Statement of
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before the

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I would like to thank Chairwoman Johnson, Ranking Member Lucas, and the members of the House Committee on Science, Space and Technology for inviting me to speak today to provide testimony based on the findings of the Intergovernmental Panel on Climate Change (IPCC) Special Report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems, more commonly known as the Special Report on Climate Change and Land (SRCCL). In response to the request of the Committee, this testimony addresses the major findings of the SRCCL report and the implications for the United States, some remaining research gaps, and recommendations for steps that Congress can take toward potential solutions.

I am an associate professor of human ecology at Rutgers University, and served as one of several US scientists on the SRCCL report.[1] The IPCC solicits lead author nominations by member governments and observer organizations, and the final selection of report authors is determined by the IPCC based on these nominees, guided by a set of criteria that aims to balance diversity in scientific disciplines, as well as ensuring geographic and gender balance. Nearly 100 scientists from around the world served as a Coordinating Lead Author, Lead Author, or Review Editor for the SRCCL report. All these scientists volunteer their time without compensation for what is a very challenging and demanding process of preparing this comprehensive report. Although I participated closely in this process, and have received feedback on this testimony from some fellow IPCC authors, I am speaking on my own behalf and not for the IPCC or Rutgers University.[2]

IPCC reports serve as the most authoritative assessments of current climate science. The reports are based on a thorough assessment of all scientific literature, following strict guidelines as to what can and should be reviewed. The IPCC does not produce 'new' research per se, but rather

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[1] The other authors representing the United States who are listed as authors of the Summary for Policymakers in the SRCCL report in addition to myself include: Dr. Katherine Calvin (Pacific Northwest National Lab), Dr. Cynthia Rosenzweig (NASA Goddard Institute for Space Studies/Columbia), Dr. Elena Shevliakova (NOAA Geophysical Fluid Dynamics Laboratory/Princeton), Dr. Koko Warner (UN Framework Convention on Climate Change), and Dr. Louis Verchot (International Center for Tropical Agriculture). Several other US-based scientists were involved with specific chapters as Lead Authors, Contributing Authors, or Review Editors.

[2] I would like to particularly thank the following authors from the SRCCL report who provided feedback on this testimony, although I alone am responsible for the statements herein: Almut Arneth, Katherine Calvin, Nathalie de Noblet-Ducoudré, Minal Pathak, Cynthia Rosenzweig, Elena Shevliakova, Pete Smith, Koko Warner, and Louis Verchot.

analyzes and synthesizes the thousands of scientific papers produced each year around different aspects of climate science.

The SRCCL report is one of three "Special Reports" completed in what is known as the 6th Assessment Cycle of the IPCC. These special reports are specifically requested by member governments of the IPCC to address specific research questions outside the traditional scope of the major Assessment Reports (AR) that the IPCC regularly produces. The Special Reports included in this cycle are: Global Warming of 1.5℃ (SR15), Climate Change and Land (SRCCL), and the Ocean and Cryosphere in a Changing Climate (SROCC) report. All IPCC reports and summaries are subject to multiple rounds of review, and the summary for policymakers is approved word by word by member governments. The SRCCL was approved by all member governments, including the US, in a plenary in August 2019 in Geneva.

Key Findings: State of Science on Land and Climate

Let me provide an overview of what the key findings from the SRCCL report were, as summarized in the release of the report last August:

- *Land is under growing pressure:* Human activities affect 70% of ice-free land areas, of which 25% are experiencing human-caused degradation. The increasing impacts of climate change are visible in many of our terrestrial ecosystems, and changes in land use in turn can amplify these signals. How we manage land must be on the table in any discussion of responding to climate change.

- *Land is part of the solution*: Luckily, there are multiple options to achieve better land stewardship and reduced greenhouse gas (GHG) emissions, such as through sustainable production, reduced food loss and waste, healthy diets, and conserving priority ecosystems. Land is a hugely important sink for anthropogenic CO_2 emissions and we need to ensure it continues to supply us with this free subsidy from nature.

- *Land cannot do it all*. However, while sustainable land management can help reduce the loss of biodiversity while meeting food security needs and storing carbon, there is a finite amount of land and it is often under intense competition. There are limits to the scale of bioenergy crops and afforestation that can be used for climate mitigation without incurring sustainability trade-offs, so we need to make smart choices.

To put these conclusions in context, land is fundamental to human civilization. Land provides the principal basis for human well-being, including the supply of food, access to freshwater, and multiple other ecosystem services, which have been valued at approximately equivalent to the annual global Gross Domestic Product.[3] Current human use directly affects more than 70% of the global, ice-free land surface, encompassing all the things we do on land: grow crops, produce timber, manage pastures for livestock, and shelter ourselves in homes and cities, among other activities.

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[3] Costanza, R. et al. 2014. Changes in the global value of ecosystem services. *Global Environmental Change* 26: 152-158.

However, the SRCCL report identified that our activities on land have contributed to increasing net GHG emissions, loss of natural ecosystems (including forests, savannas, grasslands and wetlands in particular), and declining biodiversity. These findings complement those of the IPBES Global Assessment also released last year, for which this committee held a hearing in June 2019, and for which I also served as a lead author.[4] The reinforcing findings of these two reports show that we need to rethink our relationship with land in fundamental ways if we want to achieve the global goals of climate mitigation, adaptation and sustainable development.

Land plays a hugely important role in the climate system: Land is both a source and a sink of GHGs at the global level. It also plays a key role in the exchange of energy, water, and aerosols with the atmosphere, contributing to local and regional climatic changes that are important for human activities. Agriculture, Forestry and Other Land Use (commonly known as AFOLU) activities accounted for around 13% of CO_2 emissions, 44% of methane (CH_4), and 82% of nitrous oxide (N_2O) emissions from human activities globally during 2007-2016.[5] The CO_2 emissions are largely from deforestation, while the non-CO_2 gases are largely from crop and livestock production. These sources represent 23% of total anthropogenic emissions of GHGs over that time period. However, these emissions were also partially offset by removals due to afforestation, reforestation, and other land use activities, equivalent to 29% of total CO_2 emissions.

Emissions of all GHGs from agricultural production are projected to increase into the future, driven by population and income growth and changes in consumption patterns. Over the past several decades, CH_4 and N_2O emissions from land-based sources have risen faster than CO_2 from AFOLU sources. Enteric fermentation from the digestive processes of an increasing number of ruminant animals and the expansion of rice cultivation are important contributors to methane increases. Anthropogenic N_2O emissions from soils are a result of excess or inefficient nitrogen fertilizer application, and there has also been a major growth in emissions from managed pastures. For CO_2 emissions, tropical deforestation in particular remains a concern, as intact tropical forests store and sequester large amounts of atmospheric carbon, and these functions can be disrupted by clearing and disturbance such as fires.[6] We have been seeing such dramatic fires in Brazil and Australia recently, which not only release CO_2 in the short-term, but which may have a long-term impact on forests' ability to recover and retain their sink functions.

