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CLIMATE CHANGE AND AGRICULTURE

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Summary

Farmers have always had to deal with the vagaries of precipitation and heat. At times, there might be too much rainfall or too little, or too many days of adverse temperatures that might prevent crops from ripening. While the climate has historically never ceased changing, there is now concern that human emissions of greenhouse gases, principally carbon dioxide (CO_2) from fossil fuel burning, are causing unprecedented global warming. Whether the observed approximately 1ºC (1.8ºF) warming of the past 150 or more years is primarily human-caused and whether the human factor will result in unprecedented and catastrophic future warming is fraught with uncertainty. Likewise, the impact that global warming will have on agriculture is uncertain. This issue is examined in this chapter. On a global scale, technological changes in agriculture can more than compensate for potentially adverse impacts of climate change, although some regions may be adversely affected. Further, policies to mitigate climate change could do more harm than good. Since agriculture and forestry often compete for the same land input, we discuss how policies in one of these sectors affect the other, and end by examining how the burning of wood biomass to generate electricity might be a misguided policy for mitigating fossil fuel emissions.

Introduction

Climate change is one of the most contentious policy issues of the early 21st Century. In December 2015, nations signed the Paris Agreement (see Box 1), which aims "to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change." Likewise, the U.S. Fourth National Climate Assessment (NCA) fears that "climate change creates new risks and exacerbates existing vulnerabilities in communities across the United States, presenting growing challenges to human health and safety, quality of life, and the rate of economic growth." Much like former Vice President Al Gore's 2006 movie, "An Inconvenient Truth," which predicted that the world had about 15 years to avoid the death of more than a billion people from global warming, others have sought to influence the public regarding the science and politics of climate change. For example, the NCA's assessment that the U.S. economy would see a decline of 10% in GDP was based on a study funded by two billionaires linked to the Democratic Party – Michael Bloomberg and Tom Steyer (see Bastasch 2018; Pielke 2020). Meanwhile, a Republican President, Donald Trump, pulled the United States (U.S.) out of the Paris Agreement in 2017, and stated that he did not believe the NCA's conclusion that the U.S. economy was already being harmed by adverse weather due to anthropogenic (human-induced) climate change and that the future would be worse.[1]

It is useful to keep in mind that the largest contributing greenhouse gas (GHG) is carbon dioxide (CO_2), so much so that the impact of other GHGs (i.e., methane, CH_4; nitrous oxide, N_2O; ozone, O_3; chlorofluorocarbons, CFCs; hydrofluorocarbons, HFCs and HCFCs; water vapor, H_2O) is translated into CO_2 equivalence (which is why we use CO_2 in this chapter to denote any GHG emissions). The correlation between CO_2 emissions from fossil fuel use and rising concentrations of atmospheric CO_2 is taken to constitute evidence that human activities are responsible for climate change. However, there is no straightforward causal link between human fossil fuel use and temperatures, although this remains an area of contention (van Kooten 2013, pp.37-47; McKitrick and Vogelsang 2014).

Adverse weather is perhaps the greatest risk to agriculture, which is a major sector vulnerable to climate change (Adams et al. 1996; McCarl et al. 2016). In this chapter, we focus on climate change and agriculture. Will climate change lead to greater or lesser agricultural output? Is climate change a threat to food security? Are farmers able to adapt to climate change? Can agricultural policies help society mitigate global warming? An important consideration is how climate change could redistribute income from one region to another. In this chapter, we consider climate policies related to agriculture and, to some extent, forestry, because farmers and foresters compete for the same land input. Thus, policies in the one sector might affect those in the other sector.

1. Climate Change under Uncertainty

There is a great deal of uncertainty concerning climate change (Nordhaus 2013; van Kooten 2013; Tol 2014) regarding (1) the contribution to global warming of human activities (e.g., burning of fossil fuels, land-use changes) versus that of natural factors (e.g., CO_2 release from oceans, changes in the sun's activities) (de Laat and Maurellis 2004, 2006; McKitrick and Michaels 2004, 2007; McKitrick and Nierenberg 2011); (2) the projected increase/decrease in average global temperatures (Hourdin et al. 2017; Millar et al. 2017; Lewis and Curry 2018; McKitrick and Christy 2018); and (3) the regional changes in climate that might be expected (Lomborg 2007; Pielke 2018a). The conclusions to be drawn from trends of past temperatures are controversial, as are the associated climate models, especially in projecting future temperatures and precipitation.

There is controversy over estimates of the social cost of carbon, which depends on estimates of expected damages from global warming (Pindyck 2013; Dayaratna et al. 2017; Auffhammer 2018). Many estimates of potential economic damages from climate change are related to goods and services that are not traded in markets (e.g., wetland services, biodiversity, heat and mental stress, threats to national security), and thereby not easily valued. It is difficult to determine how climate change affects these types of things, let alone attempting to place a value on them. When it comes to the agricultural sector, however, real changes in output and the location of production can be impacted by climate change, and thus are potentially measurable.

[1] See, for example, Western Producer, December 6, 2018 at https://www.producer.com/2018/12/trump-rejects-climate-change-impact-report/.

