend to be worst affected by IAPs. These invasions have been shown to substantially reduce streamflow, in some cases turning perennial streams into annual streams. It is estimated that South Africa loses 2.95% of its run-off as a direct consequence of plant invasions. In a water-scarce country, where demand exceeds available water in almost all catchments, this added stress is a major concern.

To counter these impacts the South African government has established an ambitious public works programme, called ‘Working for Water’. Since 1995 it has spent approximately US$715 million and employed over 227 000 person-years of labour, with the 2016 expenditure being approximately US$130 million. This high level of investment has helped contain the level of invasions, yet the problem continues to grow. One necessary shortcut is the introduction of biological controls, and here there have been some marked successes.

Bush encroachment in southern Africa

Woody plant densification, locally known as ‘bush encroachment’, is a common global phenomenon in savannas and woodlands. This densification is often dominated by shrub-like vegetation, and the term ‘bush thickening’ would be more appropriate as, unlike the problem of IAPs, this increased woody plant density is mostly of indigenous species that are already in the area. In some cases areas that were historically open grassland are becoming wooded thickets dominated by indigenous woody species (though IAPs may also be present). The causes of bush encroachment are multiple and complex. Overgrazing has generally been seen as the main driver. Heavy grazing not only removes the grass, hence reducing competition for woody species, but also reduces the fire load that historically would have destroyed trees, and in particular young establishing trees. Very obvious fence-line contrasts observed between areas with differing grazing histories provide strong support for this mechanism of bush encroachment. Bush encroachment has, however, also been observed in areas with light grazing. Research suggests that the global increase in CO2 is an additional factor, and there is growing evidence that the increasing CO2 levels and the different ways in which trees and grasses respond to this change give trees a competitive advantage over grasses.

In Namibia bush encroachment is seen as a relatively recent phenomenon that has become more obvious since the early 1960s. Bush encroachment has a profound impact on the flow of ecosystem services. It can be devastating to cattle management, reducing the carrying capacity by as much as 90%. Bush encroachment in Namibia is estimated to occur over 260,000 km² and has been estimated to have reduced the national cattle herd by 50%, with an annual economic cost of US$170 million. The total economic value to be gained from the clearing of bush in Namibia was estimated at US$4.7 billion over 45 years based on a 67% debushing.

Bush encroachment changes biodiversity. Tree species are favoured over grass and forb species, and the structure of the habitat is fundamentally altered. There is evidence that birds that favour more open grasslands, such as secretary birds, have shifted their range. In Namibia the endangered cheetah, which favours open savanna, is being displaced, as are open grazers.
such as zebra and wildebeest. The dense bush hinders both human and animal movement, which makes animal management difficult and reduces the tourism potential in conservation areas.

Bush encroachment changes the hydrology of the area, leading to lowered groundwater tables\textsuperscript{15}. Bush encroachment can also have devastating financial consequences from a cattle or game farmer’s perspective. Past studies have shown that, in arid areas with low livestock-carrying capacity, the costs involved in clearing invasive bush cannot be justified through the revenue gains from livestock production\textsuperscript{16, 17}. However, changes in the economics of beef production suggest that this situation may be changing.

Alternative revenue streams have been developed based on invasive bush, the principal one being charcoal production\textsuperscript{18, 19}, with Namibia estimated to produce between 85,000 and 100,000 tonnes of charcoal per year\textsuperscript{20}. Use of bush for electricity production is also being considered, and a study found that there would be more than enough biomass in the country to run several biomass power stations, generating a total of 20 MW on a sustainable basis\textsuperscript{21}. The increased carbon storage from bush is also being proposed by Namibia as an offset to anthropogenic carbon emissions, and Namibia now considers itself to be a carbon-neutral country.

Case study: Too many, too few or the wrong trees – a region-wide challenge

Bushes and trees are spreading into areas that were historically grassland. This matched pair of photographs, the first taken in 1954 and repeated in 2010 near the Kei River in the Eastern Cape Province, South Africa illustrates a wide-scale trend throughout the region of areas once predominantly grassland and now increasingly dominated by trees and shrubs. This has major impacts on the potential of the land to provide grazing for cattle and can drastically reduce the streamflow of rivers.

Changing CO\textsubscript{2} levels have profound impacts on tree growth

Acacia karroo (sweet thorn) was subjected to differing levels of CO\textsubscript{2} ranging from 150 ppm (~ minimum ice-age levels) to 260 ppm (~ pre-industrial levels), 375 ppm (approximate levels from 2010) and 450 ppm (estimates for the mid 2030s). Increased CO\textsubscript{2} results in huge increases in root growth, and root starch stores allow seedlings to grow rapidly, escaping fire and browsing, to become established trees in areas they would have struggled to colonise at low ambient CO\textsubscript{2} levels\textsuperscript{10, 23}. The increased carbon storage from bush is also being proposed by Namibia as an offset to anthropogenic carbon emissions, and Namibia now considers itself to be a carbon-neutral country.
Deforestation and forest degradation are widespread across southern Africa’s forest areas. There is a net reduction in forest area in many locations, but even when forest areas are not fully lost, they are being degraded resulting in a significant net biomass loss. Deforestation and forest degradation are largely driven by agricultural expansion, shifting cultivation and woody resource extraction for both economic gains and for charcoal production. They reduce the extent and quality of forest and woodland by changing forest structures. This can impact on biodiversity, fire regimes and the availability of natural resources and ecosystem services. Rural communities are particularly at risk, as they rely on forests and woodlands to provide ecosystem services and livelihood benefits, with forest resources estimated to support approximately 30% of rural incomes.

### Case study: Too many, too few or the wrong trees – a region-wide challenge (cont’d)

#### Southern Africa (cont’d)

Large mature Mopani trees are cut and stacked (photo 1) as the basis for a simple and inefficient mud-covered kiln, smouldering near the completion of the combustion phase (photo 2). The final product, charcoal sacks of up to 90 kg, is ready for pick-up (photo 3). A charcoal truck collects sacks of charcoal from a village in the Mabalane district of Mozambique for transport to the larger urban centres of Maputo, where an estimated 80% of households are reliant on charcoal as their primary energy source for the cooking of food (photo 4). Only about 20% of the final sales value of charcoal finds its way back to the producers, and the trees used to make the charcoal are an effect free resource to the charcoal makers, costing them only their labour and a small charcoal-licensing fee. The high demand for charcoal, coupled with loss of resources near the town, means that charcoal for Maputo is being imported from ever-increasing distances away from the city centre, with reports of some production sites now more than 300 km away.

