INTERGOVERNMENTAL PANEL ON climate change

Working Group III (WGIII) – Mitigation of Climate Change

Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SR2)

Background report for the Scoping Meeting

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ii. Foreword

This background documentation provides a summary of the available knowledge from previous IPCC reports and other relevant sources to act as a foundation upon which to build discussion at the Expert Scoping Meeting in February 2017 for the IPCC Special Report on “climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems”. The aim of the background documentation is not to provide a comprehensive exploration of all of these areas, nor to propose outcomes, but to support participants by providing a summary of relevant information before and during the scoping meeting. We review relevant reports and other outputs before providing a final section on key known unknowns and issues arising since AR5, as a means to stimulate discussion.

iii. Introduction and context

The IPCC Special Report on "climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems" arises from a cluster of several initial proposals of special reports, and will be one of the outputs of the IPCC AR6 cycle. These five topics are complexly interconnected with each other and with climate change. Additionally, many climate change impacts and adaptation and mitigation practices will affect multiple topics to be covered in this Special Report. Climate change can be a significant driver of desertification and land degradation and can affect food production, thereby, influencing food security. Delivering food security has implications for GHG emissions and climate, since agriculture is a significant emitter of GHGs and demand for different foods greatly impacts GHG emissions. Sustainable land management, on the other hand, can help to deliver food security, to reduce GHG emissions (and create carbon sinks), and to reduce desertification and degradation – but climate change might affect the sustainability of land management. The key areas outlined in the title of this special report are interdependent and so need to be tackled in a highly integrated way.

Previous IPCC reports have provided considerable detail on climate change and terrestrial greenhouse gas fluxes, and to a lesser extent on land degradation, sustainable land management and food security. There has been relatively little attention paid to desertification, perhaps because there is a separate UN convention covering desertification (the United Nations Convention to Combat Desertification: UNCCD). The development of a comprehensive report, covering all of the topic areas appearing in the title of the SR, will require close integration across all of these topics, and will require an approach that integrates across traditional IPCC WGs, and that engages input from outside usual IPCC areas of expertise.

This background document builds on previous IPCC reports, in particular AR5, the SSREN, SREX, and earlier SRs such as the SR on Land Use, Land-Use Change and Forestry (SR-LULUCF) from 2000. Other inputs include the report of the Expert Meeting on Climate Change, Food, and Agriculture held 27-29 May 2015. There are areas of potential overlap with other SRs in the AR6 cycle (e.g. GHG fluxes from terrestrial ecosystems/cryosphere; food security/oceans and competition for land for greenhouse gas removal strategies to reach greenhouse gas emission reduction pathways consistent with a 1.5 degree C temperature rise). There are additional resources from outside IPCC which are relevant to this SP, including outputs from the United Nations Convention to Combat Desertification (UNCCD), the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Technical Panel on Soils (ITPS), and the UN Sustainable Development goals. The topic is wide ranging and complex. The aim of the background documentation is not to provide a comprehensive exploration of all of these areas, nor to propose outcomes; rather its aim is to provide a summary of the relevant knowledge from all of the above-mentioned sources, thereby providing a foundation upon which to build discussion at the Expert Scoping Meeting in February 2017. We divide the report into three parts: Part I summarises previous findings from the IPCC, Part II provides key insights from previous relevant non-IPCC UN Intergovernmental processes under other Conventions, and Part III outlines key known unknowns and issues arising since AR5, as a means to begin discussion. (Most references in the text refer to the relevant IPCC reports. A bibliography for additional references is included in Section iv.)

Part 1 Previous relevant findings from IPCC

1.1 Summary of WGI AR5 findings of relevance to interactions between climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

The AR5 WGI report did not have a specific chapter focused on land surface, and relevant information is distributed across many chapters. This brief synthesis is structured around observations, detection and attribution; processes (including model evaluation, radiative forcing, climate feedbacks) and projections.

1.1.1 Observed changes, detection and attribution

Temperature. It is certain that global mean surface temperature has increased, showing a warming of 0.85 [0.65 to 1.06] °C, over the period 1880 to 2012. In addition to robust multi-decadal warming, global mean surface temperature exhibits substantial decadal and interannual variability. Due to natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. It is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. Over every continental region except Antarctica, anthropogenic forcings have likely made a substantial contribution to surface temperature increases since the mid-20th century. It is very likely that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale. It is likely that the frequency of heat waves has increased in large parts of Europe, Asia and Australia. Evidence for human influence on temperature extremes has strengthened since the SREX. It is very likely that human influence has contributed to observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century, and likely that human influence has more than doubled the probability of occurrence of heat waves in some locations.

Precipitation. Confidence in precipitation change averaged over global land areas since 1901 is low prior to 1951 and medium afterwards. Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 (medium confidence before and high confidence after 1951). For other latitudes, area-averaged long-term positive or negative trends have low confidence. There are likely more land regions where the number of heavy precipitation events has increased than where it has decreased. The frequency or intensity of heavy precipitation events has likely increased in North America and Europe. In other continents, confidence in changes in heavy precipitation events is at most medium. There is low confidence in change in intensity and/or duration of drought on a global scale. The frequency and intensity of drought has likely increased in the Mediterranean and West Africa, and likely decreased in central North America and north-west Australia. It is likely that anthropogenic influences have affected the global water cycle since 1960. Anthropogenic influences have contributed to observed increases in atmospheric moisture content in the atmosphere (medium confidence), to global-scale changes in precipitation patterns over land (medium confidence), and to intensification of heavy precipitation over land regions where data are sufficient (medium confidence).

Snow and permafrost. There is very high confidence that the extent of Northern Hemisphere snow cover has decreased since the mid-20th century. Northern Hemisphere snow cover extent decreased 1.6 [0.8 to 2.4] % per decade for March and April, and 11.7 [8.8 to 14.6] % per decade for June, over the 1967 to 2012 period. It is likely that there has been an anthropogenic contribution to observed reductions in Northern Hemisphere spring snow cover since 1970. There is high confidence that permafrost temperatures have increased in most regions since the early 1980s. Observed warming was up to 3°C in parts of Northern Alaska (early 1980s to mid-2000s) and up to 2°C in parts of the Russian European North (1971 to 2010). In the latter region, a considerable reduction in permafrost thickness and areal extent has been observed over the period 1975 to 2005 (medium confidence).

Land carbon sources and sinks. Carbon dioxide concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. Annual net CO_2 emissions from anthropogenic land use change were 0.9 [0.1 to 1.7] GtC yr^{-1} on average during 2002 to 2011 (medium confidence). From 1750 to 2011, CO_2 emissions from deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. For the same period, and out of cumulative anthropogenic emissions of 555 [470 to 640] GtC (including emissions from fossil fuel combustion and cement production as well as deforestation and other land use change), 160 [70 to 250] GtC have accumulated in natural terrestrial ecosystems (i.e., the cumulative residual land sink). The albedo change due to land use has caused an estimated radiative forcing in 2011 compared to 1750 of -0.15 [-0.25 to -0.05] Wm^{-2}.

Emissions of CO_2 alone have caused a radiative forcing of 1.68 [1.33 to 2.03] W m^{-2}. Including emissions of other carbon-containing gases, which also contributed to the increase in CO_2 concentrations, radiative forcing of CO_2 is 1.82 [1.46 to 2.18] W m^{-2}. Emissions of CH_4 alone have caused a radiative forcing of 0.97 [0.74 to 1.20] W m^{-2}. This is much larger than the concentration-based estimate of 0.48 [0.38 to 0.58] W m^{-2} (unchanged from AR4). This difference in estimates is caused by concentration changes in ozone and stratospheric water vapour due to CH_4 emissions and other emissions indirectly affecting CH_4. A proporortion of the RF in these numbers will be as a result of LUC / agricultural emissions etc. but it is difficult to attribute as the AR5 does not go into this level of detail.

1.1.2 Processes & projections

Model skills. There has been some improvement in the simulation of continental-scale patterns of precipitation since the AR4. At regional scales, precipitation is not simulated as well, and the assessment is hampered by observational uncertainties. There is high confidence that the statistics of monsoon and El Niño-Southern Oscillation (ENSO) based on multi-model simulations have improved since AR4.

Carbon feedbacks. Climate models that include the carbon cycle (Earth System Models) simulate the global pattern of ocean-atmosphere CO_2 fluxes, with outgassing in the tropics and uptake in the mid and high latitudes. In the majority of these models the sizes of the simulated global land and ocean carbon sinks over the latter part of the 20th century are within the range of observational estimates. The Radiative Concentration Pathways (RCPs) used in AR5 concentration-driven CMIP5 simulations do not consider the carbon cycle uncertainties affecting atmospheric CO_2 concentrations. Climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO_2 in the atmosphere (*high confidence*). Most models project a continued land carbon uptake under all RCPs, but some models simulate a land carbon loss due to the combined effect of climate change and land use change. Future uptake of carbon from the land is less certain than uptake from the ocean. Climate change will partially offset increases in land and ocean carbon sinks caused by rising atmospheric CO_2 due to positive feedbacks between climate and the carbon cycle. The release of CO_2 or CH_4 to the atmosphere from thawing permafrost carbon stocks over the 21st century is assessed to be in the range of 50 to 250 GtC for RCP8.5 (low confidence).

