Chapter 1: Framing and Context

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1.1 Executive summary

The current geographic spread of the human use of land, and the large and rapidly increasing appropriation of multiple ecosystem services are unprecedented in human history (*very high confidence*). Three-quarters of today's global, ice-free land surface is affected by human activities. The area of cropland, 12–14% of the land area, has increased by 15% since 1960 alone. Approximately 60–85% of the forested area is managed. Humans use one quarter to one third of terrestrial potential net primary production for food, fibre and energy (*high confidence*). In the past 50 years, global per capita food consumption increased by one fifth, consumption of dairy products and vegetable oils has almost doubled, meat consumption has almost tripled, and wood harvest has increased by one third. At the same time, global fertiliser use increased by 500%, and the world's irrigated cropland area roughly doubled (*high confidence*) with irrigation accounting for 70% of total human water use (*medium confidence*). There is large variability between countries in these global average trends, which reflects differences in wealth and degree of industrialization {1.2.2.2, 1.2.2.3, 1.3.1.4, 1.3.1.5}.

Human over-exploitation causes rapid depletion of land resources, which in future will be further exacerbated by climate change (*virtually certain*). The use of land and freshwater for food, fibre, timber and energy sustains our livelihood. Yet an estimated 821 million people are currently still undernourished, while conversion of tropical forest and savannahs into cropland continues, the rate of ecosystem degradation 5–10 million ha a^{-1}, agricultural intensification causes substantial water pollution and locally up to 75% of species have been lost. Large challenges exist in achieving more sustainable land and water use in view of continued population growth, accelerating demand for multiple ecosystem services and the increasing complexity in how the underlying socio-economic drivers interact (such as trade patterns, transportation, land ownership, urbanization or migration). These challenges will be exacerbated by detrimental climate change impacts in many regions (*high confidence*), which already reduce crop yields, freshwater availability and biodiversity (*high confidence)* {1.2.2.1, 1.2.2.3, 1.3.1.3, 1.3.1.4, 1.3.1.5, 1.4.4}.

Further inaction in the rapid reduction of anthropogenic greenhouse gas emissions raises the prospect of relying on drastic, land-based, climate change mitigation measures in order to achieve the Paris Climate Agreement (*high confidence*). This will jeopardise achievement of other sustainable development goals that depend on land-based, ecosystem services (*high confidence*). Mitigation costs increase with stringent mitigation targets and over time, with sources of uncertainty being the future availability, cost and performance of technologies or lags in decision making (*high confidence*). However, land management practices can contribute to emissions reductions (*high confidence*), with an estimated total equivalent up to 15–30% of today`s fossil fuel emissions achievable over the coming few decades (*medium confidence*). These measures can be cost-efficient if they account for the regional context. There is *very high confidence* that the measures to achieve these emission reductions would have co-benefits for soils, water use or biodiversity. The already existing large pressure on land ecosystems will with *high confidence* be further exacerbated if additional large-scale climate change mitigation efforts on land are enacted {1.3.2, 1.3.1, 1.2.2.3, 1.4.2.1}.

Adaptation strategies can produce mitigation co-benefits, promoting the effectiveness and feasibility of both adaptation and mitigation (*high confidence*). Adaptation is increasingly linked to societal resilience and to broader sustainable development goals. Adaptation is increasingly viewed as requiring shifts towards integrated and system-based governance approaches combining technology, economics and institutional innovations (*high confidence*). Many agricultural and forestry adaptation options have synergies with mitigation, including reduced soil erosion (which reduces carbon losses), reduced leaching of nitrogen and phosphorus (which maintains and enhances productivity), enhanced soil moisture (which also maintains or enhances productivity), or modification of microclimate. Combining both food production and consumption pathways for adaptation can also lower mitigation challenges and costs (*high confidence*) {1.4.4, 1.5}.

Given the increasing demands for land resources, land management to safeguard food and freshwater supply under a changing climate has by far the largest potential if, simultaneously, ambitious actions are also taken on the consumption side (*high confidence*). Land productivity can be enhanced sustainably in several ways including the promotion of crop genetic diversity, the preservation and protection of pollination services under climate change, soil management and conservation agriculture. Reduction of food waste and losses along the supply chain and on the consumer side (estimated as more than 30% of harvested materials), and shifts of diets towards a globally equitable supply of nutritious calories all have demonstrable positive impacts on land use (*high confidence*). Estimates of cost/efficient and sustainable greenhouse emissions reduction potential on land might be tripled (*medium confidence*) and pressure on the expansion of crop or pasture area substantially reduced (*high confidence*) or even reversed (*medium confidence*) if food demand-side measures are also taken {1.4.1, 1.4.2}.

If sustainability criteria are considered in the global trade of land and land-based commodities, this can reduce local vulnerabilities to climate and socio-economic changes (*high confidence*). Large differences exist between world regions in food production, degree of desertification and degradation, and recovery from past over-use. Both local action and global trade in agricultural and forestry commodities can enhance local food, timber or bioenergy supply and thus also contribute to food security and land restoration (*very high confidence*). Trade offers many opportunities, but can lead to land use displacement, if changes in demand for food, timber or bioenergy in one region are met from unsustainable production elsewhere, with unintended side-effects on biodiversity loss and supply of ecosystem services in the displaced production areas (*high confidence*). Unintended side-effects also include large-scale change in land ownership which can threaten local communities' land rights (*medium confidence*). Ecosystem services and societal impacts embodied in trade need, therefore, to be considered in the assessment of sustainable land management, mitigation and adaptation, the associated costs of these actions and the implications for decision making {1.3.1.5, 1.4.1, 1.4.2, 1.3.1}.

The response to climate change can be facilitated by cross-sectoral policies, that account for systemic understanding and multiple actors, including indigenous and local knowledge (*high confidence*). As food, energy and water security rank high on the Agenda 2030 for Sustainable Development, the promotion of synergies between sectoral policies is seen as effective strategies necessary to mitigate against the challenges of climate change, and to bring greater coordination among actors (policy makers, private actors, and land managers). Appropriate approaches include implementation of systemic, nexus approaches such as the socio-ecological systems (SES) frameworks applied to analyse how institutions affect human incentives, actions and outcomes. Adaptation or resilience pathways using the SES framework require the inclusion of indigenous and local knowledge for trust building for effective collective action. Alternatives to the sector-specific governance of natural resource use and context specific actions at regional and sub-regional levels can enhance land use in an overall fair and equitable way, with climate change mitigation, or adaptation being positive side-effects {1.5}.

Decision makers are faced with the task of developing and implementing climate policies informed in part by incomplete information, with unknowns and uncertainty to varying degree. Advances in futures analysis and modelling that better account for full environmental costs and non-monetary values in human behavioural processes would provide a more complete knowledge base for decision making (*high confidence*). Differences in land use change scenarios arise as much from variations in present-day baseline datasets, thematic land cover classes and modelling paradigms as they do from socio-economic assumptions underpinning scenarios (*medium confidence*). The most commonly used approach to represent decision-making in global scenarios is through economic optimization. This limits the capacity of global models to account for the human dimensions of land systems including equity, fairness, land tenure and the role of institutions and governance, and therefore the use of these models to quantify transformative pathways, adaptation and mitigation (*high confidence*). Pathways analysis to evaluate how desirable futures (i.e., climate change mitigation targets, SDGs) might be achieved in practice is highly relevant in support of policy, since it outlines sets of possible actions and decisions. The identification of societal and environmental co-benefits and trade-offs as part of pathways analysis implies the need to consider the wider environmental and societal aspects when exploring uncertain futures (*high confidence*).

1.2 Introduction and scope of the report

1.2.1 Objectives and scope of the assessment

Land provides the basis for our livelihoods through the supply of food, freshwater, multiple other ecosystem services and biodiversity (see Cross-Chapter Box 7: Ecosystem services, Chapter 7) (Mace et al. 2012; Hoekstra and Wiedmann 2014; Newbold et al. 2015; Runting et al. 2017; Isbell et al. 2017). Enhancing food security and reducing malnutrition whilst also reversing desertification and degradation are fundamental societal challenges that are being increasingly aggravated by the need to both adapt to and to mitigate against climate change impacts (FAO, IFAD, UNICEF, WFP and WHO, 2018). Climate change will exacerbate further the diminishing land and freshwater resources and biodiversity loss, which will intensify societal vulnerabilities, especially in regions where economies are highly dependent on natural resources as the basis.

Land use is a significant net contributor to greenhouse gas emissions and climate change (Ciais et al. 2013a; Smith et al. 2014; Tubiello et al. 2015; Le Quere et al. 2018). Yet land use is increasingly discussed as providing part of the solution to climate change. A range of different climate-change mitigation options on land are being debated, as well as their environmental and societal implications (Humpenoder *et al.*, 2014; Bonsch et al. 2016; Mouratiadou et al. 2016; Kreidenweis et al. 2016; Griscom et al. 2017a; Sanz-Sanchez et al. 2017; Meyfroidt 2018; Rogelj et al. 2018a)(see Chapter 6). Land plays a prominent role in many of the Nationally Determined Contributions (NDCs) of the parties to the UNFCCC Paris Agreement. In the current NDCs, the relative emission reductions from land-related activities by 2030 sum up to approximately one quarter of the planned total reductions (Forsell et al. 2016; Grassi et al. 2017). By 2023, progress on the NDCs will be reviewed. Within the United Nations Agenda 2030 for Sustainable Development, action on land is indispensable to achieve many of the Sustainable Development Goals (SDGs), such as SDG 13 (Climate Action), SDG 15 (Life on Land), SDG 2 (Zero Hunger), and many others.

The Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL) provides the opportunity to integrate the current state of the scientific knowledge on the issues specified in the report’s title (see also Figure 1.1). This knowledge is assessed in the SRCCL in context of the Paris Agreement, but many of the aspects addressed concern also other international conventions such as the United Nations Convention on

Biodiversity (UNCBD), the UN Convention to Combat Desertification (UNCCD), and the UN Agenda 2030 and its SDGs. The SRCCL is the first in which land is central, since the IPCC Special Report on land use, land-use change and forestry (Watson et al. 2000)(see also Box 1.1). The main objectives are to:

1) Assess the current state of the scientific knowledge on climate change and land interactions and related processes;
2) Evaluate the impacts of human-directed drivers and their interactions with climate change on land degradation, desertification and food security;
3) Outline different land-based response options to GHG mitigation, evaluate their feasibility, and assess the potential synergies and trade-offs with land ecosystem services.
4) Examine adaptation options to tackle land degradation, desertification, build resilient food systems under a changing climate, and evaluate the synergies and trade-offs between mitigation and adaptation. Delineate the policy, governance and other enabling conditions to support climate mitigation, land ecosystem resilience and food security in the context of risks, uncertainties and remaining knowledge gaps.

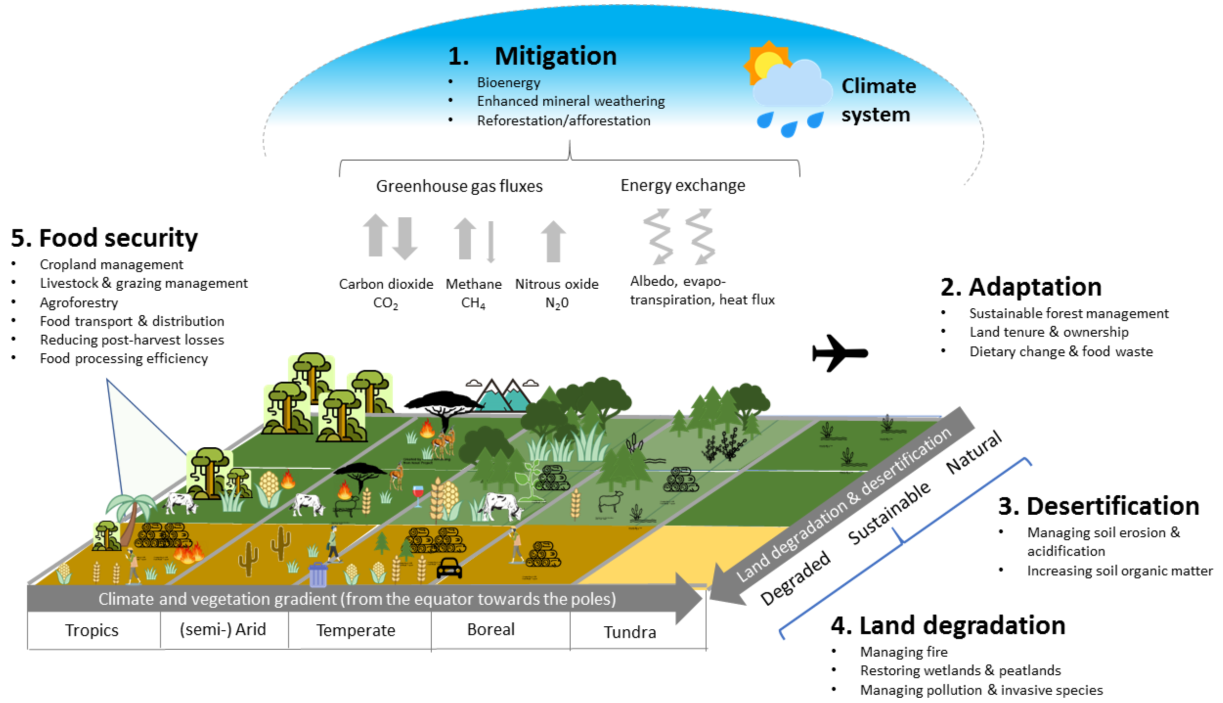


Figure 1.1 A representation of the principal land challenges and land-climate system processes covered in this assessment report. The figure shows a stylised set of landscapes that reflect a generalised climate and vegetation gradient from the equator towards the poles. Each segment shows a specific climatic zone that is consistent with different biomes (ecosystem types) and which are determined by the location along the gradient: tropics, (semi-)arid, temperate, boreal and tundra. The vegetation to the rear of the stylised landscape represents 'pristine' ecosystems (i.e. little or no human intervention), which become increasingly degraded and desertified at the front of the landscape arising from increased human pressures. The loss of ecosystem function toward the front is also concurrent with a decline in soil quality from the rear to the front of the landscape. The five 'land challenges' covered by this assessment (climate mitigation, adaptation, desertification, land degradation and food security) are shown and also relate to the types of response options that are relevant to them. The figure also demonstrates the key relationships between the land surface and the climate system. This includes greenhouse gas fluxes (principally CO$_2$, N$_2$O, CH$_4$) and energy exchanges between the land surface and the climate system through biogeophysical effects (albedo, evapotranspiration and heat flux, which primarily affect regional climates).The figure encapsulates the range of challenges and processes that are addressed by this assessment, reflecting these as the problems to be addressed through different response options and policy actions

Despite the uncertainties regarding the remaining permissible cumulative CO_2 emissions that are consistent with a warming of well below 2ºC (Rogelj et al. 2018a), *confidence is very high* that the window of opportunity (period when significant change can be made; see Chapter 7) for reversing current fossil fuel consumption is rapidly narrowing (Schaeffer et al. 2015; Riahi et al. 2015; Bertram et al. 2015; Millar et al. 2017; Rogelj et al. 2018a). Annual greenhouse gas emissions continue to increase unabatedly. In order to meet the Paris goals rapid actions are required across the energy, transport, and agricultural sectors, factoring in also human population growth (Wynes and Nicholas 2017; Le Quere et al. 2018). Land-based mitigation can offer realistic and powerful options, if these at the same time are being considered against several development and national priorities, not least energy and food security, conservation, and pollution control (Pereira et al. 2010; Harvey and Pilgrim 2011; Zhang et al. 2015; Crist et al. 2017; Meyfroidt 2018).

This report will provide evidence to enable policy decision makers to reconfigure potential future development pathways in which land can provide several fundamental needs to humanity, including climate regulation, food, water, energy, and maintaining biodiversity. The SRCCL takes up the unique opportunity to address land-related challenges and response-options in an integrative way, thus being of cross-sectoral policy relevance. In context of the stated objectives, Chapter 1 provides a synopsis of the issues addressed in this report, which are substantiated in Chapters 2–7 (see 1.6).

Box 1.1 Land in previous IPCC and other relevant reports

Previous IPCC reports have made reference to land and its role in the climate system. Threats to agriculture and forestry, but also the role of land and forest management as a contributor to climate change have been documented since the IPCC Second Assessment Report with increasing focus, and especially so in the Special report on land use, land-use change and forestry (Watson et al. 2000). Compared to these previous IPCC reports, the SRCCL offers a more integrated analysis as it embraces multiple direct and indirect drivers of natural resource management (related to food, water and energy securities) which have not received sufficient analysis previously (e.g., in the AR5). The recent IPCC 1.5 degree special report targeted specifically the Paris Agreement, without exploring the possibility of future global warming trajectories above 2ºC, and with climate change clearly at its centre (IPCC 2018). In the FAO reports, land degradation is discussed in relation to ecosystem goods and services, and land degradation is analysed principally from a food security perspective (FAO and ITPS 2015). The SRCCL also looks at land degradation from a human food security perspective and refers to the strong correlations between land degradation and poverty. It looks at incentives related to market, institutions that can trigger positive impacts between climate change, food access and biophysical drivers. The UNCCD report (2014) discusses land degradation from the prism of desertification. It devotes due attention to analyses on how land management can contribute to reversing the negative impacts of desertification and land degradation. The IPBES assessment (2018) combines biodiversity drivers, land degradation and desertification, focussing on poverty as a limiting factor, drawing attention to a world in peril in which resource scarcity conspires with biophysical and social vulnerability drivers to derail the attainment of sustainable development goals.

The SRCCL complements these previous assessment reports, while keeping the IPCC-specific “climate lens”. As the SRCCL is cross-policy it provides the opportunity to address a number of challenges in an integrative way at the same time, and it progresses beyond other IPCC reports in having a much more comprehensive perspective on land.

1.2.2 Status of (global) land use and the role of land in the climate system

1.2.2.1 Land ecosystems and climate change

Land ecosystems play a key role in the climate systems, due to their large carbon pools and carbon exchange fluxes with the atmosphere (Ciais et al. 2013b). Land use, that is the sum of human activities and arrangements aimed at harnessing services provided by terrestrial ecosystems, considerably alters terrestrial ecosystems, by changing land cover, or by changing ecosystem properties within land cover types via land management. After industry, land use is currently the largest source of anthropogenic greenhouse gas emissions (Page et al. 2011;Bodirsky et al. 2012; Ciais et al. 2013; Smith et al. 2014; Shcherbak et al. 2014; Guillaume et al. 2016; Arneth et al. 2017;Le Quere et al. 2018)(see also Chapter 2). An estimated up to 25% of total anthropogenic emissions of the greenhouse gases methane (CH_4) and nitrous oxide (N_2O), and approximately 10% of CO_2 emissions arise mainly from deforestation, ruminant livestock and fertiliser application (Ciais et al. 2013a; Smith et al. 2014; Tubiello et al. 2015; Le Quere et al. 2018)(see also 1.3.1.4). There is *very high confidence* that greenhouse-gas reduction measures in agriculture, livestock management and forestry have substantial benefits for biodiversity and ecosystem services beyond climate regulation, but the magnitude of cost-efficient emission reductions remains unresolved (1.5–5, or even 11.3 Gt CO_2-eq a^{-1} (Smith et al.2013a, 2014b; Griscom et al. 2017a)).