Land is already experiencing the impacts of climate change: All of these emissions contribute globally to rising temperatures, which in turn are experienced on land in different ways around the world. Changes in land conditions, either from land-use or climate change, affect both global

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[4] Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. 2019. *Summary for policymakers of the global assessment report on biodiversity and ecosystem services* [S. Díaz et al., eds.]. Bonn, Germany: IPBES Secretariat.

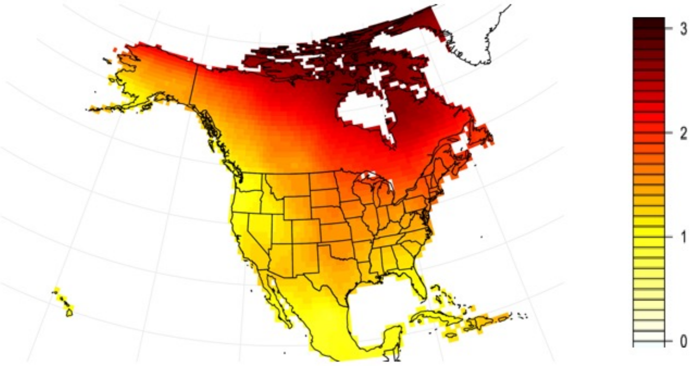
[5] This is equivalent to net CO_2 emissions of 5.2 ± 2.6 $GtCO_2$ yr-1 from land use and land-use change during the period of 2007-2016; Jia, G., E. Shevliakova, et al. 2019. Page 151 in Ch 2: Land–climate interactions. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

[6] Maxwell, S., et al. 2019. Degradation and forgone removals increase the carbon impact of intact forest loss by 626%. *Science Advances* 5 (10): eaax2546.

and regional climates. At the regional scale, changing land conditions can reduce or accentuate local/regional anthropogenic warming, even affecting temperature and rainfall in regions as far as hundreds of kilometers away. Regional land use changes (such as deforestation) can also affect the intensity, frequency and duration of extreme events, ranging from heat waves to droughts. At the global scale, emissions of GHGs from land-use activities, together with changes in land albedo, are drivers of climatic change.[7] In other words, how we use land at different scales can help us manage climate change, or it can make things worse.

Since the pre-industrial period, the land surface air temperature has risen nearly twice as much as the global average temperature, and is now at 1.53°C (2.7 °F) above preindustrial temperatures.[8] These global averages can, however, mask significant local variations (See Figure 1 for trends until 2015). The release this month of the State of the Climate assessment from NOAA confirms that in 2019 in the contiguous U.S. the average temperature was 0.7°F above average, while Alaska experienced its warmest year on record with a statewide average temperature of 6.2°F above the long-term average.[9]

Figure 1. Land air surface temperature increase in °C from preindustrial (1850-1900) to present (2006-2015)[10]



Temperature observations: *Berkeley Earth Surface Temperature dataset, Rohde et al. 2013*

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[7] Jia, G., E. Shevliakova, et al. 2019. Pages 144-150 in Ch 2: Land–climate interactions. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

[8] Ibid, page 142.

[9] NOAA National Centers for Environmental Information, *State of the Climate: National Climate Report for December 2019*, published online January 2020, retrieved on January 8, 2020 from https://www.ncdc.noaa.gov/sotc/national/201912.

[10] The Berkeley Earth Surface Temperature dataset provides land surface air temperature from 1750 to present based on almost 46,000 time series and has the longest temporal coverage of the four datasets used in the SRCCL report. See Rohde R., et al. 2013. A new estimate of the average earth surface land temperature spanning 1753 to 2011. *Geoinfor Geostat: An Overview* 1: 1. Map is courtesy of Dr. Elena Shevliakova, NOAA/Geophysical Fluid Dynamics Laboratory.

These global temperature changes create stresses on land, which the SRCCL report details, including exacerbating risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems. Global warming has led to shifts of climate zones in many regions, including expansion of arid climate zones and contraction of polar climate zones. As a consequence, many plant and animal species have experienced changes in their ranges, abundances, and shifts in their seasonal activities.[11]

At our current levels of global warming we are already experiencing moderate risks from increased dryland water scarcity, soil erosion, vegetation loss, wildfire damage, permafrost thawing, coastal degradation and tropical crop yield decline. We are increasingly confident of being able to determine with specificity how extreme climate events like storms and floods are attributable to or exacerbated by climate change, a field known as "detection and attribution", which can reveal the fingerprint of anthropogenic change.[12] We know that existing warming has resulted in an increased frequency, intensity, and duration of heat-related events, including heat waves in most land regions, and such events can stress crops, disrupt pollination, and cause severe and often fatal human health impacts. Frequency and intensity of droughts has increased in some regions (including the Mediterranean, west Asia, many parts of South America, much of Africa, and northeastern Asia) and there has been an increase in the intensity of heavy precipitation events at a global scale.[13]

Further GHG emissions will increase the pressure on land and ecosystems: Increasing impacts on land are projected under all future GHG emission scenarios. Some regions will face higher risks, while some regions will face risks previously not anticipated, or cascading risks with impacts on multiple systems and sectors.[14] Climate zones are projected to further shift poleward in the middle and high latitudes, and in tropical regions, under medium and high GHG emissions scenarios, warming is projected to result in the emergence of unprecedented climatic conditions by the second half of the century. With this increasing warming, the frequency, intensity and duration of extreme heat events are projected to increase. The frequency and intensity of droughts are projected to increase as well, globally in the Mediterranean region and southern Africa, and in the US, in the Southwest and central regions.[15] The frequency and intensity of extreme rainfall events are also projected to increase in many regions.[16]

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[11] Jia, G., E. Shevliakova, et al. 2019. Page 143 in Ch 2: Land–climate interactions. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

[12] Sippel, S., et al. 2020. Climate change now detectable from any single day of weather at global scale. *Nature Climate Change* 10: 35–41.

[13] Jia, G., E. Shevliakova, et al. 2019. Pages 146-7 in Ch 2: Land–climate interactions. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

[14] IPCC. 2019. Summary for Policymakers, p. 15. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.)]. Geneva: IPCC.