Temperature projections. Global surface temperature change for the end of the 21st century is *likely* to exceed 1.5°C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is *likely* to exceed 2°C for RCP6.0 and RCP8.5, and *more likely than not* to exceed 2°C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform. Natural internal variability will continue to be a major influence on climate, particularly in the near-term and at the regional scale. By the mid-21st century the magnitudes of the projected changes are substantially affected by the choice of emissions scenario. The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 will likely be in the range of 0.3°C to 0.7°C (medium confidence). This assessment assumes there will be no major volcanic eruptions or secular changes in total solar irradiance. Relative to natural internal variability, near-term increases in seasonal mean and annual mean temperatures are expected to be larger in the tropics and subtropics than in mid-latitudes (high confidence). Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to likely be in the ranges derived from the concentration-driven CMIP5 model simulations, that is, 0.3°C to 1.7°C (RCP2.6), 1.1°C to 2.6°C (RCP4.5), 1.4°C to 3.1°C (RCP6.0), 2.6°C to 4.8°C (RCP8.5). It is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase. It is very likely that heat waves will occur with a higher frequency and duration. Occasional cold winter extremes will continue to occur.

Water cycle projections. Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions. Changes in the near term, and at the regional scale will be strongly influenced by natural internal variability and may be affected by anthropogenic aerosol emissions. The high latitudes and the equatorial Pacific Ocean are likely to experience an increase in annual mean precipitation by the end of this century under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will likely increase by the end of this century under the RCP8.5 scenario. Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as global mean surface temperature increases. Globally, it is likely that the area encompassed by monsoon systems will increase over the 21st century. While monsoon winds are likely to weaken, monsoon precipitation is likely to intensify due to the increase in atmospheric moisture. Monsoon onset dates are likely to become earlier or not to change much. Monsoon retreat dates will likely be delayed, resulting in lengthening of the monsoon season in many regions. There is high confidence that the El Niño-Southern Oscillation (ENSO) will remain the dominant mode of interannual variability in the tropical Pacific, with global effects in the 21st century. Due to the increase in moisture availability, ENSO-related precipitation variability on regional scales will likely intensify, although confidence in projecting specific changes in ENSO and related regional phenomena for the 21st century remains low. There is low confidence in projected near-term changes in soil moisture. Regional to global-scale projected decreases in soil moisture and increased agricultural drought are likely (medium confidence) in presently dry regions by the end of this century under the RCP8.5 scenario. Soil moisture drying in the Mediterranean, Southwest US and southern African regions is consistent with projected changes in Hadley circulation and increased surface temperatures, so there is high confidence in likely surface drying in these regions by the end of this century under the RCP8.5 scenario. The range in projections of air quality (ozone and PM2.517 in near-surface air) is driven primarily by emissions (including CH_4), rather than by physical climate change (medium confidence). There is high confidence that globally, warming decreases background surface ozone. High CH_4 levels (as in RCP8.5) can offset this decrease, raising background surface ozone by year 2100 on average by about 8 ppb (25% of current levels) relative to scenarios with small CH_4 changes (as in RCP4.5 and RCP6.0). Higher surface temperatures in polluted regions will trigger regional feedbacks in chemistry and local emissions that will increase peak levels of ozone and PM2.5 (medium confidence).

The area of Northern Hemisphere spring snow cover is projected to decrease by 7% for RCP2.6 and by 25% in RCP8.5 by the end of the 21st century for the model average (medium confidence). It is virtually certain that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases. By the end of the 21st century, the area of permafrost near the surface (upper 3.5 m) is projected to decrease by between 37% (RCP2.6) to 81% (RCP8.5) for the model average (medium confidence). Global mean sea level will continue to rise during the 21st century (see Figure SPM.9) and will *very likely* exceed that observed during 1971 to 2010, due to increased ocean warming and increased loss of mass from glaciers and ice sheets. Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Accounting for warming effects of increases in non-CO_2 greenhouse gases, reductions in aerosols, or the release of greenhouse gases from permafrost will lower the cumulative CO_2 emissions for a specific warming target. Carbon Dioxide Removal (CDR) methods have biogeochemical and technological limitations to their potential on a global scale. There is insufficient knowledge to quantify how much CO_2 emissions could be partially offset by CDR on a century timescale.

1.2 Summary of WGII AR5 findings of relevance to interactions between climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

1.2.1 Observed changes and future impacts

There is new and stronger evidence of the detection of climate impacts on human systems on the inhabited continents. There is at least medium confidence in detection and attribution of climate impacts on agriculture and food systems in all the inhabited continents even though this is challenging because the behaviour of the system in the absence of climate change is driven by a large number of other factors (7.2.1), such as cultivar improvement and increased use of synthetic fertilizers, herbicides, and irrigation as well as policy impacts. In addition, the depiction of farmers' behaviour in response to climate change requires significant assumptions and has been shown to change over time (7.2.1). Assessment of many studies covering a wide range of regions and crops shows that negative impacts of climate change on crop yields have been more common than positive impacts (high confidence). The smaller number of studies showing positive impacts relate mainly to high-latitude regions, though it is not yet clear whether the balance of impacts has been negative or positive in these regions (high confidence). Climate change has negatively affected wheat and maize yields for many regions and in the global aggregate (medium confidence). Effects on rice and soybean yield have been smaller in major production regions and globally, with a median change of zero across all available data which are fewer for soy compared to the other crops (see Figure 1.11c). Observed impacts relate mainly to production aspects of food security rather than access or other components of food security. Since AR4, several periods of rapid food and cereal price increases following climate extremes in key producing regions indicate a sensitivity of current markets to climate extremes among other factors (medium confidence). {WGII SPM A-1}

At the continental or global scale, observed trends in some climatic variables, including mean summer temperatures, attributed to anthropogenic activity have had significant negative impacts on trends in yields for certain crops. At the global scale, trends in annual maximum daytime temperatures have been attributed to greenhouse gas emissions, and similar observation have been made for the occurrence of very hot nights (WGI AR5 Chapter 10.6.1.1) both of which can affect food systems. It is virtually certain that the increase in atmospheric CO_2 concentrations since preindustrial times has improved water use efficiency and yields, most notably in C_3 crops. These effects are however of relatively minor importance when explaining total yield trends. Emissions of CO_2 have been associated with tropospheric ozone (O_3) precursors. O_3 suppresses global output of major crops, with reductions estimated at roughly 10% for wheat and soy and 3-5% for maize and rice. Detected impacts are most significant for India and China, but can also be found for soybean production in the United States in recent decades.

Temperature shocks have negatively affected the growth of developing countries' exports, for which 1°C of warming in a given year reduced the growth rate of exports by 2.0-5.7% particularly of agricultural products. Regional detection and attribution of land degradation and desertification to climate influences is also challenging due to the occurrences of multiple other influences. These influences include increased extensive and intensive agriculture, deforestation, overgrazing, inappropriate land use change and population pressures especially on environmentally fragile lands subject to overuse. Some rainforest degradation and recession in the Amazon have also been attributed to climate change (low confidence, minor contribution from climate change). In other regions, higher temperatures and changes in precipitation patterns associated with climate change have affected the process of land degradation, compromising extensive agricultural areas. Degradation and desertification increase the vulnerability of communities exposed to floods, landslides and droughts, exacerbating existing social and environmental challenges.

All aspects of food security are potentially affected by projected climate changes, including food access, utilization, and price stability. For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation will negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (medium confidence). {7.4, Figure 7-4} Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10% and about 10% of projections showing yield losses of more than 25%, compared to the late 20th century. {Figure 7-5} After 2050, the risk of more severe impacts increases with this being particularly so in developing countries. {Figure 7-5} Regional Chapters 22 (Africa), 23 (Europe), 24 (Asia), 27 (Central and South America), and Box 7-1 show crop production to be consistently and negatively affected by climate change in the future in low-latitude countries, while climate change may have positive or negative effects in northern latitudes (high confidence). Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (high confidence).

Climate change will increase progressively the inter-annual variability of crop yields in many regions (medium confidence). {Figure 7-6} This may mean that food aid agencies might face additional operational challenges. Changes in climate and CO_2 concentration will in some places increase degradation through higher soil erosion rates and enhanced distribution competitiveness of agronomically important and invasive weeds (medium confidence). There is high agreement that future sea level rise will exacerbate the problems of increased degradation in deltas and coastal erosion, often compromising highly productive agricultural lands and freshwater resources.

Climate change will impact international trade volumes in both physical and value terms (limited evidence, medium agreement). Importing food can help countries adjust to climate change-induced domestic productivity shocks while short-term food deficits in low-income countries may have to be met through food aid. Options exist for adaptations within international agricultural trade (medium confidence). Deepening agricultural markets and improving the predictability and the reliability of the world trading system through trade reform, as well as investing in additional supply capacity of small-scale farms in developing countries, could result in reduced market volatility and manage food supply shortages caused by climate change.