Land ecosystems do not only respond to direct land-use, but also to changes in environmental conditions such as increasing atmospheric CO_2 concentration, or prolonged growing season in cool environments. In consequence, land also serves as a large carbon dioxide sink (Ciais et al. 2013; Canadell and Schulze 2014; Zhu et al. 2016; Le Quere et al. 2018;). Whether or not this sink will persist in future is one of the largest uncertainties in carbon cycle and climate modelling (Ciais et al. 2013; Friend et al. 2014; Bloom et al. 2016; Le Quere et al. 2018). In addition, vegetation cover changes (such as conversion of forest to cropland or grassland, and vice versa) can result in regional cooling or warming through altered energy and momentum transfer between ecosystems and atmosphere. The regional impacts can be substantial, but the sign of the effect depends on the geographic context (Lee et al. 2011; Zhang et al. 2014; Alkama and Cescatti 2016)(see also Chapter 2).

Climate change affects land ecosystems in various ways. Natural biome boundaries shift in response to warming. In addition, as a result of atmospheric CO_2 increases woody cover increases in semi-arid regions (Donohue et al. 2013; Wärlind et al. 2014; Davies-Barnard et al. 2015). Habitat shifts, together with warmer temperatures, enhances pressure on plants and animals (Pimm et al. 2014; Urban et al. 2016). Warming, in particular when combined with soil moisture deficit, can reduce yields in areas that already today are under heat and water stress (Schlenker and Lobell 2010; Lobell et al. 2011,2012; Challinor et al. 2014)(see also Chapter 5). At the same time, warmer temperatures can increase productivity in cooler regions (Moore and Lobell 2015) and might open opportunities for crop areas to expand into new regions (Pugh et al. 2016). Increasing atmospheric CO_2 increases productivity and water use efficiency in most of the world’s staple crops and in forests (Muller et al. 2015; Kimball 2016), whereas the increasing number of extreme weather events linked to climate change result in yield losses (Deryng et al. 2014; Lesk et al. 2016), and hence impact food prices. Heat waves and droughts are also weather conditions prone to wildfires (Seidl et al. 2017; Fasullo et al. 2018), and all weather extremes impacts local infrastructure and hence transportation and trade of land-related goods (Schweikert et al. 2014; Chappin and van der Lei 2014). Cleary, various adaptation measures are required to reduce these adverse impacts on land (see 1.4.4).

1.2.2.2 Current land use patterns

Around three quarters of the global 130 Mkm^2 ice-free land, and most of the highly-productive land area by now are under some sort of land use (Ellis et al. 2013; Luyssaert et al. 2014; Erb et al. 2016a; Venter et al.

2016; Erb et al. 2017)(see Table 1.1, *robust evidence*, *high agreement*). Agriculture, the sum of cropland and pastures, represents the largest land-use categories (total ca. 43–53 Mha, Table 1.1), about 70% of which is used for livestock production (i.e. including feed cereals on cropland) (Foley et al. 2011; Herrero et al. 2013; Mottet et al. 2017). Natural grasslands and savannas are with 40% of the ice-free terrestrial surface the largest global land-cover type, but it is estimated that a considerable fraction (about 85%) of these areas are under some land use, mainly for livestock grazing (*medium confidence*, Newbold et al. 2017; Stevens et al. 2017; Erb et al. 2018).

Forests cover 40 Mha, but considerable uncertainties relate to estimates of their (and of natural grasslands and savannahs) extent, due to discrepancies of definition (Putz and Redford 2010; Luyssaert et al. 2014; FAO 2015a; Schepaschenko et al. 2015; Birdsey and Pan 2015; Chazdon et al. 2016a; Erb et al. 2017; FAO 2018). Globally, 60–85%, and virtually all of temperate and southern boreal forests are under some form of use or management (Luyssaert et al. 2014; Birdsey and Pan 2015; Morales-Hidalgo et al. 2015; Potapov et al. 2017; Erb et al. 2018), 5–7% of managed forests are intensive plantations (Birdsey and Pan 2015; Erb et al. 2016a). Mining, although with 0.3–0.8 Mkm^2, and infrastructure with 0.7–1.6 Mkm^2, are both almost negligible in terms of global area coverage (Allen and Pavelsky 2018), represent a particularly pervasive land-use activities, with far-reaching ecological, social and economic implications (Cherlet et al. 2018). The globally large imprint of humans on the land surface has led to the definition of anthromes, that is, human systems with natural ecosystems embedded within them, forming ‘anthropogenic biomes’ (Ellis and Ramankutty 2008; Ellis et al. 2010).

The intensity of land use varies hugely within and among different land use types and regions. At the global level average, around 10% of the total ice-free land surface was estimated to be under intensive management, two thirds under moderate and the remainder under extensive management (Erb et al. 2016a). Practically all cropland is fertilised, albeit with large regional variation (Erb et al. 2016a). With an estimated 2200–3800 $\mathrm{km}^3\ \mathrm{a}^{-1}$, irrigation is responsible for 70% of ground- or surface water withdrawals by humans (Wisser et al. 2008; Chaturvedi et al. 2015; Siebert et al. 2015; FAOSTAT 2018). Human societies appropriates one quarter to one third of the total potential net primary production, i.e. the NPP that would prevail in the absence of land use (estimated at about 60 $\mathrm{PgC\ a}^{-1}$; Bajželj et al. 2014; Haberl et al. 2014). The total of agricultural biomass harvest (from cropland and grazing land) in the early 21st century is estimated at 6 $\mathrm{PgC\ a}^{-1}$, around 50–60% of it is consumed by livestock, forestry harvest amounts to about 1 $\mathrm{PgC\ a}^{-1}$ (*high confidence,* (Haberl et al. 2014; Smith et al. 2014; Alexander et al. 2017c; Mottet et al. 2017).

Table 1.1 Extent of global land use and management around the year 2015

LAND COVER / LAND USE IN 2015	*Mkm2*			*% of global ice-free land*			
	Low	*High*	*Best estimate*	*Low*	*High*	*Best estimate*	
Ice-free land surface	**130,00**	**130,00**	**130,00**	**100,0**	**100,0**	**100,0**	
URBAN & BUILT-UP LANDS	**0,66**	**0,73**	**0,73**	**0,5**	**0,6**	**0,6**	(1,2, 3)
AGRICULTURAL LANDS, TOTAL	**43,93**	**51,57**	**48,70**	**33,8**	**39,7**	**37,5**	
Of which, agricultural land (cropland / pastures) with trees cover (low: >30%, high: >10%)	3,74	10,12	3,74	2,9	7,8	2,9	(4)
Of which, smallholder agricultural land in developing countries			5,87			4,5	(5)
CROPLAND	**15,93**	**18,80**	**15,93**	**12,3**	**14,5**	**12,3**	(6)
Of which, cropland with multicropping			3,82			2,9	(7)
Of which, cropland without multicropping			8,32			6,4	(7)
Of which, temporary fallow			3,79			2,9	(7)
Of which, paddy rice cropland equipped for irrigation			0,66			0,5	(8)
Of which, other cropland equipped for irrigation			2,45			1,9	(8)
Of which, cropland not equipped for irrigation			12,82			9,9	(8)
Of which, cropland with >100 kg N fertilisers/ha:			1,74			1,3	(9)
Of which, cropland with 50–100 kg N fertilisers/ha:			3,50			2,7	(9)
Of which, cropland with 5–50 kg N fertilisers/ha:			7,46			5,7	(9)
Of which, cropland with <5 kg N fertilisers/ha:			3,23			2,5	(9)
PASTURES	**28,00**	**32,77**	**32,77**	**21,5**	**25,2**	**25,2**	(6)
Intensive pasture (>100 animals/km2)			2,58			2,0	(10)
Extensive pasture (Total pasture – Intensive pasture)			30,19			23,2	(11)
FORESTS	**33,34**	**42,47**	**39,99**	**25,6**	**32,7**	**30,8**	(12)
Forests managed for wood production			**28,10**	**0,0**	**0,0**	**21,6**	
Planted forests			2,79			2,1	(13)
Natural forest under formal forestry use (timber extraction)			20,54			15,8	(13)
Natural forest under other uses, including illegal / informal logging and fuelwood collection			4,77			3,7	(11)
Forested wilderness / primary forest	11,72	11,89	11,89	9,0	9,1	9,1	(14)
OTHER NON-FORESTED LAND	**52,08**	**35,23**	**40,58**	**40,1**	**27,1**	**31,2**	
Of which, potentially productive under rainfed agriculture & unforested	1,38	4,45	1,38	1,1	3,4	1,1	(15)
Other land affected by management / human activities (very extensive / rough / seasonal grazing, fires, hunting, fuelwood collection outside forests, wild products harvesting, …)	42,46*	25,6*	30,96	32,7	19,7	23,8	(11)
Non-forested wilderness (unused / undisturbed) land	9,62	9,62	9,62	7,4	7,4	7,4	(16)

* this is the residual category (difference of total land area and all other data) which results in a swap of low and high estimates

Note: This table is based on data and approaches described in (Lambin and Meyfroidt 2011, 2014); Luyssaert et al. 2014; Erb et al. 2016a), and references below. The target year for data is 2015, but proportions of some subcategories are from 2000 (the year with still most reconciled datasets available) and were scaled to the extent of the broad land use category for 2015. Sources: (1): (Luyssaert et al. 2014); (2) (Lambin and Meyfroidt 2014); (3) Global Human Settlements dataset, https://ghsl.jrc.ec.europa.eu/ ; (4): (Zomer et al. 2016); (5): (Samberg et al. 2016); (6): Low: (FAOSTAT 2018), high: (Erb et al. 2016a); (7): Proportions estimated from (Portmann et al. 2010) for 2000, scaled to 2015 cropland extent; (8) Proportions estimated from (Siebert et al. 2015) and (Portmann et al. 2010), scaled to 2015 cropland extent; (9): Proportions estimated from Potter et al. 2010 for 2000, scaled to 2015 cropland extent; (10): (FAO's Animal Production and Health Division); (11): Residual category (difference of total ice-free land surface and all other estimates; (12): Low: (Song et al. 2018); high: (FAO 2015a) corrected with (Bastin et al. 2017) for drylands; (13) (FAO 2015a); (14): Low: Primary forest in (FAO 2015a); high: Intact Forest Landscape from (Potapov et al. 2017); (15): (Lambin et al. 2013; Lambin and Meyfroidt 2014); (16): (Erb et al. 2016a).

1.2.2.3 Past and ongoing trends

Globally, the area of cropland is estimated to have increased by 70–85% (Krausmann et al. 2013; Goldewijk et al. 2017;) over the last century, by 15% since 1960 alone, and is still expanding at a rate of about 0.03 Mkm² (0,2%) per year (FAOSTAT 2018). Since the early 1970s, per capita calorie consumption has increased by 17% (Kastner et al. 2012), with pronounced changes in diet composition: dairy products and vegetable oils has almost doubled, while meat consumption has almost tripled (FAO 2017). Livestock production plays a pivotal role in cropland expansion, causing 50–65% of cropland change (Kastner et al. 2012;). Cereal yields increased nearly linearly over the last six decades, with emerging signs of reduced growth rates or stagnation (*medium confidence*) on large cropland areas (Lin and Huybers 2012; Ray et al. 2012; Elbehri, Aziz, Joshua Elliott 2015; Alexander et al. 2015). In the past 50 years, the world's irrigated cropland area roughly doubled, while global fertiliser use increased by 500% (Foley et al. 2011; Siebert et al. 2015). As a result of shifting towards industrialised livestock systems, the area classified as permanent pasture and grazing land has more or less stabilised (Goldewijk and Verburg 2013; Goldewijk et al. 2017). Urban and other infrastructure areas (Seto et al. 2012a; Friis et al. 2016; Friis and Nielsen 2017) have expanded by a factor 5 since 1910 (Krausmann et al. 2013), resulting in disproportionally large losses of highly-fertile cropland (Seto and Reenberg 2014; Martellozzo et al. 2015; Bren d'Amour et al. 2016; Seto and Ramankutty 2016; van Vliet et al. 2017).

Wood harvest increased by 30% since 1970, on shrinking forest areas (FAOSTAT 2018). Deforestation and conversion of natural forests to plantations continues especially in tropical regions (Gibbs et al. 2010; Hansen et al. 2013; Sloan and Sayer 2015; FAO 2018; Song et al. 2018b). Secondary forests and forest plantations increase mainly in the Northern Hemisphere, but these gains do not compensate for forest losses. All assessments of forest area suggest global net-loss of forest area in the last decades, whereas tree-cover change studies revealed a net gain (Song et al. 2018), with discrepancies due to differences between classifications of forest (Keenan et al. 2015), and discrepancies between remote sensing products (Song et al. 2018; Li et al. 2018a). Conversion of natural lands includes tropical dry woodlands and savannahs, for instance, about 50% of Brazilian Cerrado has been transformed to agriculture and pastures (Lehmann and Parr 2016). Large pressure has also been exerted on the South-American Catinga and Chaco regions (Parr et al. 2014a; Lehman and Parr 2016). African savannahs have been proposed to follow a similar tropical agricultural revolution pathway in order to enhance agronomical prosperity (Ryan et al. 2016).

The land-use and forestry trends are also associated with strong declines in local plant and animal species richness and abundance, in particular in areas of high-intensity land-use (Paillet et al. 2010; Newbold et al. 2015; Wilting et al. 2017). Global biodiversity loss from land-use change has been estimated around 10%, and locally impacts are as high a loss of 75% (Newbold et al. 2015). Large human appropriation of net primary productivity can lead to an irreversible decline in heterotrophic organisms at various trophic levels, especially in low productive regions (Newbold et al. 2018). Likewise, projected losses of species diversity rapidly increases with increasing temperatures (Settele et al. 2014; Urban et al. 2016; Scholes, et al., 2018; Fischer et al. 2018). Whether or not earth`s biota has entered a sixth mass extinction, it is clear that current extinction rates are far above background rates and that ecosystem restoration will be challenging from a species and functional diversity perspective (Pimm et al. 2014; Ceballos et al. 2015; De Vos et al. 2015).

This historically unprecedented and accelerating human appropriation of land resources, and its large regional variation pose large challenges for land management in future (see Figure 1.2).

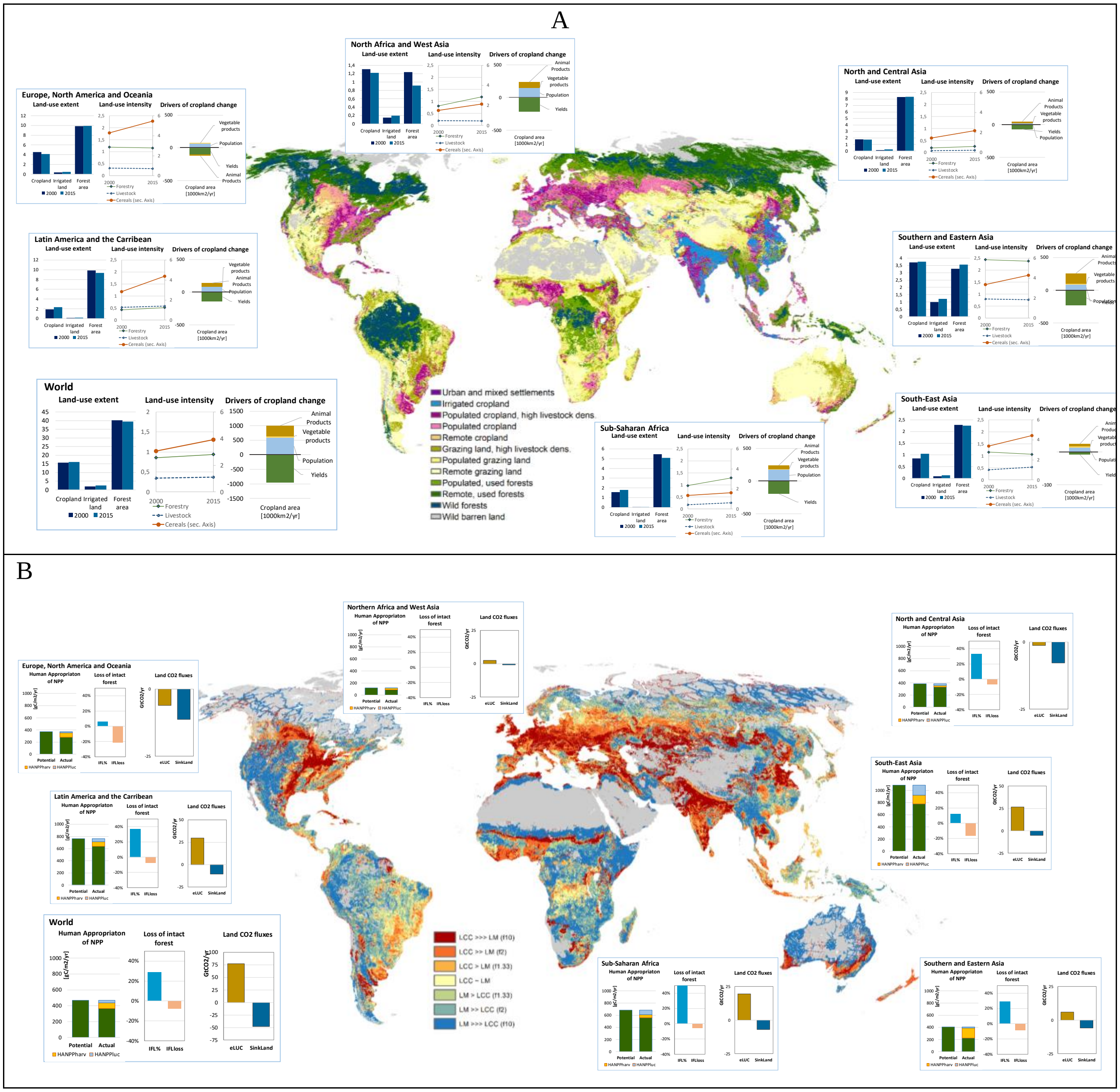


Figure 1.2 Status and trends in the global land system (note: maps will be revised for the final draft). A. Spatial patterns and major trends of the global land systems. The map show the spatial pattern of land systems and is derived from a combination of Anthromes (Ellis and Ramankutty 2008; Ellis et al. 2010), with livestock systems (FAO's Animal Production and Health Division; Nachtergaele 2008). The inlay figures

summarise key trends in the land systems and their drivers. Land-use area change between 2000 and 2015is displayed in Mkm² = 10^6 km²) and land-use intensity is expressed with three indicators: cereal yields measured in t/ha/year, forest harvest in m³/ha, and livestock density in Livestock Units per ha; all data (FAOSTAT 2018). Major drivers of the change in cropland area for food production, are expressed as annual average change of cropland in 10^3 km² between 1994 and 2011 (Alexander et al. 2015). B. Land management and land-cover conversion impacts on the Earth system processes. The maps shows the ratio of land management to land cover conversion impacts on biomass stocks (Erb et al. 2018). LCC denotes effects of land-cover conversions (changes of land cover types) caused by land use, LM effects of land management (changes within the same land cover type caused by management), and depict areas dominated by land-management or land-cover conversion impacts. The inlay figures show the regional pattern in the global Human Appropriation of Net Primary production (HANPP), the loss of intact forests and carbon fluxes in the land ecosystems. HANPP is defined as the potential NPP (NPP that would prevail in the absence of land use, but with current climate, left column) minus the combined effect of land-use induced NPP changes ($HANPP_{luc}$) and biomass harvest ($HANPP_{harv}$) (Haberl et al. 2014; Krausmann et al. 2013) that allow to calculate the amount of NPP remaining in ecosystems after human land use (right column). The data on intact forest (IFL) refers to forests and associated natural treeless ecosystems with no remotely detected signs of human activity or habitat fragmentation and large enough to maintain native biological diversity (Potapov et al. 2017). The extent of IFL refers to the year 2013, the loss of IFL refers to the change between 2000 and 2013, in percent of the IFL in the year 2000. Two CO_2 fluxes between land ecosystems and the atmosphere are displayed: the CO_2 land use flux due to land conversions and forest management, as well as the CO_2 land sink caused by the indirect anthropogenic effects of environmental change (e.g., climate change and the fertilising effects of rising CO_2 and N concentrations) on unmanaged lands. The land-use induced sink is the average of two bookkeeping models, the land sink due to environmental change represents the mean of seven dynamic vegetation models presented in the Global Carbon Budget (Le Quéré et al. 2018)