Uncertainty is not the same as risk because one cannot construct probability distributions about the variables of interest, particularly future weather events. As a result, the dilemma facing policy makers is that the Intergovernmental Panel on Climate Change (IPCC) relies on speculation or storylines based upon complex computer models (Trenberth 2007).[2] Integrated assessment models (IAMs) are then used to make such speculations explicit by projecting the path of future CO_2 emissions – providing the emissions scenarios used in the IPCC's climate reports.[3]

Scientists use the emission scenarios in computer models that then project increases in future global temperatures. When the outcomes of climate models are tested against observed data, however, they perform rather poorly – temperature predictions from climate models have been consistently too high (Santer et al. 2017; McKitrick and Christy 2018). Nor are climate models calibrated to real-world data in any comprehensive fashion (Levitt and Dubner 2009, pp.177-186; Hourdin et al. 2017). One question that needs to be addressed if we are to evaluate the costs and benefits of mitigating climate change is this: Can one base predictions of future climate (let alone future economic losses, if any) on the basis of models that are not validated by current observational data?[4]

Climate constitutes a highly complex, multi-factor system integrating the ocean and atmosphere, which consist of water and air that move unsteadily and violently on different time scales, as well as a terrestrial component. It is impossible to represent the integration of these three completely different systems by a single variable – the averaged global temperature ($\overline{T}$). It is impossible that this complex system can be controlled by less than 2% of the perturbation of the energy budget that is due to one variable, namely CO_2. Further, it may not be realistic or accurate to attempt to estimate economic damages from climate change when they are considered a function only of the average global temperature. As a result, any estimate of damages must necessarily be considered highly uncertain.

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[2] A discussion of the IPCC process is provided in Box 1. Trenberth (2007) points out that "there are no predictions by IPCC at all. And there never have been. The IPCC instead proffers 'what if' projections of future climate that correspond to certain emissions scenarios. There are a number of assumptions that go into these emissions scenarios. They are intended to cover a range of possible self-consistent 'story lines' that then provide decision makers with information about which paths might be more desirable. … There is no estimate, even probabilistically, as to the likelihood of any emissions scenario and no best guess." This is why climate scientists avoid the terms 'forecast' and 'predict', preferring the term 'project' (Hsiang and Kopp 2018, p.10). This makes it impossible to replace uncertainty with probability distributions.

[3] IAMs are discussed in Appendix A, but the ones discussed there (and below) are not the same as those used to develop the emission scenarios (rather, see van Kooten 2013, pp.102-110).

[4] As Lee Smolin (2013) points out, "if an idea is not vulnerable to falsification, it is not science" (p.139). The laws of nature play only a limited role in climate models, as projections are sensitive to unknown or uncertain initial conditions plus various parameters that can be fudged to obtain reasonable (or desirable) outcomes (Hourdin et al. 2017).

Box 1: International Climate Change Action

The Intergovernmental Panel on Climate Change (IPCC) was jointly established in 1988 by the World Meteorological Organization and the United Nations' Environmental Program to asses the risk of anthropogenic (human-induced) climate change, along with its potential impacts and how it might be prevented. Natural causes of climate changes and adaptation were not part of the IPCC's mandate. The focus on anthropogenic causes of climate change was reinforced in a a 2018 Summary for Policy Makers, which stated that "A.1 Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C" (IPCC 2018). While the causes of the Medieval Warm Period and Little Ice Age remain unexplained, anthropogenic CO_2 emissions were not responsible for these climatic periods (van Kooten 2013).

At the Earth Summit in Rio de Janeiro (Brazil) in 1992, countries signed two international treaties – the UN Framework Convention on Climate Change (FCCC) and a Convention on Biodiversity. The FCCC came into effect in 1994. Since then, there has been an annual Conference of the Parties (COP). COP3, held in Kyoto, Japan, led to the Kyoto Protocol in 1997, which required industrialized nations to reduce their emissions of CO_2 by an average of 5.2% from the baseline 1990 emissions by 2008-2012 (van Kooten 2004). For example, the European Union agreed to reduce emissions by 8%, the Untied States by 7%, and Canada and Japan by 6%. At COP7, held in Marrakech, Morocco, in 2001, countries agreed to count carbon sequestered in growing forests toward countries' commitments; as a result, countries were provided carbon credits for avoiding deforestation, and then carbon credits for protecting biodiversity. The latter has nothing to do with atmospheric CO_2, but it did link the FCCC with the Convention on Biodiversity. The Kyoto Protocol also provided industrialized countries with credits for activities that reduced CO_2 emissions in developing countries and those in transition (countries of the former Soviet Union); activities could include construction of wind turbines, planting forests, or investments to make power plants in Asia more efficient. The Kyoto instruments remain in place.

The latest agreement came at COP21 in December 2015, and is known as the Paris Agreement. Each country provided its Intended Nationally Determined Contributions (INDCs) toward the global objective to limit the increase in global mean temperature to 2°C above pre-industrial levels (or limit the atmospheric concentration of CO_2 to no more than 450 ppm compared to 409 ppm in 2018 and 280 ppm in 1750). Many developed countries indicated they would reduce CO_2 emissions by 30% within the next 15 years, while aiming to reduce emissions by 80% by 2050 compared to 1990 emissions. Realistically, there is no way for the United States, Europe, or any other country to meet this target and retain its present standard of living. Reductions in CO_2 on that scale are unachievable without severely impoverishing people. The last time the United States had CO_2 emissions that were 80% below the 1990 levels was circa 1905, when it had less than one-fifth as many people, life expectancy at birth was 48 years, and average income was 13% of current income. The costs of mitigation exceed any potential benefits. At COP24 in Katowice, Poland, countries hoped to agree on ways to prevent temperature from rising more than 1.5°C over pre-industrial levels. Interestingly, INDCs are vague and, if those commitments were truly kept, would not achieve anything near what the Paris Agreement intends.