1.2.2 Adaptation options, approaches, constraints and limits

Adaptation options. Many tools and practices developed for sustainable resource management or disaster risk reduction are co-beneficial for climate change adaptation, and vice versa, and can be integrated with mitigation objectives. Adaptation options for agriculture include technological responses, enhancing smallholder access to credit and other critical production resources, strengthening institutions at local to regional levels and improving market access through trade reform (medium confidence). Responses to decreased food production and quality include: developing new crop varieties adapted to changes in CO_2, temperature, and drought; enhancing the capacity for climate risk management; and offsetting economic impacts of land use change. Low- and no-till practices reduce soil erosion and runoff, protect crops from extreme precipitation, retain soil moisture, reduce greenhouse gas emissions and build soil organic carbon. Planting legumes and weed management on pastures enhance both forage productivity and soil carbon sequestration. Improving financial support and investing in the production of small-scale farms can also provide benefits. Expanding agricultural markets and improving the predictability and reliability of the world trading system could result in reduced market volatility and help manage food supply shortages caused by climate change. {WGII SPM B-2, SPM B-3, 7.5, 9.3, 22.4, 22.6, 25.9, 27.3} Two relevant widespread dual-benefit practices, developed to address desertification, are natural regeneration of local trees (see Box 22-2) and water harvesting. While destocking of livestock during drought periods may also address desertification and adaptation, the lack of individual incentives and marketing mechanisms to destock and other cultural barriers inhibit their widespread adoption.

Many of the options in the literature address incremental adaptation only rather than being inclusive of more systemic or transformational adaptation. In many cases, transformational change requires a greater level of commitment, access to more resources, and greater integration across all levels of decision making that encompass both on- and off-farm knowledge, processes and values.

Constraints and limits to adaptation. Despite the abundance of potential adaptation options, however, physical, social, cultural, institutional, and economic factors frequently constrain their implementation (high confidence; see also Section 25.4.2). Physical constraints have important implications for human adaptation (high agreement, medium evidence). Human consumption of freshwater increasingly is approaching the sustainable yield of surface and groundwater systems in a number of global regions. Water-dependent enterprises in such regions may therefore have reduced flexibility to cope with transient or long-term reductions in water supply, which influences the portfolio of adaptation actions to manage risk to water security and, subsequently, agriculture and food as well as energy security. Similarly, water quality and soil quality can constrain agricultural activities and therefore the capacity of agricultural systems to adapt to a changing climate. Ecological degradation also reduces the availability of ecosystem goods and services for human populations (very high confidence) reducing adaptation potential. Soil degradation and desertification can reduce crop yields and increase climate risk to agricultural and pastoral livelihoods. While these factors constrain adaptation, the recent literature also identifies some 'hard' limits to adaptation e.g. from climate thresholds for agricultural crops, species of fish, forest and coral reef communities, and humans. However, for most regions and sectors, there is a lack of empirical evidence to quantify magnitudes of climate change that would constitute a future adaptation limit.

Adaptation synergies and trade-offs with other adaptation objectives. Specific adaptation actions can create synergies or trade-offs with other adaptation objectives. For example, biotechnology may contribute to the development of drought and pest resistant cultivars that can maintain or enhance yields despite more challenging climate conditions. Yet, ecological and public health concerns over the use of biotechnology and genetically modified crops, in particular, can constrain the use of such technologies (Table 16-2). Agricultural producers may view biotechnology as an adaptive response, while some consumers may view it as a maladaptation that increases risks to ecosystems and food security. A challenge in adaptation planning and implementation is determining who decides what options are adaptive or maladaptive and successful or unsuccessful. The potential for maladaptation or for some adaptation options to undermine sustainability suggests that actors may choose to regulate adaptation and deliberately constrain possible options to avoid adverse externalities (very low confidence).

Many adaptation options reduce GHG emissions (medium evidence, medium agreement) including measures that reduce soil erosion and loss of nutrients such as nitrogen and phosphorus and for increasing soil carbon, conserving soil moisture, and reducing temperature extremes by increasing vegetative cover. Agroforestry practices provide carbon storage and may decrease soil erosion, increase resilience against floods, landslides, and drought, increase soil organic matter, reduce the financial impact of crop failure, as well as have biodiversity benefits over other forms of agriculture. However, not all actions are synergistic. For example, a review of 25 specific climate change-associated land use plans from Australia, found that 14 exhibited potential for conflict between mitigation and adaptation. Some mitigation activities such as biofuel production may impact negatively on food security via increased food prices, land use change and competition for water.

Table 16-2: Examples of potential trade-offs associated with an illustrative set of adaptation options that could be implemented by actors to achieve specific management objectives.

Sector	Actor's Adaptation Objective	Adaptation Option	Real or Perceived Trade-Off	References
Agriculture	Enhance drought and pest resistance; enhance yields	Biotechnology and genetically modified crops	Perceived risk to public health and safety; ecological risks associated with introduction of new genetic variants to natural environments	Howden *et al.* (2007); Nisbet and Scheufele (2009); Fedoroff *et al.* (2010)
	Provide financial safety net for farmers to ensure continuation of farming enterprises	Subsidized drought assistance; crop insurance	Creates moral hazard and distributional inequalities if not appropriately administered	Productivity Commission (2009); Pray *et al.* (2011); Trærup (2011); O'Hara (2012); Vermeulen *et al.* (2012)
	Maintain or enhance crop yields; suppress opportunistic agricultural pests and invasive species	Increased use of chemical fertilizer and pesticides	Increased discharge of nutrients and chemical pollution to the environment; adverse impacts of pesticide use on non-target species; increased emissions of greenhouse gases; increased human exposure to pollutants	Gregory *et al.* (2005); Howden *et al.* (2007); Boxall *et al.* (2009)

Economic approaches to adaptation. A key example of economic approaches to adaptation in land-based sectors is the use of water markets, which facilitate transfer from lower to higher-valued uses. A few studies make the case that water markets and pricing improves climate change adaptation but in many cases, the projected increase in climate-induced water demand (particularly in the agriculture sector), coupled with a projected decrease in water supply, suggests that adaptation to functioning water markets will be needed to protect social and environmental outcomes that may not have high monetary values. Many countries have instituted structures for water pricing in the household and agricultural sectors. Nevertheless such prices are unevenly applied, collection rates are low, metering is rarely implemented (at least for the agricultural sector, which is typically the largest water user) and pricing is often based on annual rather than usage-based fees. In many countries, a number of important institutional barriers to water markets and pricing remain. These include a lack of property rights including an thorough consideration of historical and current entitlements, limits on transferability, legal and physical infrastructures and institutional shortcomings coupled with issues involved with return flows, third part impacts, market design, transactions costs, and average versus marginal cost pricing. Payments for environmental services (PES) schemes are another economic instrument that encourages adaptive behaviour. This approach pays landholders or farmers for actions that preserve the services to public and environmental health provided by ecosystems on their property, including services that contribute to both climate change mitigation and adaptation.

Path dependence. A key factor constraining future adaptation options and costs is path dependence (very high confidence). Adjusting large-scale, complex systems and institutional behaviour established by past decision-making can be costly. A key example for this from land-based sectors is large-scale water management reforms. In order to avoid adverse outcomes associated with path dependence, the literature on flexible adaptation pathways emphasizes the implementation of reversible and flexible options that allow for ongoing adjustment and that recognise explicitly the value of flexibility and delayed investments as e.g. in the 'real options' approach.

Ecosystem Based Approaches to Adaptation. Ecosystem-based adaptation (EBA) integrates the use of biodiversity and ecosystem services into climate change adaptation strategies, taking into account the multiple social, economic, and cultural co-benefits for local communities. EBA can be combined with, or even a substitute for, the use of engineered infrastructure or other technological approaches. EBA offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes. Examples of EBA in sustainable land management include sustainable water management, sustainable management of grasslands and rangelands, establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision, and management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes.

1.3 Key regional and global vulnerabilities

Climate change is projected to undermine food security, and climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty (high confidence). All aspects of food security are potentially affected by climate change, including food production, access, use and price stability (high confidence). Global temperature increases of ~4°C or more above late 20th century levels, combined with increasing food demand, would pose large risks to food security, both globally and regionally (high confidence). The risks reflected in the Reasons for Concern framework have been updated in the AR5, reflecting in part new knowledge about risks relating to food security. Food security features explicitly in two key risks from climate change and the evaluation of "dangerous anthropogenic interference with the climate system" in the terminology of UNFCCC Article 2:

- Risk of food insecurity and the breakdown of food systems linked to warming, drought and precipitation variability particularly in regions that are characterized by poorer populations in urban and rural settings. [reflecting the Reasons For Concern # 2, 3 and 4]
- Risk of loss of rural livelihoods and income of rural residents due to insufficient access to drinking and irrigation water, and reduced agricultural productivity, as well as risk of food insecurity, particularly for farmers and pastoralists with minimal capital in semi-arid regions. [reflecting the Reasons For Concern # 2 and 3]

Interactions of climate change impacts on one sector with changes in exposure and vulnerability, as well as adaptation and mitigation actions affecting the same or a different sector are generally not included or well integrated into projections of risk. However, their consideration leads to the identification of a variety of emergent risks that were not previously assessed or recognized [high confidence], including links between food security, land degradation and ecosystem services, groundwater, health and malnutrition. Land degradation often reduces efficiency of water and energy use (e.g., resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security. On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat, but may reduce renewable water resources. [3.7, 4.4, Boxes 25-10 and CC-WE]

Emergent risks arise from indirect, trans-boundary, and long-distance impacts of climate change. Examples of this include increasing prices of food commodities on the global market due to local climate impacts, in conjunction with other stressors, which decrease food security and exacerbate food insecurity at distant locations; management of transboundary water resources; and mitigation measures taken in one location with long-distance or indirect impacts on biodiversity and/or human systems, such as the development of biofuels as energy sources.