1.3 Key challenges related to land use change

1.3.1 Climate change, land degradation, desertification and food security

1.3.1.1 Future trends in the global land system

Human population is projected to increase to close to 9.8 (± 1 bio) by 2050 (https://www.un.org/development/desa/publications/2018-revision-of-world-urbanization-prospects.html). More people, a growing global middle class (Crist et al. 2017), continued rapid rates of urbanisation (Jiang and O'Neill 2017) and changes in diets (Kastner et al. 2012; Billen et al. 2015; Alexander et al. 2015; Myers et al. 2017) all enhance the pressure towards expanding crop and pasture area, and intensifying land management. The already existing large pressure on land ecosystems will with *high confidence* be further exacerbated if large-scale climate change mitigation efforts on land are enacted (Smith et al. 2016)(see also 1.3.2 and Chapter 6). Woody and crop biomass commodities are increasingly traded internationally leading to a spatial disconnect between production and consumption. The resulting large-scale interdependencies and global telecoupling in the land system allows for efficiency gains, for example, related to land-demand, but also to complex cause-effect chains and indirect effects such as land competition and leakage, or biodiversity loss in the production rather than consumption regions (Lapola et al. 2010; Liu et al. 2013; Kastner et al. 2014; Baldos and Hertel 2015; Billen et al. 2015; Jadin et al. 2016; Erb et al. 2016b; Chaudhary and Kastner 2016; Wood et al. 2018; Schröter et al. 2018)(see also 1.3.1.5).

Climate change will affect agriculture and forest productivity in most regions, thereby accentuating existing challenges (Schlenker and Lobell 2010; Lipper et al. 2014; Challinor et al. 2014; Rosenzweig et al. 2014; Myers et al. 2017)(see Chapters 2 and 5), although increasing atmospheric CO_2 concentrations can counteract some of the detrimental climate change effects on productivity (Weigel and Manderscheid 2012; Kimball 2016). The expansion of global drylands is anticipated to accelerate in the 21st century (see 2.3.2

and Chapter 3). In those developing countries where pressure on land is high, climate change impacts are expected to further imperil large populations who rely substantially on agriculture and who have a high prevalence of hunger (Baldos and Hertel 2015)(see also 1.3.1.4 and Chapter 5).

The extent of urban areas is projected to increase significantly (up to a factor of 2 to 3) until 2030 (Seto et al. 2012; van Vliet et al. 2017; Jiang and O'Neill 2017), estimated to result in a further loss of fertile (crop)land. These losses are expected to occur in regions of high population density and agrarian-dominated economies with limited capacity to compensate for these losses, and in biodiversity hotspots, and with far-reaching effects on food security (*high confidence* (Seto et al. 2012; Güneralp et al. 2013; Aronson et al. 2014; Martellozzo et al. 2015; Bren d'Amour et al. 2016; Seto and Ramankutty 2016; van Vliet et al. 2017).

Given the large uncertainties underlying the many drivers of land use, including future net primary productivity, yield developments, demand, production-consumption dynamics, trade, and conservation, future trends in the global land system are explored in scenarios and models that seek to span across these uncertainties (e.g.,(Ray et al. 2013; Coelho et al. 2013; Popp et al. 2014; Schmitz et al. 2014; Billen et al. 2015; Prestele et al. 2016; Engstrom et al. 2016; van Ittersum et al. 2016; Alexander et al. 2016, 2017a)(see Cross-Chapter Box 2: Scenarios).

1.3.1.2 Desertification

Desertification is a persistent negative trend in land condition causing long-term reduction or loss of the biological productivity of dry lands, their ecological complexity, and/or their human values. The IPCC has in previous reports adopted the definition of the UNCCD of desertification being land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climate variations and human activities (see glossary, Chapter 3). Desertification may be non-reversible (Tal 2010) in that it causes persistent loss of ecosystem function and productivity due to diverse disturbances (e.g., soil fertility loss, soil erosion, vegetation cover loss, and plant species changes) from which the land cannot recover unaided (Bai et al. 2008). While climatic variability can change the intensity of desertification process, some authors exclude climate impact, emphasising that desertification is purely human-induced process of land degradation with different levels of severity and consequences (Sivakumar 2007). A critical challenge is also to identify a "non-desertified" reference state (Bestelmeyer et al. 2015).

As a consequence of widely varying definitions, the area of desertification varies widely (see (D'Odorico et al. 2013; Bestelmeyer et al. 2015), and references therein). Arid regions of the world cover around 45.4% of the total terrestrial surface (about 60 Mkm2; (Pravalie 2016), see also Chapter 3). More than two billion people reside in dryland regions (D'Odorico et al. 2013; Maestre et al. 2016). The combination of low rainfall with frequently infertile soils renders these regions, and the people who rely on the land's resources, vulnerable to both the climate change, and unsustainable land management. In spite of the national, regional and international efforts to combat desertification, it is still one of the major environmental problems (Abahussain et al. 2002; Cherlet et al. 2018).

1.3.1.3 Land Degradation

In this report, land degradation is defined as a negative trend (or persistent decline) in land condition resulting in the long-term reduction or loss of the biological productivity of land, its ecological complexity, and/or its human values, caused by direct and/or indirect anthropogenic processes, including climate change (see Chapter 4).

Due to loss of productivity carbon storage, biodiversity, and other ecosystem services, degradation of soil and land resources is a critical issue for ecosystems around the world (Ravi et al. 2010; Abu Hammad and Tumeizi 2012; Mirzabaev et al. 2015; FAO and ITPS, 2015; Cerretelli et al. 2018). Land degradation can be considered in terms of the loss of actual or potential productivity or utility; it is driven to a large degree by unsustainable agriculture and forestry, socioeconomic pressures, such as rapid urbanisation and population growth, and unsustainable production practices in combination with climatic factors (Beinroth et al. 1994; Abahussain et al. 2002; Franco and Giannini 2005; Lal 2009; Abu Hammad and Tumeizi 2012; Field et al. 2014; Ferreira et al. 2018).

Global estimates of total degraded area vary from less than 1 billion ha to over 6 billion ha, with equally wide disagreement in their spatial distribution in various literature (*medium confidence*; Gibbs and Salmon 2015). Increasing at an estimated 5–10 million ha a^{-1} (Stavi and Lal 2015), the loss of total ecosystem services from degraded lands have been estimated to be equivalent to about 10% of the world's GDP in the year 2010 (Sutton et al. 2016). Although land degradation is a common risk across the globe, poor countries remain most vulnerable to its impacts. Soil degradation is of particular concern, due to the long period necessary to restore soils (Lal 2009;Stockmann et al. 2013; Lal 2015), as well as the rapid degradation of so-called "intact" forests through fragmentation (Haddad et al. 2015). Land degradation is an important factor contributing to the prevailing uncertainties of the mitigation potential of land-based ecosystems (Smith et al. 2014).

1.3.1.4 Food security, food systems and linkages to land-based ecosystems

The High Level Panel of Experts of the Committee on Food Security define the food system as to "*gather all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socio-economic and environmental outcomes*" (HLPE 2017). Likewise, food security has been defined as "*a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life* " (FAO 2017). Under this definition, food security is distinguished in terms of food availability, economic and physical access to food, food utilisation and food stability over time. Food and nutrition security is one of the key outcomes of the food system (Figure 1.3).

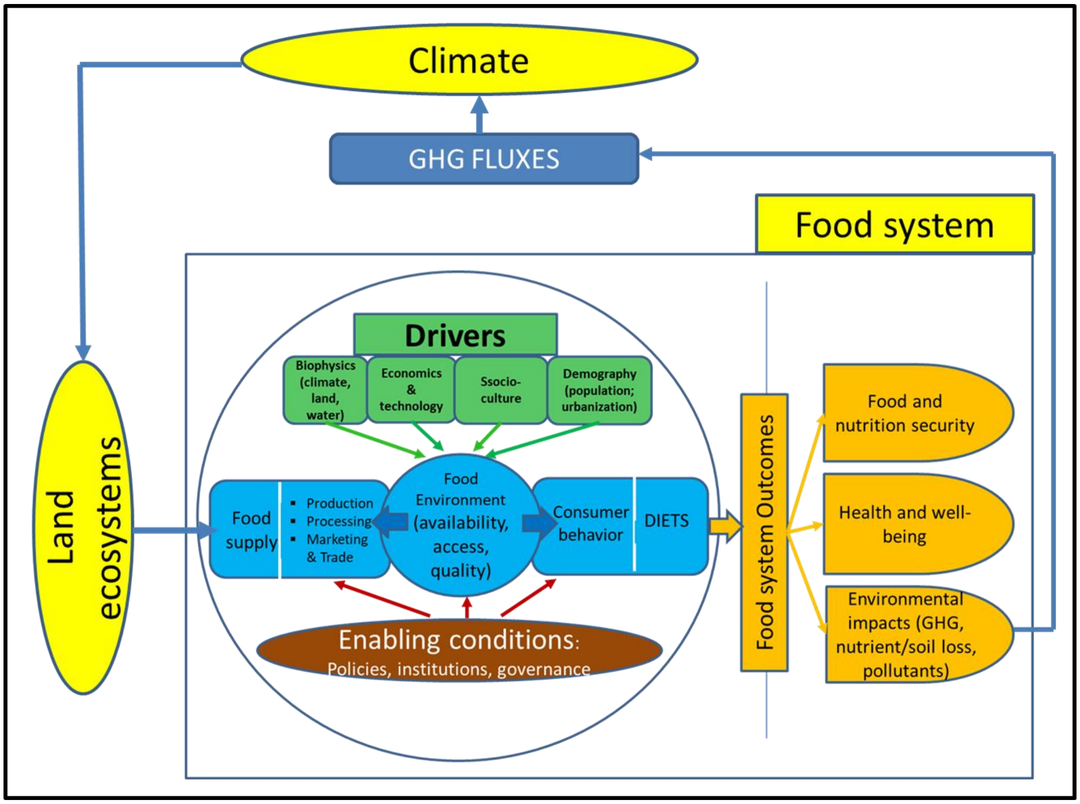


Figure 1.3 Food system: The food system is conceptually represented by three core components (supply, demand and food environment), four sets of drivers (biophysical, technology and economics, political and socio-cultural, and demographics) and three outcome categories (food and nutrition security, health and wellbeing including reduced hunger and poverty, and environmental impacts including GHGs, nutrients, water, and pollutants).The food system is also impacted by policies, governance and institutions. Finally, the food system is linked to land (through ecosystem services of which food production is one) and climate (via GHG fluxes) (see chapter 5)

In its 2018 annual report on the State of Food Insecurity, FAO and its international partners reported that after a prolonged decline, world hunger appears to be on the rise again with the number of undernourished people having increased to an estimated 821 million in 2017, up from 804 million in 2016 and 784 million in 2015, although still below 900 million reported in 2000 (FAO, IFAD, UNICEF, WFP and WHO, 2018). The same report also states that child undernourishment continues to decline, but levels of overweight and obesity are increasing. The food security situation has worsened in particular in parts of sub-Saharan Africa, and Latin America and was relatively stable in South-Eastern and Western Asia. Deteriorations have been observed most notably in situations of conflict and conflict combined with droughts or floods (Smith et al. 2017; Cafiero et al. 2018). FAO also estimated that close to 2000 million people suffer from micronutrient malnutrition (FAO 2018b).

Climate change affects the food system via productivity on land (Iizumi and Ramankutty 2015) (and the ocean), the nutritional quality of food (Loladze 2014; Myers et al., 2014; Ziska et al. 2016; Medek et al., 2017), water supply (Nkhonjera 2017), increased incidences of pests and diseases (Bett et al., 2017); Curtis et al., 2018) as well as weather-linked production variability (Osborne and Wheeler, 2013; Tigchelaar et al., 2017). These factors impact also on human health and increase morbidity and incidences of diseases which affect human ability to process ingested food (Franchini and Mannucci 2015; Wu et al. 2016; Raiten and Aimone 2017). At the same time, the food system generates negative externalities in the form of greenhouse gas emissions (1.2.2.1), pollution and food waste and loss (environmental or ecological "footprints")(van Noordwijk and Brussaard 2014; Thyberg and Tonjes 2016; Goldstein et al., 2016; Sala et al., 2017; Clune et al., 2017; Borsato et al. 2018; Kibler et al. 2018) with direct and indirect impacts on climate change and reduced resilience to climate. As food systems are assessed in relation to their contribution to global warming and/or to land degradation (e.g., livestock systems) it is critical to evaluate their contribution to food security and livelihoods and to consider alternatives, especially for developing countries where food insecurity is prevalent (Röös et al. 2017; Salmon et al. 2018).

1.3.1.5 Challenges arising from land governance

Land use change can be a double-edged sword – on the one hand it can lead to economic growth and on the other it can constitute a source of tension and social unrest leading to elite capture, and competition (Tucker 2015, Hunsberger 2018). Competition for land plays out continuously among different use types (cropland, pastureland, forests, urban spaces, and conservation and protected lands) and between different users within the same land use category (subsistence vs. commercial farmers). Competition is mediated through economic and market forces (expressed through land rental and purchases, as well as trade and investments). In the context of such transactions, power relations often disfavour disadvantaged groups such as small scale farmers, indigenous communities and women. These drivers are influenced to a large degree by policies, institutions and governance structures. Land governance determines not only who can access the land, but also the role of land ownership (legal, formal, customary or collective) which influences land use, land use change and the resulting land competition.

Globally, competition for land is grounded in the finiteness of the land resource and that most highly-productive land is already being exploited by humans (Lambin and Meyfroidt 2011; Lambin 2012; Venter et al. 2016). Driven by growing population, urbanisation, demand for food and energy, as well as land degradation, competition for land is likely to accentuate land scarcity in the future (Tilman et al. 2011; Foley et al. 2011; Lambin, 2012; Popp et al. 2016)(*robust evidence, high agreement*). Climate change influences land use both directly and indirectly (see 5.2, 5.4 and 1.3.2)(Haberl et al. 2014； Rosenzweig et al. 2014; Haberl 2015; Daliakopoulos et al. 2016; Pugh et al. 2016; Coyle et al. 2017; Schauberger et al. 2017; Alexander et al. 2018), *robust evidence, high agreement*). Climate policies can also a play a role in increasing land competition via forest conservation policies, afforestation. or energy crop production (see 1.3.2), with serious implications for food security (Hussein et al. 2013) and large-scale people dispossession.

An example of large-scale change of land ownership (especially in the global south) is the much-debated large-scale land acquisition (LSLA) by foreign investors which peaked in 2008 during the food price crisis, the financial crisis, and the search for biofuel investments. Since 2000, almost 50 million hectares of land, have been acquired, and there are no signs of stagnation in the foreseeable future (Matrix 2018). The LSLA phenomenon, which targets largely agriculture, touches much of the global south, including Sub-Saharan Africa, Southeast Asia, Eastern Europe and Latin America (Rulli et al. 2012; Nolte et al. 2016; Constantin et al. 2017). LSLAs are promoted by investments and host governments on economic grounds (infrastructure, employment, market development)(Deininger et al. 2011) but their social and environmental impacts can be negative and significant (Dell'Angelo et al. 2017).

Much of the criticism of LSLA focuses on their social impacts, especially the threat to local communities' land rights (especially indigenous people, women) (Anseeuw et al. 2011) and displaced communities creating secondary land expansion (Messerli et al. 2014; Davis et al. 2015). The aspiration that LSLAs would develop efficient agriculture on non-forested, unused land (Deininger et al. 2011) has so far not been fulfilled. However, LSLAs is not the only outcome of weak land governance structures (Wang et al. 2016b), other forms of inequitable land acquisition can also be home-grown pitting one community against a more vulnerable group (Xu 2018) or land capture by urban elites (McDonnell 2017). As demands on land are increasing, building governance capacity and securing land tenure becomes essential to attain sustainable land use, which has the potential to mitigate climate change, promote food security, and potentially reduce risks of climate induced migration and associated risks of conflicts.