### Forest cover loss between 2000 and 2014

Although charcoal is only one of many causes of deforestation its impact is growing in line with the growth in urban demand.

<table>
<thead>
<tr>
<th>Country</th>
<th>Total forest 1990 (Thousand hectares)</th>
<th>Rate of loss 1990-2000</th>
<th>Rate of loss 2005-2015</th>
<th>Total forest 2015 (Thousand hectares)</th>
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<tbody>
<tr>
<td>Angola</td>
<td>60,836</td>
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<td>Zambia</td>
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Annual rate of forest loss, In most countries the rate is high and increasing. Source: Food and Agriculture Organization of the United Nations (FAO).
Charcoal case study: Mabalane district, Gaza province, Mozambique

Charcoal production is a major economic activity in sub-Saharan Africa, with a value in most southern African countries of around 2-3% of GDP. Charcoal provides affordable energy to 70-90% of the urban population. In Mozambique, woodfuels account for 81% of energy consumption, with charcoal the dominant fuel in urban centres. Charcoal production in Mozambique employs an estimated 214,000 people, supporting 1.2 million dependents — equivalent to 5% of the country’s population. Despite the importance of charcoal to rural economies and the wide extent of participation, very little is known of the impacts of charcoal production on other ecosystem services, nor on rural livelihoods. Charcoal production has the potential to severely degrade, or even deforest, woodlands if intensities are high.

To address the need for studies on the impact of charcoal production on other ecosystem services and on rural populations, a large-scale interdisciplinary study (for example the ACES project: https://miomboaces.wordpress.com) was conducted in the Mabalane district of Gaza province, southern Mozambique, collecting biophysical and social data in seven villages across a charcoal ‘boom and bust’ frontier.

Gaza province is currently one of the major supply areas of charcoal to the capital Maputo, and is at the edge of the expanding charcoal frontier. Most of the charcoal from this area is produced from the tree species Colophospermum mopane. High demand for good-quality charcoal drives this selectivity, given the high-density timber for the species.

Using biophysical data on woodland structures and species composition, in combination with social data on ecosystem services uses and preferences, the study found that charcoal production was most likely to impact on firewood and woody construction material availability, and to reduce the carbon stocks and storage potential of the woodlands.

Villages with longer histories of charcoal production had already experienced decreases in one or more of these services. However, even under intense charcoal-production scenarios, all of the ecosystem services assessed were still available to some degree at the local scale. Villages where ecosystem services availability and biodiversity were low will be more vulnerable to further degradation of woodlands in future, and reducing the impacts of further charcoal production or woodland degradation is becoming a key challenge.

If wood extraction for charcoal production were to become less selective in future, further trade-offs with other ecosystem services and greater losses of ecosystem services availability can be expected. Therefore, charcoal production must remain selective in nature, or risk further degradation or even loss of woodlands and associated ecosystem services. However, avoiding non-selective charcoal extraction is difficult if the demand for charcoal remains high, with increasing prices and incentives to make charcoal. It will require coordination of the charcoal licensing regime at provincial level to ensure the frontier keeps moving away from Maputo, rather than becoming more intensive. Enforcement is still a major challenge.

The majority of the villages in the district are involved in charcoal production, generating much-needed income for rural households with few alternative income sources. However, the study found that the majority of the charcoal-production income did not remain with local communities. This is due to governance challenges in the forestry sector and a lack of support for community management initiatives. The real income is accrued by large-scale migrant producers. Providing alternatives to charcoal production and supporting local management initiatives is therefore a key challenge in southern Mozambique.

Conclusions

Major changes in tree density are being experienced across southern Africa. The vast savannas and woodlands that dominate much of the region are under strong threat from deforestation. This results in a loss of many other ecosystem services that are of importance to local livelihoods, though grazing may be enhanced. Drivers of deforestation are largely linked to agricultural expansion but clearing of woodlands and forest for charcoal production is a large and growing problem.

Ironically, whilst vast parts of the region are experiencing deforestation, for some areas an increasing density of bush, shrubs and trees has become the key driver of reduced productivity. Some of this is the result of introduced exotic invasives, but, over vast areas and especially in and around, it is indigenous species that are invading grasslands and changing the tree density of what were previously open grasslands or woodlands. The type of degradation is largely related to the levels and types of human intervention, for instance over-harvesting or over-grazing, but climate and vegetation type also play a role. Increased levels of global CO2 appear to be favouring woody species growth over grasses.
South American Chaco, Argentina and Paraguay

The Gran Chaco is located west of the Paraguay River and east of the Andes, and is mostly an alluvial sedimentary plain shared between Argentina, Bolivia and Paraguay. While the floral characteristics of the Gran Chaco are variable, owing to the large geographical span of the region, the dominant vegetative structure is xerophytic deciduous forests with multiple layers of trees, shrubs and herbs. Less famous than the iconic rainforests of the Amazon some 1,000 km to the north, it has several endemic species and high levels of biodiversity, including 3,400 plant species, 500 birds, 150 mammals and 220 reptiles and amphibians. Its position at the heart of the continent makes it an important refuge for migrating birds. Jaguars prowl its forests, hunting tapir, peccary, giant armadillo, capybara and giant anteaters. Much of the land in the sparsely populated Chaco is the ancestral territory of various indigenous groups. The Chaco is one of South America’s last agricultural frontiers. Very sparsely populated and lacking sufficient all-weather roads and basic infrastructure, it has long been too remote for crop planting.

Agricultural expansion in the South American Chaco

The South American or Gran Chaco is the biggest continuous dry forest in the world and it is the second largest forest ecosystem in South America after the Amazon. During the last decade, the Gran Chaco region in Argentina, Bolivia and Paraguay has emerged as a global deforestation hotspot due to agricultural expansion and intensification. Cattle ranching and soybean cultivation expand into forests, and soybean cultivation replaces grazing lands. Thus, between 1985 and 2013, more than 142,000 km² of the Gran Chaco forests, equaling 20% of its total area, were replaced by croplands (38.9%) or grazing lands (61.1%). It appears that the Gran Chaco is one of the most threatened ecoregions worldwide because of its agricultural potential and the growing global demands for agricultural products. This is aggravated by the fact that the Gran Chaco harbours a high level of biodiversity, but only 9% of the region is actually protected.

