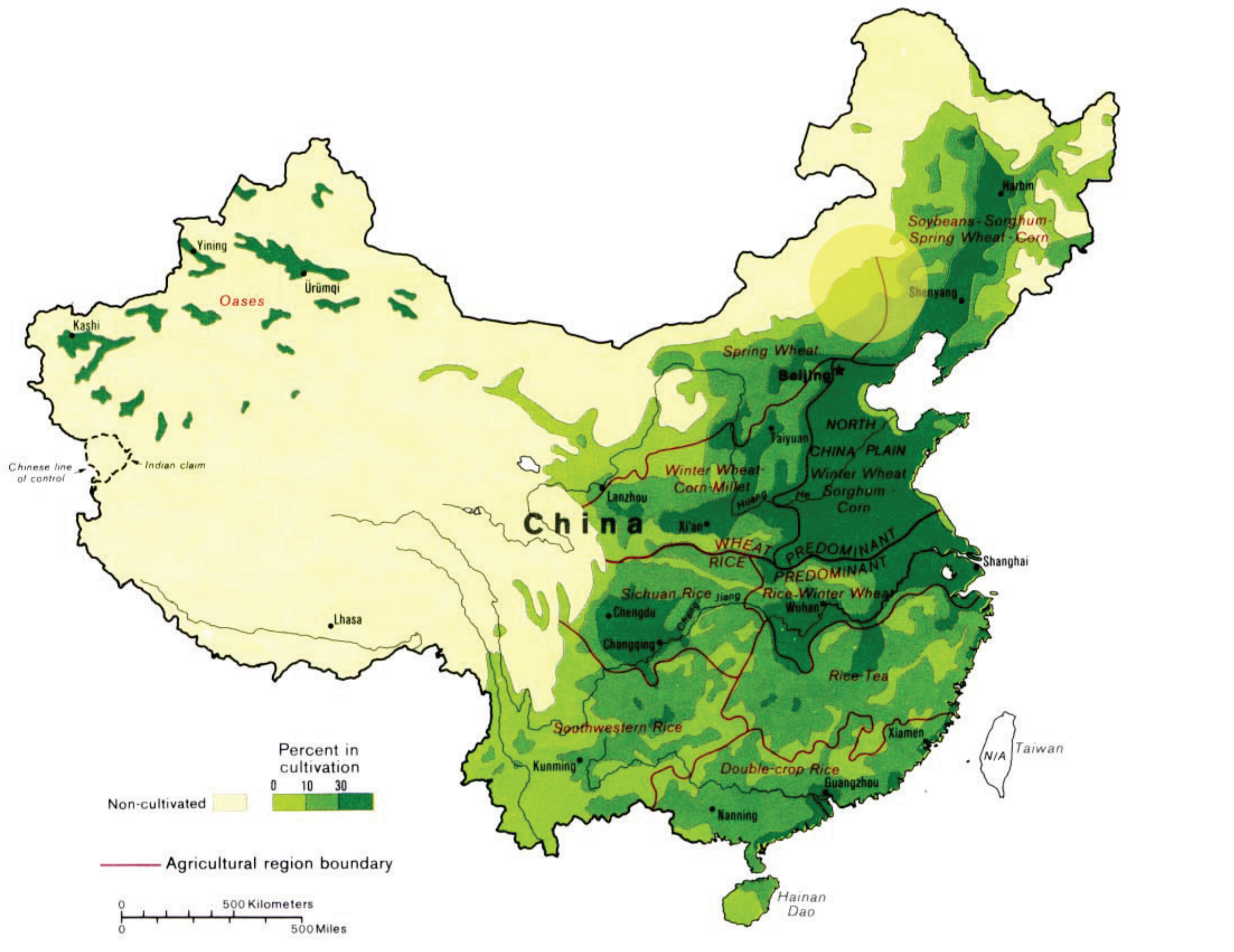
Case study: Agriculture expansion calls for trade-offs in ecosystem services

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[1]. Recent climate-change studies have identified trends of warmer and drier conditions in Inner Mongolia[2].



Horqin Sandy lands (yellow circle) extend in the north-east of China.
Source: Map No 800635 (544061) 5-86 — produced by the US Central Intelligence Agency.