There are two particular sticking points. First, developing countries argue that, if climate change is occurring and is harmful to them, rich countries should pay for cleaning up the mess. In 2010-2011, the United Nations (UN) established a Green Climate Fund (GCF) to which rich countries pledged to contribute US$10.3 billion ($4.7 billion from the European Union, $3.0 billion from the United States). The GCF would grow to $100 billion by 2020 and would compensate developing countries for past CO_2 emissions by developed countries through a redistribution of income. Second, developing countries are unwilling to impede development by controlling their own GHG emissions. China is now the largest consumer of coal, followed by India, and China's CO_2 emissions exceed those of the United States and the European Union combined. Neither China nor India wants to deal with this issue, but could be made to do so if CO_2 emissions were part of trade negotiations.

Emission reductions of as little as 25% would be difficult and costly to achieve, requiring huge investments in nuclear power, massive changes in transportation infrastructures, and impressive technical breakthroughs in everything from biofuels to battery technology. Few countries can afford such costly investments. Without global cooperation, the impact on climate change will be small (BP Global 2018; International Energy Agency 2018). Because fossil fuels are currently abundant, ubiquitous, and inexpensive relative to alternative energy sources, any country would be foolish to impair economic development by abandoning fossil fuels. Whether or not anthropogenic global warming is real or the climate model projections are accurate, fossil fuels will continue to be the major driver of economic growth and wealth into the foreseeable future.

One of the many parameters that the climate modeler needs to set is the equilibrium climate sensitivity (ECS), which is the expected increase in temperature from a doubling of the atmospheric concentration of CO_2 from 280 parts per million (ppm) by volume in pre-industrial times (circa 1750) to 560 ppm, while the early 2019 concentration is about 410 ppm. In climate models, it is the critical, climate sensitivity parameter that converts atmospheric CO_2 into temperature increases. While earlier IPCC reports were much more assertive about the size of the climate sensitivity parameter, stating a likely range of 2.0˚C to 4.5˚C with a best estimate of 3.0˚C, the 2014 Fifth Assessment Report (AR5) is much less certain about the climate sensitivity parameter, reducing its lower likely bound to 1.5˚C and offering no best estimate (IPCC 2013, 2014). Empirical evidence suggests that climate sensitivity to CO_2 is much less than originally anticipated – that human activities, while contributing to global warming, are less likely to lead to dangerous global warming. Recent studies have reported ECS values that are as low as 0.5˚C (Lewis and Curry 2015, 2018; Mauritsen and Pincus 2017). This has important implications when we consider the economic side of the ledger because the ECS is used to determine the social cost of carbon (SCC). The SCC is the present value of all future damages caused by emitting one extra metric ton (tonne) of CO_2, denoted tCO_2.

We can determine the effect of ECS on the social cost of carbon using a climate-economic model, DICE, that was developed by the Nobel prize-winning economist, William Nordhaus (see Appendix A). We used the DICE model (version 2016R2-083017, August 2017) to inform the value of the SCC that the U.S. Environmental Protection Agency employs in its cost-benefit analyses of environmental regulations. If society were to employ a carbon tax, then the tax should be set to the SCC. We used the DICE model to simulate values of the SCC for different parameter value of the ECS. The original version of the model employs an ECS of 3.1ºC, and we compare this to values of 2.0ºC and 1.0ºC. The results are provided in Figure 1 for forecasted periods 2015 to 2100. When the ECS is 3.1ºC, the current value of the social cost of carbon is about $35/tCO_2$ (measured in 2005 U.S. dollars), rising to nearly $100/tCO_2$ by 2050. However, if the ECS is 1.0ºC, the current SCC is only $6.5/tCO_2$ and its value in 2050 is less than $45/tCO_2$. The difference between a carbon tax based on an ECS of 3.1ºC and one based on 1.0ºC is enormous, with the difference having major implications for climate policy.