[15] Jia, G., E. Shevliakova, et al. 2019. Section 2.5.1. in Ch 2: Land–climate interactions. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

[16] Hoegh-Guldberg, O., et al. 2018. Impacts of 1.5°*C* Global Warming on Natural and Human Systems. In: *Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels*

Projected future land impacts from climate change will occur in a range of ecosystems, including forests, savannas, coastal systems and agricultural lands.[17] For forests, future projections include continued increases in the intensity of wildfires and pest outbreaks, potentially leading to forest dieback conditions in some areas, and in high-latitude regions, boreal forests are at particular risk.[18] While aggressive fire control measures in the past decades have been able to globally diminish total fire outbreaks, the climate suitability for fire will continue to increase, and with it, wildfire risks. As we are seeing play out in Australia right now, warmer and drier conditions facilitate fires that spread over larger areas and are harder to contain. There is potential for fire frequency to increase over substantial portions of the global land area in the next two decades.[19] There is also strong evidence to link increased forest fire frequency in North America over 1984–2015 to increasing fuel aridity that is a result of anthropogenic climate change; these conditions have doubled the western USA forest fire area compared to what we would expect without these impacts.[20] All of these conditions put extreme stress on our forests, and the many species who live within them.[21]

Climate change also exacerbates land degradation, particularly in low-lying coastal areas, river deltas, drylands, and in permafrost areas; this happens through changes in rainfall intensity, flooding, drought frequency and severity, heat stress, dry spells, wind, sea-level rise and wave action, and permafrost thaw.[22] Over the period 1961-2013, the annual area of drylands in drought has increased on average by more than 1% per year, and in 2015, about 500 million people lived within areas that had experienced desertification. In the US, the Southwestern region has experienced decreases in vegetational activity (e.g. browning).[23]

Food security is particularly at risk from climate change: Climate change has already affected food security due to warming, changing precipitation patterns, and greater frequency of some extreme events. Some crops do respond to CO_2 fertilization with increased yields, but these are often offset by water and heat stress at higher temperatures. Many staple crops, such as wheat,

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and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., et al. (eds.)]. Geneva: IPCC.

[17] Ibid.

[18] Seidl, R., et al. 2017. Forest disturbances under climate change. *Nature Climate Change* 7: 395–402, doi:10.1038/nclimate3303.

[19] Moritz, M.A., et al. 2012. Climate change and disruptions to global fire activity. *Ecosphere*, 3(6), art49, doi:10.1890/es11-00345.1.

[20] Abatzoglou, J.T. and A.P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*, 113(42), 11770–11775, doi:10.1073/pnas.1607171113.

[21] Lewis, D. 2020. 'Deathly silent': Ecologist describes Australian wildfires' devastating aftermath. *Nature* (10 Jan): *doi: 10.1038/d41586-020-00043-2*

[22] IPCC. 2019. Summary for Policymakers, p. 8. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.)]. Geneva: IPCC; IPCC. 2019. Summary for Policymakers, p. 16. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, et al (eds.)]. Geneva: IPCC.

[23] Jia, G., E. Shevliakova, et al. 2019. Section 2.3.4. in Ch 2: Land–climate interactions. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

corn, rice and soybeans, are projected to have reduced yields in the long run.[24] The tropics and subtropics are projected to be most vulnerable to crop yield decline; in many lower-latitude regions, yields of some crops (e.g., corn and wheat) have already declined, while in many higher-latitude regions, yields of some crops (e.g., corn, wheat and sugar beets) have increased in recent decades. Climate change has also resulted in demonstrably lower animal growth rates and productivity in pastoral systems in regions such as Africa.

There is also increasing evidence that higher atmospheric CO_2 levels can lower the nutritional quality of crops through changes in micronutrients; such micronutrient deficiencies already affect over 1.5 billion people. Higher CO_2 concentrations increase photosynthesis in certain plants (including wheat, rice, potatoes, and barley), but field studies simulating future growing conditions show that these crops have lower nutritional quality as plants accumulate less minerals (particularly iron and zinc), which can negatively affect human nutrition.[25] These deficiencies are not made up by technological improvements or market expansions in modelling studies.[26] Other concerns about the food supply under climate change include worries about increases in contaminating organisms such as mycotoxins, bacteria and enteric microbes (like salmonella) that can enter the human food chain. Degradation and spoilage of products in storage and transport can also be affected by changing humidity and temperature, notably from microbial decay, which can lead to reduced food quality and affect availability.

The stability of food supply is projected to decrease in the future under climate change, as the magnitude and frequency of extreme weather events that disrupt food chains increases. The potential for multi-breadbasket failure (that is, multiple crops in a region or across regions failing at once) increases at higher temperatures as compound events may occur.[27] In future scenarios, global crop and economic models project increases in cereal prices by 2050 due to climate change, leading to higher food prices and increased risk of food insecurity and hunger. The most vulnerable people (the poor, women and children, and those in stressed regions) will be more severely affected.[28]

Risks to land systems increase with temperature rise: All these risks are projected to become more severe with increasing temperatures. At around 1.5°C of global warming the risks from dryland water scarcity, wildfire damage, permafrost degradation and food supply instabilities are projected to be high. At around 2°C of global warming the risk from permafrost degradation and food supply instabilities are projected to be very high. Additionally, at around 3°C of global warming risk from vegetation loss, wildfire damage, and dryland water scarcity are projected to

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[24] Zhao, C., et al. 2017. Temperature increase reduces global yields. *Proceedings of the National Academy of Sciences* 114 (35): 9326-9331.

[25] Myers, S., et al. 2014. Increasing CO_2 threatens human nutrition. *Nature* 510: 139–142.