1.3.2 Future challenges identified in large-scale land-based climate change mitigation scenarios

A number of options exist for land management to contribute to climate change mitigation. As discussed in Section 1.4.4 and Chapter 6, these have the potential to create co-benefits for adaptation and ecosystem restauration, but realising these potentials depend strongly on regional contexts and the portfolio of response options implemented.

With the exception of socio-economic scenarios that explore strong reductions in animal protein or energy demand, high energy efficiency and early action policies (Rogelj et al. 2018a) most scenarios that aim to achieve global warming of 2ºC or well below rely on bioenergy (in combination with carbon capture storage, BECCS) or afforestation/reforestation (AR) as part of decarbonisation strategies, (Rogelj et al. 2018a; de Coninck et al. 2018; Smith et al. 2016; Popp et al. 2016; Anderson and Peters 2016; Rogelj et al. 2018b)(see also Cross-Chapter Box 2: Scenarios). Estimate of bioenergy crop area required by 2050 range from about 50 to 500 Mha (2ºC trajectories) and 100 to 700 (1.5ºC trajectories) (Rogelj et al. 2018a). Forest area changes by between -100 to >800 Mha and -80 to > 900 Mha (2ºC, and 1.5ºC trajectories, respectively (Rogelj et al. 2018a). Projected annual carbon uptakes in 2050 for bioenergy pathways (1–2.2 GtC a^{-1}) and afforestation/reforestation (0.1–1 GtC a^{-1}) would require enhancement of today`s land carbon sink by an additional one third to three quarters within three decades. Given the foreseen degree of land mitigation contributions in low warming scenarios, jointly with the projected extremely rapid technical and societal uptake rates for the land-related mitigation measures, and the possibly large trade-offs for ecosystem services and food prizes there is *high confidence* that these cannot be achieved sustainably (see below, and Chapter 6). In developing regions, land-based climate mitigation might have particularly severe consequences that are in conflict with the achievement of sustainable development goals such as no poverty, zero hunger and life on land (UN 2015; Doelman et al. 2018; Roy et al. 2018).

1.3.2.1 Reforestation and afforestation

Reducing deforestation (and generally: forest management practices that target avoiding carbon losses, and carbon enhancement) has for over a decade been put forward as a cost-effective measure to reduce carbon emissions from land use change. Co-benefits for biodiversity and local communities can be large, although in existing efforts until now not all expectations have been met (Matthews and van Noordwijk 2014; Turnhout et al. 2017a). Large added value arises if priority regions for carbon sequestration and biodiversity overlap (Strassburg et al. 2010, 2012; Visseren-Hamakers et al. 2012; Magnago et al. 2015; Simonet et al. 2016; Ojea et al. 2016; Turnhout et al. 2017).

Most future global scale land-related emission reduction scenarios therefore include reduced deforestation, but combined with large-scale reforestation and afforestation efforts (Humpenoder et al. 2014; Popp et al. 2014; Smith et al. 2016; Griscom et al. 2017a). The carbon uptake potential of these scenarios has been estimated to be of similar magnitude to bioenergy, combined with carbon capture and storage (Humpenoder et al. 2014; Popp et al. 2014; Krause et al. 2017; Humpenoeder et al. 2018)(see also 1.3.2.2 and Chapter 6), with caveats being that the models used for these projections typically do not represent the forestry sector explicitly, and poorly account for changes in soil carbon stocks from past land-use change (Schmitz et al. 2014; Krause et al. 2017). Recently, large uncertainties have been identified, in that land-carbon uptake in land-use models of Integrated Assessment models may be consistently higher compared with uptake calculated in dynamic global vegetation models when confronted with similar land-use change scenarios (Krause et al. 2017).

Incentives towards afforestation and reforestation will only be successful if these address the potentially large adverse side effects biodiversity and other ecosystem services, as well as socio-economic aspects such as higher food prices due to area competition between forested and cropped land(Shi et al. 2013; Barcena et al. 2014; Fernandez-Martinez et al. 2014; Searchinger et al. 2015; Kreidenweis et al. 2016; Stevanovic et al. 2017; Graham et al. 2017b; Hong et al. 2018; Humpenoeder et al. 2018) (see also Cross-Chapter Box 1: Large scale reforestation and afforestation).

Cross-Chapter Box 1: Large scale reforestation and afforestation

Contributing authors: Almut Arneth (Ch1), Baldur Janz (Ch1), Werner Kurz (Ch 4), Francesco Cherubini (Ch6), Kaoru Kitajima (Ch2), Eduardo Davin (Ch 2), Aziz Elbehri (Ch 1)

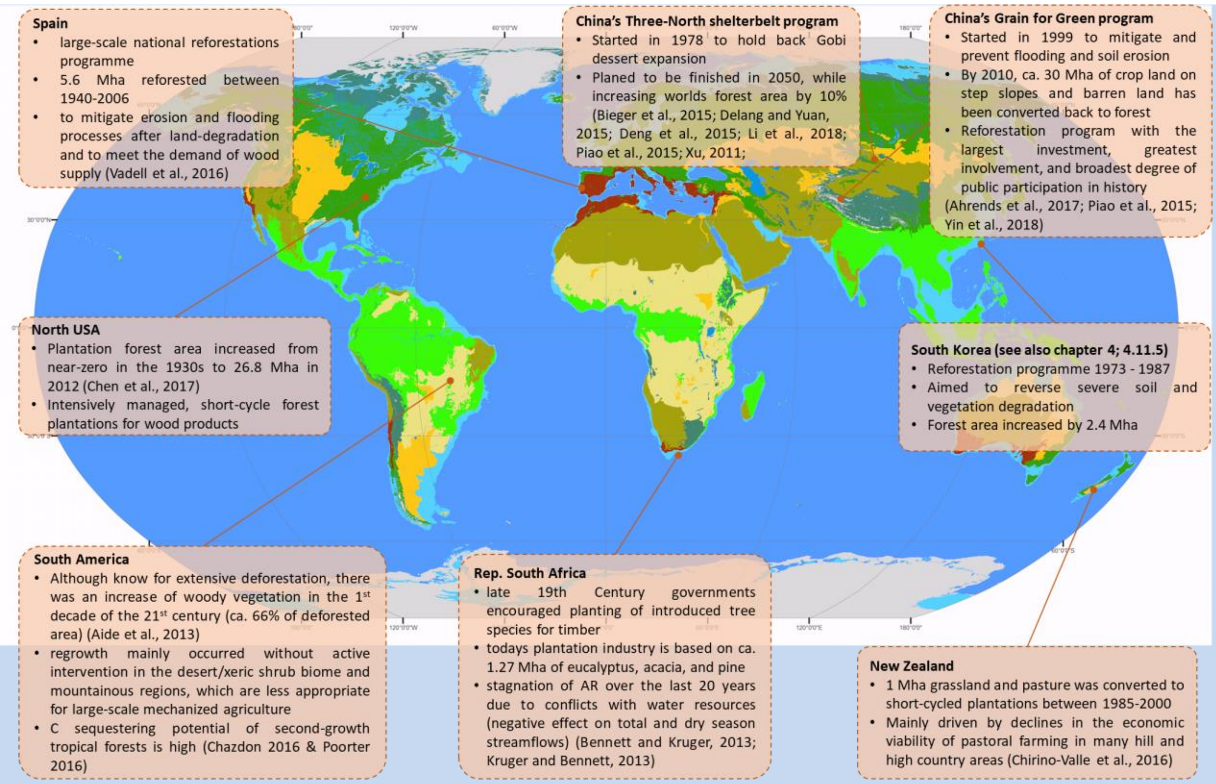
Efforts to increase forest area through afforestation and reforestation (AR)

Afforestation and *reforestation* (AR) refer to establishment of trees on non-forested land, reforestation refers to replanting of forest on land that had recent tree cover, whereas afforestation refers to land that has been without forest at least for the last 50 years (see glossary).

Expansion of managed forest area in the past has occurred for a variety of aims, from meeting anticipated needs for forest goods (mostly for wood fuel or timber) (Shoyama 2008; Joshi et al. 2011; Zaloumis and Bond 2015; Payn et al. 2015; Vadell et al. 2016; Chirino-Valle et al. 2016) to targeting environmental services (biodiversity conservation, soil erosion, water resource management, carbon sequestration) (Wuethrich 2007; Salvati et al. 2014; FAO 2016; Filoso et al. 2017; Ogle et al. 2018). Net forest area expansion in recent decades has been evident in both high-income countries (North America, Europe) and some developing countries (e.g., China, Vietnam, Georgia, India, Chile, Costa Rica) (FAO 2016b) with China far in the lead motivated largely to alleviate severe soil erosion, desertification and overgrazing (Deng et al. 2015; Wang et al. 2016; Cao et al., 2016; Ahrends et al. 2017; Yin et al. 2018)(Cross-Chapter Box 1, Figure 1).

AR activities have been widely accepted as cost-effective climate change mitigation mechanisms when compared to mitigation options in the energy and transport sector (Smith et al. 2016; Griscom et al. 2017; de Coninck et al. 2018). The international community continues to promote large-scale forest expansion as mitigation mechanism (e.g., the Bonn Challenge - a global initiative to restore 350 Mha worldwide by 2030 (http://www.bonnchallenge.org); or the Trillion-Tree-Campaign - a volunteer tree planting initiative).

Recent data show that net forest area additions outweighed forest loss. A recent analysis of satellite remote sensing data estimated a net forest area gain, driven by forest expansion in extratropics outweighing tropical deforestation, of 224 Mha since 1982 (Song et al. 2018). But uncertainties of forest area changes are large, due to differences in methodology and forest classification (FAO 2015a). In many cases, forest area expansion included also replacing native forests with plantations as in Chile (Heilmayr et al. 2016), China (Hua *et al.*, 2018) or Cambodia (Scheidel & Work, 2018).



Spain
- large-scale national reforestations programme
- 5.6 Mha reforested between 1940-2006
- to mitigate erosion and flooding processes after land-degradation and to meet the demand of wood supply (Vadell et al., 2016)

China's Three-North shelterbelt program
- Started in 1978 to hold back Gobi dessert expansion
- Planed to be finished in 2050, while increasing worlds forest area by 10% (Bieger et al., 2015; Delang and Yuan, 2015; Deng et al., 2015; Li et al., 2018; Piao et al., 2015; Xu, 2011;

China's Grain for Green program
- Started in 1999 to mitigate and prevent flooding and soil erosion
- By 2010, ca. 30 Mha of crop land on step slopes and barren land has been converted back to forest
- Reforestation program with the largest investment, greatest involvement, and broadest degree of public participation in history

(Ahrends et al., 2017; Piao et al., 2015; Yin et al., 2018)

North USA
- Plantation forest area increased from near-zero in the 1930s to 26.8 Mha in 2012 (Chen et al., 2017)
- Intensively managed, short-cycle forest plantations for wood products

South Korea (see also chapter 4; 4.11.5)
- Reforestation programme 1973 - 1987
- Aimed to reverse severe soil and vegetation degradation
- Forest area increased by 2.4 Mha

South America
- Although know for extensive deforestation, there was an increase of woody vegetation in the 1st decade of the 21st century (ca. 66% of deforested area) (Aide et al., 2013)
- regrowth mainly occurred without active intervention in the desert/xeric shrub biome and mountainous regions, which are less appropriate for large-scale mechanized agriculture
- C sequestering potential of second-growth tropical forests is high (Chazdon 2016 & Poorter 2016)

Rep. South Africa
- late 19th Century governments encouraged planting of introduced tree species for timber
- todays plantation industry is based on ca. 1.27 Mha of eucalyptus, acacia, and pine
- stagnation of AR over the last 20 years due to conflicts with water resources (negative effect on total and dry season streamflows) (Bennett and Kruger, 2013; Kruger and Bennett, 2013)

New Zealand
- 1 Mha grassland and pasture was converted to short-cycled plantations between 1985-2000
- Mainly driven by declines in the economic viability of pastoral farming in many hill and high country areas (Chirino-Valle et al., 2016)

Cross-Chapter Box 1, Figure 1 Efforts to increase forest area through afforestation and reforestation in the world (Xu 2011; Kruger and Bennett 2013; Bennett and Kruger 2013; Aide et al. 2013; Bieger et al. 2015; Piao et al. 2015; Delang and Yuan 2015; Deng et al. 2015; Vadell et al. 2016; Chirino-Valle et al. 2016; Chazdon et al. 2016b; Poorter et al. 2016; Chen et al. 2017; Ahrends et al. 2017; Yin et al. 2018; Li et al. 2018b)

What are the impacts on ecosystems?

The environmental impacts of AR depend largely on the state of land's degradation, prior land use and natural land cover, the selected tree species, and the management practices used for their establishment and maintenance (Laestadius et al. 2011; Dinerstein et al. 2015; Veldman et al. 2017)(see also Chapter 4). Costs and trade-offs with other ecosystem services are increasingly examined and requiring a more careful approach to AR policies as climate change mitigation mechanism.

(1) Impacts on biogeochemical and biophysical processes

AR on abandoned croplands with low soil fertility will increase C stocks rapidly, while they have been shown to decrease (non-significantly) or remain at similar levels after conversion from managed grasslands (Li et al. 2012; Shi et al. 2013; Bárcena et al. 2014). Forests in the temperate zone did not show significant differences in soil C accumulation between conifer and deciduous species (Poeplau et al. 2011), whereas in the boreal northern Europe C sequestration was greater when conifer species were planted compared with deciduous and mixed forests (Bárcena et al. 2014). AR activities also affect N and P dynamics in soil. While total soil N pools and P availability tends to increase with time after afforestation, in tropical plantations substantial declines in total P stocks have been observed (Li et al. 2012; Deng et al. 2017; Liu et al. 2018) . In arid and semi-arid regions planting broadleaf deciduous trees accumulated the highest C and N in soil compared to coniferous or broadleaf evergreen forest (Liu et al. 2018).

Biophysical effects following land cover change are important for local climate and the water cycle (Perugini et al. 2017). Both modelling and satellite estimates have shown that AR in the tropical zones induces a cooling (compared to agricultural land) through increased evapotranspiration and surface roughness that is greater than the warming effect from reduced albedo. In boreal areas the lower albedo of forests dominates (especially in spring) and results in a net warming effect (Arora and Montenegro 2011; Alkama and Cescatti 2016; Perugini et al. 2017). Thus, in tropical areas, AR (and: reduced deforestation) can be a win-win for both global and local mitigation of climate warming when considering biophysical processes, as well as biogeochemical processes (C sequestration) (Perugini et al. 2017), whereas outside tropical regions, and regarding global-scale impacts of biophysical effects the picture is very complex (see 2.2 and 2.6).

(2) Impacts on water balance

Forests tend to impact water flows and quality by reducing runoff and soil particles and nutrients transported in run-off (Salvati et al. 2014). Planting of fast-growing species in semi-arid regions or replacing natural grasslands with forest plantations for industrial use can deplete soil water resources, including groundwater recharge due to higher water consumption from evapotranspiration (Silveira et al. 2016; Zheng et al. 2016; Cao et al. 2016). The most documented cases of AR-induced water scarcity are from China where afforestation programs appear not to have been tailored to local precipitation conditions resulting in water shortages and increased water scarcity (Li et al. 2014; Yang et al. 2014; Feng et al. 2016; Cao et al. 2016). The lesson is that in drylands, afforestation faces the challenge of increased water scarcity (Zheng et al. 2016). Even in tropical conditions, the mitigation benefits from large-scale planting of woody vegetation must be weighed against the potential to reduce the ecosystem's resilience against climate change through hydrological cycle that may create long-term risks of water conflicts (Zheng et al. 2016).

(3) Impacts on biodiversity

Impacts of AR on biodiversity depend mostly on vegetation cover they substitute: afforestation on natural grasslands or other naturally non-wooded ecosystems with plantations of exotic tree species can have significant negative impacts on biodiversity (Parr et al. 2014; Veldman et al. 2015a; Bond 2016; Abreu et al. 2017; Griffith et al. 2017; de Coninck et al. 2018). There are also concerns regarding the impacts of some commonly used plantation species (e.g., Acacia and Pinus species) to become invasive (Padmanaba and Corlett 2014).

Reforestation with mixes of native species, especially in areas that retain fragments of native forest, can support biodiversity recovery, with positive social and environmental co-benefits (Cunningham et al. 2015; Locatelli et al. 2015a;Dendy et al. 2015; Chaudhary et al. 2016). Even though species diversity in regrowing forests is typically lower than primary forest, commercial plantations potentially can support biodiversity unless plantations are monocultures (Brockerhoff et al. 2013; Pawson et al. 2013; Thompson et al. 2014). Reforestation has been shown to improve links among existing remnant forest patches, increasing movement, gene flow and effective population sizes of native species (Lindenmayer and Hobbs 2004; Barlow et al. 2007; Gilbert-Norton et al. 2010).

(4) Impacts on other ecosystem services and societies

In principle, AR activities could benefit recreation, preservation and strengthening of cultural heritage and indigenous values, ethnic medicine, and improved livelihoods (reduced resource conflicts, restoration of local resources degraded by remote causes). However, there has been little assessment of these co-benefits owing to a lack of suitable frameworks and evaluation tools (Baral et al. 2016).

Conversions of natural forests to industrial forest management are in conflict with needs of forest-dependent people and community-based forest managements over access to natural resources (Gerber 2011; Baral et al. 2016) and/or loss of customary rights over land use (Cotula et al. 2014; Malkamäki et al. 2018). A common result is out-migration from the rural areas diminishing local uses of ecosystems as they are replaced by monocultures (Gerber 2011). Policies promoting large-scale tree plantations should be reappraised that is government subsidies that have crucially supported fast-wood plantations must be reoriented towards community and other small-scale forest management (Bull et al. 2006).

AR scenarios for land-based climate change mitigation

Griscom et al. (2017) estimate the median mitigation potential from reforestation as 10 Gt CO$_2$ a^{-1} until 2030 (95% confidence: 2.7–17.9 Gt CO$_2$ a^{-1}) if all grazing land in forested ecoregions was reforested. Without assessing substantial demand-side measures, ranges calculated by integrated assessment models (IAM, see Cross-Chapter Box 2: Scenarios) were 3.5-9.6 GtCO$_2$ a^{-1} (Humpenöder et al. 2014; Kreidenweis et al. 2016) for area changes of about 1500 vs. about 2580 Mha. Likewise, Houghton et al. (2015) estimate about 500 Mha to be available in the tropics on lands previously forested but not currently used productively. This could sequester at least 3.7 GtCO$_2$ a^{-1} for decades. In all AR efforts, the sequestration potential will eventually saturate unless the area keeps expanding or harvested wood is either used for long-term storage products or as part of BECCS (Houghton et al. 2015; Fuss et al. 2018)(see also Chapter 2).