Farming replaces pastoralism.
Source: Hill, J.

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[3].

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.

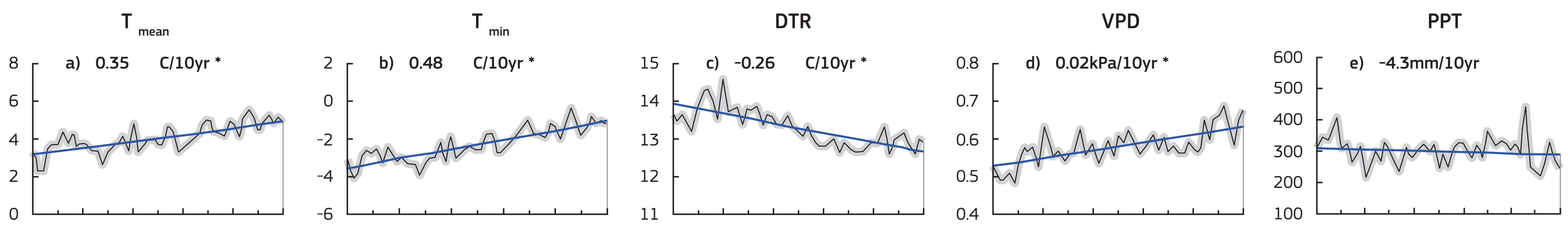
In recent decades, three peaks of land reclamation from grassland to cropland occurred in 1955-1956, 1958-1962 and 1971-1973 under new policies such as 'giving prominence to food production'[4]. In particular, the Great Leap Forward policy in 1958-1962, including the introduction of a long-lasting mandatory 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[4].

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[5].

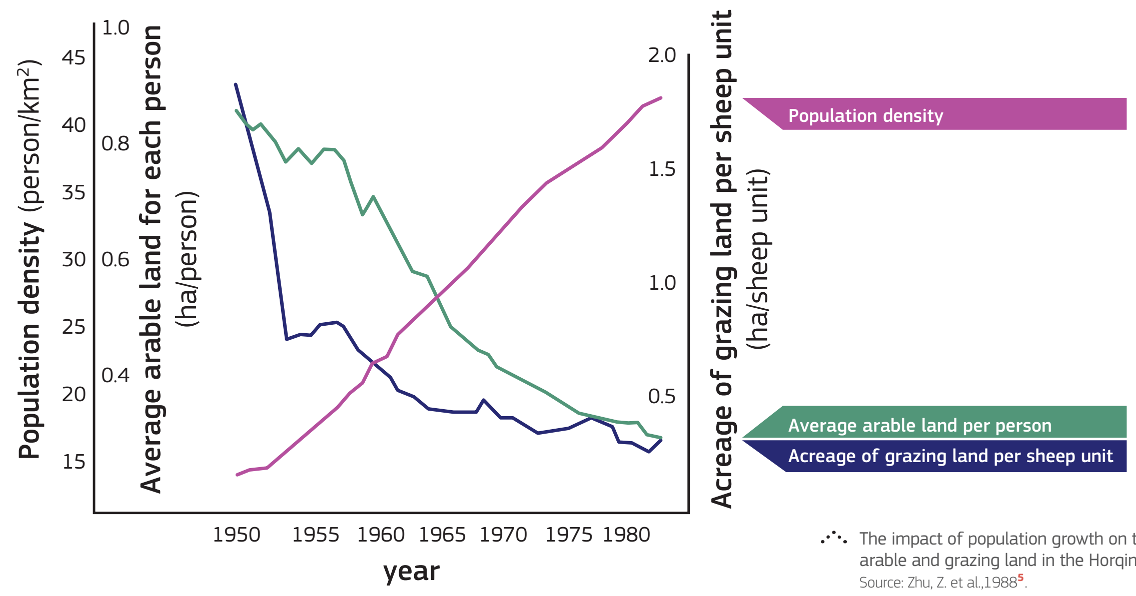
The intense and rapid cultivation of extended rangeland areas and the growth in livestock numbers has increased grazing pressure around newly established settlements and brought large-scale pastoral movements between seasonal pastures to an end[6]. This policy took place at the expense of important ecosystem 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[6, 7].