The forest loss in the region results from the synergistic convergence of climatic, technological and socioeconomic factors. Three issues in particular accelerated the agricultural expansion in the region:

1. the introduction of Roundup Ready soybean cultivars in 1997, which allowed the expansion of no-tillage systems,
2. an increase in mean annual precipitation; and
3. economic factors, both at local (changes in currency exchange rates) and global (commodities price increases) scales.

Located in the south of the Americas, Argentina has a total area of 3,761,274 km², including the Antarctic territory and islands in the southern Atlantic Ocean. The continental part of the country extends for 3,700 km from north to south, spanning between 22° and 55.5° S and covering a total area of 2,791,810 km². This great expanse encompasses a wide climatic diversity, from subtropical in the north to cold climates in the extreme south and the mountainous areas, with a predominance of temperate climates in the majority of the country. The drylands comprise 55% of the country and account for a great proportion of the agricultural and livestock production.

Aerial view of the National Park El Impenetrable, Chaco, Argentina.
Source: Lucas8W8L. Wikimedia Commons.

Dry and Humid Lands of Argentina

Dry and humid lands of Argentina (2010) and location of the Argentine Dry Chaco.
Source: © Greenpeace Argentina / Martín Katz (c/o Almut Therburg).
Clearing forest in the Dry Chaco: an example of the expansion of agriculture due to the advance of soybean monoculture in Argentina

In Argentina the Chaco region is the most forested area, and represents 70% of the country’s forests (Red Agroforestal Chaco Argentina, 2012). The Argentine Dry Chaco is among the most dynamic deforestation frontiers in South America due to a booming soybean economy oriented toward the global market. Land clearing in the Argentine Dry Chaco is easily monitored by Landsat satellite imagery owing to the strong contrast between natural vegetation and the parcel structure in cleared areas. The deforested area had reached more than 11 428 000 ha by 2015 (see bar chart below). This region has experienced particularly high deforestation rates during the last two decades, especially in the north Argentine Dry Chaco (see map below).

In 2007 the Argentine government passed the Law of Minimum Standards of Environmental Protection for Native Forests, which provides incentives for the sustainable management of forests and conservation. Although this Native Forest Law for controlling the clearing process has had a measurable effect upon the deforestation rate, it does not ensure the conservation and stability of the Chaco forests in Argentina (see map below). Initially, deforestation occurred in areas with the highest agriculture aptitudes in the region (high mean annual precipitation, low mean slopes and good soil conditions), located in the east and west of the Chaco area (see map on the left page). Since the 1990s, agriculture has expanded to the central (drier) area of the region, with substantial ecological and social consequences.

Recent studies confirm that deforestation affects soil organic carbon (SOC) stocks in the Dry Chaco region in different ways:
1. SOC stocks decreased due to cropping after deforestation;
2. SOC loss was positively associated with the proportion of soybean in the rotation;
3. forest-to-cropland conversion modified SOC vertical distributions; and
4. SOC loss in deeper soil layers was high due to cropping after deforestation.

The agricultural expansion and intensification in the Chaco also results in significant carbon emissions, loss of biodiversity, and changes in water dynamics. Social conflicts go hand in hand with the process of landscape transformation and land ownership concentration in the Dry Chaco. The traditional land use, food security and access to resources of the Creole peasants and indigenous communities are increasingly placed under risk. In the region, about 95% of the land is subject to some kind of land tenure conflicts and 60% of the indigenous communities lack secure land tenure of their ancestral lands.

During the first decade of the 21st century, land change in Latin America and Caribbean included extensive deforestation, but there was also an increase in >360 000 km² of woody vegetation across the region; equivalent to approximately 66% of the deforestation. The majority of deforestation in LAC occurred in South America (52%), particularly in Argentina, Brazil, Bolivia, and Paraguay, where extensive areas were converted to agricultural lands (e.g. soybeans) and cattle pastures, a response attributed to the increasing global demand for meat.
Case study: Industrial cultivation takes over dryland forests (cont’d)

South American Chaco, Argentina and Paraguay (cont’d)

Soybean boom in Argentina and soil degradation

The increasing global demand for soybean (Glycine max (L.) Merr.) as feedstuff for large-scale beef production has caused the expansion and dominance of this legume in Argentina during the past 50 years (Figure 4). Soybean production boomed after the implementation of the soybean “technological package,” which included improved genetics, the use of purchased inputs and the adoption of non-tillage or direct seeding practices. These developments meant a complete change in the ecological, economic and political parameters of agricultural production. It increased yields and economic gains, and transformed the production model into agribusiness.

These changes also resulted in marginal land cultivation, physical soil degradation (through wind and water erosion and soil compaction), soil organic matter (SOM) depletion, nutrient losses and the presence of glyphosate and AMPA concentrations in different environmental matrices.

A study by Wingeyer et al. (2015) comparing soil-quality indicators for pristine and agricultural soils shows a general reduction in SOM content, aggregate stability and an increase in bulk density with agricultural use. Thus, soils with 10-20 years of continuous agriculture had 64%, 48% and 116% of the pristine values, respectively.

Alternative land use for the Dry Chaco forest

Studies conducted by researchers from the National University of Salta (Argentina) along with Creole cattle ranchers of Chaco have led to the generation of an appropriate, alternative technology to the dominant business model. This alternative land use allows the forage supply to be improved while protecting the many ecosystem services provided by the Chaco forest. The technology consists of pasture implantation on deschampado (cleared understory) patches and requires minimal intervention on the shrub layer of the forest. There is a light pruning of the low branches that hinder the circulation of the animals, the fallen branches are removed, the non-forage sub-shrubs and the sick trees are cleared, and afterwards shade species (sciophytes) are sown.

Charcoal for Europe and the United States

The agricultural sector has always been of fundamental importance to the economy of Paraguay and its future growth. During the mid 1990s it produced more than one quarter of the country’s gross domestic product, employed almost half the workforce and generated 90% of registered exports. More than half of industry’s added value came from agro-industry, and almost half of Paraguay’s population lived in the rural areas.