None of the scenario studies assessed biodiversity conservation, impacts on water balances, or other ecosystem services as constraints. Considerable uncertainty in these estimates is also introduced by potential forest losses from fire or pest outbreaks (Dantas et al. 2013a,b; Bond 2016; Abreu et al. 2017) . REDD+-related forest conservation policies may generate unintended side-effects if cropland expansion for agriculture is shifted to non-forested carbon-rich areas such as savannahs or temperate grasslands that are of high biodiversity but not subject to forest conservation schemes (Don et al. 2008; Popp et al. 2014; Parr et al. 2014a; Veldman et al. 2015; Fernandes et al. 2016; Abreu et al. 2017). AR benefits may also be undercut by land use displacement, through trade of land-based products, especially from poor countries that experience forest loss (e.g., Africa) (Bhojvaid et al. 2016; Jadin et al. 2016). And like all large-scale land-uses, competition for land will impact food prices with detrimental societal impacts in regions where GDP increase cannot compensate (Kreidenweis et al. 2016a).

Conclusion

AR offers low-technology and cost-effective options to enhance carbon sinks on suitable and available land. Maintenance of that sink will require sustainable forest management, including harvest and utilisation of the wood for long-lived wood products. While large-scale AR can have significant co-benefits, it will at large-scales also lead to increased competition for land, with potentially adverse side-effects on food prices, biodiversity, non-forest ecosystems and water availability for human consumption (Bryan and Crossman 2013; Smith et al. 2013; Kreidenweis et al. 2016; Boysen et al. 2017). Reforestation should be managed with both adaptation and mitigation objectives in mind, and carbon sequestration benefits must be designed to maximise synergies among diverse objectives (beyond carbon), and to avoid trade-offs, some of which can be costly or unsustainable (Egginton et al. 2014; Locatelli et al. 2015a; Cao et al. 2016).

1.3.2.2 Bioenergy and Bioenergy with carbon capture and storage (BECCS)

Median BECCS net carbon uptake rates of >3 GtC a^{-1} by 2100 (delivering around 150–400 EJ yr^{-1}) have been projected with Integrated Assessment Models in scenarios of achieving a 2ºC warming target (Slade et al. 2014; Smith et al. 2016; Rogelj et al. 2018), resulting in increases in cropland between about 10% and 40%, or even 100%, compared to present-day (Smith et al. 2016; Bonsch et al. 2016; Popp et al. 2016; Krause et al. 2017). Modelled median land-use conversion rates exceed by more than threefold historical observations of the most rapidly expanding crop (soybean; (Turner et al. 2018)). The large range of results is based on varying assumptions on future land use intensity and rates of land use conversions (Smith et al.

2016; Bonsch et al. 2016; Krause et al. 2017; Turner et al. 2018). For comparison, the estimated carbon sink on land for 2008–2017 was about 3.5 Gt C a^{-1}, while global primary energy consumption in 2011 was about 560 EJ (Slade et al. 2014; Le Quere et al. 2018).

Confidence in the net BECCS carbon uptake potential is *low*, due to: diverging assumptions on bioenergy crop yields, the CCS energy demand and thus the net-GHG-saving of bioenergy systems, the cumulative carbon-loss arising from natural vegetation clearance for bioenergy crops and subsequent land management regimes, incomplete representation of important ecosystem processes such as legacy effects of historical deforestation, tree growth and mortality, and gross changes in land use per regions (Anderson and Peters 2016; Bentsen 2017; Searchinger et al. 2017; Bayer et al. 2017; Fuchs et al. 2017; Pingoud et al. 2018; Schlesinger 2018; Krause et al. 2018). Bioenergy provision under politically unstable conditions may also be an issue (Erb et al. 2012; Searle and Malins 2015). It is *virtually certain* that growth of bioenergy crops poses large challenges for maintaining food production and food prices, and avoiding detrimental effects on other important ecosystem services and biodiversity (Creutzig et al. 2015; Smith et al. 2016; Bonsch et al. 2016; Santangeli et al. 2016; Bren d'Amour et al. 2016b; Williamson 2016; Krause et al. 2017; Boysen et al. 2017; Heck et al. 2018; Henry et al. 2018; Humpenoeder et al. 2018)

1.3.2.3 Mitigation costs, efficiency measures, and mitigation-adaptation integration

Mitigation costs are analysed through several metrics (social or private cost of carbon, carbon price, or reduction in the gross domestic product) and measured at different scales (project, technology, sector or the economy). The social cost of carbon (SCC) –measured in monetary units– refers to the present value of costs that incur from marginal damage caused by an additional ton of CO_2 emissions. Estimates of SCC depends on the time horizon, discount rate and the baseline emission scenario. Recent estimates of the social cost of carbon for a middle of the road scenario are a global median of USD 417 with some of the largest emitting countries incurring also an over-proportional share of these costs (Ricke et al. 2018). SCC is also linked to the "costs of inaction" that arise either from the economic damages due to continued accumulation of GHGs in the atmosphere and from the diminution in value of ecosystem services or the cost of their restoration when feasible (Rodriguez-Labajos 2013; Ricke et al. 2018). At the macroeconomic level, cost estimation considers the impacts of policies across all sectors and markets and analyses report cost measures in terms of “GDP loss”, “consumption loss” or “reductions in growth rates”.

Generally, mitigation costs increase with stringent mitigation targets and over time, with sources of uncertainty being the future availability, cost and performance of technologies (Rosen and Guenther 2015; Chen et al. 2016) or lags in decision making, which have been demonstrated by the uptake of land use policies (Alexander et al. 2013; Hull et al. 2015; Brown et al. 2018b). There is growing evidence of significant mitigation gains through conservation, restoration and improved land management practices (Griscom et al. 2017b) but the mitigation cost efficiency can vary according to region and specific ecosystem (Albanito et al. 2016). Recent model developments that treat process-based human-environment interactions have recognised feedbacks that notably reinforce or dampen the original stimulus for land use change (Robinson et al. 2017; Walters and Scholes 2017). For instance, land mitigation interventions that rely on large-scale land use changes (bioenergy, afforestation) would need to account for the rebound effect whereby rising land prices raise the cost of land-based mitigation (Vivanco et al. 2016).

Adaptation can benefit mitigation in two ways – either by lowering mitigation opportunity cost or alternatively, adaptation, trough substitute or complement technologies may also shift the mitigation cost lower for a given level of output. Several studies report that combining adaptation with mitigation generate co-benefits to society (see 1.4.4) including positive impacts on land/soil restoration (countering land degradation and desertification) and raised land productivity (for food security) (Altieri and Nicholls 2017;

Hof et al. 2017; Thierfelder et al. 2017; Di Gregorio et al. 2017; Nkonya et al. 2016) and biodiversity protection (Tilman et al. 2017).

1.3.3 Uncertainties in assessing land processes in the climate system

In order to reflect various sources of uncertainties in the state of scientific understanding, IPCC assessment reports provide estimates of confidence (Mastrandrea et al. 2011; Allen et al. 2018). The confidence language is also used in the SRCCL. In general, the identification of anthropogenically forced changes in climate and other environmental records (detection), and the assessment of the roles various contributors play (attribution) remains a taxing aspect in both observations and models (Rosenzweig and Neofotis 2013; Gillett et al. 2016; Lean 2018)(see also Chapter 2).

1.3.3.1 Nature and scope of uncertainties related to land use

Uncertainties in observations

The detection of changes in vegetation cover and structural properties, as a fundamental requirement to assess land-use change, degradation and desertification, is continuously improving by enhanced space observation capacity (Hansen et al. 2013; He et al. 2018; Ardö et al. 2018; Spennemann et al. 2018;) (see also Table SM 1 in Supplementary Materials). The relative shortness of the satellite record, data gaps, and differences in the definitions of major vegetation cover classes still provide major obstacles when aiming to apply satellite observations to the detection of trends (Chen et al. 2014; Yu et al. 2014; Lacaze et al. 2015; Alexander et al. 2017a). Analogously to remote sensing-based data, the picture of how soil organic carbon, and greenhouse gas and water fluxes respond to land use change continues to improve through advances in methodologies and sensors (Brümmer et al. 2017; Valayamkunnath et al. 2018Kostyanovsky et al. 2018), but here, too, measurements of the key variables related to land use change are affected by spatial and temporal scale limitations, instrumentation resolution and data treatment algorithms (Smith and Gregory 2013; Peterson et al. 2017; Song 2018). In many developing countries, the costs of satellite remote sensing analyses still remain a challenge, although technological advances can help to overcome this problem (Santilli et al. 2018), while ground-based observations networks are often not available. Integration of multiple data sources in model and data assimilation schemes reduces uncertainties (Li et al. 2017; Clark et al. 2017; Lees et al. 2018).

Uncertainties in early warning and decision support systems

Early warning systems are a key feature of decision support systems and are becoming increasingly important for sustainable land management and food security (Shtienberg 2013; Jarroudi et al. 2015) (see also Chapter 7). Early warning systems can help to optimise fertiliser and water use, aid disease suppression, and/or increase the economic benefit by enabling strategic farming decisions on when and what to plant (Caffi et al. 2012; Watmuff et al. 2013; Jarroudi et al. 2015; Chipanshi et al. 2015). Their suitability depends on the capability of the methods to accurately predict phenological crop or pest developments, which in turn depends on expert agricultural knowledge, and the accuracy of the weather data used to run the phenological models (Caffi et al. 2012; Shtienberg 2013).

Uncertainties in model structures, parameterisations and inputs

The lack of understanding which and how important process in climate, land and socio-economic systems should best be described through algorithms are chief sources of uncertainty across models. Quantifying model skill in benchmarking exercises, the repeated confrontation of models by observations to establish a track-record of model developments and performance, is an important development to support the design and the interpretation of the outcomes of model ensemble studies (Randerson et al. 2009; Luo et al. 2012; Kelley et al. 2013)

The currently most widely used approaches to quantify model uncertainty in climate change, land use change and ecosystem modelling are intercomparisons, often associated with the calculation of model-ensemble means. Using means across a range of models implies that some of the structural and parameter-related uncertainties diminish. But the use of model intercomparisons might unintentionally also lead to models being “re-tuned” to fit better to the average model response results (Buisson et al. 2009; Parker 2013; Prestele et al. 2016). Although statistical methods to quantify impacts of within-model structural characteristics on simulation results are available, they are computationally costly (Zaehle et al. 2005; Wramneby et al. 2008; Arora and Matthews 2009; Booth et al. 2012; Xia et al. 2013; Ahlström et al. 2015). In view of the often still untested model structural and parameter uncertainties, deriving estimates of uncertainty from model intercomparison must be interpreted with caution (Parker 2013).

Uncertainties arising from unknown futures

Since AR5, an increasing number of studies have highlighted the large differences that exist in the extent and location of future cropland, pasture and forest, both between scenarios, but also even within a single scenario (Fuchs et al. 2015; Eitelberg et al. 2016; Popp et al. 2016; Prestele et al. 2016; Alexander et al. 2017a; Krause et al. 2017; Rogelj et al. 2018). Recently it was also shown that differences in projected land cover changes caused by different model structure is similar in magnitude to differences attributable to scenarios (Prestele et al. 2016; Alexander et al. 2017a) (see also Cross-Chapter Box 2: Scenarios). This raises concerns if for a given RCP/SSP combination output from only one land-use model is harmonised (Hurtt et al. 2011) since climate change or ecosystem models cannot investigate robustly the uncertainties arising from uncertainties in land use change projections.

Initial studies have found that the uncertainty in ecosystem responses to different historical or future land cover and land use estimates is at least of equal magnitude to that caused by different climate change projections (Ahlstrom et al. 2013, 2012; Fuchs et al. 2016; Bayer et al. 2017; Arneth et al. 2017; Krause et al. 2017, 2018). A broader range of harmonised scenarios available to the climate change and ecosystem modelling community is therefore desirable. Likewise, for questions of sustainable land management, or other questions of sustainable development, futures that achieve a number of set targets need to be explored more explicitly (Reilly and Willenbockel 2010; Le Mouel and Forslund 2017). For instance, Erb et al. (2016b) using a solution-oriented scenario analysis approaches, found it possible to meet global food demand under the constraint of only little (or no) deforestation by 2050, contingent to decreasing meat consumption or increasing yields (Erb et al. 2016b). Another study that explicitly explored within-model parameter uncertainty found it impossible to stay within a global crop-area limit in addition to also supplying sufficient food and limited bioenergy (Henry et al. 2018b). As normative scenarios are designed to support sustainable visions their increasing use offers a useful way forward.

Cross-Chapter Box 2: Scenarios

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About this box

The future is intrinsically unpredictable. This leads to large uncertainties in how land use might evolve into the future. Yet a number of different methods (collectively known as *futures analysis*) can support the exploration of future uncertainties, by making these uncertainties explicit and highlighting their consequences in support of decision-making and strategic planning. Futures analysis comprises a number of different and widely used methods, such as scenario analysis (Rounsevell and Metzger 2010), envisioning or target setting (Kok et al. 2018), pathways analysis[1] (IPBES 2016; IPCC 2018) or conditional probabilistic futures (van Vuuren et al. 2008; Engstrom et al. 2016; Henry et al. 2018a)(see also Cross-Chapter Box 2, Table 1). All chapters of this assessment draw conclusions from futures analysis and so, this cross-chapter box seeks to highlight the principle methods used, their application domains, their uncertainties and limitations, and potential ways forward.

Scenario analysis

There is an extensive literature reporting on scenarios and their quantification in climate change and land use change studies. This includes scenarios of climate change (Dokken 2014), land-based mitigation (Humpenoeder et al. 2018) as well as climate impacts and adaptation (Warszawski et al. 2014). Many of these scenarios are based on common scenario frameworks such as SRES (Smith et al. 2010) or the RCPs/SSPs (Popp et al. 2016; Riahi et al. 2017; Doelman et al. 2018). Or, they are based on stylised approaches that make stated assumptions about climate change solutions e.g. dietary change, food waste reduction, afforestation areas (Pradhan et al. 2013, 2014; Kreidenweis et al. 2016; Rogelj et al. 2018b; Seneviratne et al. 2018; Vuuren et al. 2018). Because of the diversity of available scenarios, attempts have been made to categorise them into common sets of related scenarios or ‘archetypes’ based on the similarity between their assumptions (IPBES 2018). Archetypes are useful in communicating the outcomes of a diverse range of alternative scenarios (see Chapter 2).

The scenario method commonly combines a qualitative part based on ‘storylines’ or descriptive narratives of the underlying causes (or drivers) of change (Rounsevell and Metzger 2010; O’Neill et al. 2014). These storylines are often (but not always) quantified using computer models. There are many different types of models that are used for this purpose based on very different modelling paradigms, baseline data and underlying assumptions (Alexander et al. 2017a). In this box, we refer mostly to Integrated Assessment Models (IAMs), land use models, ecosystem models (e.g., DGVMs, crop models) and Earth System models (ESMs), since these model types are commonly applied at the global scale or for large regions (see Cross-Chapter Box 2, Figure 1). It is important to note that there is large variability in the way individual models represent processes even within the same generic model type. Hence, it is critical to understand the uncertainties associated with the use of models as well as the uncertainties inherent within unknown futures (Prestele et al. 2016; Alexander et al. 2017a). Scenarios can be implemented by domain experts, or include a co-creation part that integrates the perspectives of stakeholders through participatory approaches (Kok et al. 2014). Participatory approaches are often used when creating visions or targets as desired futures, since these are designed to reflect stakeholder values, especially at regional scales. There are hardly any examples, however, of the use of indigenous knowledge in participatory scenario approaches (IPBES 2018).

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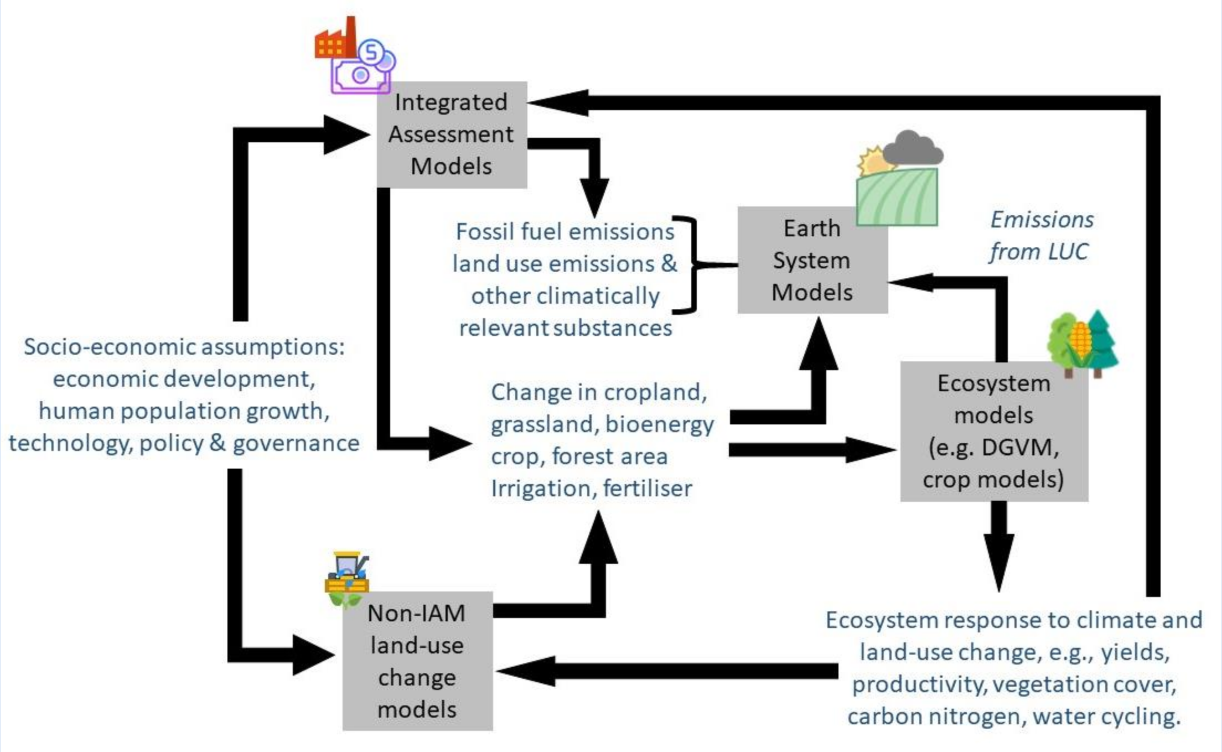
[1] FOOTNOTE: Different communities have a different understanding of the concept of *pathways*, as noted in the cross chapter box on scenarios in (IPCC 2018). Here we refer to pathways as solution-oriented trajectories that describe the actions required to move from today’s world to a set of future goals (IPCC 2018). It should be noted that the common use of the term pathways in the climate change literature as a synonym for projections or trajectories (e.g. RCPs/SSPs) is different from the use of the term elsewhere and this can lead to confusion.