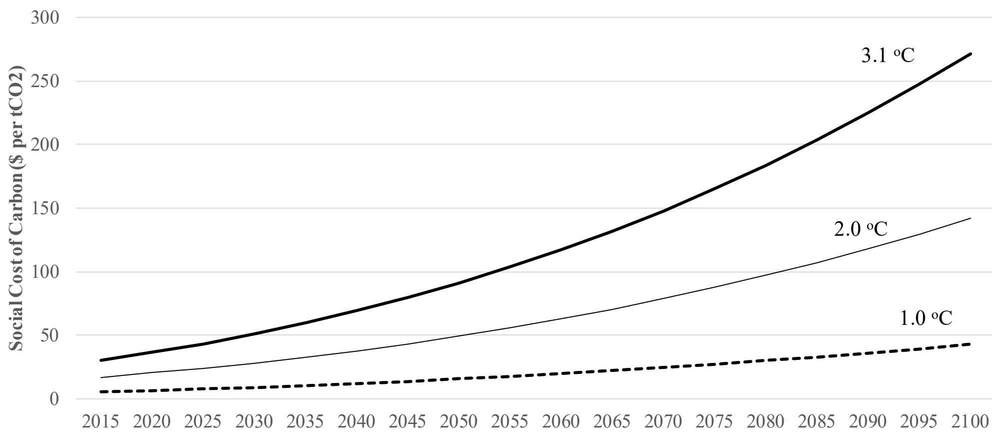

Figure 1: Path of the Social Cost of Carbon, 2015-2100, for Three Values of the Equilibrium Climate Sensitivity Parameter, DICE Model (US$2005 pet tCO_2)

The benefits of mitigating climate change today are given by the discounted stream of net damages that are supposedly prevented in the future. What are the expected damages from global warming? The list of potential damages includes those from sea level rise, more frequent and more intense storms, heat waves and drought, increased risk of disease, loss of biodiversity, increased international tensions and climate refugees, and even psychological damage as noted by Doherty and Clayton (2011) and Hayes et al. (2018). Upon investigating the potential damage from each of these possible effects, there may well be potential benefits from some warming. Fewer people die from heat than from cold (Gasparrini et al. 2015), so global warming might improve life expectancy. Crop yields might also improve due to a CO_2-fertilization effect and more heat (as discussed in section 3). Second, many of the claimed disastrous consequences that appear in the literature and media do not exist. There is no evidence that storm frequency or intensity is increasing; rather, damages from storm events have increased over time because more people and more valuable property are in harm's way (e.g., see Lomborg 2007, 2010; van Kooten 2013, pp. 224-252; Pielke 2018b). Let us examine some of the most prominent weather extremes.

Hurricanes

Consider, for example, the number and severity of hurricanes affecting the United States (making landfall or having an impact on the United States) over the period 1851-2018. The data are from the Hurricane Research Division of the Atlantic Oceanographic & Meteorological Laboratory of the National Oceanic and Atmospheric Administration (NOAA),[5] and are summarized in Figure 2 and Table 1. They indicate that the average number of severe hurricanes striking the United States each year since 1950, after which anthropogenic CO_2 emissions rose fastest, is lower than it was prior to this time. Indeed, Weinkle et al. (2018) even found that the damage from hurricanes has declined over time.

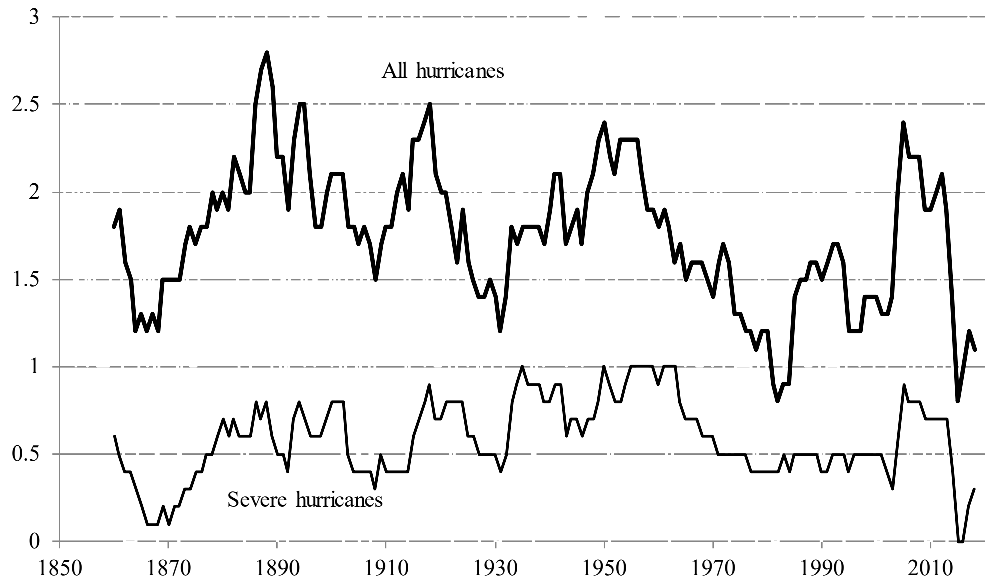

Figure 2: Total and Severe Hurricanes Impacting the United States, 10-year Moving Average, 1851-2018 (Source: http://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html)

Table 1: Average Annual Hurricanes of Categories 3, 4, or 5 Impacting the United States, 1851-2018

Period	Average	Period	Average
1851-1900	0.54	1951-2018	0.56
1851-1950	0.61	1976-2018	0.49
1851-1975	0.62	2000-2018	0.53
1951-2000	0.56	Entire period (1851-2018)	0.59

Source: Authors' calculations using NOAA data.

In a major study of hurricanes at the global level, Curry (2019) concludes:

> *"The relatively short historical record of hurricane activity, and the even shorter record from the satellite era, is not sufficient to assess whether recent hurricane activity is unusual for during the current interglacial period. ... Global hurricane activity since 1970 shows no significant trends in overall frequency, although there is some evidence of increasing numbers of major hurricanes and of an increase in the percentage of Category 4 and 5 hurricanes. In*

[5] Data are at http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html [accessed November 1, 2018].

the North Atlantic, all measures of hurricane activity have increased since 1970, although comparably high levels of activities also occurred during the 1950's and 1960's."