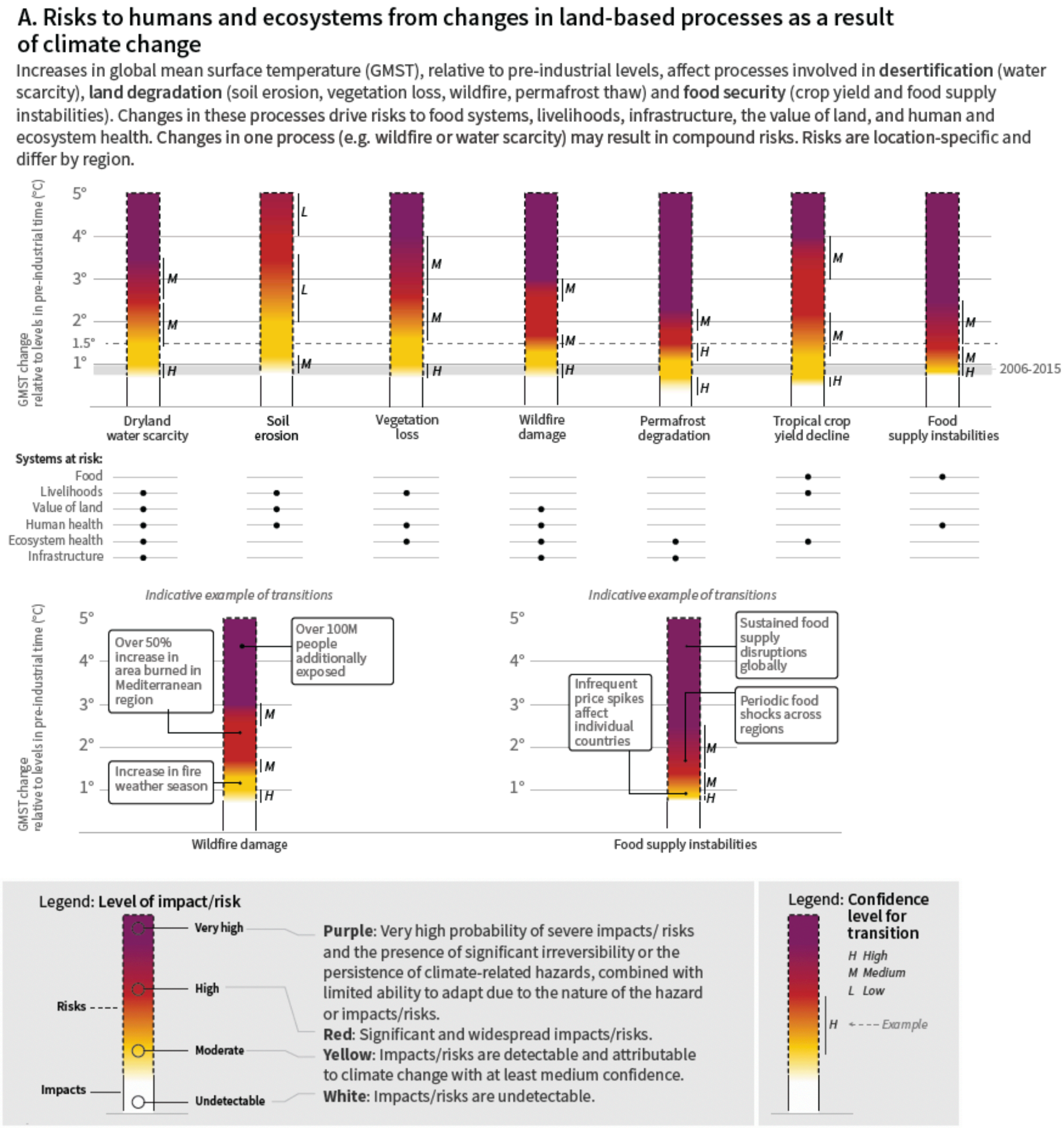
[26] Beach, R., et al. 2019. Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study. *The Lancet Planetary Health* 3 (7): e307-e317.

[27] Zscheischler, J., et al. 2018. Future climate risk from compound events. *Nature Climate Change* 8: 469–477.

[28] IPCC. 2019. Summary for Policymakers, p. 15. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.)]. Geneva: IPCC;

be very high. Risks from droughts, water stress, heat related events such as heatwaves and habitat degradation simultaneously increase between 1.5°C and 3°C warming (see Figure 2).

Figure 2. Risks to land based ecosystems[29]



The level of risk posed by climate change depends both on the level of warming and how population, consumption, production, technological development, and land management patterns continue to evolve. The SRCCL report uses scenarios known as Shared Socio-Economic

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[29] Taken from figure SPM.2 of the SRCCL report. Please see SPM for discussion of the methods used to generate figure (p. 14-15)

Pathways (SSPs) to explore how these factors interact. In modelled pathways with higher demand for food, feed, and water, more resource-intensive consumption and production, and more limited technological improvements in agriculture, we see higher risks from water scarcity, land degradation, and food insecurity as a result. Development pathways in which incomes increase and the demand for land conversion is reduced, either through reduced agricultural demand or improved productivity, can lead to reductions in risks of food insecurity.[30] The SSP that reflects a highly cooperative open trade world with more sustainable consumption and lower population growth has a higher capacity to deal with higher temperatures than a divisive "go it alone" high-consumption world.

There are also the many indirect effects of changes in climate on human settlement and living patterns. For example, warming and associated changes in land productivity can amplify migration both within countries and across borders. Extreme weather and climate or slow-onset events may lead to increased displacement, threatened livelihoods, and contribute to exacerbating stresses for conflict.[31] In most cases, we see climate change as a threat multiplier of existing vulnerabilities, as it is difficult to separate out the direct impacts of climate alone. In some cases, social stress, conflicts and other human health impacts can contribute to destabilization of communities.[32]

Implications for the US

US land systems are already feeling climate change impacts: The SRCCL report was global in nature and did not focus on any particular country. For a more localized view of what the implications of the impacts and projections noted above mean for the US, the Fourth National Climate Assessment that came out last year is the gold standard, and for which this committee held a hearing in February 2019. In that report, the authors note that many of the trends that SRCCL has identified with global implications are also important in the US. For example, our agricultural lands, particularly in the Midwest, are likely to see more droughts, more heat, and more extreme rainfall events into the future.[33]

Several land-climate interactions in the US have been in the news recently. First, wildfires in California have brought much damage and lives lost in the past few fire seasons. To what degree are these driven by anthropogenic climate change? The evidence suggests that, as elsewhere, "human emissions have increased the probability that low-precipitation years are also warm" and

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[30] IPCC. 2019. Summary for Policymakers, p. 15-16. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.)]. Geneva: IPCC

[31] Scheffran, J., and Battaglini, A. 2011. Climate and conflicts: the security risks of global warming. *Reg Environ Change* 11: 27–39.

[32] Sellers, S., et al. 2019. Climate change, human health, and social stability: Addressing interlinkages. *Environmental Health Perspectives* 127(4): 045002-1-045002-10

[33] USGCRP. 2018. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., et al. eds.]. U.S. Global Change Research Program, Washington, DC. doi: 10.7930/NCA4.2018

it is the combination of drought and warm temperatures that create the conditions for which fires can spread.[34]

Second, floods in the Midwest this spring caused several billion US dollars' worth of damage and left 19 million acres unplanted.[35] We know that a warmer atmosphere holds more moisture, creating more potential for intense rainfall events and thus floods, which can be exacerbated by other land cover changes (e.g. deforestation, soil sealing). Yield variability of corn in particular in the Midwest is already noticeable and linked to rainfall extremes.[36] Interestingly, preliminary evidence suggests that farmers in the Midwest that were able to plant this spring were more likely to be ones who had had a higher average number of years with conservation tillage, no-till practices, and winter green cover.[37] In other words, proactive land conservation practices conferred adaptation benefits to farmers experiencing these extreme events.

The US is also vulnerable to increasing droughts in some areas, with particular impacts so far on species. In Colorado, drylands experiencing temperature changes have damaged biocrust communities with associated species loss, while in Southern California deserts climate change-driven extreme heat and drought may surpass the survival thresholds of some desert species.[38] Another related problem is the expansion of invasive species who thrive in warming climates at the expense of native ecosystems. For example, US sagebrush ecosystems have declined by nearly half since the late 1800s, and one major culprit is non-native cheatgrass (*Bromus tectorum*). Cheatgrass provides a fuel that increases the intensity, frequency and spatial extent of fires, severely impacting livestock producers, as grazing is not possible for several years after fire. Furthermore, cheatgrass and wildfires reduce critical habitat for wildlife, including vulnerable species like the greater sage-grouse.[39]

Land use contributes to overall US emissions, and there is room for emissions reductions: Here in the US, we also need to take stock of not just how our land and agriculture sectors might be impacted by climate change, but also understand the potential contributions of the sectors to both the problem and solutions. The EPA has estimated that the contribution of the agricultural sector is around 9% of total US anthropogenic emissions of CO_2, CH_4 and N_2O.[40] These land-based

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[34] Diffenbaugh, N. et al. 2015. Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences* 112 (13): 3931-3936.