Economies that are disproportionately comprised of climate-sensitive sectors such as agriculture, forestry and fisheries, may be particularly vulnerable to the effects of climate change and may encounter greater constraints on their capacity to adapt (very high confidence). Such economies occur disproportionately in the developing world, although multiple studies have explored climate-sensitive regional economies in developed nations as well.

1.4 Integration with sustainable development

Climate change poses a moderate threat overall to current sustainable development and a severe threat to future sustainable development (high confidence; high agreement, medium evidence). Added to other stresses such as poverty, inequality, or diseases, the effects of climate change will make sustainable development objectives such as food and livelihood security, poverty reduction, health, and access to clean water more difficult to achieve for many locations, systems, and affected populations. [20.2.1]. In developing countries, there is high confidence that adaptation could be linked to other development initiatives aiming for poverty reduction or improvement of rural areas. Studies show that both development and adaptation can be enhanced via: climate-adapted road development; installation of agricultural management, technology and infrastructure that enhances income, heat tolerance and drought adaptability; or improvements in public health infrastructure that increase capability to deal with climate-enhanced disease and other diseases. Thus development goals can be generally consistent with adaptation goals, with one possibly being an ancillary effect of the other, although this is not always the case. Explicit consideration of interactions among water, food, energy and biological carbon sequestration plays an important role in supporting effective decisions for climate adapted pathways (medium evidence, high agreement). Both biofuel-based power generation and large-scale afforestation designed to sequester carbon can reduce catchment run-off, which may conflict with alternative water uses for food production, human consumption or the maintenance of ecosystem function and services (see also Box 3.4). Conversely, irrigation can reduce risks in food and fibre production but can reduce water availability for other uses. {WGII Box CC-WE, Box TS.9}. An integrated response to urbanization provides substantial opportunities for more effective risk management, reduced emissions and more sustainable development (medium confidence). Compact development of urban spaces and intelligent densification can preserve land carbon stocks and land for agriculture and bioenergy. {WGII SPM B-2, SPM C-1, TS B-2, TS C-1, TS C-2, WGIII SPM.4.2.5, TS.3}

1.4.1 Impacts of climate change on GHG fluxes from terrestrial ecosystems

The natural carbon sink provided by terrestrial ecosystems is partially offset at the decadal timescale by carbon released through the conversion of natural ecosystems (principally forests) to farm and grazing land and through ecosystem degradation (high confidence). Carbon stored in the terrestrial biosphere (e.g., in peatlands, permafrost, and forests) is susceptible to loss to the atmosphere from both the direct effects of climate change such as high temperatures, drought, and windstorms and indirect effects including increased risk of fires, erosion, vegetation change and pest and disease outbreaks [4.2, 4.3, Box 4-3]. The net transfer of CO_2 from the atmosphere to the land is projected to weaken during the 21st century (medium confidence). Experiments and modelling studies provide medium confidence that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water use efficiency, but at a diminishing rate; and high confidence that low availability of nutrients, particularly nitrogen, will limit the response of many natural ecosystems to rising CO_2. There is medium confidence that other factors associated with global change, including high temperatures, rising ozone concentrations, and in some places drought, decrease plant productivity (and hence carbon inputs into ecosystems) by amounts comparable in magnitude to the enhancement by rising CO_2. There are few field-scale experiments on ecosystems at the highest CO_2 concentrations projected by RCP8.5 for late in the century, and none of these include the effects of other potential confounding factors. {4.2.4, 4.2.4.1, 4.2.4.2, 4.2.4.3, 4.2.4.4, 4.3.2.2, 4.3.3.1, Box 4-3, Box CC-VW, WGI AR5 6.4.3.3}.

The vulnerability of permafrost to thawing and degradation with climate warming is critical not only for determining the rate of a boreal-tundra biome shift and its associated net feedback to climate, but also for predicting the degree to which the mobilization of very large carbon stores frozen for centuries could provide additional warming (high confidence; WGI AR5 Chapters 6 and 12; see also Section 4.3.3.4). The release of greenhouse gases (GHGs) due to permafrost degradation may have substantial impacts on the climate, but these processes are not yet well represented in global climate models. Increases in total precipitation, increased runoff from glaciers, permafrost degradation, and the shift of precipitation from snow to rain will further increase soil erosion and sediment loads in colder regions.

1.5 Summary of WGIII AR5 findings of relevance to interactions between climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

1.5.1 Key challenges in the interactions between climate change, land and food

There is large, cost-competitive greenhouse gas mitigation potential in the AFOLU sector. Implementing mitigation options described in AR5 will require efforts to address key challenges that are either related to the drivers of emissions, or to establishing implementation frameworks, tools and financial or political instruments to move any mitigation agenda forward. These challenges are:

- Defining mechanisms (policy, technological and practical) to promote proven, cost-effective measures to enhance removals of GHGs, as well as the rapid transitions in land-use systems, mostly in developing countries, which complicate efforts to reduce of emissions through management of land and livestock.
- The diversity in values, uncertainties of land process and their links with a diversity of livelihoods of many social groups, and large regional differences in farming systems and natural resource management.
- Uncertainties which are particularly large for greenhouse gas emissions associated with agriculture and changes in land use (C-1). Knowledge gaps make it especially difficult to estimate how future climatic and atmospheric composition change will impact on ecological processes (C-2), and thereby impact upon mitigation potential, particularly for carbon sinks.
- Rapid increases in population, and projected changes in dietary preferences, will increase risks to the availability and security of energy and food supply, especially in the least-developed countries (C-1), impacting in return various land dynamics.
- High food costs which have amplified concerns about competition between food production and efforts to mitigate emissions, notably through the growing of bioenergy crops (C-1)

1.5.2 Emission from the AFOLU sector

The total GHG emissions have risen since 1970 mostly in energy systems. AFOLU is unique with its slow increase in total GHG emission during the last decade (2000-2010) and decline relative to emissions in the 1990s, mainly because of declining CO_2 emissions from FOLU. Many countries have adopted and implemented various policies that lead to better protection of forests, improved yields in agriculture and there have been large land restoration efforts (C-1 and C-5). Per-capita emissions decreased from 1.8 to 1.7 tCO_2eq/cap/yr because of a rapid population increase, mostly in developing countries and economies in transition (C-5).

By sector, agriculture, forestry and land-use (AFOLU) accounted for 24% of anthropogenic GHG emissions globally (about 9-12 Gt CO2eq/yr) mainly from deforestation and agricultural emissions from livestock, soil and nutrient management, C-11). Agricultural emissions account for 5.0-5.8 Gt CO2eq/yr GHG flux/yr and land use change (FOLU) for 4.3-5.5 Gt CO2eq/yr. Total GHG emissions from AFOLU increased by 20% from 9.9 GtCO2eq in 1970 to 12 GtCO2eq in 2010 (±45%), with a slower increase in agricultural emissions in recent years (C-5 and C-11). From a lifecycle perspective, food production and consumption have one of the greatest climate impacts, accounting for nearly 20% of Global Carbon footprint (C-4).

Within the agriculture sub-sector, methane from enteric fermentation and rice cultivation, and nitrous oxide mainly from soil and application of synthetic and manure fertilizer manure management had the largest contribution (≥80%) to total emissions in 2010 (C-5). For the period 1970-2010, emission of methane increased by 20% whereas emission of nitrous oxide increased by 45-75% mostly in Asia (C-5). The other sectors are biomass burning (6-12%) and manure management (7-8%) C-11. Agricultural soils—manure deposited on pasture (15%) and synthetic fertilizer (12%) are the largest emitting categories of AFOLU after enteric fermentation (32-40% of total agriculture emissions) C-11.

1.5.3 Uncertainties in GHG emissions impacts the certainty of some mitigation options

Emissions due to Land-use change (LUC) are highly uncertain, with estimates of 3.3 or ±50-75% GtCO2/yr (Ciais et al., 2013), C-5. Estimating uncertainty for land-use change emissions is a big challenge because of limited data on a number of relevant land processes in various geographical regions (Houghton et al., 2012), C-5. These uncertainties in land-use change emissions are sufficiently high to make trends over recent decades uncertain in direction and magnitude (C-5). This has implications when it comes to developing strategies for managing GHG emissions in the AFOLU sector when, in particular, the magnitude of the emissions often cannot be detected given the error bounds associated with the measurement process (C-2).

To address these uncertainties, there is a need to improve MRV (monitoring, reporting and verification) systems using stock and flow data for carbon and other GHGs, mostly in developing countries where more data gaps and higher uncertainties persist (C-2).

1.5.4 Drivers of GHG emissions in AFOLU and food systems

Many of the critical factors affecting or modulating GHG emissions are uncertain in their magnitude but their trends are often very clear. These include the effects of population growth, economic and technological developments, changes in behaviour over time that are very dependent on cultural and normative backgrounds, market structures and incentives. These human dimensions and diversity of social context translate into different demands for food, fibre, fodder and fuel, as well as in the development of the agriculture, aquaculture and forestry sectors.