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)[5, 8]. Yet the question arises as to whether and how the impact of these political incentives can be objectively assessed on landscape level.


Land protection against 'sandification'.
Source: Hill, J.



Climate records show trends of warmer and drier conditions in Inner Mongolia. The annual daily mean and minimum temperature increased whereas the diurnal temperature range decreased. The decreasing trend of annual precipitation was not significant. However, the vapour pressure deficit increased significantly[2].
Source: Lu, N. et al., 2009[2].



The impact of population growth on the availability of arable and grazing land in the Horqin Sandy Lands[5]
Source: Zhu, Z. et al.,1988[5].


Expanding agriculture creates pressure on the remaining rangelands.
Source: Hill, J.

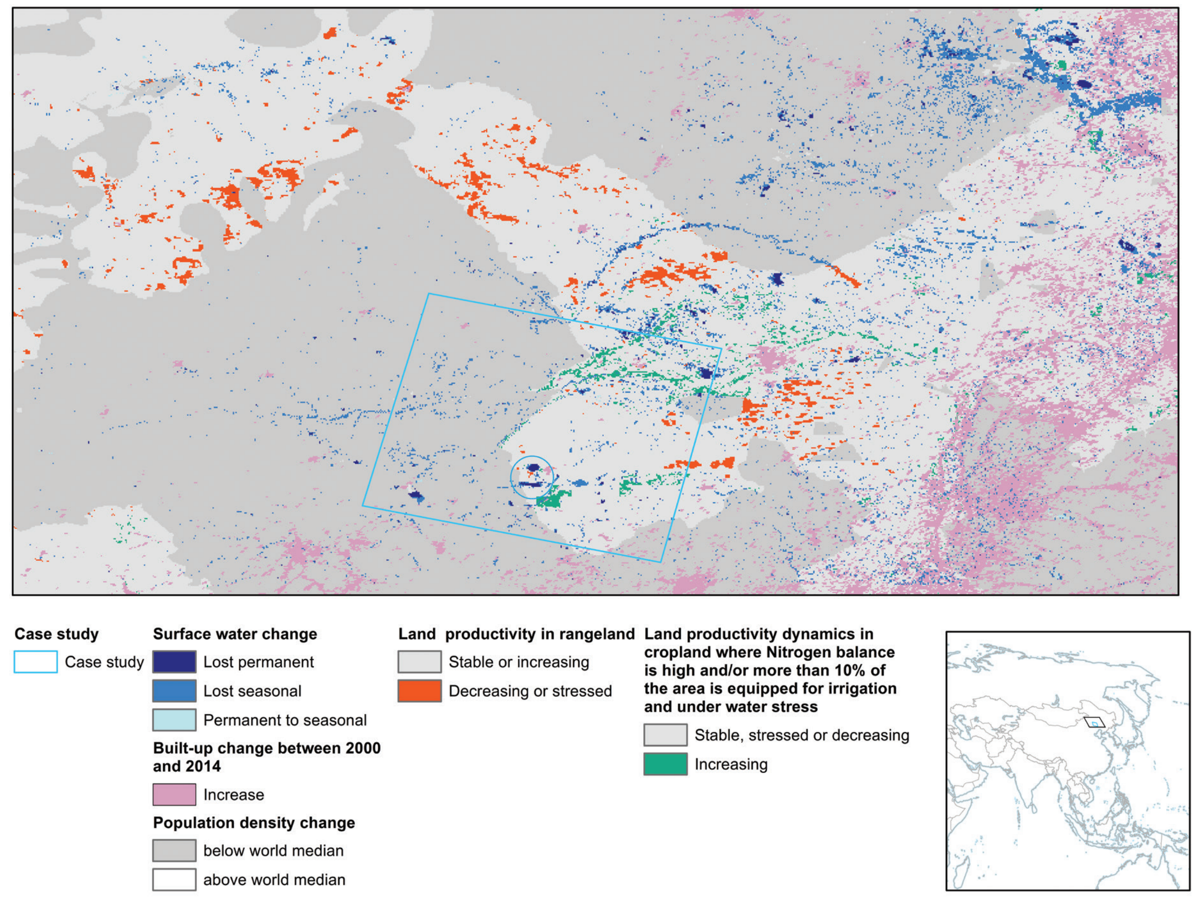

Traditionally, Horqin was home to Mongolian nomads.
Source: Hill, J.