Wildfires

Using data from the National Interagency Fire Center, and as shown in Figure 3, the number of wildfires and area burned since the 1920s has declined significantly.[6] There is no discernable trend in the numbers of fires since the mid-1980s, although the area burned may have increased slightly. Several factors are important when considering the number of fires and area burned. First, fire suppression is more advanced today than it was in the first half of the previous century. Second, efforts to reduce fuel load may have had an impact, but it is unclear to what extent. And certainly, climate factors have played a role, although it is unclear whether climate change increased or reduced the probabilities of wildfire. The evidence indicates that U.S. wildfires are now less prevalent than in the past. Support for this observation at the global level comes from Arora and Melton (2018), who find that the area burned by wildfires and the CO_2 emissions from wildfires in the United States, have declined since the 1930s.[7]

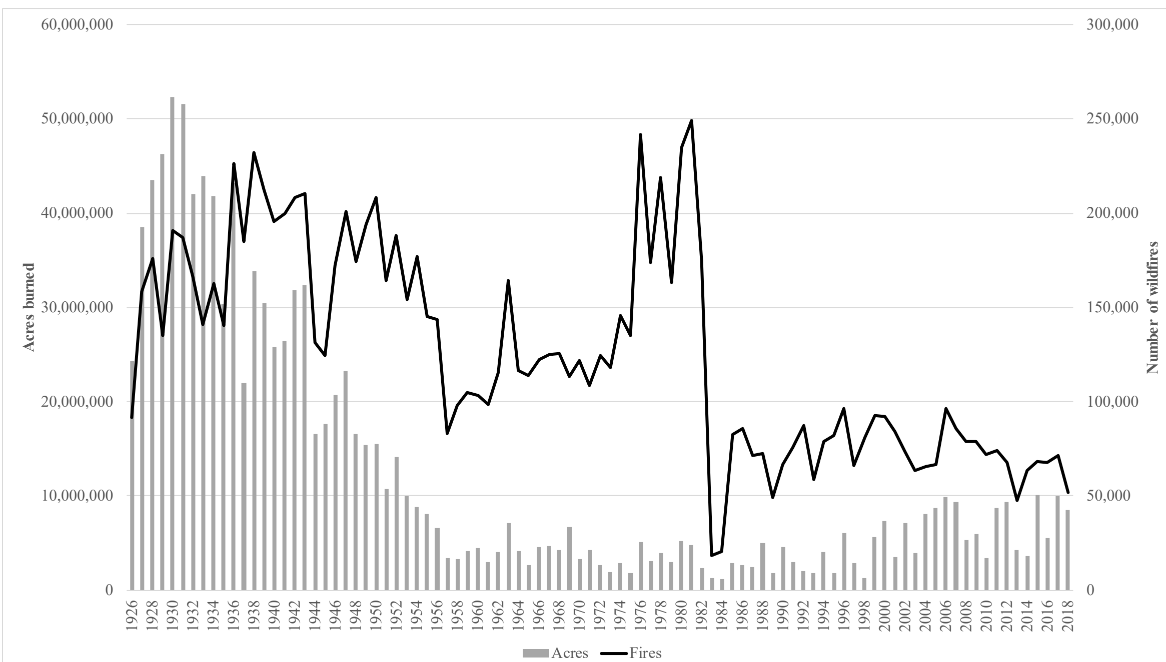

Figure 3: Numbers of Wildfires and Area Burned (acres), United States, 1926-2018
Source: https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html

Wildfires in Australia during the southern spring summer of 2019-2020 drew the world's attention

[6] National Interagency Fire Center at https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html [accessed November 15, 2018]. Data for 2018 are year-to-date to November 15, 2018. The deadly California fires of late 2018 were not outside the norm, except perhaps in terms of lives lost – people in harm's way.

[7] The total number of square kilometers burned each year fell by roughly 25% between 2003 and 2019 (NASA 2019). Also see Andela et al. (2017).

because of their scope, with media and pundits blaming the fires on climate change. It turns out, however, that the fires were not unusual after all and temperatures during this period were not the highest recorded in Australia (Marohasy 2020). Wildfires in 1851 burned some five million hectares and the highest temperatures during the Australian fire season were recorded in 1938/1939, with the highest temperature ever recorded in Australia reaching 51.7ºC (125ºF) at the Bourke Post Office on January 3, 1909. Large-scale wildfires are due primarily to a failure to address fuel load.

Prior to mid-20th Century, indigenous people in Australia would practice 'cool' firing – setting fires during winter season to reduce fuel load. The same practice was used by indigenous people in Canada to open up the forests, thereby increasing production of wild berries and habitat for ungulates and other wildlife (Pyne 2007). These 'controlled burns' reduced fuel loads so that wildfires that occurred during fire season were less frequent and less intense so that mature trees had a greater chance of survival. During the past 70 or more years, forest managers stopped using controlled burns to reduce fuel load, partly as a result of pressure by environmentalists who felt that humans should not interfere with nature. While climate change is a contributing factor once fires start, the chances of natural ignition are reduced. The reason is that, as CO_2 warms the atmosphere, it is the increase in moisture that this warming brings about that is the major driver of climate change. But greater humidity reduces the chances of ignition, so climate change should actually reduce the number of wildfires.