In the past two decades Paraguay has also experienced a radical transformation of its landscape and economy. The country is increasingly dominated by the large-scale industrial production of soy and beef for export. With a population of just 6 million people it is now the sixth-largest exporter of soy beans and ranks eighth among the biggest exporters of beef.

The highest average annual rainfall (1320 mm) is in the east, and precipitation gradually decreases to about 750 mm in the far west. Although the rainfall normally would be adequate for agriculture, roughly a third to half of the total comes in the hot summer. Evaporation losses give the Chaco an arid nature. Great temperature contrasts exist, and the highest recorded temperatures for the South American continent occur in the Chaco (absolute maximums may reach 47°C). But heat-resistant soy strains are under development, and cattle ranching has become an additional important economy and has replaced traditional uses of forest resources in the Chaco (e.g. collection of tannins from the Quebracho hardwood trees). As with soy, cattle ranching is dominated by large farms controlled by agribusiness companies.
The expansion of large-scale agricultural holdings into the western Chaco of Paraguay has led to a tremendous increase in deforestation in the Chaco. According to data published by Global Forest Watch, the conversion rates coincide with the rise of Paraguay’s beef exports. Deforestation in the three departments that comprise the Paraguayan Chaco tripled between 2006 and 2007, and has remained dramatically high in the years since. By 2013, due in large part to the situation in western Paraguay, the forests of the Chaco were disappearing at a rate faster than any other tropical forests in the world.

The analysis, by the University of Maryland, covered the 12 years after 2000, a period in which the dominant story about South America’s forests was the remarkable success in reducing deforestation in the Brazilian Amazon. The rampant destruction of the Chaco, which stretched up to the borders of Brazil’s Amazon states, had gone under the radar. Yet by any measure the extent of forest loss in this lesser-known corner of South America merited global attention. Only four countries lost more tropical forest during the 12 years than Paraguay: Brazil, Indonesia, Congo and Malaysia. But these countries had a lot more left to lose. Of all the countries with significant tracts of tropical forests, only Malaysia had a higher rate of forest loss than Paraguay.

Figures 6, 7 and 8: Progressing deforestation (2000-2017) around ‘Teniente Ochoa’ (Boquerón Province, Paraguay), depicted by Landsat Earth-observation imagery.
The Aral Sea is a classic and prominent case of pollution and environment degradation resulting from massive agricultural development. An almost endless series of reports has raised public awareness through pictures of children running past ruined ships abandoned in the sand of the dry seabed, abandoned harbour facilities now located on dry wasteland and satellite images showing vast areas left dry following the rapid contraction of the Aral Sea on the borders between Kazakhstan and Uzbekistan. By 1997 the Intergovernmental Panel on Climate Change had highlighted the importance of the Aral Sea as ‘a case study of the multiplicative effects of resource overuse, which can lead to local environmental and even climate change’, and in an effort to identify archetypical schemes of human-environment interactions, scientists have coined the term ‘Aral Sea Syndrome’. Today it is used as a descriptor for similar patterns of environmental degradation, socioeconomic problems and conflicts caused by dams and irrigation schemes in other parts of the world, such as the Tamir Basin of western China.

At around 67,500 km in 1960, the Aral Sea was the world’s fourth-largest inland water body. It is a terminal lake, mainly fed by two rivers, the Amu Darya and the Syr Darya, which originate in the snowfields and glaciers of the Pamir and Tian Shan mountains. Located in a region with primarily arid climates, the extent of the Aral Sea depends on the equilibrium between annual fresh-water inflow and evaporation. From the mid 17th century until the 1960s, lake-level variations were likely less than 4.5 m, and during the first six decades of the 20th century they were less than 1 m. As a brackish lake with salinity averaging near 10 g/l, the lake was home to freshwater fish species, supporting a major fishery industry.

The delta of the Syr Darya and the Amu Darya sustained diverse flora and fauna. But they were also of considerable economic importance, supporting irrigated agriculture, animal husbandry, hunting and trapping, fishing and the harvesting of reeds, which served as both fodder for livestock and building materials. The lands that now constitute five of the seven basin states (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan) were part of the Russian Empire and its successor, the Soviet Union. From the late 19th century until the collapse of the USSR in 1991, Irrigation was practised in the Aral Sea basin for millennia without substantially diminishing inflow to the Aral Sea. However, with the introduction
The consequences were dramatic. With the shrinkage of the fourth-largest lake in the world, a huge saline desert emerged on the former seabed, called the Aralkum. From an ecological point of view it is considered the world’s largest area where primary succession is taking place. The rich and diverse ecosystems of the Amu Darya and Syr Darya deltas (Uzbekistan) have suffered greatly due to reduced river flows, the virtual elimination of spring floods (owing to the construction of upstream storage reservoirs and reduced river flows) and the lowering of groundwater levels. Unique tugay vegetation complexes stretched along all the main rivers and distributary channels and covered 100,000 hectares in the Amu Darya delta in 1950. Once forming important habitats for mammals, birds and amphibians, they were reduced to only 20,000 to 30,000 hectares by 1999.

The fishing industry that once employed 40,000 workers and supplied one sixth of the Soviet catch was totally eradicated, causing widespread economic distress, ultimately throwing tens of thousands of people out of work. Navigation on the Aral also ceased by the 1980s. The fishing ports of Maynak (in the delta of the Amu Darya in Uzbekistan) and Aralsk (in the delta of the Syr Darya in Kazakhstan) have literally perished, the former now lying 60 km from the Aral Sea’s current shores.
Case study: Overuse of water for irrigation – an old concern revisited (cont’d)

Aral Sea, Kazakhstan and Uzbekistan (cont’d)

Traditional forms of irrigated agriculture in the deltas paid a high price for the expansion and intensification of agriculture in the upper reaches, as inflow into the deltas decreased owing to heavy upstream consumptive use. The water that does reach the deltas has elevated salinity from the leaching of salts deposited in fields in the middle and upper courses of the rivers. The consequences are reduced crop yields and, in conjunction with insufficient drainage of irrigated fields, secondary soil salinisation\(^{4,6}\). Animal husbandry, in both the deltas and the desert regions adjacent to the Aral Sea, has been damaged by a reduction in the area and declining productivity of pastures resulting from desertification, failing groundwater levels and the replacement of natural vegetation suitable for grazing with inedible species\(^{9,10}\). The diminution of the Aral Sea water-surface area was also coupled with increasing pollution of the remaining water bodies (primarily from irrigation run-off containing salts, fertilisers, pesticides, herbicides and cotton defoliants). Highly subsidised prices within the context of a planned farm economy in the former Soviet Union prior to 1990 provided no incentive for efficient use of agro-chemicals (which were also more contaminating than those now available on the world market)\(^{10}\).