[35] USDA. 2019. Crop Acreage Data: https://www.fsa.usda.gov/news-room/efoia/electronic-reading-room/frequently-requested-information/crop-acreage-data/index

[36] Jia, G., E. Shevliakova, et al. 2019. Section 2.3.5.4. in Ch 2: Land–climate interactions. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

[37] https://www.nature.org/content/dam/tnc/nature/en/documents/Dagan_Prevented_Planting.pdf

[38] Mirzabaev, A., J. Wu et al., 2019: Section 3.5.2. in Ch 3: Desertification. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

[39] Mirzabaev, A., J. Wu et al., 2019: Section 3.7.3.4. in Ch 3: Desertification. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

[40] This is lower than our global estimate in the SRCCL report of 23%, primarily because fossil fuel emissions in the US are proportionately higher, and our forest sector is a net sink. Source of emissions data and trends: US EPA,

emissions have been increasing in recent years, although at a slower rate than fossil fuel emissions. Half of these agricultural emissions relate to how we manage our soil, and one third relate to livestock production. Thus there are significant potentials for GHG emissions reductions in US agriculture and food processing, as well as a need to increase attention to adaptation options for these sectors.

Our forestry and land sector have resulted in net removals of CO_2 since 1990 in the US, and therefore serves as an important sink. However, between 1990 and 2017, total carbon sequestration by the land/forestry sector in the US actually decreased by 11.5 percent. This was primarily due to a decrease in the rate of net carbon accumulation in forests and croplands, as well as land conversion (primarily urbanization).[41] Therefore reversing this trend by looking for opportunities to increase carbon storage in our soils, grasslands, wetlands and forests is an important area for attention.

Further, some changes in how we grow biofuels in the US could also be of interest. The report notes that some models indicate that switching from annual crops to perennial plantations (such as *Miscanthus*) could lead to regional cooling due to increases in evapotranspiration and albedo, thereby somewhat counterbalancing warming trends. If we expanded perennial bioenergy across suitable abandoned and degraded farmlands, models show a near-surface cooling up to 5°C during the growing season.[42]

Looking for Solutions

Despite these problems, we have a number of solutions that are ready and available to use. *We do not need to wait for new scientific and technological breakthroughs for these to be implemented*; they are here now, and many are low cost. We can both reduce emissions from sources on land, as well as improve land's ability to act as a sink. The latter is particularly important if we want to reach net-zero emissions by 2050; that is, not all fossil-fuel emissions can easily be eliminated, so we need to offset those that cannot (e.g. airline emissions may be particularly difficult). Land can help us to achieve net-zero goals.

Sustainable land use reduces emissions and land degradation and helps us adapt: First, we need to use land more sustainably, both to reduce GHG emissions from the land sector and to reduce the impacts of existing climate changes. As a bonus, this can enable our lands to store more carbon as well, further reducing atmospheric CO_2. Sustainable land management (SLM) and policies promoting land degradation neutrality (LDN) can reduce the negative impacts of multiple stressors, and these are particularly important in many developing nations. Reducing and reversing land degradation, at scales from individual farms to entire watersheds, can provide cost effective, immediate, and long-term benefits to communities and support several Sustainable Development Goals (SDGs) with co-benefits for both adaptation and mitigation.

Inventory of US Greenhouse Gas Emissions and Sinks, 1990-2017. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

[41] Ibid.

[42] Jia, G., E. Shevliakova, et al. 2019. Section 2.7.1.5. in Ch 2: Land–climate interactions. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

While they can require upfront investment, many SLM technologies and practices are profitable within 3 to 10 years, as they can improve crop yields and the economic value of lands. SLM options that reduce vulnerability to soil erosion and nutrient loss include growing green manure crops and cover crops, crop residue retention, and reduced/zero tillage. Farming systems such as agroforestry, regenerative agriculture, precision agriculture, and use of perennial crops can substantially reduce erosion and nutrient leaching while building soil carbon. For example, experiments with Kernza grains show the potential of soil carbon increases through perennial grain production.[43] Other practices that provide both mitigation and adaptation benefits on croplands include erosion control, improved fertilizer management and integrated nutrient management, and use of adapted varieties for heat and drought tolerance.

Improvements in soil health, which increases carbon sequestration, can also improve productivity and secure new revenue streams for farmers. Soils that are carbon-rich are also more resilient to water stress or excess, and the USDA's existing working lands programs are a good example of how to help farmers meet goals of better soil health and land stewardship.[44] But there is always more demand for these than can be met at current funding levels, and only around 5% of US croplands receive funds under the two largest conservation programs.[45] Several farm and environmental organizations have supported adding 100 million acres of farmland into these programs, such as through increasing the Conservation Reserve Program acreage cap. Other potentially new ideas might include carbon storage rewards programs (e.g. price floors for sequestration) or voluntary or regulatory markets for soil carbon.

Land restoration is another important solution to provide both short-term positive economic returns and longer-term benefits in terms of climate change adaptation and mitigation, as well as biodiversity and enhanced ecosystem functions and services.[46] Restoration can result in benefit-cost ratios of between three and six in terms of the estimated economic value of restored ecosystem services in drylands in particular. Restored lands are more resilient to extreme events, which can buffer economic losses as well, and they also store more carbon. For example, increasing woody plant cover in open rangeland ecosystems in Texas led to a 32% increase in

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[43] Olsson, L., H. Barbosa, et al., 2019. Section 4.9.2. in Ch. 4: Land Degradation. In: C*limate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds]. Geneva: IPCC.

[44] These include Conservation Reserve Program (CRP), Conservation Stewardship Program (CSP), the Environmental Quality Incentives Program (EQIP), the Agricultural Conservation Easement Program (ACEP), and the Regional Conservation Partnership Program (RCPP).