Increased livestock numbers is a major driver of emissions and is linked to rising demand for animal products, area under agriculture, deforestation, use of fertilizer, area under irrigation, per capita food availability, and consumption of animal products. Global agricultural land increased by 7%, from 4560 Mha to 4900 Mha between 1970 and 2010 (FAOSTAT, 2013) when global population increased by about 90% from 3.6 to 6.9 billion during the same period (C-5). Rapid increase in the demand for food has been addressed by intensification of farming systems mostly in developed countries and in economies in transition. Crop productivity increased considerably during the period. For example, cereal production has doubled from 1.2 billion ton to 2.5 billion ton and average yield of cereals increased from 1600 kg ha-1 to 3000 kg ha-1 (C-5). To enable this increase, use of nitrogenous fertilizer increased by 230% from 32 M ton in 1970 to 106 M ton in 2010, which was a major driver for increased N_2O emissions. A similar trend is observed in the livestock sector with increased population of cattle, sheep and goats by 1.4-fold and that of pigs and poultry by 1.6 and 3.7-fold, respectively with subsequent increase in GHGs emission directly and also through manure production. Global daily per-capita food availability and consumption of animal products increased, particularly in Asia.

Increase in irrigated cropped area during the past 40 years, mostly in rice fields has driven significant increases in non-CO_2 emission. Traditional and irrigated paddy rice cultivation is an important source of CH_4. After enteric fermentation and agricultural soils which account for about 70% of total emissions, paddy rice is the next greatest source in the agriculture sector, accounting for 9-11% of the emissions, and is hence a major source of global CH_4 emissions, which in 2010 were estimated to be 493-723 Mt CO_2eq/yr (C-11)

Markets and product price indirectly affect emissions, for example, through global land-use change as a result of changes in behaviour on consumption modulated by economic forces, but technological, political, cultural, psychological and environmental factors also affect emissions (C-4, C-5). Because the food chain involves land use, infrastructure, transportation and energy production systems, at each stage, emissions can be influenced by available agricultural and fishing technologies, by players along the supply chain, by consumers and by technology choices (C-5).

Food waste is a large driver of emissions. One-third of food produced for human consumption (about 1.3 billion tons per year) is wasted globally, adding to GHG emissions for food production. It is estimated that substantially more food is wasted by consumers in developed countries than in developing countries (C-5), though pre-consumer waste is often higher in developing countries. In Europe and North-America, per-capita food waste by consumers is estimated at 95-115 kg/year, while in Sub-Saharan Africa and South/Southeast Asia is about 6-11 kg/year (C-5).

Land use changes and management drive a great portion of emissions in developing countries and are affected by many factors, including a few related to mitigation efforts such as bioenergy production. The key forces associated with land based mitigation are 1) the demand for bioenergy, 2) the demand to store carbon in land by reducing deforestation, encouraging afforestation, and altering soil management practices, and 3) reductions in non-CO_2 GHG emissions by changing management practices. Other forces include demand for food and fibre and forest products, land for growing urban environments, and protecting lands for environmental, aesthetic and economic purposes (C-6).

Urban development is another driver of emissions in the AFOLU sector. Conversion of agricultural, forested, or otherwise undeveloped land to urban use, and unsustainable harvesting of wood fuels to supply large urban and industrial markets, contribute significantly to forest degradation (C-12).

Emissions from desertification and land degradation were not quantified as separate explicit categories in WGIII AR5, though land restoration was included as a potential mitigation measure.

1.5.5 Options for mitigation by sources

AR5 suggests that mitigation measures that can be ranked from simple interventions such as land-use, land management and livestock sector interventions (C-2) to more complex CDR (Carbon Dioxide Reduction) techniques, such as afforestation, soil carbon storage and biomass energy with carbon capture and storage (BECCS). The AFOLU chapter (C-11) in AR5 identifies two categories of mitigation pathway:

- *Supply side*: emissions from land use change, land management and livestock management can be reduced, terrestrial carbon stocks can be increased by sequestration in soils and biomass, and emissions from energy production can be saved through the substitution of fossil fuels by biomass.
- *Demand side*: GHG emissions could be mitigated by reducing losses and waste of food, changes in diet, and changes in wood consumption

Increasing productivity of agricultural systems has offset some of the emissions increases that would have occurred otherwise. The emission intensity has fallen significantly for most food products, by between 38% (milk) and 75% (chicken) between the 1960s and 2000s. If rising food demand had been met without concurrent increases in productivity, agricultural emissions today would be twice as large as they are. At the same time, improved productivity has not only increased food production for a given land area but also increased emissions per unit of land. Improving productivity is therefore both a driver of emissions increases, as well as a potentially powerful mitigation approach that can address both climate and food security concerns.

Net CO_2 emissions from land-use change (LUC) result from an interplay between the use of land to produce food and other non-food products, to produce bioenergy, and to store carbon in land. In general, most scenarios project declining CO_2 emissions from land-use changes as a result of declining deforestation rates, both with and without mitigation, and many scenarios project a net uptake of CO_2 as a result of reforestation after 2050 (C-6).

Bioenergy could play a critical role in stabilizing climate change, if conversion of high carbon density ecosystems (forests, grasslands and peatlands) is avoided and best-practice land management is implemented (C-11). Food *vs.* energy competition necessitates nexus thinking for improved use of large land areas for afforestation or for bioenergy. These changes could increase food prices, and compromise food security, if land normally used for food production is converted to bioenergy or forests (C-6). Solutions include enabling and integration and optimization of climate change policies with other priorities such as land use planning and protection of water resources (C-1). Management of demand (through dietary change or waste reduction) could alleviate pressure on land by reducing the land footprint of food production. It is important to assess and develop adequate interventions based on available technologies that could affect prices, which in turn affect consumer preferences, and consumer preferences can influence the development and distribution of technologies (C-5). This cycle of influence should also be related to teleconnection and displacement of economic activities, mostly in economies in transition and developing countries.

Many transformation pathways include reductions of non-CO_2 GHGs from agriculture. The effectiveness of such transformation will depend on whether mitigation is achieved through reduced absolute emissions, or through reduced emissions per unit of agricultural product. The changes expected will also depend on the role of large scale intensive agriculture, which has often not been implemented sustainably (e.g., large areas of monoculture food or energy crops or intensive livestock production, potentially damaging ecosystem services) (C-6). In particular, linking land productivity to an increase in water irrigation demand in the 2080s to maintain similar current food production, offers a scenario at high-risk from climate change, mostly in developing countries (C-14). At the same time, those developing countries need to address food demand and to respond to adaptation needs (C-14).

1.5.6 Considerations for sustainability

Any large-scale change in land use, for biomass for energy, or for sequestration in vegetation, will likely increase the competition for land, water, and other resources, and conflicts may arise with important sustainability objectives such as food security, soil and water conservation, and the protection of terrestrial and aquatic biodiversity. These can also affect desertification and land degradation trends and increase synergies with other international agreements, including the United Nations Convention to Combat Desertification (UNCCD, 2011) or the Convention on Biological Diversity (CBD) (C-11).

It is important therefore to support integrated approaches to address the following sustainability issues:

- Financing, poverty, institutional, ecological, technological development
- Feedbacks of mitigation on adaptation and conservation
- Competition between different land-uses
- Addressing landscape multi-functionality, e.g. ecosystem co-benefits and the needed to integrate multiple objectives, increase co-benefits and reduce adverse side-effects.
- Minimise competition for land for food production from large scale greenhouse gas removal (GGR) methods and assess and address uncertain distributive consequences (C-3).

1.6 Summary of outcome of IPCC Expert Meeting on Climate Change, Food, and Agriculture held 27-29 May 2015

This Expert Meeting considered different options to address climate change, food and agriculture in the AR6, and considered that an IPCC Special Report would integrate AR5 findings and new material relevant to all Working Groups, enhancing trans-disciplinary assessment in the AR6. As part of a continuing series of IPCC products, a Special Report would be a timely way to assess new knowledge in a policy-relevant product.

Several topics emerged in discussions of outlines for possible future IPCC products or efforts in the scientific community. Cross-Cutting themes included socioeconomic dimensions, regional dimensions, temporal dimensions, sustainable development, inequalities (poverty, gender, and governance).

- Climate change, food, and agriculture :
- Food production, including agriculture, livestock, fisheries, and other food systems ;
- Direct and indirect links between climate change, climate change responses, and food security ;
- Interactions among climate, water, economies, nature, and food.

- Adaptation, mitigation, food security, and their interaction:
- Resilient food system

- Healthy diets
- Synergies and tradeoffs: production and consumption

- Managing fundamental limits: land and water resources:
- Competition for land and water: food vs. other uses
- Policies

- Sustainable development and food security:
- Opportunities for co-benefits
- Decision-making frameworks including robust decision making

Meeting discussions also identified a number of knowledge gaps, such as:

- Metrics for measuring food security across local and regional contexts, given different drivers of vulnerability
- Climate change interactions with drivers of food demand and dietary patterns
- Climate-agriculture interactions, including effects of climate variability, weeds, pests, and diseases
- Effects of climate change on non-commodity crops
- Effects of climate change on fisheries and interactions with food security and livelihoods
- Effects of climate change on post-harvest components of food systems
- Nutrition and production in a changing climate
- Effectiveness of adaptation options, both incremental and transformational
- Quantification of mitigation potential in the AFOLU and energy sectors, including role of greenhouse gas metric
- Implications of biomass-based mitigation options for potential land and water competition, surface albedo, and non-CO_2 greenhouse gas emissions
- Integrated regional assessments, linking bottom-up and top-down approaches
- Integration of food and land-use trade-offs and co-benefits in integrated assessment modeling
- Characterizing adaptation and mitigation interactions, co-benefits, and trade-offs across scales
- Direct and indirect consequences of policies affecting land use, supply-demand interactions, and international trade.