Cross-Chapter Box 2, Table 1 Description of the principle methods used in land and climate futures analysis

Futures method	Description	Application domain	Time horizon	References
Exploratory scenarios	Trajectories of change in system components from the present to contrasting, alternative futures based on plausible and internally consistent assumptions about the development of the underlying drivers. There are 3 subsets of exploratory scenarios: a) Long-term trajectories; b) Business-as-usual scenarios; c) Policy scenarios	a) Climate system, land system and other components of the environment (e.g. biodiversity, ecosystem functioning, water resources and quality) b) A continuation into the future of current trends in key drivers to explore the consequences of current trajectories in the near-term c) Ex Ante analysis of the consequences of alternative policies based on known policy options or already implemented policy measures	a) 10-100 years b) 5-10 years c) 5-10 years to 10-100 years	(Warszawski et al 2014; Popp et al. 2016; Riahi et al. 2017; Alexander et al. 2018; Wolff et al. 2018; Calvin and Bond-Lamberty 2018;)
Stylised scenarios	Prescribed assumptions about specific components of the land system that are not necessarily internally-consistent with other drivers, and for which the feasibility may be unknown	Afforestation/reforestation areas, bioenergy areas, protected areas for conservation, consumption patterns (e.g. diets, food waste)	10-100 years	(2011; Pradhan et al. 2013, 2014; Humpenöder et al 2014; Foley et al. Boysen et al. 2017; Krause et al. 2017; Vuuren et al. 2018)
Normative scenarios (visions, target seeking scenarios)	Desired futures or outcomes that are aspirational	Environmental quality, societal development, human well-being, the RCPs	5-10 years to 10-100 years	(van Vuuren et al. 2011, 2015; Riahi et al. 2017; Henry et al. 2018b; Brown et al. 2018a)
Pathways	Alternative sets of choices, actions or behaviours that lead to a future vision (goal or target)	Socio-economic systems, governance and policy actions	5-10 years to 10-100 years	(Dokken 2014; Erb et al. 2016b; Brown et al. 2018a; IPBES 2018;)
Conditional probabilistic futures	Ascribe probabilities (as confidence ranges) to uncertain drivers that are conditional on scenario assumptions	Where some knowledge is known about driver uncertainties, e.g. population, economic growth, land use change	10-100 years	(Neill 2004; van Vuuren et al. 2008; Brown et al. 2014; Engstrom et al. 2016; Henry et al. 2018b)

Cross-Chapter Box 2, Figure 1 outlines how scenarios are quantified with models. This includes the different components of the land and climate systems, how models can quantify these components as well as the interactions between them. Scenario outputs for a given system component can be analysed in themselves, or they can be input to other models, such as land use change inputs to ecosystem models or Earth system models.



Cross-Chapter Box 2, Figure 1 Interactions between land and climate system components and models in scenario analysis

There are global-scale scenarios of food security (Foley et al. 2011; Pradhan et al. 2013, 2014)(see also Chapter 5) and land-based, climate-change mitigation for example reforestation/afforestation, avoided deforestation and bioenergy (Kraxner et al. 2013; Humpenöder et al. 2014; Krause et al. 2017)(see also Chapter 2). There are fewer scenarios of desertification, land degradation and restoration (Wolff et al. 2018)(see also Chapters 3 and 4). These studies have indicated that the role of socio-economic drivers is often more important for land use change than the role of climate change (Harrison et al. 2014, 2016). Of the socio-economic drivers considered, technological development is found to be important in many land use change scenario studies since it affects the production potential (yields) of food and bioenergy production as well as the feed conversion efficiency of livestock (Rounsevell et al. 2006; Foley et al. 2011; Wise et al. 2014; Pradhan et al. 2014). Furthermore, land management, especially intensification of crop and livestock systems can reduce yield gaps and thus the area of land needed for food production (Foley et al. 2011; Weindl et al. 2017; Kreidenweis et al. 2018) . Trends in consumption patterns, e.g. diets, waste reduction, have also been found to be critical in affecting land use change (Pradhan et al. 2013; Bajželj et al. 2014; Alexander et al. 2016; Weindl et al. 2017; Alexander et al. 2017b; Vuuren et al. 2018). Land-based mitigation through large-scale bioenergy production and afforestation will lead to trade-offs with food security (food prices), water resources and biodiversity (Humpenoder et al. 2014; Kreidenweis et al. 2016; Krause et al. 2017; Calvin and Bond-Lamberty 2018; Heck et al. 2018).

In addition to global scale, land use change scenarios, regional scale scenarios have demonstrated that the regional impacts of climate change are highly variable geographically because of differences in both the climate change and socio-economic change scenarios (Harrison et al. 2014). Moreover, the capacity to adapt to these impacts is strongly dependent on the regional socio-economic context and coping capacity (Dunford et al. 2014). It has been shown that regional scenarios need to account for cross-sectoral and cross-scale interactions to avoid either over- or under-estimating impacts (Harrison et al. 2016). Many regional scale scenarios are co-created through stakeholder participatory methods, which provide additional richness and context to storylines, as well as providing saliency and legitimacy for local stakeholders (Kok et al. 2014).

Visions and pathways analysis

Pathways analysis is important in moving beyond the *what if?* perspective of exploratory scenarios to evaluate how desirable futures might be achieved in practice, recognising that there are often multiple pathways to achieve the same future vision. Pathways analysis is highly relevant in support of policy, since it outlines sets of actions and decisions to achieve future targets. Unlike scenario analysis, however, studies that quantify pathways to achieve stylised assumptions or normative visions are still rare, especially at the global scale, and this is a major gap in current knowledge (Dokken 2014). This includes quantified pathways to achieve sustainability targets such as the SDGs (IPBES 2018). Whilst targets may be clearly articulated, we do not know what societal choices, behaviour and transitions are needed to attain them, nor how these socio-economic processes and decisions evolve through time. Improving capacity to quantify pathways would greatly contribute to decision-making, especially with respect to achieving sustainable development goals. Exploratory scenarios have focused more on the sustainable supply of land-based good and services and less on sustainable consumption, with the exception of diets and reducing waste (Bajželj et al. 2014; Pradhan et al. 2014; Springmann et al. 2018; Vuuren et al. 2018). Conversely, pathways analysis focuses more on consumption and behavioural changes through transitions and transformative solutions (IPBES 2018).

Although largely qualitative in nature, pathways analyses have shown that multiple alternative pathways exist to achieve the priorities for future sustainable development set by governments and societal actors that mitigate trade-offs. Of these alternatives, the most promising tend to focus on long-term societal transformations through continuous education, awareness raising, knowledge sharing and participatory decision-making (IPBES 2018). In spite of this, there are almost always trade-offs in pathways that achieve multiple sustainability targets (IPBES 2018). Priority in pathways is often given to cross-scale integration and the mainstreaming of environmental objectives across policy sectors (IPBES 2018). Targets for land restoration and protection could have the co-benefits of increasing global tree cover and increasing forest and soil carbon stocks as well as protecting the land area with the highest value for both biodiversity and carbon storage (Wolff et al. 2018).

Probabilistic futures analysis

Conditional probabilistic approaches are explicit about the uncertainties associated with scenario parameters, and seek to explore the consequences for modelled outputs of the uncertainty ranges of these parameters (Neill 2004). Whilst probabilities are ascribed to scenario parameter uncertainties (through a probability density function), this is not the same as ascribing probabilities to outcomes, which occurs with forecasts. Although forecasting in common in short-term weather prediction, the approach is unsuited to the analysis of land use futures because of the longer time-horizons over which land use changes, and the difficulties in ascribing probabilities to human-mediated processes. Only a few studies have applied the conditional probabilistic approach to land use futures (Brown et al. 2014; Engstrom et al. 2016; Henry et al. 2018b). These studies show that accounting for assumed uncertainties in the key drivers across different scenarios leads to large ranges in land use change, for example global cropland areas of 893–2380 Mha by the end of the 21st Century (Engstrom et al. 2016). They also find that normative land use futures may not be achieved, even across a wide range of scenario parameter settings, because of trade-offs arising from the competition for land (Henry et al. 2018b). Accounting for uncertainties across scenario assumptions can lead to convergent outcomes for land use change, which implies that certain outcomes are more robust across a wide range of uncertain scenario assumptions (Brown et al. 2014).

What are the limitations of land use futures?

The frameworks used to derive scenarios of land system change often derive from those developed within the climate change community (e.g., SRES, RCPs/SSPs). This facilitates comparison and integration of scenarios of climate change and land system change, but means that it can be difficult to apply these frameworks to non-climate change questions (Rosa et al. 2017). This is because there is a wider range of drivers (beyond climate change) that affect land systems and these drivers are not considered adequately in storylines, parameter quantification, and outputs from models that are used to quantify scenarios. By not adequately representing key drivers and processes in models, a narrow 'climate-centric' perspective can limit the value of scenario studies.

Furthermore, for climate mitigation scenarios it is becoming increasingly important to assess the impact of mitigation actions on the broader (non-climate) environment for example, biodiversity, ecosystem functioning, air quality, food security, desertification/degradation and water cycles (Rosa et al. 2017). There is also a need to assess how land use and climate change affect more broadly affect the wider environment. This implies the need for a more encompassing and flexible approach to creating scenarios that considers other environmental aspects, not only as a part of impact assessment, but also during the process of creating the scenarios themselves.

There are a limited number of models that can quantify land use change scenarios at the global scale (Dokken 2014) and there is large variance in the outcomes of these models (Alexander et al. 2017a). In some cases, there is greater variability between the models themselves than between the scenarios that they are quantifying, and these differences vary with geography (Prestele et al. 2016). These differences mostly arise from variations in baseline datasets, thematic classes and modelling paradigms (Alexander et al. 2017a). With all models, it is important to be aware of the underlying assumptions in order to interpret model output and the conclusions that are drawn from these studies. For this purpose, model evaluation is critical in augmenting confidence in the outcomes of modelled futures (Ahlstrom et al. 2012; Kelley et al. 2013). Not all land use change models have, however, been evaluated against observational data, and the extent of model evaluation is often not transparent. Hence, there is a clear need for more transparency in modelling, especially concerning model evaluation and testing, including making model code available along with complete sets of scenario outputs.

Modelled projections of global land-use change do not account well for human behaviour and social interaction and how dynamically changing interactions between agents affect land use decision-making (Rounsevell et al. 2014; Calvin and Bond-Lamberty 2018). This is largely because of the limitations of representing these processes at global scales, but also because of a lack of understanding about how to model human behaviour. The most commonly used approach to represent decision-making in global models is through economic optimisation (Arneth et al. 2014). This limits the capacity of global models to account for the human dimensions of land systems including equity, fairness, land tenure and the role of institutions and governance, and therefore the use of these models to quantify transformative pathways, adaptation and mitigation (Arneth et al. 2014; Rounsevell et al. 2014; Wang et al. 2016b). An important human behavioural process that is rarely modelled is the diffusion of knowledge (Brown et al. 2018b) and its effect on uptake rates of novel land use and management practices (Alexander et al. 2013; Turner et al. 2018). No model exists at present that is able to represent complex human behaviours at the global scale, although approaches for doing so have been discussed in the literature (Rounsevell et al. 2014; Arneth et al. 2014; Robinson et al. 2017; Brown et al. 2017; Calvin and Bond-Lamberty 2018).

What are the ways forward?
On-going, model and scenario inter-comparison exercises (O'Neill et al. 2016) are important in understanding differences between models and hence why models generate different land use and climate futures, and this contributes to the further development of existing models. However, the next generation of global scale, land use models need to better account for human behaviour and decision-making processes (Rounsevell et al. 2014; Arneth et al. 2014; Calvin and Bond-Lamberty 2018), which would make them better adapted to quantifying transitions to sustainable futures. For example, explicit inclusion of time lags in land use decision-making (Alexander et al. 2013), involving the exchange of knowledge through social networks (Brown et al. 2018b), would enable models and scenarios to better reflect rates of land transformation (Turner et al. 2018). Such development would create a step-change in the capacity to model pathways to sustainable futures such as the SDGs. More progress in applying pathways analysis, especially in their quantification, would enable science to better support governmental policy processes. In spite of the limitations, futures analysis remains the methodological bedrock of how to explore future uncertainties in support of policy.

1.3.3.2 Uncertainties in decision making

Decision makers are faced with the task of developing and implementing policies that are based to varying degrees on many knowns but also many unknowns (e.g., (Rosenzweig and Neofotis 2013; Anav et al. 2013; Ciais et al. 2013; Stocker et al. 2013)(see also Chapter 7). Standard decision theory focuses mostly on the *uncertainty of consequences*. In the context of IPCC, *risk* refers to the potential for adverse consequences (e.g., arising from climate change impacts or from climate change mitigation measures) where something of value is at stake and where the occurrence and degree of an outcome is uncertain (see glossary and 7.2.2). How to discuss (and deal with) more information-poor decisions that go beyond the uncertainty of consequences is much less clear (see Table SM2). In the context of climate change projections, the term *deep uncertainty* is frequently used to denote situations where either the analysis of a situation is inconclusive, or parties to a decision cannot agree on a number of criteria that would help to rank model results in terms of likelihood (e.g., Hallegatte and Mach 2016; Maier et al. 2016) (see also Chapter 7).

Decision making in the face of uncertainty
The spectrum of the multitude of ways to deal with uncertain consequences can be spanned by two extreme decision approaches: an (economic) cost-benefit analysis and a precautionary approach. A typical variant of cost benefit analysis is the minimisation of negative consequences. This approach needs reliable probability estimates (Gleckler et al. 2016; Parker 2013). The other end of the spectrum of decision approaches, the precautionary approach provides a decision method that does not take into account probability estimates (cf. Raffensperger and Tickner 1999):[2] In a nutshell, the focus here is on the worst outcome only and it is to be avoided at any cost (Gardiner 2006).

In between these two extreme cases, various decision approaches are suggested that try to not only avoid the deficits of cost-benefit analysis and a precautionary approach, but also addresses some of the other uncertainties in a more reflective manner. Climate-informed decision analysis may combine various approaches that start with exploring real options and the vulnerabilities and sensitivities of certain decisions.

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[2] FOOTNOTE: Note that there are different versions of the precautionary approach. This is sometimes referred to as strong formulation of the precautionary principle in order to distinguish it from meta-decision criteria, so called weak formulations, as given, for example in the Rio Declaration on Environment and Development 1992.

Such an approach includes stakeholder involvement (e.g., elicitation methods), and can be combined with for example, analysis of climate or land-use change modelling (Hallegatte and Rentschler 2015; Luedeling and Shepherd 2016) (see also 7.1).

Though current decision making, despite faced with various uncertainties, often assumes that the future can be predicted and thus develop optimal plans for some probable or likely future, flexibility in decision making is facilitated by decisions are not set in stone and can change over time (Walker et al. 2013; Hallegatte and Rentschler 2015). As regards COP21, one may argue that the breakthrough in agreeing on a temperature threshold was made possible, amongst many other things, by a shift towards a “reasonable pluralism” (e.g., Boran 2014), by starting to address various types of uncertainties. Generally, within the deep uncertainty community a paradigm is emerging that requires to develop a strategic vision of the long- or mid-term future, while committing to short-term actions and establishing a framework to guide future actions (Haasnoot 2013).

1.4 Response options to the key challenges

The complexity of climate change and changes in the global socio-economic environment requires a systemic link between food production and consumption, and land-resources more broadly to address the identified challenges (Bazilian et al. 2011; Hussey and Pittock 2012). The ‘Nexus thinking’ emerged as an alternative to sector-specific governance of natural resource use to achieve global securities of water (D’Odorico et al. 2018), food and energy (Hoff 2011; Allan et al. 2015), and to address also biodiversity concerns (Fischer et al. 2017). Yet to date there is no agreed upon definition of “nexus” nor a uniform framework to approach the concept, which may be land-focused (Howells et al. 2013), water-focused (Hoff 2011) or food-centred (Ringler and Lawford 2013; Biggs et al. 2015). Significant barriers remain to establish nexus approaches as part of a wider repertoire of responses to global environmental change, including challenges to cross-disciplinary collaboration, complexity, political economy and incompatibility of current institutional structures (Hayley et al. 2015; Leck et al. 2015; Wichelns, 2017) (see also Chapter 7).

A number of responses have been identified in the literature that underpin solutions to the challenges arising from land management’s greenhouse gas emissions, and the loss of productivity arising from degradation and desertification. These options rely on a) land management, b) value chain management and c) risk management (see Figure 1.4). None of these response options are mutually exclusive, and it is their combination in a regionally, context-specific manner that is most likely to achieve co-benefits between climate change mitigation, adaptation and other environmental challenges in a cost efficient way (Griscom et al. 2017a; Kok et al. 2018). Sustainable solutions affecting both demand and supply need to rely on more than the carbon footprint and should be extended to other vital ecosystems like water, nutrients, and biodiversity footprints (van Noordwijk and Brussaard 2014; Cremasch 2016). Here we use a select number of examples that cut most prominently across food security, desertification, and degradation to illustrate these concepts (see Chapter 6).