Sea level rise

Nor is there evidence to indicate that climate change is causing sea levels to rise (Howard et al. 2015), although one might expect this if oceans undergo thermal expansion due to warming and glaciers located over land melt (as melting sea ice does not increase sea levels). The problem is that some coastal areas are subsiding (partly due to groundwater withdrawals), while others are lifted up due to natural forces (e.g., tectonic plate movements); measurement is also a problem as gauges are affected by storm surges and subsidence, amongst other factors. Indeed, invalidated concerns about sea level rise may be interfering with sound coastal management (Parker 2018). Other researchers find that many islands are actually increasing rather than decreasing in size, opposite to what one might have expected with global warming (Duvat 2018; see also Kench et al. 2018; Curry 2018).[8]

Biodiversity

Polar bears are a charismatic species that are considered a harbinger of climate change's negative impact on biodiversity, but polar bear populations appear to be increasing, and not decreasing, with much bear mortality the result of hunting and not global warming (e.g., Crockford 2018). Since higher concentrations of atmospheric CO_2 also enhance tree growth (see discussion in next section with respect to plants more generally), there may be greater production of wood products from a smaller forested area, thereby enhancing natural habitat; this could, in turn, offset potential

[8] Duvat (2018) studied 30 Pacific and Indian Ocean atolls and 709 islands, finding that no atoll contracted in area while 88.6% of islands were either stable or increased in area, with only 11.4% getting smaller.

losses in biodiversity and might even enhance global biodiversity (Sohngen and Mendelsohn 1998; Sohngen et al. 1999, 2001). Goklany (2009) also reports that net biome productivity could increase as a result of climate change and that less wildlife habitat will be converted to cropland as a result of global warming. Conversely, some climate-mitigation techniques that use wood biomass to generate electricity could have the opposite effect of reducing biodiversity, especially if proper forest management is not implemented. Biodiversity loss is difficult to evaluate and its value is even more difficult to measure (van Kooten and Bulte 2000).

Other climate-related issues

Other climate-related issues are interesting but also controversial. With regard to health, the most frequently cited example concerns the spread of mosquito-borne diseases if tropical temperatures were to shift pole-ward. These diseases, such as malaria and dengue fever, however, are not necessarily tropical diseases, but rather diseases associated with poverty; as an example, it infected nearly 10 million, killing more than 20%, in Siberia in the 1920s and 1930s. Malaria has been eradicated in rich countries through investments in mosquito control and public health efforts and is on track to be eliminated in other WHO regions by 2020.[9] Recent *Ebola* and *Zika* virus outbreaks have shown that the global health may be better served by economic development that lifts people out of poverty rather than investments in mitigating climate change (Goklany 2009).

A more recent assessment of the impact of climate change on the United States (USGCRP 2018) finds that the 1930s 'dust bowl' era remains a "benchmark drought and extreme heat event." The USGCRP also finds that there is no evidence to suggest that flooding has worsened or flood events have increased in the United States, nor that anthropogenic GHG emissions might have any impact on the frequency or severity of floods (in contrast, say, to deforestation of mountain sides). While the report indicates that U.S. GDP might be 10% lower by 2100, this is rather insignificant given that GDP is projected to increase by 300% in any event and that in the intervening 80 years much is likely to happen in the way of technological advancements in health, agriculture, and so on (Lomborg 2018).

The point of the foregoing discussion is not to disprove the climate change story, but, rather, to highlight the uncertainty that is involved. As Trenberth (2007) has made clear: the climate change story consists of storylines that may never come true but are meant as a possible guide to help decision makers. Despite dire warnings, it is impossible to know how the climate will evolve in the future, especially at the regional level. "The uncertainties about climate change are … so vast that the standard tools of decision making under uncertainty and learning may not be applicable" (Tol 2009, p.30). It is impossible to know how technology will evolve to either facilitate mitigation of GHG emissions (e.g., carbon capture and storage) or provide solutions that enable society to effortlessly adapt to new climate regimes. Likewise, it is difficult to say anything definitive about the potential damages from climate change. As shown above, even changes in the equilibrium climate sensitivity parameter can result in a markedly different path of damages (Pindyck 2017),

[9] See https://www.who.int/malaria/publications/world-malaria-report-2017/wmr2017-regional-profiles.pdf [accessed January 21, 2019].

but so can changes in other climate parameters (Lewis 2018). There is a great deal of uncertainty about the future global mean surface temperatures, precipitation, and regional weather patterns.

2. Measuring the Economic Impacts of Climate Change on Agriculture

Economists have employed two methods to estimate the potential damages of climate change in the primary sectors. These are described in more detail in Appendix A. The first method uses regression analysis to determine how growing-season and even off-season weather factors, such as precipitation and temperatures (heat units), affect crop yields or farmland values. Once a regression/statistical model has been estimated, projected changes in rainfall and heat units from climate models are applied to determine the expected climate-induced yield or land value. Under the second method, economists use mathematical programming (MP) models to mimic a decision maker's (e.g., a representative farmer's) behaviour given the economics, policy, and biophysical (including climate) constraints that he or she faces.