Chinese immigrants into the Horqin area.
Source: Hill, J.

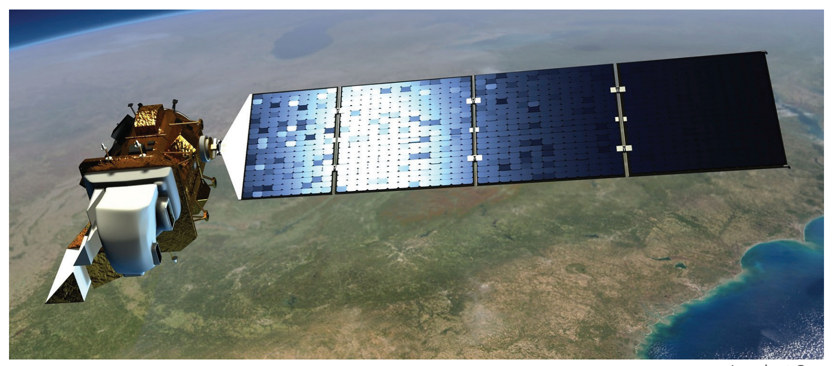
Earth observation data, such as from Landsat or Sentinel satellites, are in constant use for agricultural management, production forecasting and insurance, for land use and cover change, for forestry, water resource management, study of ecosystem services and functioning, for climate science and climate-change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

Satellite observations provide valuable surrogates linked to land-use changes, and can reveal conversions and modifications that connect to the condition of ecosystems. 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 × 30 m²) and length of observation of the imagery has made the Landsat archives an invaluable information source for science, management and policy development[9].

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[7].



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], GHSL[11], GPW v4[12], LPD (see page 114), Nitrogen balance on landscape[13], GMIA v5[14], Aqueduct 2.1[15].


Landsat 8.
Source: NASA

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 level[16].

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 %[16] (see graphs at the bottom of this page).

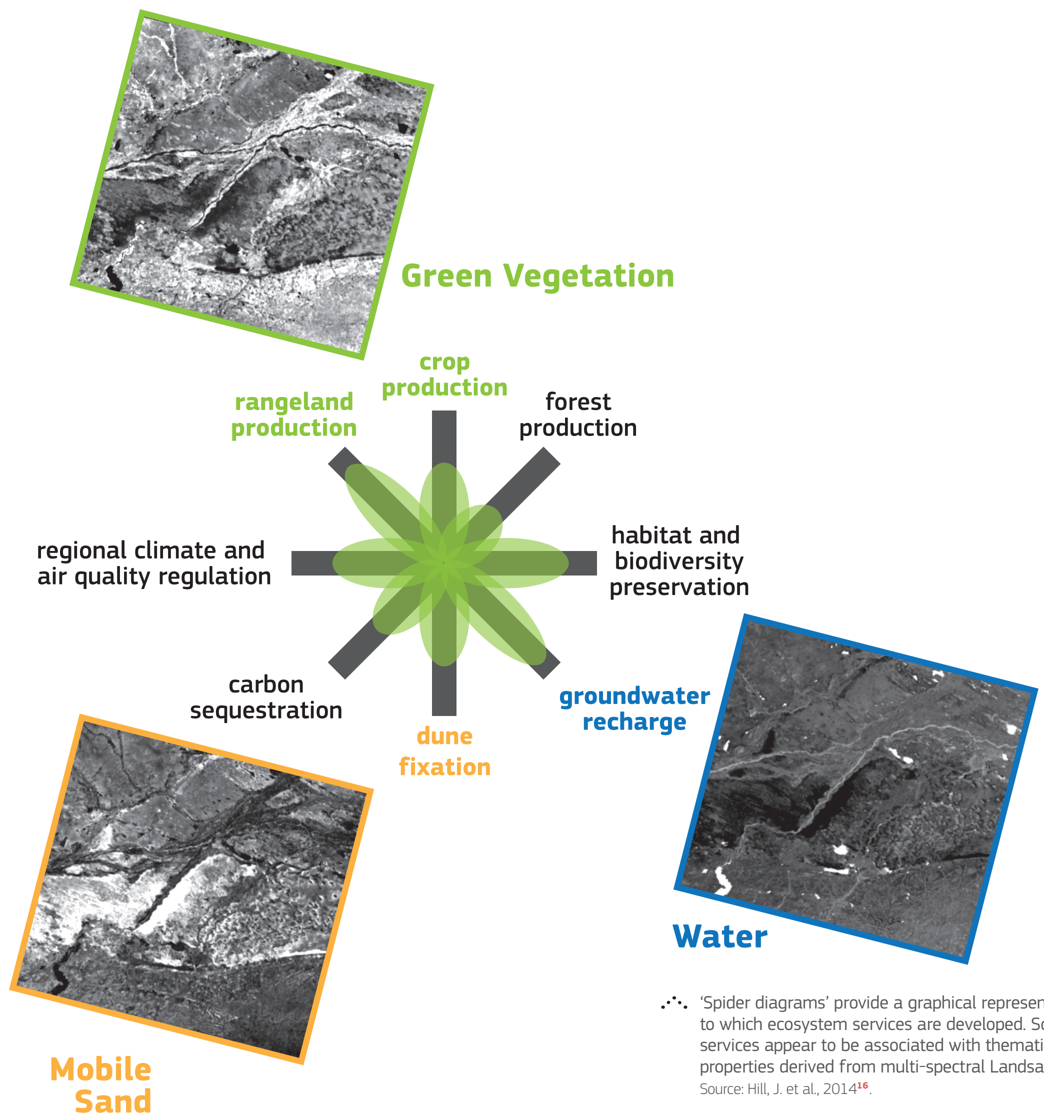
The observed changes in land-surface properties emerge from the consequences of new economic policies in the agricultural sector. Since then, the objective of improving rural livelihoods had been pursued by a combination of incentives aimed at increasing agricultural productivity, combined with enforced regulations directed towards protecting rangeland resources at risk[3, 8, 17, 18]. An important issue was to render agricultural production less dependent on climatic risks (i.e. 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 %), and the irrigated surface has grown from roughly 24 000 to 88 000 ha[19]. 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 in the remaining rangelands, where widespread areas with declining productivity prevail.