Nowadays strong winds blow toxically charged sand, salt and dust particles from the drier bottom of the Aral Sea onto the surrounding lands, which limits plant growth and reduces yields\(^3\). These storms are between 150 and 300 km wide and salt content in the dust reaches 30-40% of the volume, and in extreme cases can be as high as 90%. Sometimes the Aralkum salts even reach intensively irrigated and cultivated lands far from the Aral Sea region\(^{10}\).

Health experts consider airborne salt and dust, as well as the chemical pollution and excessively high salinity of drinking water, to be major causes of high levels of respiratory illnesses and cancerous diseases in the region. Substantial dioxin residues have been found in mothers’ milk, and waterborne diseases such as typhus, paratyphoid and viral hepatitis have increased enormously over the past decades in the midstream and downstream areas of the Amu Darya and Syr Darya\(^{4,6,7,8}\).

Hypersaline environments, such as the Aralkum, are also sources for a multitude of volatile halogenated organohalogeners (VOX). These compounds can affect the ozone layer of the stratosphere and play a key role in the production of aerosols\(^9\).

VOX emissions are expected to increase in the future as long as the area of salt-affected soils expands.

In the late 1980s, under Soviet governance, significant efforts were made to restore wetlands, improve habitat conditions and reduce pollution. In 1993, after the collapse of the Soviet Union, the new states of the region assumed responsibility for dealing with the Aral situation and signed a formal agreement. Together with international donors a number of restoration and construction projects have improved the situation.

In 2012 the Aral Sea consisted of four residual water bodies. While the flow of the Amu Darya, on the Uzbekistan side, does not reach the Aral, the waters of the Syr Darya in Kazakhstan still flow into the sea for part of the year. With help from the World Bank, in 2005 Kazakhstan built the Kok-Aral dam to retain water from the Syr Darya in the Small Aral Sea, once a bay of the original lake in the north. The dam has raised the water level by over 12 m from its 2003 low.

Ecological conditions have improved within this smaller part of the Aral Sea, with positive changes in biodiversity and habitats, and increasing numbers of migratory birds, waterfowl and fish. By autumn 2011 the water salinity in the open part of the Small Sea dropped to 8-12 g/l, and a recent increase in fish harvests has been accompanied by an increase in employment (fishermen) and the return of the fish-processing industry. However, the other three main water bodies, Tohe-bas Gulf and the East and West basins of the Large Aral, represent hyperhaline (very high salinity) conditions, too high to support any fish species\(^{4,11}\).

Would it be possible to restore the Aral to its former volume and extent? Given current land-use practices in the basin, the only realistic option to substantially increase inflow into the Aral is to...
reduce the consumptive use of water upstream for irrigation (which amounts to more than 90% of withdrawals from the rivers)\textsuperscript{,6,13}. Modelling studies have shown that the impacts of water use will surpass the impact of climate change in the region\textsuperscript{15}. Improvements to irrigation infrastructure and technologies have been initiated that aim to limit leakage and evaporative losses (i.e. to increase efficiency). However, a substantial and comprehensive approach will be extremely costly and is obviously beyond the ability of basin states, even in combination with international donors. Moreover, the technical condition of the existing irrigation systems is steadily deteriorating\textsuperscript{6}. Finally yet importantly, technical improvements must be coupled with strong institutional changes in irrigation water and drainage management that involve the more realistic participation of water users. The present high level of state subsidies results in differential support for specific crops yet discourages changes and the efficient use of water resources.

A change in agricultural practices (agroforestry) and the conversion of more of the irrigated area to less water-intensive crops than cotton and rice (such as winter wheat, soybeans, fruits and vegetables) led to a reduction in irrigation withdrawals during the 1990s, although irrigated area increased by 10% at the same time. However, this effect will remain limited, primarily because Uzbekistan and Turkmenistan (which account for 54% and 22% of all irrigation withdrawals, respectively) seem intent on expanding irrigation. The motive is to maintain cotton as a major export crop to earn foreign currency, but also to increase food production to meet the nutrition needs of a growing population\textsuperscript{2,6}. 

Reductions in the irrigated area are therefore unlikely in the near to mid-term future, and the fact that Tajikistan has begun to build the world’s tallest hydropower dam might introduce additional complications. Maintaining the existing water bodies in their present condition seems possible. However, a viable option to refill the Aral Sea is not an option, given the strong dependence of 40 million people (70% of them rural) on irrigated agriculture in the basin. The Aral Sea case is thus a striking example of the systematic couplings in human-environment systems, such as reciprocal effects, feedback loops, human-aided resilience and legacy effects\textsuperscript{16}. 

Agriculture shrinking due to the salinisation (in red the decrease of water occurrence). 
Case study: Facing inherited degradation and restoration concepts

San Simon Valley, Arizona, USA

Background

The San Simon Valley on the border of south-eastern Arizona and south-western New Mexico is one of the most dramatic examples of historical land degradation and subsequent restoration efforts in the drylands of the American south-west. The ephemeral San Simon River is a tributary of the Gila River, the major east-west river system of southern Arizona. Rising in the Black Range of south-western New Mexico, the Gila flows more than 1000 km west across Arizona to join the Colorado River just north of the US border with Mexico. It has served as an oasis and corridor for wildlife and human settlement in an arid and semi-arid region. The lands along the main stem of the Gila have been occupied and cultivated by multiple cultures for millennia. Today, the Gila is a primary source of water for one of the most important farming areas of Arizona, the San Carlos Irrigation District.