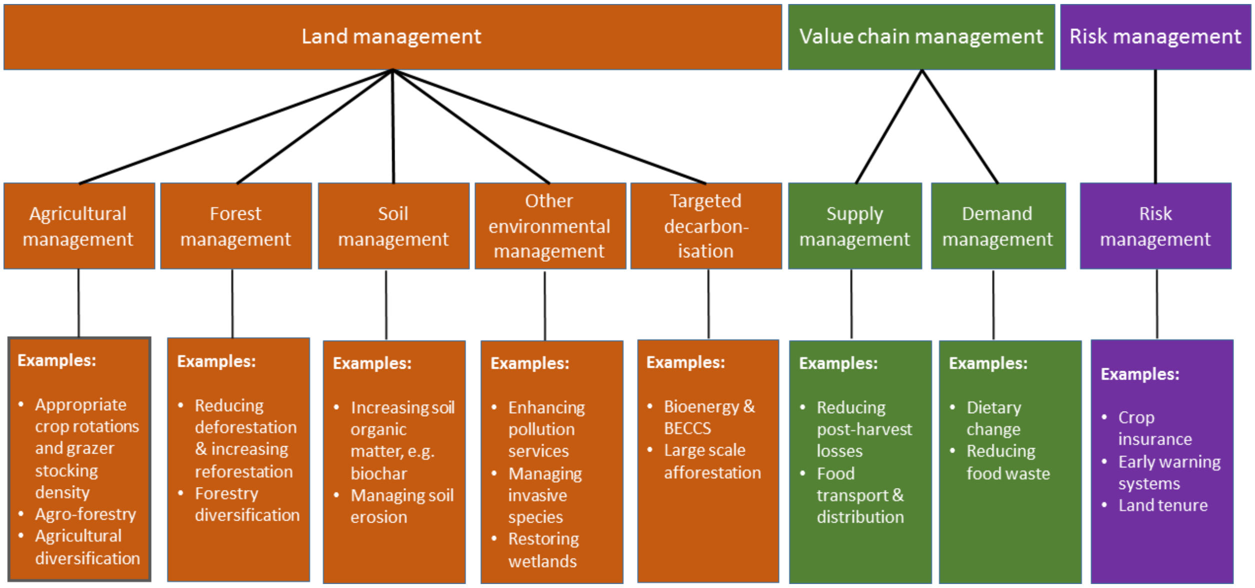

Figure 1.4 Broad categorisation of response options, categorised into three main classes and eight sub-classes. For illustration, figure includes examples of individual response options, for a complete list and description, see Chapter 6

1.4.1 Land Management

1.4.1.1 Agricultural, forest and soil management

Sustainable land management describes "*the use of land resources for the production of goods to meet changing human needs while assuring the long-term productive potential of these resources and the maintenance of their environmental functions*" (Alemu 2016, Altieri and Nicholls 2017)(see also Chapter 6), and conceptually includes ecological, technological and governance aspects.

The choice of SLM strategy employed is a function of regional context and land use types, with *high agreement* on (a combination of) choices such as agroforestry, conservation agriculture and forestry practices, crop and forest species diversity, appropriate crop and forest rotations, organic farming, integrated pest management, the preservation and protection of pollination services, rain water harvesting, range and pasture management, and precision agriculture systems (Stockmann et al. 2013; Ebert, 2014; Schulte et al. 2014; Zhang et al. 2015; Sunil and Pandravada 2015; Poeplau and Don 2015; Agus et al. 2015; Keenan 2015; MacDicken et al. 2015; Abberton et al. 2016). Conservation agriculture and forestry uses management practises with minimal soil disturbance such as no tillage or minimum tillage, permanent soil cover with mulch combined with rotations to ensure permanent soil surface, or rapid regeneration of forest following harvest (Hobbs et al. 2008; Friedrich et al. 2012). Precision agriculture is characterised by a "management system that is information and technology based, is site specific and uses one or more of the following sources of data: soils, crops, nutrients, pests, moisture, or yield, for optimum profitability, sustainability, and protection of the environment" (USDA 2007).

Enhancing the carbon content of soil and/or use of biochar (see Chapter 4) have increasingly moved into focus in recent years as a climate change mitigation option with possibly large co-benefits for other ecosystem services. Enhancing soil carbon storage and addition of biochar can be practised without competition for land area, but evidence is limited and impacts of large scale application of biochar on the full greenhouse gas balance of soils, or human health are yet to be explored (Gurwick et al. 2013; Lorenz and Lal 2014; Smith 2016).

1.4.2 Value chain management

1.4.2.1 Supply management

Food losses from harvest to retailer. Approximately one third of loss and waste occurs between crop production and foods being eaten, increasing substantially if losses in livestock production and overeating are included (Gustavsson et al. 2011; Alexander et al. 2017c). These losses combine losses on-farm and from farm to retailer, as well as at the retailer and consumer level (see 1.4.2.2).

Post-harvest food loss on farm and from farm to retailer is a widespread problem especially so in the global south (Xue et al. 2017). For instance, averaged for eastern and southern Africa an estimated 10–17% of annual grain production is lost (Zorya et al. 2011). Across 84 countries, median losses in the supply chain before retailing were estimated as about 28 kg per capita in case of cereals or about 12 kg per capita in case of eggs and dairy products (Xue et al. 2017). For the year 2013, using FAO data, losses prior to the reaching retailers were estimated as 20% (dry weight) of the production amount (22% wet weight) (Gustavsson et al. 2011; Alexander et al. 2017c). Advancing harvesting technologies, storage capacity and efficient transportation could all contribute to reducing these losses with co-benefits for food availability, land area needed for food production and related greenhouse gas emissions.

Stability of food supply, transport and distribution. Increased climate variability enhances fluctuations in world food supply and price variability (Warren 2014; Challinor et al. 2015; Elbehri et al. 2017). “Food price shocks” need to be understood regarding their transmission across sectors and borders and impacts on poor and food insecure societies (Lehmann et al. 2013; LE 2016; FAO 2015b). Trade can play an important stabilising role for food supply, especially for regions with agro-ecological limits to production, including water scarce regions, as well as regions that experience short term production variability due to climate, conflicts or other economic shocks (Gilmont 2015; Marchand et al. 2016). Detrimental consequences in countries in which trade dependency may accentuate the risk of food shortages from foreign production shocks could be reduced by increasing domestic reserves or importing food from a diversity of suppliers (Gilmont 2015; Marchand et al. 2016).

Climate mitigation policies might create new trade opportunities (e.g., biomass) (Favero and Massetti 2014) or alter existing trade patterns (e.g., eco-labels like “mile food”; “local food”; carbon footprints). Food trade can either increase or reduce the overall environmental impacts of agriculture. In the absence of sustainable practices and when the ecological footprint falls outside the market system, trade can also exacerbate resource exploitation and environmental leakages, thus weakening trade mitigation contributions (Mosnier et al. 2014; Dalin and Rodríguez-Iturbe 2016; Elbehri et al. 2017).

Ensuring stable food supply while pursuing climate mitigation and adaptation, will benefit from evolving trade rules and policies that allow internalisation of the cost of carbon (and costs of other vital resources such as water, nutrients). Likewise, future climate change mitigation policies will gain from measures designed to internalise the environmental costs of resources (Elbehri et al. 2017).

1.4.2.2 Demand management

Dietary change. Environmental impacts of the animal-rich “western diets” are being examined critically in the scientific literature (Tilman and Clark 2014; Jalava et al. 2014; Hallström et al. 2015; Alexander et al. 2015, 2016; Aleksandrowicz et al. 2016; Poore and Nemecek 2018). A study that assumed today’s average diets from different countries to be eaten globally found the potentially required agricultural land area necessary to sustain the different diets to vary 14-fold, depending on the degree of ruminant protein in the average food intake (-55% to +178% compared to existing cropland)(Alexander et al. 2016). Reduction of animal protein intake has been estimated to reduce global green and blue water use by 11% and 6%

(Jalava et al. 2014). A study that investigated the effect if consumers were to avoid meat only from producers with above-median greenhouse gas emissions while halving their animal-product intake found to free about 2100 Mha of agricultural land currently used for feed and fodder production and reduction in greenhouse gas emissions by nearly 5 $GtCO_2$-eq a^{-1} (Poore and Nemecek 2018).

Redirecting food diets towards being more healthy, equitable (addressing growing global nutrition imbalances that emerge as undernutrition, malnutrition, and obesity) and climate-compatible requires a combination of economic, social and policy responses. Food diets can be location and community specific, are rooted in culture and traditions while responding to changing lifestyles driven by urbanisation and changing income. Changing dietary and consumption habits would require a combination non-price (government procurement, regulations, education and awareness raising) and price (Juhl and Jensen 2014) incentives to induce consumer behavioural change.

Reduced waste and losses in the food demand system. Solutions to food waste and loss need to tackle not only technical solutions (see Chapter 5) but also the economics of food since loss and waste of food arises as an unintended side effect of supply chain efficiency and low cost food. Food waste at household level is also derived from consumer behaviour, including overeating. Globally, overconsumption was found to waste a similar amount of food to discarding by the consumer (9–10% to food bought; (Alexander et al. 2017c)). Consumer food waste has been shown to predominantly occur in rich countries, increasing with per capita GDP and levelling at about 100 kg cap^{-1} above about 70 000 USD cap^{-1} (Xue et al. 2017). Across countries median retailing losses for cereals, and eggs and dairy products were approximately one third of losses post-harvest to retailer (Xue et al. 2017). Globally, retail losses are estimated as 3.6% dry weight and 5.7% wet weight (Gustavsson et al. 2011; Alexander et al. 2017c).

Food waste and loss, both on the supply and the demand-side, requires a combination of responses that are technical, economic and institutional. This require more accurate data on the loss-source, -magnitude and -causes along the food supply chain, and the deployment of economic instruments that can internalise the cost of food waste reduction into the product price and induce a shift in consumer behaviour towards less waste and perhaps even more nutritious, or alternative, food intake (FAO 2015d; Alexander et al. 2017c; FAO 2018b).

1.4.3 Risk management

Risk management refers to the actions that individual land users or collectives of users can apply in mitigating the risks associated with environmental change. Insurance and early warning systems are obvious examples of risk management, but risk can also be reduced (or resilience enhanced) through land ownership, seed sovereignty, livelihood diversification, reducing land loss through urban sprawl or through the reduction of “land-grabbing”. Early warning systems support farmer decision making on management strategies (see 1.3.3) and are a good example of an adaptation measure with mitigation co-benefits such as reducing carbon losses (see 1.4.4 and Chapter 6). Primarily designed to avoid yield losses, early warning systems also support fire management strategies in forest ecosystems, which also prevents carbon losses (de Groot et al. 2015). Given that over recent decades on average around 10% of cereal production was lost through extreme weather events (Lesk et al. 2016), where available and affordable, insurance can buffer farmers and foresters against the financial losses incurred through such weather and other (fire, pests) extremes (Falco et al. 2014). Decisions to take up insurance are influenced by a range of factors such as the removal of subsidies or targeted education (Falco et al. 2014). Enhancing access and affordability of insurance in low-income countries is a specified objective under the UNFCCC (Linnerooth-Bayer and

Mechler 2006). A global mitigation co-benefit of insurance schemes may also include the possible incentivisation of future risk reduction (Surminski and Oramas-Dorta 2014).

1.4.4 Adaptation measures and scope for co-benefits with mitigation

Seeking to integrate strategies for achieving adaptation and mitigation goals is attractive as without integrations these two agendas can compete for limited resources (Lobell et al. 2013; Berry et al. 2015), or are considered as discrete response actions, therefore amounting to missed opportunities for exploiting interrelationships. Adaptation tackles the underlying causes (informational, capacity, financial, institutional, and technological) of both biophysical and socio-economic vulnerability (Huq et al. 2014) and is increasingly linked to resilience and to broader development goals (Huq et al. 2014). Adaptation measures can increase performance of mitigation projects under climate change and legitimise mitigation measures through the more immediately felt benefits from adaptation (Locatelli et al. 2011; Campbell et al. 2014; Locatelli et al. 2015b). But, trade-offs between adaptation and mitigation also exist and these need to be understood (and avoided) to establish win-win situations (Porter et al. 2014; Kongsager et al. 2016).

In the context of SRCCL, adaptation measures include improving land productivity, land restoration and rangeland management (Derner and Augustine 2016; Fick et al. 2016), soil health restoration (including water and nutrients, soil carbon) (Chen et al. 2014a; FAO and ITPS 2015; Stavi et al. 2016), managing water scarcity and equitable access to water (Brauman et al. 2013; Granados et al. 2015; Lemieux et al. 2014; Scheierling and Treguer 2016; Maskey et al. 2015); protecting pollination services (Bartomeus et al. 2013; Woodcock et al. 2014; Holland et al. 2015); sustainable cropping practices, agroecology and genetic diversity (including minor, but locally significant crops) (Ebert and W. 2014; Sunil and Pandravada 2015; Gaba et al. 2015; Janila et al. 2016); agroforestry (Schroth et al. 2016; van Noordwijk et al. 2014); and building resilient livestock systems (e.g., adapted livestock breeds in drylands) (Weindl et al. 2015; Leroy et al. 2016). These agricultural adaptation options have been shown to have positive synergies with mitigation, including reduced soil erosion and reduced leaching of nitrogen and phosphorus (which reduces soil carbon loss and maintains and enhances productivity), enhanced soil moisture (which also maintains or enhances productivity), or modification of microclimates (Mader et al. 2002; Smith and Olesen 2010; Jarvis et al. 2011).

From a forestry perspective, *Tropical reforestation* of degraded lands through mechanisms such as REDD+ (reducing emissions from deforestation and forest degradation) can produce large synergies between mitigation, through forests' function as carbon storage, and adaptation (Locatelli et al. 2011; Rahn et al. 2014). Reforestation projects, if well managed, can increase communities' economic opportunities that encourage conservation (Nelson and de Jong 2003), capacity building through training of farmers and installation of multifunctional plantations with income generation (Reyer et al. 2009), strengthened local institutions (Locatelli et al. 2015a) and increased cash-flow to local forest stakeholders from foreign donors (West 2016). Increasing adaptive capacity in forested areas has the potential to prevent deforestation and forest degradation (Locatelli et al. 2011). Permeability of storage can be secured through management practices (Kant and Wu 2012). Reforestation is associated with improved water filtration, ground water recharge and flood control (Ellison et al. 2017; Griscom et al. 2017a), reduced flooding through decreased river peak flow, improved water quality and groundwater recharge (Berry et al. 2015), and reduced climate impacts on biodiversity (Locatelli et al. 2015a), although not all of these aims have been achieved with existing large-scale reforestation efforts (see Cross-Chapter Box 1: Large scale reforestation and afforestation).

1.5 Enabling the response

1.5.1 Governance to enable the response

Governance (see Chapter 7) includes all of the processes, structures, rules and traditions that govern, which may be undertaken by formal and informal actors including governments, markets, organisations, and their interactions with people. Two types of governance actors may be distinguished: those affecting driving forces such as policies and markets, and those directly changing land (Hersperger et al. 2010). The former includes governments and administrative entities, large companies investing in land, non-governmental institutions and international institutions. It also includes UN agencies that are working at the interface between climate change and land management, such as the Food and Agriculture Organization and the World Food Programme that have *inter alia* worked on advancing knowledge to support food security through the improvement of techniques and strategies for more resilient farm systems. Farmers and foresters directly act on land (actors in proximate causes) (Hersperger et al. 2010)(see also Chapter 7).

Policy implementation is often strongly sectoral. For example, agricultural policy might be concerned with food security, but with little concern for environmental protection or human health. As food, energy and water security and the conservation of biodiversity rank high on the Agenda 2030 for Sustainable Development, the promotion of synergies between sectoral policies is important (IPBES, 2018) in order to reduce the risks of anthropogenic climate forcing through mitigation, and to bring greater collaboration among scientists, policy makers, private sector and land managers in adapting to climate change (FAO 2015a). Adaptive governance (see Chapter 7) starts with nationally and globally collective decision making, and the development of coherent policy mixes arising from a cross-sectoral, systemic ways of thinking. It further involves the continuous and pragmatic assessment of the effectiveness of a policy mix and its flexible adjustment.

Appropriate policy mixes that underpin response options may be fostered by a systemic understanding of the multiple environmental and socioeconomic challenges at hand. Implementation of systemic, nexus approaches (see 1.4) has been achieved through socio-ecological systems (SES) frameworks that emerged from the institutional analysis and development framework applied to studies of how institutions affect human incentives, actions and outcomes (Ostrom and Cox 2010). These frameworks (Ostrom 2009) laid the basis for alternative formulations to tackle the sustainable management of land resources focusing specifically on institutional and governance outcomes (Lebel et al., 2006; Ribor et al., 2006) and addressing the scale concordance between the social and ecological dimensions (Veldkamp et al. 2011; Myers et al. 2016; Azizi et al. 2017) (see also 6.2.2).

Adaptation or resilience pathways within the SES framework require several attributes, including indigenous and local knowledge (ILK) and trust building for deliberative decision making and effective collective action, polycentric and multi-layered institutions and responsible authorities that pursue just distributions of benefits to enhance the adaptive capacity of vulnerable groups and communities (Lebel et al. 2006). The nature, source, and mode of knowledge generation are critical to ensure that sustainable solutions are community-owned and fully integrated within the local context (Mistry and Berardi 2016; Schneider and Buser, 2018). Integrating local and indigenous knowledge with scientific information is a prerequisite for such community-owned solutions. ILK is context-specific, transmitted orally or through imitation and demonstration, adaptive to changing environments, collectivised through a shared social memory, and situated within (Mistry and Berardi 2016). ILK is also holistic since indigenous people do not seek solutions aimed at adapting to climate change alone, but instead look for solutions to increase their resilience to a wide range of shocks and stresses (Mistry and Berardi 2016). ILK can be deployed in the practice of climate governance especially at the local level where actions are informed by the principles of decentralisation and autonomy (Chanza and de Wit 2016). ILK need not be viewed as needing confirmation or disapproval by formal science, but rather it can advance science and serve to complement scientific knowledge (Klein et al. 2014).

The capacity to apply individual policy instruments, and in combination to apply instruments as policy mixes, is influenced by governance modes. These modes include hierarchical governance that is centralised and imposes policy through top-down measures, decentralised governance in which public policy is devolved to regional or local government, public-private partnerships that aim for mutual benefits for the public and private sectors and self or private governance that involves decisions beyond the realms of the public sector (IPBES 2018). These governance modes provide both constraints and opportunities for key actors that affect the effectiveness, efficiency and equity of policy implementation.

1.5.2 Gender agency as a critical factor in climate and land sustainability outcomes

Women farmers make up more than half of the agricultural workforce in some low- and middle-income countries and, in that role, play a crucial role for the management of natural resources (FAO 2017). The overall gender disparity between rights and actual rural land ownership between men and women continues to have implications for land use (Omolo 2010; Deere and León de Leal 2014). Rural and indigenous women continue to have limited access to and property rights for forests and agricultural land (Bose et al. 2017). Women’s traditional knowledge can add value to a society’s knowledge base and support adaptation practices towards climate change (Lane and McNaught 2009), but this knowledge is also under increasing pressure considering the rate, severity and distribution of climate change impacts. It is important to address gender related asymmetries in creating a level playing field amongst social groups and to reduce the tendencies of unequal societies and entrenched incidences of poverty (Bose et al. 2017). This involves respecting countries with unique social values, cultures and institutional mechanisms and, in turn, identify the ways in which these social norms play a role in women's social and economic empowerment, including entrepreneurship (see 6.2.2).

1.5.3 Policy Instruments

Policy instruments enable governance actors to respond to environmental and societal challenges through policy action. Examples of the range of policy instruments available to public policy-makers is given in Table 1.2, based on four categories of instruments: legal and regulatory instruments, rights-based instruments and customary norms, economic and financial instruments and social and cultural instruments.