1.7 Summary of relevant work by the Task Force on Inventories

The Task Force on National GHG Inventories develops methodologies to estimate anthropogenic emissions by sources and removals by sinks of GHG not controlled by the Montreal Protocol, to allow countries to apply comparable methodologies when developing and updating their inventories. The national inventories are one important tool to monitor the global effort to reduce net emissions, to identify relevant sources and sinks and their uncertainties, and thus guide relevant decisions in the Climate Change Convention. Developed countries have to provide annual GHG inventories to the Convention, whereas developing countries have a less rigorous commitment, submitting their inventories every four years (with updates every 2 years). Traditionally, the methodologies used by developed and developing countries are also distinct, since developing countries can use less updated IPCC Guidelines to report their emissions.

LULUCF can have an important impact on national efforts to reduce GHG emissions. The latest data on the site of the UNFCCC (see FCCC/SBI/2015/21) indicates that for some countries, LULUCF contributes to the reduction of their net emissions (for example, for the Russian Federation, the emission reduction in 2013, relative to 1990, was 29 per cent without LULUCF and 43.2 per cent with LULUCF), whereas for others. it has the opposite effect (for instance, for New Zealand, from 1990 to 2013, emissions have increased by 21,3 per cent without LULUCF and by 42.4 per cent with LULUCF).

This has severe implications for comparability and accuracy. The Task Force periodically updates the IPCC Guidelines for National GHG Inventories so as to include new methodologies for anthropogenic sources and sinks that have not been included in previous Guidelines or Guidance due to the lack of representative global studies and default emission factors. The use of these new methodologies and guidance, after approval and acceptance by the IPCC, have to be adopted by the Climate Change Convention before countries start using them regularly to inform their net emissions from all sectors. The application of new guidelines under the Convention is first carried out by developed countries and may take years after the IPCC Guidelines have been approved and accepted. New and more advanced methodologies for new and old anthropogenic sources and sinks, therefore, are not immediately applied and many gaps in inventory exist.

The most recent relevant work by the Task Force has been in addressing emissions from Wetlands and in particular addressing drainage and rewetting of peatlands. The Supplement covers inland organic soils and wetlands on mineral soils, coastal wetlands including mangrove forests, tidal marshes and seagrass meadows and constructed wetlands for wastewater treatment, areas that were not covered in the *2006 IPCC Guidelines.*

Supplementary methods have also been developed for estimating anthropogenic greenhouse gas emissions by sources and removals by sinks resulting from LULUCF activities relevant to the Kyoto Protocol (including afforestation, reforestation, deforestation, forest management). Although these supplementary methods (KP Supplement) are meant to be used by countries that are Parties to the Kyoto Protocol (KP countries), it provides important contributions to the national reporting, particularly with regard to harvested wood products. For example, for deforestation, most countries assume instantaneous oxidation instead of a decay function and hence, annual emissions from this activity could be overestimated. Another area of improvement in the KP Supplement is with regard to the treatment of natural disturbance. The managed land proxy adopted by IPCC for LULUCF, to avoid including emissions from natural sources, can have severe implications for KP countries that are affected by more frequent and intense natural events.

The inventory for LULUCF is considered to be the most complex and the most uncertain. This is due to the lack of adequate data, particularly for developing countries, which can rely on the use of default data provided in the IPCC Guidelines and Guidance. However, the uncertainty can be high. The weakest part of the LULUCF reporting is related to soils – it is a slow process to identify the changes in the soil organic carbon from land-use conversion, and most countries rely on the use of the default values of the IPCC.

In 2017, the Task Force will start updating methodologies and emission factors to reflect the scientific advances since its latest IPCC 2006 Guidelines was adopted. Methodologies to include emissions from flooded land (including reservoirs) and tier 3 methods to address inter-annual variability are among the areas to be updated (for more information see the full document with proposed changes in IPCC-XLIV/L.3, agenda item 7.2).

No matter how uncertain and incomplete the reporting of national net emissions may be, it constitutes the main reference for monitoring the aggregated global efforts to reduce emissions, and a good indicator of where mitigation actions may be more relevant.

Part 2 Key insights from previous relevant non-IPCC UN Intergovernmental processes under other Conventions

2.1 Outputs from the United Nations Convention to Combat Desertification (UNCCD) relevant to interactions between climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

Documentation from the UNCCD is more policy proactive than that emerging from IPCC processes. Much of the supporting research and analysis material supporting published UNCCD reports predate the AR5 report. In the SR there may be a need to consolidate which aspects of the UNCCD definition of **Desertification** are most relevant to the discussion of Climate Change or to recognise that there is inherently a value judgement to be made regarding the selection (and priority given) to indicators of the land degradation, which in turn demand a policy response.

1) Literature on adaptation to desertification and drylands tends to identify specific measures which address local and region drivers, and often draw on traditional and community knowledge and structures.

2) Recent scientific literatures point to co-benefits between adaptation in dry regions (improved resilience) and mitigation with respect to the enhanced sequestration of carbon to soils and improved efficiency of food production. The literature has been reviewed extensively, particularly in the FAO publications. The FAO address global region and local approaches to implementation of improved land management practices to achieve adaptation and mitigation including indicators to quantify actions. (Asfaw, Coromaldi, and Lipper 2015; FAO 2016a; Asfaw and Lipper 2016; Rioux et al. 2016; FAO 2016b; Heidinger, Raymundo, and Carbajal 2016).

3) *Mitigation and Irrigation*: Irrigation increases carbon in arid and semi-arid soils, regardless of land use. However, soils under natural vegetation tend to have higher soil carbon than soils under arable/cropland (Trost et al. 2013). It is not immediately apparent from the literature whether the availability of water resources required to implement irrigation at global scale has been fully assessed (Valipour 2015).

4) *Carbon Management*: (Plaza-Bonilla et al. 2015) review the potential for enhanced carbon uptake in dry/semi-arid regions, whilst also noting significant co-benefits respect to adaptation, soil erosion, food security and production efficiency. However, they note challenges with respect to export of carbon due of use of residuals (e.g. for bioenergy). They also note the

barriers to long term adoption of improved management (poverty, access to markets, access to capital and finance, education and training).

5) *Observations of changes in climatology of drylands*: Recent analysis suggests that 45% of global lands are drylands, this is an increase on previous estimate of 41%. The revision is largely due to improved data (Pravalie 2016). However, also there is increasing body of evidence that semi-arid lands are expanding (Huang et al. 2015). In some regions (mainly North America, east coastal Australia, and possibly South America) arid lands are in transition to semi-arid condition, due to increase in precipitation. The trend is driven by enhancement of westerlies. However, in other regions, the observed transition is from sub-humid/humid to semi-arid conditions - in other words, tending towards drier conditions. This appears to be occurring in China, east Australia and regions of southern Africa. The trend in these areas appears to be driven by weakening of regional monsoon conditions. The region of southern Sahel appears also to be tending to drier conditions, also largely driven by a weakening of the West African Monsson. However, there is a complex climatology at play in this region with additional influence from the Indian Ocean which historically has contribution to an intensification of historic drought in the region. Literature related to the Sahel presents conflicting evidence with different studies drawing very different conclusions (Rasmussen et al. 2016). “Greening of the Sahel”: a number of recent studies have identified an apparent increase in the vegetation productivity in the region. These studies are mainly based on the analysis of time series of remote sensing products, such as NVDI, based on platforms in operations since the 1970’s. However, other studies, and especially those based on local field sampling, have observed an increase in land degradation, including an expansion of agricultural areas, leading to adverse impacts on biodiversity, soil condition etc., but these activities may improve the economic return from the land.

6) *Land Degradation - mineral soils*: in humid and sub-humid regions, climate change will impact on carbon content of mineral soils, however, detection is challenging as the processes involved tend to be relatively slow and can be masked by direct impacts of changes in land use and land management, and inter-annual variability. The impact of land use change and land management on GHG fluxes and quality of mineral is well covered by IPCC AR5 and IPCC Inventory Guidelines. The direct impact of climate on mineral soil carbon stocks is also quite well understood: wetter soils have high carbon content, and higher temperatures mineral soils tend to have lower soil carbon content. Seasonality is an important indicator, with meteorological conditions during growing season driver significant variability in year to year carbon fluxes.

7) *Land Degradation - organic soils*: In humid and sub-humid regions, organic soils are very sensitive to changes in climate conditions. Intact wetland/peatlands tend to be relatively resilient to short term fluctuations in seasonal meteorology. Drained organic soils, and rewetted organic soils are more sensitive to fluctuations. Drained organic soils are very sensitive to increasing temperature. While rewetted systems tend to show greater sensitivity to water table. The IPCC Inventory Guidelines capture some aspects of this. However, the coarse climate zones provided for in Tier 1 approach to estimate carbon losses, do not adequately capture the highly non-linear response to higher temperatures and lower water table in degraded and vulnerable ecosystems.