Land rents and the regression/statistical approach

Rising food prices lead to an expansion of agricultural production onto marginal land that could not be profitably cultivated at a lower price. At the margin, farmers would earn enough to cover all expenses, including an adequate return on capital investment. When marginal land is brought into production, owners of better land – that is more fertile, experiences better weather outcomes or is situated nearer markets – will earn a differential rent. This concept can be applied in the context of climate change, as illustrated with the aid of Figure 4, where three crop choices are available to a farmer. The factor determining differences in rent is the expected number of growing degree days (GDDs).[10] Rents determine the use to which the land is put, with the landowner able to choose, in this illustration, among wheat, corn, and sorghum.

GDDs in a particular region are presumed to increase with global warming. Prior to climate change taking place, suppose heat units were less than G_1. Land earns a rent only if wheat is grown, with attempts to grow maize or sorghum resulting in below normal profits or an outright loss. As GDDs increase beyond G_1, the landowner will first switch from wheat to maize, but, as global warming continues so that the available heat rises beyond G_2, there is too much heat (and probably too little rainfall) so growing sorghum becomes more profitable, as sorghum requires less moisture and can better withstand heat. In Figure 4, A and B represent *intensive* margins of land use – the point where land transfers from one use to another – whereas points α and β represent *extensive* margins (van Kooten and Folmer 2004, pp.38-41). Changes in land use occur at the intensive margins where the rent for one use is driven to zero *if* the cost of the next land use is included as an opportunity cost. The extensive margins occur where the rent-heat functions intersect the horizontal axis – all differential rent associated with the activity is dissipated.

[10] GDD=$\sum_{j=1}^{N}(\bar{T}_j - 5^oC)$, where $\bar{T_j}$ is the average temperature on day *j* and *N* is total days in the growing season.

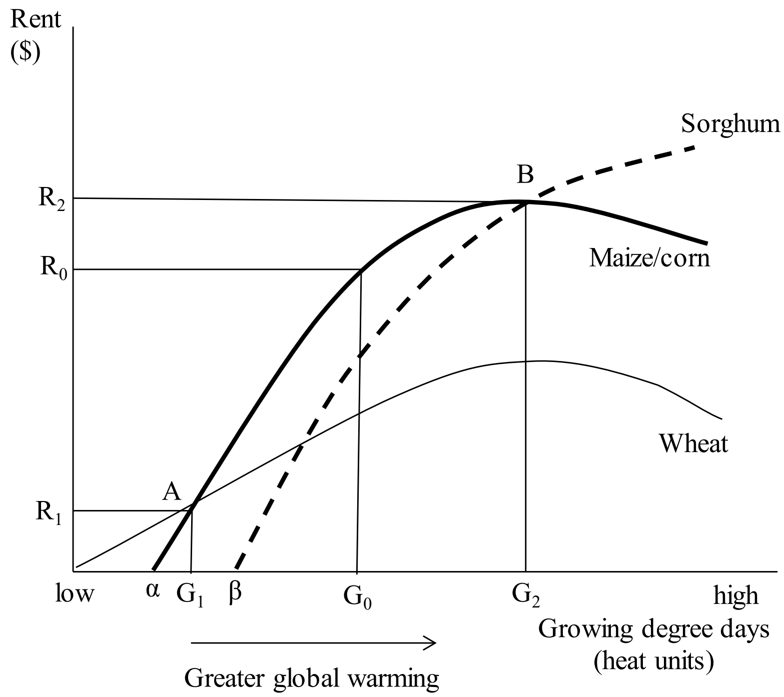

Figure 4: Impact of Changing Heat Availability on Crop Choice

Now assume Figure 4 pertains to a particular parcel of farmland. If available heat is projected to increase from G_1 to G_0, for example, it is the difference between R_0 and R_1 that constitutes a measure of the benefit (in this case) to agriculture of climate change. Conversely, if there were a reduction in heat units (as measured by GDDs) from G_2 to G_0 as a result of global warming, then the difference G_2–G_0 would be a measure of the damages. The statistical approach assumes that landowners will adjust the use of inputs to maximize the rent accruing to the land, choosing the crop that is best suited to the expected number of growing degree days.

Beginning with research by Mendelsohn et al. (1994), land-rent models have become the most widely used approach for determining any economic damage from climate change, mainly because it relies on actual market data. Regressions models are unreliable when attempting to project crop yields or land values outside the range (temperature increases of 0ºC to 5ºC) used to estimate the model parameters. Nonetheless, some commentators argue that, beyond a temperature increase of 5ºC, say, a catastrophe is likely; it is the potential cost associated with a possible catastrophe that is considered to be the only worthwhile cost of climate change to take seriously (see, e.g., Nordhaus and Sztorc 2013, p.11; Pindyck 2013, p.869-870), which is discussed further in the next subsection.