While the San Simon is a major tributary to the Gila in terms of area — the watershed covers 580 000 ha — it contributes only 0.33 m³ s⁻¹ in annual streamflow to the natural discharge of the Gila of ~ 54 m³ s⁻¹ (of which just 6.7 m³ s⁻¹ is actually discharged due to diversion and flood control). The insignificant streamflow is due to the arid climate of the watershed, with precipitation ranging from 200 mm/year in the lowlands to a maximum of 760 mm/year in the uplands. In addition to being arid, most of the watershed is flat and is composed of very fine lacustrine sediments. Valley-floor sediments have been entrenched on stretches of the river. Because of high soil erosion, the San Simon has been a major source of suspended sediment entering the Gila River, which has posed a threat to the Coolidge Dam and San Carlos Irrigation District. Vegetation cover in the valley consists of Chihuahuan-Sonoran desert shrublands in the lower portion and Chihuahuan-Sonoran semi-desert grasslands in the middle portion of the watershed. Mesquite is a dominant woody species in the bottomlands and has encroached on grasslands in adjacent uplands, as a result of interplay between human (land use) and environmental (drought, geomorphology) factors. This non-equilibrium system is assumed to have crossed a threshold as early as the turn of the 20th century from a grassland to a shrubland, which has persisted despite variations in rainfall and grazing pressure.

Today, the major land use remains rangeland (98% of the watershed), albeit with relatively low stocking rates compared to the cattle boom in the past. Croplands and forest are very restricted (USDA, 2007). Carrying capacity for livestock is limited as a result of historic vegetation changes and mesquite dominance. Gully erosion is widespread despite management interventions. While the pressure from livestock grazing on the land is light nowadays compared to the past, channel downcutting along the main stem of the San Simon and irrigation has lowered the groundwater table. In restricted areas, recreational activities (i.e. off-road vehicles) have put additional stress on the ecosystem in general.

Multiple stakeholders are involved in the use and management of the San Simon valley. Over 41% of the valley is managed by the US Department of Agriculture Bureau of Land Management, a federal agency with the mission to manage public lands for a variety of uses. Another 26% of the valley is state trust land, 19% is private land and 13% is managed by the US Department of Agriculture Forest Service. Land users include cattle ranchers, owners of ranchettes (rural subdivisions), hunters, Farmers and urban populations, who derive different ecosystem services from the valley. A multi-stakeholder platform, the Gila Watershed Partnership, brings all key stakeholders together. The partnership works across physical, political, social, economic and cultural boundaries to address major issues affecting the watershed, such as water quality and quantity, soil erosion, invasive weeds and flooding.

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Mesquite is a dominant woody species in the bottomlands and has encroached on grasslands in adjacent uplands as a result of interplay between human (land use) and environmental (drought, geomorphology) factors. This non-equilibrium system is assumed to have crossed a threshold as early as the turn of the 20th century from a grassland to a shrubland, which has persisted despite variations in rainfall and grazing pressure.
History of land use

According to observations by early settlers from around 1880, vegetation conditions in the San Simon were well suited for cattle, with lush meadows covered by nutritious grama grasses. In 1880 a transcontinental railroad pushed across the southern tier of states in the United States and passed through much of the southern part of the Gila watershed. With access to markets to the east and west provided by the railroad, large-scale cattle operations were quickly undertaken throughout the region. By the early 1890s an estimated 50,000 cattle were grazing in the San Simon valley. The limited land initially granted to settlers (65 ha through the Homestead Act of 1862, until the Enlarged Homestead Act in 1909 allowed 130 ha allotments) was inadequate for any sustainable use and discouraged settlement. As a consequence, the ‘open ranges’ of the arid west encouraged overgrazing.

Severe overstocking led to a degradation of the vegetation cover from the 1880s onwards. Many tracts of land, often already degraded, ended up being sold to large mining and livestock companies, which also strove to obtain public lands. A ‘tragedy of the commons’-type situation, in which unregulated resources are depleted by individuals acting in their own self-interest, prevailed until more effective legal frameworks were established in the 1930s.

Drought cycles and floods

Following the dramatic increase in stocking of the 1880s, the 1890s were dominated by drought. This served to further degrade vegetation and decimated the herds of livestock that relied on these largely marginal rangelands. An unusually high number of El Niño years (1887-1889, 1896-1897, 1899-1900, 1902, 1905, 1907) interrupted the droughts by bringing heavy rains to the region. In a landscape largely stripped of grasses, the consequent run-off resulted in catastrophic erosion which caused the main channel of the San Simon to incise as much as 20 metres. Overall, most rainfall in this highly variable system caused the main channel of the San Simon to incise as much as 20 metres. Overall, most rainfall in this highly variable system has little geomorphological impact, but occasional high-intensity rainfall events have continued to drive gully erosion and arroyo development and sediment pulses ever since the first incision at the turn of the 20th century.

Run-off and the sediment it carried had disastrous effects on the agricultural fields downstream at the confluence of the San Simon and Gila Rivers. This sparked demand from Farmers that the run-off and sediment yield from the San Simon be controlled. In 1928 the Coolidge Dam was completed 90 km downstream of the Gila–San Simon confluence to impound water that would irrigate 40,000 ha of Arizona farmland. As a consequence, sediment from the periodic floods of the San Simon not only had a direct impact on adjacent farmlands, but also threatened the function and longevity of the Coolidge Dam and the vast farmlands that it served.

Erosion-control interventions

The US federal government responded to the demands for run-off and sediment control with intense intervention and investment in the San Simon valley from the 1930s onwards. Between 1935 and 1942 the Civilian Conservation Corps built numerous small structures to slow slope run-off on the uplands and improve vegetation cover, install small gully plugs, contour furrows and low spreaders built of brush and loose rocks. Beginning in the 1930s, the Bureau of Land Management also invested in a variety of mechanisms aimed at stabilising soil and slowing erosion. The range of interventions has included:

i. construction of 19 major detention dams to control the movement of water and sediment;
ii. biological treatments (i.e. reseeding) to increase vegetation cover on surrounding uplands to enhance infiltration and reduce run-off; and
iii. management of grazing intensity to reduce pressure on scant vegetation resources. The maintenance of all these structures remains an ongoing budget challenge to the Bureau of Land Management.