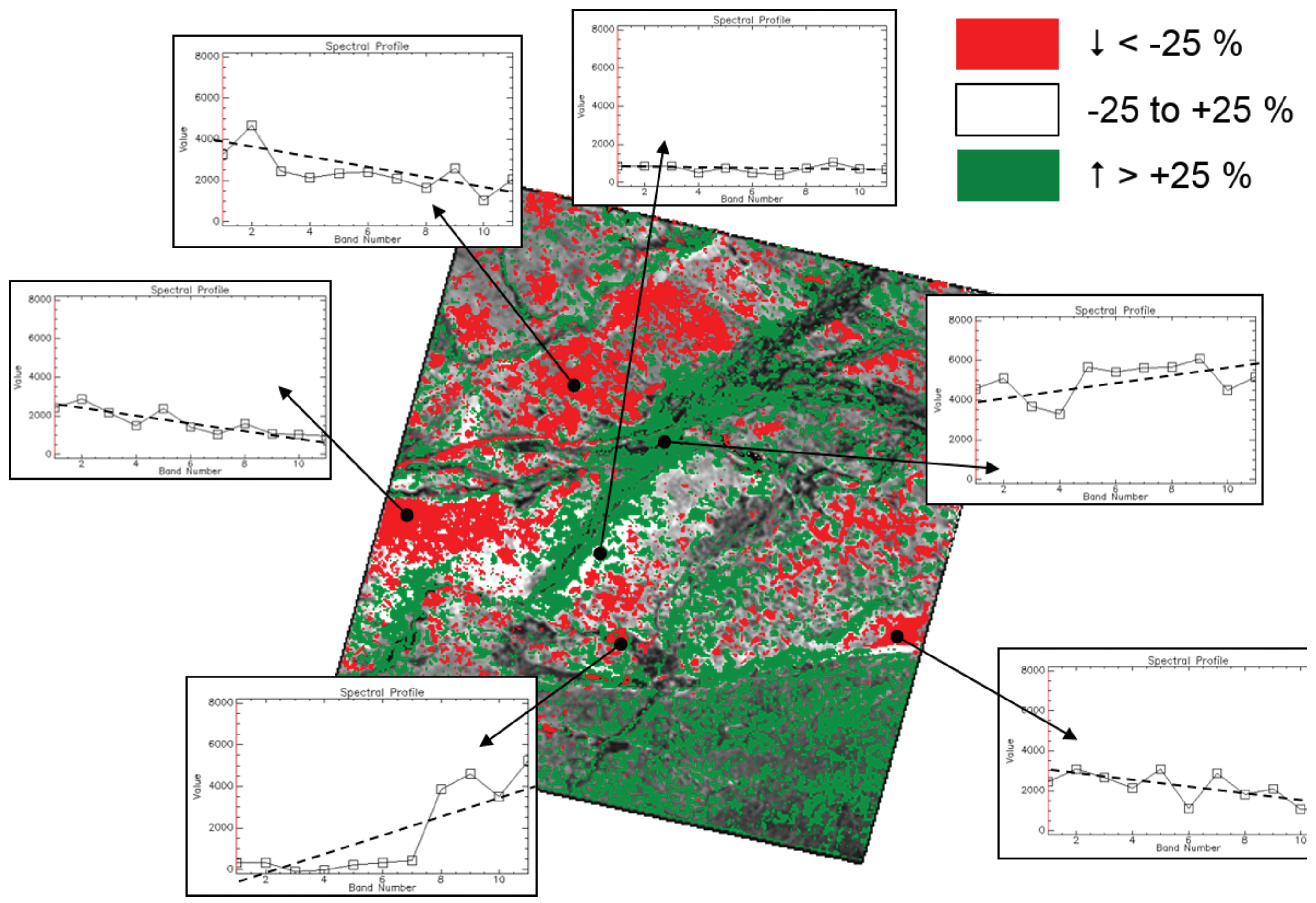
A synoptic representation of changes in ecosystem services[16] suggests that over the past 20 years the 'agricultural production' provisioning service was optimised at the cost of other services, primarily 'groundwater recharge' (see circular representation on the right). Cropland has been invading former 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 counteracts dune fixation and increases the availability of sand particles for dust storms).