Table 1.2 Categorisation of the different policy instruments that are relevant to the land challenges addressed in this assessment, and examples (IPBES 2018)(see also Chapter 7)

Legal and regulatory	*Economic and financial*	*Rights-based and customary norms*	*Social and cultural*
• ***Legislation*** • Environmental standards • Liability rules • Technology requirements	• ***Taxes, tax relieves*** • ***Fees, charges*** • Emissions trading • Subsidies • Payment for ecosystem services • Compensation payments	• ***Human rights*** • Collective (access) rights, e.g., common land • Heritage (sacred sites, peace parks) • Institutions of indigenous people and local communities	• ***Education, Information*** • Certification • Voluntary agreements • Corporate social responsibility

1.5.3.1 Legal & regulatory instruments

Legal and regulatory instruments deal with all aspects of intervention by public policy organisations to correct market failures, expand market reach, or intervene in socially relevant areas with inexistent markets. Such instruments can include legislation to limit the impacts of intensive land management, for example, protecting areas that are susceptible to nitrate pollution or soil erosion. But also setting standards or threshold values, for example, mandated water quality limits, organic production standards, or geographically defined regional food products. Legal and regulatory instruments may also define liability rules, for example where environmental standards are not met, as well as establishing long-term agreements for land resource protection with land owners and land users.

1.5.3.2 Economic and financial instruments

Economic and financial instruments deal with the many ways in which public policy organisations can intervene in markets. This includes established market-based instruments such as taxes, but also the subsidies that are provided to land users to encourage certain production strategies or for cross-compliance with environmental quality objectives, for example, nature protection or water quality. Trading, for example, emissions trading, habitat trading (and banking) and ecological fiscal transfers, are also important methods in generating beneficial outcomes for land resources from markets.

Effective, market-led responses for climate mitigation depend on business models that fully internalise the cost of emissions into economic calculations. Such “business transformation” would itself require integrated policies and strategies that aim to achieve full accounting of emissions for economic activities (Biagini and Miller 2013; Weitzman 2014; Eidelwein et al. 2018). Market-based policies such as carbon taxes or green payments have been promoted to encourage markets and businesses to contribute to climate mitigation, but their effectiveness to date has not always matched expectations (Grolleau et al. 2016). International initiatives such as REDD+ and agricultural commodity roundtables (beef, soybeans, palm oil, sugar) are also expanding the scope of private sector participation in climate mitigation (Nepstad et al. 2013), but their impacts have not always been effective (Denis et al. 2014). Moreover, commodity roundtables seek to exclude unsustainable farmers from commodity markets through international social and environmental standards (Nepstad et al. 2013).

Payments for environmental services (PES) defined as "*voluntary transactions between service users and service providers that are conditional on agreed rules of natural resource management for generating offsite services*" (Wunder 2015) have not worked as effectively as originally theorised (Börner et al. 2017). PES in forestry were shown to be effective only when coupled with appropriate regulatory measures (Alix-Garcia and Wolff 2014). Better designed and expanded PES schemes would encourage integrated soil-water-nutrient management packages (Stavi et al. 2016), services for pollinator protection (Nicole 2015), water use governance under scarcity and engage both public and private actors (Loch et al. 2013). Effective PES also requires better economic metrics to account for human-directed losses in terrestrial ecosystems and to food potential, and to address market failures or externalities unaccounted for in market valuation of ecosystem services.

For climate change adaptation, much is required to mobilise private sector financial resources and technical capacity, supported by government policies and regulations in developing innovative climate services and adaptation technologies (Biagini and Miller 2013). Governments, private business, and community groups could also partner to develop sustainable production codes (Chartres and Noble 2015), and in co-managing land-based resources (Baker and Chapin 2018), while private-public partnerships can be effective mechanisms in deploying infrastructure to cope with climatic events (floods) and for climate-indexed insurance (Kunreuther 2015).

Resilient strategies for climate adaptation can also rely on the construction of markets through social networks, as in the case of livestock systems (Denis et al. 2014) or when market signals encourage adaptation through land markets (Anderson et al. 2018). Adequate policy support (through regulations, investments in research and development or support to social capabilities) must compliment private initiatives for effective solutions to restore degraded lands (Reed and Stringer 2015), or mitigate against risk and to avoid shifting risks to the public (Biagini and Miller 2013). Private initiatives that depend on trade for climate adaptation and mitigation require reliable trading systems that do not impede climate mitigation objectives (Elbehri et al 2015; Mathews 2017).

1.5.3.3 Rights-based instruments and customary norms

Rights-based instruments and customary norms deal with the equitable and fair management of land resources for all people (IPBES 2018). These instruments emphasise the rights in particular of indigenous peoples and local communities, including for example, recognition of the rights embedded in the access to, and use of, common land. Common land includes situations without legal ownership (e.g., hunter-gathering communities in south America or Africa and bushmeat), where the legal ownership is distinct from usage rights (Mediterranean transhumance grazing systems), or mixed ownership-common grazing systems (e.g., Crofting in Scotland). A lack of formal (legal) ownership has often led to the loss of access rights to land, where these rights were also not formally enshrined in law, which especially impacts indigenous communities, for example, deforestation in the Amazon basin. Overcoming the constraints associated with common-pool resources (forestry, fisheries, water) are often of economic and institutional nature (Hinkel et al. 2014) and require tackling the absence or poor functioning of institutions and the structural constraints that they engender through access and control levers using policies and markets and other mechanisms (Schut et al. 2016). Other examples of rights-based instruments include the protection of heritage sites, sacred sites and peace parks (IPBES 2018). Rights-based instruments and customary norms are consistent with the aims of international and national human rights, and the critical issue of liability in the climate change problem.

1.5.3.4 Social and cultural instruments

Social and cultural instruments are concerned with the communication of knowledge about improved land management through awareness raising, education and the communication of quality and provenance of land-based products. Examples of the latter include ecolabelling and certification, which target consumers in making more informed choices about their consumption habits. Eco-labels (Appleton 2009) and institutions (agricultural commodity roundtables; social networks) (Nepstad et al. 2013; Denis et al. 2014) are also expanding the scope of private sector participation in climate mitigation. Footprint labels can be an effective means of causing behavioural change by consumers. However, private labels focusing on a single metric (e.g., carbon) may give misleading signals if they target a portion of the life cycle (e.g., transport) (Appleton 2009) or ignore other ecological indicators (water, nutrients, biodiversity)(van Noordwijk and Brussaard 2014). Social and cultural instruments also include approaches to self-regulation and voluntary agreements, especially with respect to environmental management and land resource use. This is becoming especially important in the increasingly important domain of corporate social responsibility.

1.6 Introduction of the remaining chapters & story of the report

Land use is an environmental challenge but can also contribute to address climate change, hence, land gives us an opportunity to maximise the several solutions that exist, beyond energy based solutions. Thus, land use is at the heart of sustainable development as formalised in the Sustainable Development Goals (SDGs) (see Figure 1.5). This report should help us to assess how land can be used in a way to contribute to achieving the SDGs. Chapter 2 concentrates on the natural system dynamics, assessing recent progress that has been made towards understanding impacts of climate change on land, and feedbacks arising from altered biogeochemical and biophysical exchange fluxes. Chapters 3 to 5 concentrate on the report's key terms "desertification", "degradation" and "food security.

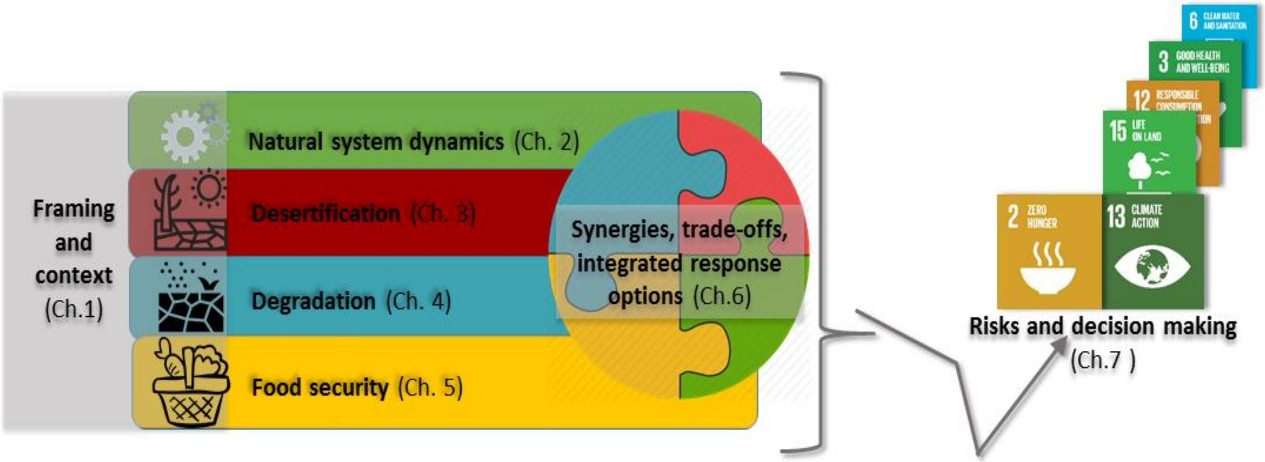

Figure 1.5 Overview over the SRCCL

Chapter 3 examines how the world's dryland populations are uniquely vulnerable to desertification and climate change, but also have significant knowledge in adapting to climate variability and addressing desertification. Chapter 4 assesses the urgency of addressing land degradation. Despite accelerating trends of land degradation, reversing these trends seems attainable through proper implementation of SLM, which is expected to improve resilience to climate change, mitigate climate change, and ensure food security for generations to come. Food security is the focus of Chapter 5, with an assessment of the risks and opportunities that climate change presents to food systems, considering how mitigation and adaptation can contribute to both human and planetary health.

Chapters 6 and 7 continue the exploration of the issues identified in Chapter 1 and to provide a cross-chapter synthesis which brings out the key messages related to the manifold interlinkages, and identify integrative (win: win) response options, related to the SDGs. Chapter 7, highlights these aspects further, especially regarding the challenges and opportunities that arise in the broader climate land interactions.

Frequently Asked Questions

FAQ 1.1 What is the role of technology and innovation in land-based mitigation and adaptation options?

The role of technologies and innovations is to facilitate and provide more robust and efficient options for mitigation and adaptation to climate changes. Recent advances include IoT devices (internet of Things), which were developed mostly for industry applications, and are now frequently applied in agriculture management with low cost, highly dense sensor networks. Space observations and aerial digital imaging are supporting farm operations via increased availability of satellite products and the development of unmanned airborne platforms (i.e. drones). Furthermore, big-data analytics and biogeochemical models are becoming increasingly used in new decision supporting tools. New crop varieties, new soil carbon accumulation technologies, and a variety of low inputs agriculture practices (including livestock management) have been made available to farmers. The suites of such technologies are often referred as Climate Smart Agriculture or Forestry. Although great progress is occurring in technology and innovation in land use, still implementation, particularly in developing economies, is lagging behind. Technological innovation will need to play a key role – but is not enough. Managerial and institutional innovations are likely to be even more important in dealing with the heterogeneous and uncertain impacts of climate change.

FAQ 1.2 How region-specific are the impact of different land-based adaptation and mitigation options?

Land based adaptation and mitigation options are closely related to regional specific features for several reasons. Climate change has a definite regional pattern with some regions already suffering from enhanced climate extremes and others being impacted little, or even benefiting. From this point of view increasing confidence in regional climate change scenarios is becoming a critical step forward towards the implementation of adaptation and mitigation options. Biophysical and socio-economic impacts of climate change depend on the exposures of natural ecosystems and economic sectors, which are again specific to a region, reflecting regional sensitivities due to governance. The overall responses in terms of adaptation or mitigation capacities to avoid and reduce vulnerabilities and enhance adaptive capacity, depend on institutional arrangements, socio-economic conditions, and implementation of policies, many of them having definite regional features. However global drivers, such as agricultural demand, food prices, changing dietary habits associated with rapid social transformations (i.e. urban versus rural, meat versus vegetarian) may interfere with regional specific policies for mitigation and adaptation options and require the global level to be addressed.

FAQ 1.3 What is the difference between desertification and land degradation? And where are they happening?

The difference between land degradation and desertification is geographic. Land degradation is a general term used to describe a negative trend in land condition anywhere in the world, resulting in long -term reduction or loss of the biological productivity of land, its ecological integrity or its value to humans, caused by direct or indirect human-induced processes, including climate change. Desertification is land degradation when it occurs in arid, semi-arid, and dry sub-humid areas, which are also called drylands. Contrary to some perceptions, desertification is not restricted to expansion of deserts. Desertification is also not limited to irreversible forms of land degradation. Desertification includes all forms and levels of land degradation in arid, semi-arid, and dry sub-humid areas.

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Supplementary Material

Table S 1 Observations related to variables indicative of land management, and their uncertainties (possible table/box to be placed in the chapter)

LM-related process	Observations methodology	Scale of observations (space and time)	Uncertainties[3]	Pros and cons	Select literature
GHG emissions	Micrometeorological fluxes (CO_2) Micrometeorological fluxes (CH_4) Micrometeorological fluxes (N_2O)	1-10 ha 0.5hr- >10 y	5-15% 10-40% 20-50%	Pros Larger footprints Continuous monitoring Less disturbance on monitored system Detailed protocols Cons Limitations by fetch and turbulence scale Not all trace gases	(Richardson et al. 2006; Luyssaert et al. 2007; Foken and Napo 2008; Mauder et al. 2013; Peltola et al. 2014; Wang et al. 2015; Rannik et al. 2015; Campioli et al. 2016; Rannik et al. 2016; Wang et al. 2017a; Brown and Wagner-Riddle 2017; Desjardins et al. 2018)
	Soil chambers (CO_2) Soil chambers (CH_4) Soil chambers (N_2O)	0.01-1 ha 0.5hr - 1 y	5%-15% 5%- 25% 53%- 100%[4]	Pros Relatively inexpensive Possibility of manipulation experiments Large range of trace gases Cons Smaller footprint Complicate upscaling Static pressure interference	(Vargas and Allen 2008; Lavoie et al. 2015; Barton et al. 2015; Dossa et al. 2015; Ogle et al. 2016; Pirk et al. 2016; Morin et al. 2017; Lammirato et al. 2018)
	Atmospheric inversions (CO_2) Atmospheric inversions (CH_4)	Regional 1->10 y	50% 3-8%	Pros Integration on large scale Attribution detection (with 14C)	(Wang et al. 2017b) (Pison et al. 2018)

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[3] FOOTNOTE: Uncertainty here is defined as the coefficient of variation CV. In the case of micrometeorological fluxes they refer to random errors and CV of daily average

[4] FOOTNOTE: > 100 for fluxes less than 5g N_2O-N ha^{-1} d^{-1}

				Rigorously derived uncertainty Cons Not suited at farm scale Large high precision observation network required	
Carbon balance	Soil carbon point measurements	0.01ha-1ha >5 y	5-20%	Pros Easy protocol Well established analytics Cons Need high number of samples for upscaling Detection limit is high	(Chiti et al. 2018; Castaldi et al. 2018; Chen et al. 2018; Deng et al. 2018)
	Biomass measurements	0.01ha – 1ha 1-5 y	2-8%	Pros Well established allometric equations High accuracy at plot level Cons Difficult to scale up Labour intensive	(Pelletier et al. 2012; Henry et al. 2015; Vanguelova et al. 2016; Djomo et al. 2016; Forrester et al. 2017; Xu et al. 2017Marziliano et al. 2017; Clark et al. 2017; Disney et al. 2018; Urbazaev et al. 2018; Paul et al. 2018)
Water balance	Soil moisture (IoT sensors, Cosmic rays, Thermo-optical sensing etc.)	0.01ha – regional 0.5hr-<1y	3-5% vol	Pros New technology Big data analytics Relatively inexpensive Cons Scaling problems	(Yu et al. 2013; Zhang and Zhou 2016; Iwata et al. 2017; McJannet et al. 2017; Karthikeyan et al. 2017; Iwata et al. 2017; Cao et al. 2018;Amaral et al. 2018; Moradizadeh and Saradjian 2018; Strati et al. 2018)
	Evapotranspiration	0.01ha – Regional 0.5hr->10y	10-20%	Pros Well established methods Easy integration in models and DSS Cons Partition of fluxes need additional measurements	(Zhang et al. 2017; Papadimitriou et al. 2017; Kaushal et al. 2017; Valayamkunnath et al. 2018; Valayamkunnath et al. 2018; Tie et al. 2018; Wang et al. 2018)
Soil Erosion	Sediment transport	1 ha – Regional 1d - >10y	-21-34%	Pros Long history of methods	(Efthimiou 2018; García-Barrón et al.

				Integrative tools Cons Validation is lacking Labour intensive	2018; Fiener et al. 2018)
Land cover	Satellite	0.01ha – Regional 1d - >10y	16 - 100%	Pros Increasing platforms available Consolidated algorithms Cons Need validation Lack of common Land Use definitions	(Olofsson et al. 2014; Liu et al. 2018; Yang et al. 2018)

Table S2 Possible uncertainties decision making faces (following (Hansson and Hadorn 2016)

Type	Knowledge gaps	Understanding the uncertainties
Uncertainty of consequences	Do the model(s) adequately represent the target system? What are the numerical values of input parameters, boundary conditions, or initial conditions? What are all potential events that we would take into account if we were aware of them? Will future events relevant for our decisions, including expected impacts from these decisions, in fact take place?	Ensemble approaches; downscaling Benchmarking, sensitivity analyses Scenario approaches
Moral uncertainty	How to (ethically) evaluate the decisions? What values to base the decision on (→ often unreliable ranking of values not doing justice to the range of values at stake, cp. Sen 1992), including choice of discount rate, risk attitude (risk aversion, risk neutral, …) Which ethical principles? (i.e. utilitarian, deontic, virtue, or other?)	Possibly scenario analysis Identification of lock-in effects and path-dependency (e.g. Kinsley et al 2016)
Uncertainty of demarcation	What are the options that we can actually choose between? (not fully known because "decision costs" may be high, or certain options are not "seen" as they are outside current ideologies). How can the mass of decisions divided into individual decisions? e.g. how this influences international negotiations and the question who does what and when (cp. Hammond et al. 1999).	Possibly scenario analysis
Uncertainty of consequences & uncertainty of demarcation	What effects does a decision have when combined with the decision of others? (e.g. other countries may follow the inspiring example in climate reduction of country X, or they use it solely in their own economic interest)	Games
Uncertainty of demarcation & moral uncertainty	How would we decide in the future? (Spohn 1977; Rabinowicz 2002)	

References S1

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