[45] US Department of Agriculture. 2018. *Summary Report: 2015 National Resources Inventory*. Natural Resources Conservation Service, Washington, DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1422028.pdf

[46] Hobbs R.J. 2017. Where to from here? Challenges for restoration and revegetation in a fast-changing world. *The Rangeland Journal* 39, 563-566.

aboveground carbon stocks.[47] Rehabilitation of abandoned or underused croplands is one option with strong potential.[48]

Sustainable forest management aimed at providing timber, fiber, biomass, non-timber resources and other ecosystem functions and services can lower GHG emissions and contribute to adaptation.[49] For example, the expansion of forests in the US in recent years helps offset continued deforestation elsewhere. Forests are very useful at dampening the impacts of extreme events, and play important roles in modulating local climate (e.g. more evapotranspiration means more energy taken from the soil and thus surface cooling). Preserving and restoring natural ecosystems such as peatlands, mangroves, wetlands and forests, along with biodiversity conservation measures, have the potential to make positive contributions to sustainable development, enhancement of ecosystem functions and services, and other societal goals. For example, in the US, preservation of coastal wetlands provides storm protection services estimated at a value of 23.2 billion USD yr^{-1}.[50]

Improving our food production and consumptions systems can be a win-win: Food production can be a big part of the solution as well, if we focus on increased food productivity, improved distribution and access, better dietary choices, and reduced food losses and waste, all of which can reduce demand for land conversion. Because beef, lamb and farmed shrimp have the highest GHG emissions and environmental footprint of many foods, reducing the emissions intensity of these products through either management practices or reduced demand can help.[51] Serious reductions can be made in the emissions contributions of the livestock sector on the order of at least 30 percent if producers adopted the practices applied by those with the lowest emission intensity.[52] Further scientific breakthroughs, such as use of special disruptors of methane production in ruminant stomachs, also have the potential to bring down emissions from this sector.[53]

Balanced diets featuring plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and

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[47] Mirzabaev, A., J. Wu et al. 2019: Section 3.3.3. in Ch 3: Desertification. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.]. Geneva: IPCC.

[48] Benayas, J., et al. 2007. Abandonment of agricultural land: an overview of drivers and consequences. *CAB Rev.* 2, 1–14; Xie, Z. et al. 2019. Conservation opportunities on uncontested lands. *Nat Sustain* in press: doi:10.1038/s41893-019-0433-9

[49] Lewis, S., et al. 2019. Restoring natural forests is the best way to remove atmospheric carbon. *Nature* 568 (7750): 25-28.

[50] Costanza, R., et al. 2008. The value of coastal wetlands for hurricane protection. *AMBIO A J. Hum. Environ.*, 37: 241–248.

[51] Poore, J and T. Nemecek. 2018. Reducing food's environmental impacts through producers and consumers. *Science* 360: 987–992.

[52] Gerber, H., et al. 2013. *Tackling Climate Change Through Livestock: A Global Assessment of Emissions and Mitigation Opportunities.* FAO, Rome.

[53] Hristov, A., et al. 2013. Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *J. Anim. Sci.*, 91, 5045–5069, doi:10.2527/ jas2013-658; Maia, M., et al. 2016. The potential role of seaweeds in the natural manipulation of rumen fermentation and methane production. *Scientific Reports* 6**:** 32321. doi:10.1038/srep32321

low-GHG emission systems, present major opportunities for adaptation and mitigation while generating significant co-benefits in terms of human health. The good news is that diets that are better for the planet also better for our health. For example, "nuts, minimally processed whole grains, fruits, vegetables, legumes, olive oil, and fish are associated with significantly reduced mortality and/or reduced risk for one or more diseases."[54] Public health policies to improve nutrition, such as increasing the diversity of food sources in public procurement, financial incentives, and awareness-raising campaigns can all potentially influence food demand, reduce healthcare costs, and contribute to lower GHG emissions.

Additionally, around 25-30% of total food produced is lost or wasted, and from 2010-2016, global food loss and waste contributed 8-10% of total anthropogenic GHG emissions. The EPA says food waste and packaging account for 45% of materials sent to landfills in the US.[55] Options to reduce loss and waste across the supply chain globally include improved harvesting techniques, on-farm storage, infrastructure and transport, packaging, retail options, and education. Even small tweaks across a range of sectors, from more flexitarian diets to the use of food waste as feed for animal production, can add up to reduced demands for land, with one estimate of a reduction of up to 37% of the current agricultural area through a series of small aggregated actions.[56]

Policies that operate across the food system should aim to enable more sustainable land-use management, enhanced food security and low emissions trajectories. Diversification in the food system (e.g., implementation of integrated production systems and healthier diets) can also help adapt to and reduce the risks from climate change. Adaptation and enhanced resilience to extreme events impacting food systems can be facilitated by comprehensive risk management, including risk sharing and transfer mechanisms, agricultural diversification, and advance preparation for increasing supply chain disruption. Changes in our current subsidy regimes to promote less GHG-intensive foods, and increase production efficiencies, would also help reflect the costs of many of the environmental externalities within the food system.[57]

Improving conservation of natural ecosystems is important for both mitigation and adaptation: There is increasing evidence for the success of 'nature-based solutions' and 'natural climate solutions' in recent years, with some estimates concluding that these options can provide over one-third of climate mitigation needed between now and 2030 to stabilize warming to below 2°C in a cost-effective manner.[58] Some of our land-based mitigation solutions can have immediate impacts, including the conservation of high-carbon ecosystems such as peatlands, wetlands, rangelands, mangroves and forests. Examples that provide multiple ecosystem services and

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[54] Clark, M., et al. 2019. Multiple health and environmental impacts of foods. *Proceedings of the National Academy of Sciences* 116 (46): 23357-23362.

[55] US EPA. 2015. *Reducing Wasted Food & Packaging: A Guide for Food Services and Restaurants*. https://www.epa.gov/sites/production/files/2015-08/documents/reducing_wasted_food_pkg_tool.pdf

[56] Alexander, P., et al. 2019. Transforming agricultural land use through marginal gains in the food system. *Global Environmental Change* 57: 101932

[57] Mamun, A. et al. 2019. *Reforming Agricultural Subsidies for Improved Environmental Outcomes*. Washington DC: International Food Policy Research Institute.

[58] Griscom, B., et al. 2017. Natural climate solutions. *Proceedings of the National Academy of Sciences* 114 (44): 11645-11650.

functions, but which may take more time to deliver, include reforestation (preferably with local species adapted to local environments) as well as the restoration of high-carbon ecosystems, agroforestry, and the reclamation of degraded soils. However, some caveats do apply here: land-based options that deliver carbon sequestration in soils or vegetation do not continue to sequester carbon indefinitely. Trees do grow faster under higher CO_2 concentrations; however, the lifetime of trees may be shortened, meaning that the long-term sequestration effect is also affected.[59] When vegetation matures or when vegetation and soil carbon reservoirs reach saturation, the annual removal of CO_2 from the atmosphere declines towards zero. In other words, land-based options can be tricky, and do not cancel out the need to also simultaneously reduce fossil fuel emissions.[60] There is no magic get-out-of-jail free card for us.