While the geomorphologic and vegetation changes in the San Simon were initially attributed solely to the immigration of European settlers and the open-range cattle production they introduced, these changes are now understood to result from a combination of anthropogenic (land use and management) and climatic (drought cycles) factors and positive feedback cycles among those factors.
Gully erosion and arroyo cutting

Loss of grass cover from a combination of excessive grazing followed by subsequent drought exposed the soil to wind and water erosion. Wagon and cattle trails further concentrated flow and acted as catalysts for gully development that led to the current situation. Gully formation and arroyo cutting have remained concerns in the lower part of the valley where the impacts were greatest but have been controlled through the construction of large concrete water-control structures. The incision of the main channel resulted in the conversion of the once fertile, broad valley floor into a channel with steep banks. In the process, riparian vegetation and wildlife habitat were lost. However, these large structures have essentially stopped further downcutting. In the more gentle-sloping upper parts of the valley, comparatively modest earthen dikes have restored, to some extent, riparian function and meadow-like vegetation. For now, erosion is largely under control.

Soil loss and sedimentation

Intense rainfall events have triggered soil loss on the slopes and major sediment pulses in the San Simon. Annually sediment yield in the San Simon is high, reaching approximately 140 t per square kilometre. Soil accumulation behind the aging erosion-control structures poses a risk of their rupture and emphasises the need for often costly maintenance. As budgets continue to shrink for the federal agencies charged with managing and maintaining those erosion-control structures, there are more pointed questions about the ultimate value of large structures and whether or not to continue the maintenance commitment.

During flood events, suspended sediments are released into the Gila River, where they pose a threat to agricultural activities downstream, including Native American agriculture and high-value crops. The sediment load also threatens to silt up the San Carlos reservoir behind the Coolidge Dam.

Shrub encroachment

The degradation of the grass cover and the proliferation of mesquite beans fed to horses and cattle encouraged an increase in shrub cover, notably Prosopis spp. (mesquite). Mesquite, once established in a site, has superior drought tolerance and the potential to out-compete the more vulnerable grama grass cover. A positive feedback cycle of loss of grass cover, greater run-off and erosion, and increased concentration of nutrients and soil moisture leading to further loss of grass cover caused a transition from a grass-dominated to a shrub-dominated state of the ecosystem. This transition is generally considered undesirable for livestock because it reduces the carrying capacity of a rangeland.

It is not only livestock grazing and drought that are held responsible for this transition; fire suppression and higher than usual winter precipitation might have played a role as well. The changes in woody cover persisted even when livestock pressure was reduced. The density of woody shrubs increased threefold in a study area in the San Simon between the 1970s and 1990s, even in sites excluded from grazing, illustrating the complexity of the response of the ecosystem to both natural perturbations and human activities.

Expected outcome or ecosystem service trade-offs; solutions (or possible solutions)

The ongoing San Simon valley saga illustrates the enduring challenges of managing arid lands. The story began with the overstocking of very marginal grassland with livestock almost 130 years ago, which was terminated by an intense drought. When rains returned, run-off — now largely unimpeded by vegetation — was intense and the main stream channel was quickly downcut. This essentially destroyed most of the modest grazing potential in the lower part of the valley. For the next three decades, infrequent rainfall events that generated run-off carried sediments into farmers' fields at the confluence of the San Simon and Gila Rivers, affecting a large area. Despite the destruction that these events caused, significant action on the part of the federal government had to wait until the construction of a large dam to serve a 20 000 ha irrigation district further downstream. This was more than 30 years after initial entrenchment occurred. Over the next 50 years a few large water-control structures were built along the main stem of the stream, and many smaller structures were built on the uplands throughout the valley. Sediment movement out of the valley was halted; downcutting was arrested in the deeply incised lower valley, and erosion was largely reversed in the less-affected upper part of the valley. While the substantial initial investment in structures has already been made, there is the continuing issue of maintenance. As budgets have contracted there is increasing pressure to scale back maintenance. The trade-offs between the costs of maintenance and the costs of addressing the outcomes of failure are unknown but are an ongoing topic of debate.

Convergence of evidence

San Simon Valley is mostly covered by rangeland, hence intended as land dominated by shrub or grass that supports livestock. The whole is arid and suffers from severe to extreme water stress. On 95 % of the rangeland area, these two GCIs coincide with low nitrogen balance. On around 55 % of the rangeland area, 4 to 7 GCIs coincide, adding decreasing or stressed land productivity (45 %), population change (22 %), irrigation (7 %), high population density (5 %), fires (4 %), climate and vegetation trends (3 %) or high livestock density (1 %) to omnipresent GCIs. Nowhere in the San Simon rangeland more than 7 GCIs accumulate.
Case study: Land and water conservation for sustainable agriculture expansion

Central India

A fundamental requirement of dynamically developing societies is that food production keeps in equilibrium with the demand imposed by the growing population, growing incomes and fast-paced urbanisation. Boosting agricultural production depends on a wide range of different measures, such as:

- increasing yields on existing croplands (i.e. closing yield gaps through improved crop varieties, fertiliser and pesticides, surplus irrigation in drylands, etc.) and management practices,
- expanding agricultural lands into natural ecosystems, often at the loss of critical eco-systems and biodiversity hotspots,
- re-allocating current agricultural production to more productive uses (e.g. shifting grains from animal feed to human consumable food, with vast improvements in overall system efficiency).

Each of these options has potential benefits and disadvantages, as well as significant associated challenges. The fundamental issue is whether the required gains in yields will be possible without significantly damaging other ecosystem goods and services that society is dependent on. Observing trade-offs between these services is crucial, especially with respect to the risk that intensively managed agricultural lands may eventually become degraded and less productive.

India accounts for only 2.4% of world’s geographic area, yet supports about 16.7% of world’s human population. It has only 0.5% of world’s grazing land but supports 18% world’s cattle. 69% of India’s geographic area falls under drylands. Population growth and economic development has considerably increased the pressure on land resources, leading in many regions to land degradation and desertification.