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[7]. 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[20, 21]. 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[22]. 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.

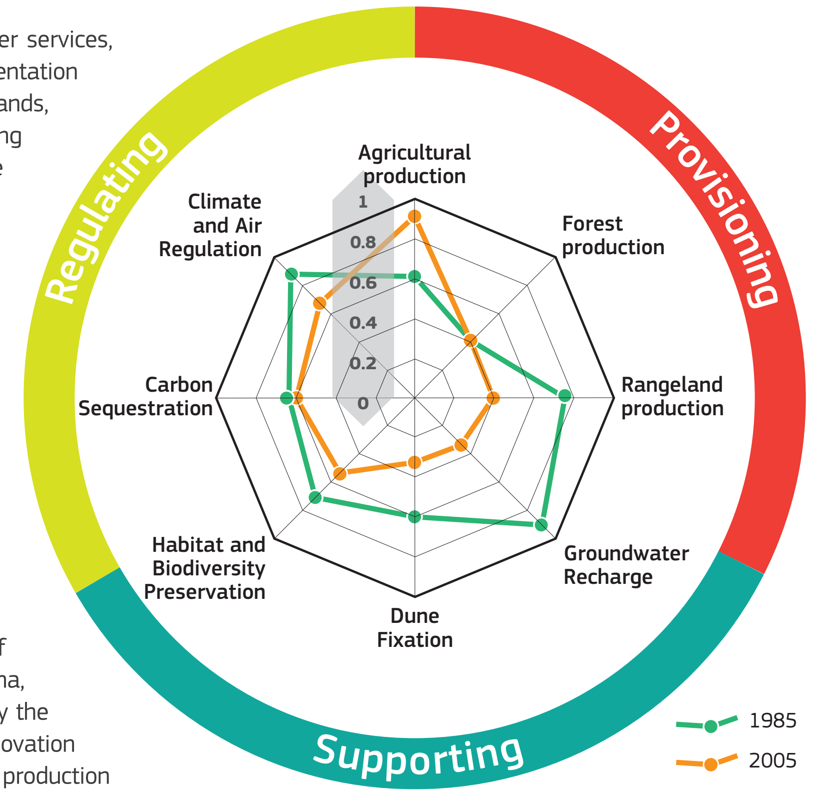


'Spider diagrams' provide a graphical representation of the extent to which ecosystem services are developed. Some of the ecosystem services appear to be associated with thematic layers of land-surface properties derived from multi-spectral Landsat observations.
Source: Hill, J. et al., 2014[16].