However, there are big tradeoffs with some land-based mitigation options: We also have opportunities to use the land sector to make more aggressive mitigation cuts, but the SRCCL report cautions that these come with tradeoffs. There are limits to the deployment of land-based mitigation measures such as bioenergy crops or afforestation. Although it may not be widely recognized by the public, all assessed modelled pathways that limit warming to 1.5ºC or well below 2°C *require* land-based mitigation and land-use change, with most including different combinations of reforestation, afforestation, reduced deforestation, and bioenergy crop plantations. Indeed, most mitigation pathways include *substantial* deployment of bioenergy technologies. Only a small number of modelled pathways limit warming to 1.5ºC without high dependence on bioenergy and/or bioenergy with carbon capture and storage (BECCS) and other carbon dioxide removal (CDR) options.[61]

Afforestation, reforestation, and the use of land to provide feedstock for bioenergy (with or without BECCS), or for biochar can greatly increase demand for land conversion if applied at the scale necessary to remove several $GtCO_2yr^{-1}$ (that is, a scale of several millions of km^2 globally). For example, biomass feedstock for biofuels can compete directly with food production for land and water use.[62] Modelled pathways limiting global warming to 1.5°C use up to 7 million km^2 for bioenergy in 2050; the bioenergy land area needed is smaller in 2°C (0.4 to 5 million km^2) and 3°C pathways (0.1 to 3 million km^2). At large scales, we are likely to see adverse side effects for water scarcity, biodiversity, land degradation, desertification, and food security. These impacts are context specific and depend on the scale of deployment, initial land use, land type, bioenergy feedstock, initial carbon stocks, climatic region and management regime. If bioenergy is integrated into sustainably managed landscapes at appropriate scales and with best practices, we can ameliorate many of these adverse impacts.

Adaptation of our land systems to existing and future warming is also crucial: Finally, we also need to explicitly focus our solutions on adaptation to the global warming we are already

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[59] Büntgen, U. et al., 2019. 'Limited capacity of tree growth to mitigate the global greenhouse effect under predicted warming', *Nature Communication* 10 (2171)

[60] Anderson, C.M., et al. 2019. Maximize natural climate solutions - and decarbonize the economy. *Science* 363, 933-934. doi: 10.1126/science.aaw2741.

[61] These non-bioenergy pathways have however even more reliance on rapid and far-reaching transitions in energy, land, urban systems and infrastructure, and on behavioural and lifestyle changes compared to other 1.5°C pathways.

[62] Slade, R., A. Bauen, and R. Gross, 2014. Global bioenergy resources. *Nature Climate Change* 4(2), 99–105, doi:10.1038/nclimate2097

experiencing and the warming that has already been committed to, unless dramatic action to reduce GHG emissions is taken quickly.[63] Adaptation actions that also bring mitigation benefits are ideal, and examples of these co-benefits for both mitigation and adaptation include increased food productivity, improved cropland management, improved grazing land management, improved livestock management, agroforestry, improved forest management, increased soil organic carbon content, better fire management, and reduced post-harvest losses.[64] However, adaptation practices that increase GHG emissions (such as subsidies that might reward land conversion) or mitigation that makes adaptation harder (such as widespread BECCS) will involve tradeoffs we should try to avoid.

Research Gaps

Below I identify a few research gaps that emerged from work on the SRCCL report, as well as my own experience in reviewing this area. Many of these research gaps were also identified in a draft USDA Climate Resilience Science Plan, not yet released to the public, but which contains an excellent list of research priorities across categories of climate impacts, mitigation, adaptation, decision-support, indicators and metrics, and coordinated action.[65] The below gaps are areas in which we can fill in some details with more research, but they by no means should stop us from continuing to take action; indeed, because we don't fully know how some of our ecosystems and social systems respond to climate stressors, that is all the more reason to take strong mitigative action now.

How will our land sinks respond to future warming? The natural sink response of land to human-induced environmental changes is important and resulted in global net removals of 29% of our anthropogenic CO_2 emissions during 2007-2016.[66] Future net increases in CO_2 emissions from vegetation and soils due to climate change (e.g. permafrost thawing) are projected to counteract any increased removals due to CO_2 fertilization and longer growing seasons (e.g. vegetation greening). Yet the balance between these processes is a key source of uncertainty for determining the persistence and future of the land-carbon sink. Some additional evidence beyond the SRCCL report suggests that tropical forests in particular are likely to diminish their sink function and become a net carbon source in the future, as a result of continued deforestation and impacts from climate change alters forests' ability to sequester carbon dioxide.[67] Further work in

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[63] IPCC. 2018. Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., et al. (eds.)]. Geneva: IPCC.

[64] Smith, P. et al. 2019. Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Global Change Biology* in press DOI: 10.1111/gcb.14878; McElwee, P. et al. 2020. The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN Sustainable Development Goals. Under review with *Global Change Biology*.

[65] USDA Climate Resilience Science Plan, draft of September 14, 2017

[66] This is of course offset by AFOLU emissions, giving a total net land-atmosphere flux that removed 6.0+/-2.6 $GtCO_2$ yr^{-1}. See Table SPM.1 in: IPCC. 2019. Summary for Policymakers. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, et al. eds.)]. Geneva: IPCC.

[67] Mitchard, E. 2018. The tropical forest carbon cycle and climate change. *Nature* 559: 527-534.

this area is ongoing and will be important to clarify these processes and improve our scientific understanding of land-climate feedbacks.

How can we explain and deal with increases in methane emissions? We also need further research on understanding trends in methane emissions, particularly because methane is such a potent heat-trapping gas. Methane emissions come from both anthropogenic and natural sources, and the globally averaged atmospheric concentration of methane showed a steady increase between the mid-1980s and early 1990s, slower growth thereafter until 1999, a period of no growth between 1999-2006, followed by a resumption of growth in 2007. We need to know more about these trends, and if atmospheric methane has been increasing since 2007 as a consequence of climate change (such as the loss of sink functions) or of our direct emissions and if so, from what sectors? Currently extensive work is being conducted with robust debate to understand how these trends can be explained, such as through underestimated fossil fuel methane sources in the US.[68] Current preparations to launch a methane-monitoring satellite by the NGO Environmental Defense Fund will be an important source of data, but highlights the fact that we should have had more federal leadership in this area already. Wetlands, particularly in the tropics, are a hugely important part of this picture and we need more research and mapping of their role in these processes and how they are responding to climate and other land use changes. This is important because the rise in methane since 2007 has serious implications for achieving the targets of the Paris Agreement.[69]

How can we anticipate and prevent land-based climate 'tipping points'? There is also a great deal of concern about whether we are beginning to see signs of climate 'tipping points', where the rate of change of a system accelerates rapidly, often in unpredictable ways, often with self-amplifying effects. Some scientists have recently warned that we may see tipping points even at lower temperature thresholds, including Antarctic ice sheet melt or dieback of the Amazon forest, with potentially irreversible consequences.[70] Tipping points were addressed in all three of the IPCC special reports, and the US National Climate Assessment devoted a chapter to these 'potential surprises'[71] but there is much more we need to know through continued robust research on these trends and feedbacks. We also need better ways to understand the economic impacts of these low probability but high impact events. The presence of medium-term warning systems from which we can anticipate tipping points (for example, in terms of land degradation) would be very important to cope with these changes.