It is estimated that approximately 32% (105.4 million ha) of the land is subject to various processes of land degradation, such as vegetation degradation, water and wind erosion, water logging, salinisation, the impact of mining operations, logging, salinisation, the impact of mining operations, salinisation, increase in basin size, etc. Among the Indian states of Rajasthan, Punjab and Haryana (including Delhi) was being depleted at a mean rate of 4.0 ± 1.0 cm yr⁻¹ between 2002 and 2008. Terrestrial observations of changes in groundwater storage, together with the NASA Gravity Recovery and Climate Experiment (GRACE) satellites, have shown that groundwater over the Indian states of Rajasthan, Punjab and Haryana (including Delhi) was being depleted at a mean rate of 4.0 ± 1.0 cm yr⁻¹ between 2002 and 2008. (see maps on next page and ‘Groundwater changes’ page 94).

The Jhabua and Dhar districts in the state of Madhya Pradesh are located in central India. The districts have human population of about 1.75 and 2.2 million (2011 census) respectively, of which more than 60% are organised in tribal structures. The main livelihood of these tribal people stems from agriculture. The two adjoining districts, with a total area of about 1.4 million ha, are located in the dry sub-humid agro-climatic zone with an average annual rainfall of about 850 mm. Both, Jhabua and Dhar districts are prone to drought and thus covered by the “Drought Prone Area Program” (DPAP) of the government. Land degradation processes cause substantial problems which affect the life of the people. Under DPAP the integrated watershed management approach primarily features soil and moisture conservation measures.

Sustainable Land Management

Slightly more than half of India’s land area is used for agriculture, of which only 35% are under irrigation. The dwindling groundwater resource of India has been of great concern in recent years. Terrestrial observations of changes in groundwater storage, together with the NASA Gravity Recovery and Climate Experiment (GRACE) satellites, have shown that ground water over the Indian states of Rajasthan, Punjab and Haryana (including Delhi) was being depleted at a mean rate of 4.0 ± 1.0 cm yr⁻¹ between 2002 and 2008. (see maps on next page and ‘Groundwater changes’ page 94). As part of watershed development programs, sustainable land management practices (SLM) have been implemented to combat land degradation, desertification and drought (LDD). Such practices aim at preserving and improving land and water resources, as well as to upgrade the ecological and environmental conditions. Improving the availability of water is a fundamental prerequisite to expand agricultural productivity and to enhance food security. The districts of Jhabua and Dhar in the state of Madhya Pradesh in central India represent an outstanding example of the positive impact of SLM implementation on combating desertification (see satellite image above).

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In the frame of combating land degradation, desertification and drought (LDD), a suite of appropriate sustainable land management (SLM) practices have been implemented in these districts over more than two decades. The actions focus on different kinds of soil and moisture conservation strategies and the construction of rainwater harvesting structures, with the aim to increase soil moisture storage, reduce runoff and subsequent erosion, improve ground water recharge and establish new water reservoirs for domestic use and as backup for the expansion and intensification of agriculture.

Desertification/Land Degradation status map of India.

Source: Ajai.
SLM: the Space Component

India promotes the operational use of Earth Observation (EO) satellite data for inventorying and monitoring the environment and natural resources, as well as for mitigating natural disasters. The country has launched a series of EO satellites, named IRS (Indian Remote Sensing Satellites). Data from the IRS series of satellites are routinely used for mapping, monitoring and management of agriculture, forests, wastelands, water resources, land use and land cover change, land degradation and desertification monitoring, watershed development, coastal and marine resources and more.

The Gravity Recovery and Climate Experiment (GRACE) twin satellites launched in March 2002, are making detailed measurements of Earth’s gravity field which lead to discoveries about gravity and, indirectly, ground water storage volumes. Continued observations of groundwater trends across India (2003–2014) using data from the GRACE satellites have revealed surprising trends.

In contrary to the well-documented Indian groundwater depletion due to rapid and unmanaged groundwater withdrawal, regional-scale groundwater storage (GWS) replenishment is reported for the first time. The analysis used long-term in situ (1996–2014, using more than 19000 observation locations) and decadal (2003–2014) satellite-based groundwater storage measurements. In parts of western and southern India, in situ ground water storage (GWS) has been decreasing at the rate of \(-5.81 \pm 0.38 \text{ km}^3/\text{year}\) (in 1996–2001) and \(-0.92 \pm 0.12 \text{ km}^3/\text{year}\) (in 1996–2002), but reversed to replenish at the rate of \(2.04 \pm 0.20 \text{ km}^3/\text{year}\) (in 2002–2014) and \(0.76 \pm 0.08 \text{ km}^3/\text{year}\) (in 2003–2014), respectively. It appears that the paradigm shift in Indian groundwater withdrawal and management policies for sustainable water utilisation has started replenishing the aquifers in western and southern parts of India (see maps below).

Implementing SLM measures in the Jhabua and Dhar districts has made it possible to extend the agricultural area from 13,370 ha (1998) to 15,700 ha in 2013. Within the same period, the number of water ponds has been increased from 210 to 270.

The evolution shown on the two satellite images from 1998 and 2013 (see zooms of the 2013 satellite images - on the right and bottom) demonstrate the positive effects of the sustainable land management (SLM) practices (seen in 2013 image). Surface water bodies created through construction of water harvesting structures (W), presence of water in the seasonal river through construction of a series of back-to-back check dams (D), are clearly seen on the satellite image of 2013. It is also evident that areas under agricultural use (A) could be substantially expanded in the consequence of the successful implementation of soil and moisture conservation measures (see satellite image zooms (middle next page) sowing more detail on agricultural expansion between 1998 and 2013).

**Central India (cont’d)**

Case study: Land and water conservation for sustainable agriculture expansion (cont’d)

Sustainable land management practices include various kinds of soil and moisture conservation measures and the construction of rainwater harvesting structures to create surface water bodies for irrigation and domestic use. The soil and water preserving measures include contour bunding and trenching, gully plugging/nala bunds, farm bunds and others. Rainwater harvesting is supported by the construction of check/stop dams, nala bunds, farm ponds etc.

Source: Ajai.
Central India (cont'd)

Case study: Land and water conservation for sustainable agriculture expansion (cont'd)

IRS LISS-III false color composites of the Jhabua and Dhar districts from February 1998 (left) and February 2013 (right).
Source: IRS satellite imagery.

1998 - red colour indicates mostly agricultural fields.

2013 - note the expansion of agricultural area (in red) as compared to the 1998 situation (left).

Zoom-in on a check dam (D) that has created a water harvesting body.

Zoom-in on a check dam (D) that has created a water harvesting body.