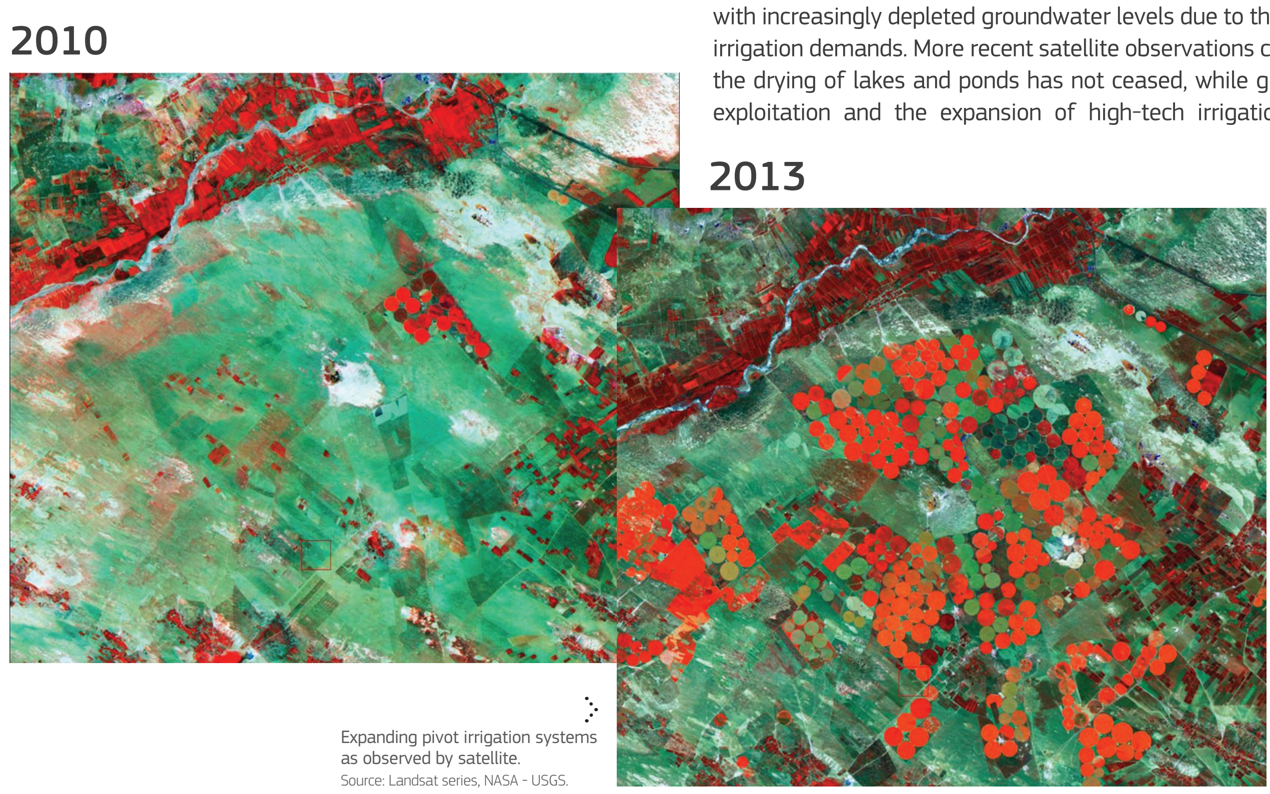
Increased water pumping for expanding irrigation cultivation in the Horqin sandy lands, China.
Source: Hill J.



Selected diagrams of a trend analysis of Landsat-derived estimates for the cover with green vegetation (GV). Positive GV trends relate to areas where the vegetation productivity increased throughout the observation period (1987-2007), and negative trends to areas where vegetation cover was reduced owing to various disturbance effects (e.g. shifting sands). Green and red colours indicate areas where the changing GV quantities exceeded a threshold of plus or minus 30 % of the value in 1987. The dashed lines are land-use strata, where R1, R2 and R3 indicate areas with predominant rangeland use, IA irrigated and RA rainfed cropland and R/A a mixture of farmland and grazing ranges.
Source: Hill, J. et al., 2014[16].