2.2 Outputs from the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Technical Panel on Soils (ITPS) relevant to interactions between climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

2.2.1 Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES)

The following information is taken from the IPBES website. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is the intergovernmental body which assesses the state of biodiversity and of the ecosystem services it provides to society, in response to requests from decision makers. Established in 2013, it is placed under the auspices of the UNEP, UNESCO, FAO and UNDP. The work programme of the IPBES 2014-2018 includes a number of assessment activities at global and regional scales, and across a number of thematic areas.

At the IPBES-4 Feb 2016, the plenary approved the SPM of the **Thematic Assessment Report on pollinators, pollination and food production**, Deliverable 3(a) of the work programme. The report notes "*The ranges, abundances and seasonal activities of some wild pollinator species (e.g., bumble bees and butterflies) have changed in response to observed climate change over recent decades. Generally, the impacts of ongoing climate change on pollinators and pollination services to agriculture may not be fully apparent for several decades, owing to a delayed response in ecological systems. Adaptive responses to climate change include increasing crop diversity and regional farm diversity and targeted habitat conservation, management or restoration. The effectiveness of adaptation efforts at securing pollination under climate change is untested.*"
Although AR5 is an important reference for this report, the discussion includes more recent literature (up to 2014).

Work on Deliverable 3(b)(i): **Thematic assessment on land degradation and restoration** is on-going, with final report and SPM due for presentation at IPBES-6 March 2018. The First Order Draft of the assessment report has undergone expert external review. Second Order Draft is in preparation, to be submitted for government and expert review in May 2017. The IPCC Scoping meeting for SR should consider the agreed scope of the IPBES assessment and the degree of overlap with the Special Report, and aim to avoid duplication of effort.

The scope of Deliverable 3(b)(ii) **Thematic assessment on invasive alien species and their control** was agreed at IPBES-4. This assessment focuses on the threat that invasive alien species pose to biodiversity, ecosystem services and livelihoods and the global status of and trends in impacts of invasive alien species by region and sub-region, taking into account various knowledge and value systems. Although climate change is not explicitly mentioned in the text, the Chapter Outline indicates chapter 3 will provide analysis and synthesis of the direct and indirect drivers the introduction, spread, abundance and dynamics of invasive species. Chapter 4 will assess the environmental, economic and social impact of invasive species. The IPCC Scoping meeting for SR should consider the agreed scope of the IPBES assessment and the degree of overlap with the Special Report, and aim to avoid duplication of effort. The work programme of the IPBES also includes an initiative to build an on-line catalogue of global, regional and national biodiversity assessments. Work on this has commenced and can be viewed at the IPBES website. This may be a useful resource to access grey material relevant to the scope of the SR.

2.2.2 Intergovernmental Technical Panel on Soils (ITPS)

The following text is taken from the communications brochure of the Status of the World's Soil Resources report, which provides highlights from the Technical Summary, which in turn summarise the report itself, where full details can be found.

"The overwhelming conclusion of the first-ever comprehensive report on the world's soil resources, prepared by the Intergovernmental Technical Panel on Soils (ITPS), is that **the majority of the world's soil resources are in only fair, poor or very poor condition...** and that conditions are getting worse in far more cases than they are improving. Further loss of productive soils will severely damage food production and food security, amplify food price volatility, and potentially plunge millions of people into hunger and poverty. But the report also offers evidence that this loss of soil resources and functions can be avoided.

Careful soil management, using proven methods and technologies, can increase the food supply and provide a valuable lever for climate regulation and safeguarding ecosystem services.

Soils are the foundation of food production and food security. And soils also provide other ecosystem services that are vital for the functioning and resilience of Earth's environment. They store vast quantities of carbon, helping regulate CO2 emissions and climate processes. **They function as Earth's largest water filter and storage tank, controlling the quantity and quality of freshwater resources.** They cycle and store nitrogen, phosphorus and other essential nutrients. And they host a quarter of the planet's biodiversity.

Over 35 percent of the planet's ice-free surface has been cleared of natural vegetation to grow crops or graze livestock, exposing it to sharp increases in erosion and steep losses in soil organic carbon, soil nutrients, and biodiversity.

Rapid growth of cities, industries, and industrialized agriculture has accelerated losses of soil organic carbon and biodiversity; contaminated soils with excess salt, acidity, and heavy metals; and sealed them permanently under asphalt and concrete.

Most of the world's soils are only in fair, poor, or very poor condition. And their condition is getting worse in far more cases than it is improving.

Erosion carries away 25 to 40 billion tonnes of topsoil every year, significantly reducing crop yields and the soil's ability to store and cycle carbon, nutrients, and water. If action is not taken to reduce erosion, total crop yield losses projected by the year 2050 would be equivalent to removing 1.5 million km^2 of land from crop production – or roughly all the arable land in India.

Proven technologies exist that can curtail and even reverse degradation of the Earth's vital soil resources. Erosion can be brought down to sustainable levels, for example, by reducing or eliminating tillage and using crop residues and cover crops to protect the soil surface. The challenge for policy makers is to develop and implement policies that will foster adoption of sustainable land use and soil management practices."

2.3 Links with the UN Sustainable Development Goals (SDGs)

The following information is taken from the UN SDG website:

https://sustainabledevelopment.un.org/content/documents/2328Global%20Sustainable%20development%20report%202016%20(final).pdf

The UN Sustainable Development Goals were adopted in 2015. In total, there are 17, as follows: Goal 1 - End poverty in all its forms everywhere; Goal 2 - End hunger, achieve food security and improved nutrition and promote sustainable agriculture; Goal 3 - Ensure healthy lives and promote well-being for all at all ages; Goal 4 - Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all; Goal 5 - Achieve gender equality and empower all women and girls; Goal 6 - Ensure availability and sustainable management of water and sanitation for all; Goal 7 Ensure access to affordable, reliable, sustainable and modern energy for all; Goal 8 - Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all; Goal 9 - Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation; Goal 10 - Reduce inequality within and among countries; Goal 11 - Make cities and human settlements inclusive, safe, resilient and sustainable; Goal 12 - Ensure sustainable consumption and production patterns; Goal 13 - Take urgent action to combat climate change and its impacts; Goal 14 - Conserve and sustainably use the oceans, seas and marine resources for sustainable development; Goal 15 - Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss; Goal 16 - Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels; Goal 17 - Strengthen the means of implementation and revitalize the global partnership for sustainable development.

Three of the 17 sustainable Development Goals, SDGs, are directly related to the topic of the Special Report: *2: Zero Hunger*; *13: Climate Action*; and *15: Life on Land*. If seafood is included in the scope of the SR then *14: Life Below Water* is also relevant. Arguments can also be made for linking *3: Good Health and Well-being* and *12: Responsible Consumption and Production* to the scope of the SR.

The Global Sustainable Development report notes "*Coping with the increasing impacts of climate changes"* and the "*Reduction of future agricultural yields due to climate change, especially in Africa*", as an emerging issue based findings from an expert prioritization exercise.

The report sets a goal to "*Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning*". This is clearly relevant to the SR.

Part 3 Known unknowns and Issues arising since AR5

3.1 Summary of key knowledge gaps and issues that have become more prominent since AR5

Below we list issues and, where appropriate, open questions identifying knowledge gaps, and issues that have become prevalent since AR5. Since integration across traditional IPCC working groups, and across other disciplines and UN conventions is necessary for this special report, we note after each issue, the topic area of relevance for this report. All are relevant to climate change, but we also note the interaction with desertification (**Des**), land degradation (**Deg**), sustainable land management (**SLM**), food security (**FS**) and GHG emissions from terrestrial ecosystems (**GHG**). The multiple topic areas noted for many of the issues demonstrates well the highly integrated nature of the challenges.

3.1.1 Issues mainly related to the climate system

- Confidence in global precipitation change over land is low prior to 1951 and medium afterwards because of data incompleteness (**Des, Deg, SLM, FS, GHG**).
- There is low confidence in an observed global-scale trend in drought or dryness (lack of rainfall), due to lack of direct observations, methodological uncertainties and choice and geographical inconsistencies in the trends (**Des, Deg, SLM, FS, GHG**).
- Paleoclimate reconstructions and Earth System Models indicate that there is a positive feedback between climate and the carbon cycle, but confidence remains low in the strength of this feedback, particularly for the land (**Des, Deg, GHG**).
- Observational uncertainties for climate variables other than temperature, uncertainties in forcings such as aerosols, and limits in process understanding continue to hamper attribution of changes in many aspects of the climate system (**Des, Deg, GHG**)
- Changes in the water cycle remain less reliably modelled in both their changes and their internal variability, limiting confidence in attribution assessments. Observational uncertainties and the large effect of internal variability on observed precipitation also precludes a more confident assessment of the causes of precipitation changes (**Des, Deg, SLM, FS, GHG**).
- Modelling uncertainties related to model resolution and incorporation of relevant processes become more important at regional scales, and the effects of internal variability become more significant. Therefore, challenges persist in attributing observed change to external forcing at regional scales (**Des, Deg, GHG**).
- The ability to simulate changes in frequency and intensity of extreme events is limited by the ability of models to reliably simulate mean changes in key features (**Des, Deg, SLM, FS, GHG**).
- In some aspects of the climate system, including changes in drought, confidence in attribution to human influence remains low due to modelling uncertainties and low agreement between scientific studies (**Des, Deg, GHG**).
- Projected changes in soil moisture and surface run off are not robust in many regions (**Des, Deg, SLM, FS, GHG**).
- There is low confidence in magnitude of carbon losses through CO_2 or CH_4 emissions to the atmosphere from thawing permafrost. There is low confidence in projected future CH_4 emissions from natural sources due to changes in wetlands (**Deg, SLM, GHG**).