Social and economic research gaps: how to internalize externalities in socially acceptable and economically feasible ways? There are also a number of policy and social science research gaps,

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[68] Schwietzke, S., *et al.* 2016. Upward revision of global fossil fuel methane emissions based on isotope database. *Nature* 538: 88–91; Alvarez, R. et al. 2018. Assessment of methane emissions from the U.S. oil and gas supply chain. *Science* 361 (6398): 186-188

[69] Nisbet, E. et al. 2019. Very strong atmospheric methane growth in the 4 years 2014–2017: Implications for the Paris Agreement. *Global Biogeochemical Cycles* 33(3): 318-342.

[70] Lenton, T. et al. 2019. Climate tipping points — too risky to bet against. *Nature* 575 (28 Nov): 592-595 https://www.nature.com/articles/d41586-019-03595-0

[71] Kopp, R.E., et al. 2017. Potential surprises – compound extremes and tipping elements. In: *Climate Science Special Report: Fourth Nation- al Climate Assessment, Volume I* [Wuebbles, D.J., et al. (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 411-429.

although these receive far less support and funding. Between 1990 and 2018, the natural and technical sciences received 770% more funding than the social sciences on climate, with only 0.12% of all research funding spent on the social aspects of climate change mitigation.[72] This is a particularly important gap as we look for socially acceptable and economically viable solutions around land use. For example, how policies like carbon taxes would result in land-based mitigation incentives are less well known than the potential impacts in the fossil fuel use sectors. Current bills before the Congress to incentivize farmers to adopt soil conservation practices and to provide tax credit to farmers and ranchers who store carbon on farm and rangelands would benefit from more analysis of social and economic impacts and barriers to effective policy implementation.[73] This has not stopped some groups from moving ahead, including an Ecosystem Services Market Consortium and private investors who hope to generate offset credits on a voluntary soil carbon market. Yet the results of research on land-based offsets shows that these can potentially undercut gains in other sectors by providing an 'out' to avoid concrete emissions reductions, and we need further work in this area.[74]

How can we improve modelling of socio-economic pathways and future climate impacts?
Finally, the models that we use to project social and economic changes in response to climate and other impacts can also be improved. For example, most modelled mitigation pathways exclude the impacts of climate change, so we have limited understanding within Integrated Assessment Models (IAMs) of how adaptation can alter pathways. Many policy choices that we might be able to make are also not easily reflected in such models.[75] Having more clear ideas of what works for adaptation, that are measurable in terms of mitigation, and that bring economic benefits could create an "atlas of best practices" to assist consumers, producers, local communities and state governments to help them in decision-making.

Many of these research gaps above can be tackled by our land-grant universities, like my home institution of Rutgers. We combine both high-level scientific research with practical applications and engagement with farmers, producers and consumers through agricultural extension services, 4-H, and other interactions. The Foundation for Food and Agriculture Research, the public-private partnership founded in the 2014 Farm Bill, can play a role in funding such research. Overall, improvements in partnerships of researchers, scientists and agencies around agricultural and ecosystem conservation practices and their environmental outcomes can promote learning, adaptive management, and innovation.[76] These partnerships can expand the measuring and monitoring of land use and climate change through the use of new information and communication technologies, and provide a one-stop-shop for research findings combined with ways to make results useful to local areas, including communities and landowners.

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[72] Overland, I and B. Sovacool. 2020. The misallocation of climate research funding. *Energy Research and Social Science* 62: 101349.

[73] Amundson, R and L. Biardeau. 2016. Soil carbon sequestration is an elusive climate mitigation tool. *Proceedings of the National Academy of Sciences* 115 (46): pp. 11652–11656

[74] Lovell, H., et al. (2009). Carbon offsetting: Sustaining consumption? *Environment and Planning A: Economy and Space*, *41*(10), 2357–2379; Galatowitsch, S.M. 2009. Carbon offsets as ecological restorations. *Restoration Ecology* 17: 563-570.

[75] Burke, et al. 2016. Opportunities for advances in climate change economics. *Science* 352 (6283): 292-293.

[76] Briske, D. et al (2017). Assessment of USDA-NRCS Rangeland Conservation Programs: recommendation for an evidence-based conservation platform. *Ecological Applications* 27: 94–104.

Conclusions

In conclusion, the land sector is both threatened by, but can also potentially be a way to reduce many impacts of, climate change. The modelling done for the SRCCL report indicates that rapid reductions in anthropogenic GHG emissions across all sectors (that is, *both* fossil fuels and land) following ambitious mitigation pathways aimed at limiting warming to 1.5°C *would substantially reduce the negative impacts of climate change on land ecosystems and food systems*. On the other hand, continuing to delay climate mitigation and adaptation responses across sectors *would lead to increasingly negative impacts on land, including biodiversity and ecosystem loss, and reduce the prospect of global sustainable development*.

Improving the way we use and manage land can't fix all our problems, but it can contribute significantly to addressing the climate change problem and adapting our economies to new realities. *We cannot achieve our global objectives without dealing with land-based emissions, but taking action on land cannot be an excuse for not taking action on fossil fuels. We need to do both.* Delays will only make things worse, as the 1.5°C report pointed out clearly. Deferral of GHG emissions reductions until a later point in time will result in increasingly serious and more costly trade-offs. These include some irreversible losses in land ecosystem functions and services required for food, health, habitable settlements and production, leading to major economic impacts on many countries in many regions of the world.

Delays in avoiding or reducing land degradation and promoting ecosystem restoration risks long-term impacts, including rapid declines in productivity of agriculture and rangelands, permafrost degradation and difficulties in peatland rewetting. Once some of these ecosystems are gone, they are gone. Delaying action, as is assumed in high emissions scenarios, could result in not only irreversible impacts but have the potential in the longer-term to lead to substantial additional GHG emissions due to amplifying feedbacks from changing ecosystems.

Delayed action across sectors also leads to an increasing need for widespread deployment of land-based adaptation and mitigation options in the future, such as BECCS, with increasingly higher initial costs and long-term tradeoffs, including biodiversity loss and food insecurity. The higher temperatures get, though, the harder these options become to use, as there is decreasing potential for the array of these options and limitations to their current and future effectiveness. For example, the potential for some response options, such as increased soil organic carbon, decreases as climate change intensifies, as soils have reduced capacity to act as sinks for carbon sequestration at higher temperatures and with reduced soil moisture.[77]

Thus, acting now may avert or reduce risks and losses and generate benefits to society. Prompt action on climate mitigation and adaptation aligned with improved land management and sustainable development can reduce the risk to millions of people from climate extremes, desertification, land degradation, and food and livelihood insecurity. Thank you for allowing me to present this testimony today.

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[77] Green, J.K. *et al.* 2019. Large influence of soil moisture on long-term terrestrial carbon uptake. *Nature* 565: 476–479.