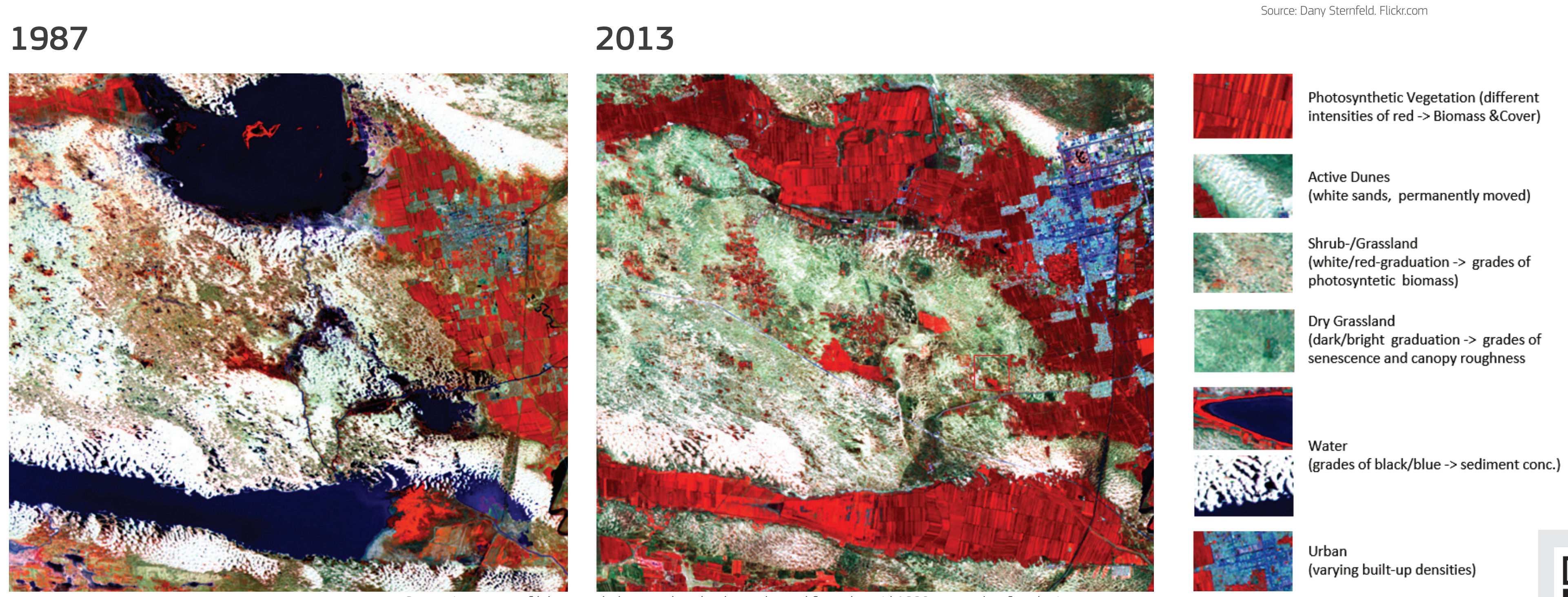
Observed trade-offs in ecosystem services linked to the intensification of agricultural cropping systems in the drylands of northern China.
Source: redrawn after Hill, J. et al., 2014[16].



Expanding pivot irrigation systems as observed by satellite.
Source: Landsat series, NASA - USGS.

More than 100 high-tech pivot irrigation systems were installed within only 3 years (2010-2013).

Pivot irrigation systems.
Source: Dany Sternfeld. Flickr.com



Successive retreat of lakes, ponds, bogs and wetlands accelerated from the mid 1990s onwards, after the impact of the excessive use of groundwater for irrigation purposes became evident. In 2013, approximately 30 years after the introduction of the new policies in the agricultural sector, important lakes have entirely disappeared and their former area has been converted to intensely managed cropland.
Source: Images from the Landsat satellite series, NASA - USGS.