- There is low confidence in projections of many aspects of climate phenomena that influence regional climate change, including changes in amplitude and spatial pattern of modes of climate variability (**Des, Deg, SLM, FS, GHG**).
- Attribution of desertification to drivers is challenging, due to (lack of) robustness of several methodologies (linked to focus on short periods, lack of data / inconsistencies in datasets etc.) (**Des**).
- The role of dust in affecting the climate system, human health and ecosystem degradation is poorly understood and requires further assessment (**Des**).
- The relative impacts of different GHGs depend upon the metrics chosen to compare them (e.g. global warming potential, emissions per unit of land / product, social costs) and implications need further research (**GHG**).

3.1.2 Issues mainly related to the impacts of, and adaptation to, climate change

- Improving confidence in detection and attribution of climate impacts on agriculture, food systems, land degradation/desertification and associated GHG fluxes (**Des, Deg, SLM, FS, GHG**)
- Enhanced research and data focusing on the vulnerability and adaptation options for cross-sectoral and non-production aspects of the food system. such as food processing, distribution, access, stability, consumption and waste (**Des, Deg, SLM, FS, GHG**).
- Assessment of climate and non-climate drivers of variability in the quantity and quality of food production and their implications for food security, especially given observed price fluctuations associated with recent climate events (**Deg, SLM, FS, GHG**)
- The role of weeds, pests, and diseases, including animal diseases in response to climate change and adaptations as these affect food security, land degradation and GHG emissions (**Deg, SLM, FS, GHG**)
- Improved understanding of the potential for systemic and transformational adaptation options and their implementation paths, including *via* governance changes, to be robustly incorporated into food security assessments. This research must be open to participatory and action research approaches that build on both local and scientific knowledge, and foster learning for adaptation and capacity building among rural people (**Deg, SLM, FS**).
- Improved understanding of the co-benefits, constraints and limits to adaptation and path-dependency in land-based sectors, including more informative and realistic assessments of synergies and trade-offs between adaptation and mitigation activities (**SLM, FS, GHG**).
- Exploration of how of individual incentives, market mechanisms and removal of cultural or other barriers may enhance adoption of practices that address desertification, land degradation and adaptation during climate extremes such as drought (**Des, Deg**)
- Improved understanding of how climate change itself may affect GHG emissions from the land sector, particularly when integrated with climate impacts and adaptation responses, governance changes and achievement of Sustainable Development Goals (**Des, Deg, SLM, FS, GHG**).
- Integrated research on synergies and trade-offs between land-use changes under climate change, including non-agricultural land uses such as conservation and tourism. This should examine the tradeoffs and synergies between adaptation and mitigation and between climate and non-climate policies in rural areas, and governance structures to manage natural resources at a landscape level (**SLM, FS, GHG**).

- Information and decision-support tools to inform strategic choices about intensification and extensification options and their consequences (**Des, Deg, SLM, FS, GHG**).
- Community-based adaptation (CBA) is extremely relevant regarding land degradation and food security and the evidence base needs to be strengthened (**Des, Deg, SLM, FS, GHG**).
- The role of human security, in terms of (violent) conflict was not discussed in detail in AR5but is an emerging topic with new literature available. It is highly relevant to this report (**Des, Deg, SLM, FS, GHG**).
- The connection between land degradation/desertification and human migration is an important emerging topic (**Des, Deg, SLM**).
- Data availability across regions is uneven and implications need to be considered (**Des, Deg, SLM, FS, GHG**).

3.1.3 Issues mainly related to mitigation of climate change

- Defining the location of displaced activities in the AFOLU sector remains a significant challenge and the impacts of indirect land use change impacts remain difficult to quantify (**SLM, GHG**).
- Since AR5, many more papers have been published on the likely mitigation potential (and food security and health benefits) of demand-side measures such as dietary change, and to a lesser extent waste reduction (**SLM, FS**).
- The spatial coverage and resolution of land cover / land use datasets and land models is improving continually, providing enhanced opportunities to study the land-climate-development nexus (**Des, Deg, SLM, FS, GHG**).
- The greater prominence of land based greenhouse gas removal technologies (also called negative emissions technologies) since the Paris Agreement has placed further emphasis of competition for land for food, fibre, energy, greenhouse gas removal, biodiversity conservation and the delivery of other ecosystem services (**Des, Deg, SLM, FS, GHG**).
- There is increasing attention to approaches to mitigate GHG emissions from livestock via enhancing the productivity and efficiency of production systems, and the synergies this can create with food security, rural livelihoods and broader development goals. Additional work is needed to understand synergies but also potential trade-offs of such approaches with resilience and adaptation to climate change (**Deg, SLM, FS, GHG**).
- Understanding differences between the theoretical potential for soil carbon sequestration to contribute to mitigation outcomes, and their practical feasibility, barriers to implementation and ability to monitor, report and verify changes especially in the context of increasing impacts of climate extremes on land-based systems (**SLM, GHG**).

iv. References[1]

Asfaw, Solomon, Manuela Coromaldi, and Leslie Lipper. 2015. “Adaptation to Climate Risk and Food Security: Evidence from Smallholder Farmers in Ethiopia.” *FAO*, no. February: 1–50. file:///Articles/2015/Asfaw/FAO 2015 Asfaw-2.pdf.

Asfaw, Solomon, and Leslie Lipper. 2016. “Managing Climate Risk Using Climate-Smart Agriculture.” *FAO*. doi:10.13140/RG.2.1.4000.0409.

FAO. 2016a. *Climate Change and Food Security: Risks and Responses*. ROME: FAO.

FAO. 2016b. *The State of Food and Agriculture*. *FAO*. Rome. http://books.google.com/books?id=V1qrPwAACAAJ&dq=intitle:Livestock+in+the+balance&hl=&cd=15&source=gbs_api\npapers2://publication/uuid/F6B30CC3-5968-4026-8CAD-676C21F4EDBC.

Heidinger, Haline, Rubi Raymundo, and Mariela Carbajal. 2016. “A Methodology for Greenhouse Gas Emission and Carbon Sequestration Assessments in Agriculture.” 187. *FAO*. Rome. doi:10.2139/ssrn.701181.

Huang, Jianping, Mingxia Ji, Yongkun Xie, Shanshan Wang, Yongli He, and Jinjiang Ran. 2015. “Global Semi-Arid Climate Change over Last 60 Years.” *Climate Dynamics* 46 (3). Springer Berlin Heidelberg: 1131–50. doi:10.1007/s00382-015-2636-8.

Plaza-Bonilla, Daniel, José Luis Arrúe, Carlos Cantero-Martínez, Rosario Fanlo, Ana Iglesias, and Jorge Álvaro-Fuentes. 2015. “Carbon Management in Dryland Agricultural Systems. A Review.” *Agronomy for Sustainable Development* 35 (4): 1319–34. doi:10.1007/s13593-015-0326-x.

Pravalie, Remus. 2016. “Drylands Extent and Environmental Issues. A Global Approach.” *Earth-Science Reviews* 161. doi:http://dx.doi.org/10.1016/j.earscirev.2016.08.003.

Rasmussen, Kjeld, Sarah D’haen, Rasmus Fensholt, Bjarne Fog, Stephanie Horion, Jonas Ostergaard Nielsen, Laura Vang Rasmussen, and Anette Reenberg. 2016. “Environmental Change in the Sahel: Reconciling Contrasting Evidence and Interpretations.” Article. *REGIONAL ENVIRONMENTAL CHANGE* 16 (3, SI): 673–80. doi:10.1007/s10113-015-0778-1.

Rioux, Janie, Marta Gomez San Juan, Constance Neely, Christina Seeberg-Elverfeldt, Kaisa Karttunen, Todd Rosenstock, Josephine Kirui, et al. 2016. *Planning, Implementing and Evaluating Climate-Smart Agriculture in Smallholder Farming Systems - The Experience of the MICCA Pilot Projects in Kenya and the United Republic of Tanzania*.

Trost, Benjamin, Annette Prochnow, Katrin Drastig, Andreas Meyer-Aurich, Frank Ellmer, and Michael Baumecker. 2013. “Irrigation, Soil Organic Carbon and N2O Emissions. A Review.” Article. *AGRONOMY FOR SUSTAINABLE DEVELOPMENT* 33 (4). 22 RUE DE PALESTRO, PARIS, 75002, FRANCE: SPRINGER FRANCE: 733–49. doi:10.1007/s13593-013-0134-0.

Valipour, Mohammad. 2015. “Future of Agricultural Water Management in Africa.” Article. *ARCHIVES OF AGRONOMY AND SOIL SCIENCE* 61 (7): 907–27. doi:10.1080/03650340.2014.961433.

[1] Note: most text is summarised from IPCC documents. These references are only for areas not covered by IPCC reports)

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