It is difficult to use statistical models estimated for a current period to project how the same land might be used some 50 to 100 years later. Since the same estimated parameters are used to determine the current as well as climate-induced value of farmland, land-rent models do not take into account technological and economic changes that might occur, nor can they be expected to do so. Statistical models do not account for changes in agricultural policies (viz., farm subsidies) and technological advancements in crops due to genetic engineering, say, and equipment, chemicals, and farm management techniques. The land-rent approach also fails to take into account the fertilizer impact of CO_2 (discussed in Appendix B). Despite these flaws, the land-rent method is one of the few statistical approaches that can be used to determine potential damages from global warming, and it is solidly rooted in economic theory.

What are the projected damages (or benefits) in the agricultural sector as based on an analysis of land-use values? Mendelsohn et al. (1994) projected a small increase in U.S. GDP as a result of global warming. Subsequently, Schlenker et al. (2005) argued that the Mendelsohn et al. (1994) model was mis-specified; when account was taken of irrigated areas, the earlier conclusions were reversed. Similarly, based on the land-rent approach, Schlenker et al. (2006) found that climate change would unambiguously impose net costs upon agriculture in dryland regions of the United States, although some dryland areas in the northern U.S. states would gain. The authors examined the deleterious effects of high temperatures (30°C or more) on crop yields (although yields increased over a broad range of higher temperatures). They also believed that "climate change will impose a net economic cost on agriculture in irrigated counties, whether in the form of higher costs for replacement water supply or lower profits due to reduced water supply." Other econometric studies employing mainly U.S. data also concluded that the overall effect of climate change would be negative (e.g., Schlenker and Roberts 2009; Chen et al. 2017; Arunanondchai et al. 2019).

In a study of Canadian agricultural land values, Weber and Hauer (2003) found that agricultural landowners could gain substantially as a result of climate change. They projected average gains in land values of more than 50% in the short term (to 2040) and upwards of 75% or more in the longer term (to 2060).

Mathematical representation of landowner decisions

A second class of models uses economic theory to develop a mathematical representation of land-use allocation decisions (see Appendix A). Upon comparing econometric results with those from mathematical programming (MP) models, we find that the results of Weber and Hauer, as well as those of Schlenker et al. (2006) for the northern U.S., are in line with those reported by Darwin et al. (1995) for Canada. As discussed in Appendix A, Darwin et al. used a land-use model linked to a computable general equilibrium model to estimate the global welfare impacts of climate change as it affects output in the primary sectors. They found that, if landowners were able to adapt their land uses to maximize net returns (as assumed in land-rent analyses), global GDP would increase by 0.2% to 1.2% depending on the particular climate model's projections employed.

Using a similar approach but then to examine past agricultural land-use decisions, Stevenson et al. (2013) found that increases in atmospheric CO_2 led to a fertilization effect that reduced the area needed to produce the globe's food supply. Over the period 1965-2004, this prevented the conversion of some 18-27 million hectares (ha) of forested land into agriculture. Further, they find that, in the absence of crop productivity improvements associated with the Green Revolution, "greenhouse gas emissions would have been 5.2-7.4 Gt higher than observed in 1965-2004."

Based on more recent information about the adverse consequences of global warming on crop yields, Moore et al. (2017) changed the damage function in Richard Tol's FUND integrated assessment model to reflect a greater reduction in crop yields than previously thought. The economic consequences of reduced crop yields are then calculated using the GTAP CGE (see Appendix A). The authors estimate that an agricultural sector benefit of \$2.70 per tonne of CO_2 becomes a cost of \$8.50 per tonne of CO_2, thereby resulting in as much as a doubling of the social cost of carbon (see also Yang et al. 2018). This research exemplifies the direction that research on damages in the agricultural sector has taken: although information is taken from a broad range of agricultural studies (some from studies like those reviewed earlier, others from computer modeling, and yet others based on 'expert opinion'), adverse effects of climate change in the agricultural sector are subsumed with damages from other sectors in the damage equation of an IAM such as DICE.

The majority of studies of damages to the agricultural and forestry sectors are for the United States, Canada and, more recently, Europe. The general conclusion is that the U.S. agricultural sector will likely be harmed by climate change but damages may be minor compared to the size of the sector, while Canada's sector will benefit overall (although some regions could be harmed). In a study of the impacts of global warming on individual countries, William Cline (2007) concluded that there could be gains to global agriculture in the short run, but in the longer run the sector's output will decline. Cline includes the potential CO_2-fertilization benefits that would cause crops and trees to grow faster, which accounts for the short-term benefits of climate change. However, he argues that diminishing returns from CO_2-fertilization along with adverse effects of excessive warming will inevitably lead to declines in crop yields in the longer run.

Auffhammer (2018) makes a similar point as follows: Suppose you have a distribution of crop yields as a function of temperatures. Assume the variance does not change, but the distribution shifts to the right – toward higher temperatures. Then the probability of lower yields associated with higher temperatures, and the potential for catastrophically low yields, increases. Of course, this neglects the role of technological change, planting of different crop and so on that could shift the entire distribution of yields.

Expected damage to agriculture from climate change: Summary

Agriculture is one of the sectors that is expected to be most impacted by climate change. Early estimates of potential climate change damages in agriculture employed crop simulation models and assumed that farmers would continue to plant the same crops and variety of crops with the same methods as those employed prior to the change in climate. Later analyses showed that farmers adjusted to climate possibilities. The damages from potentially higher temperatures were found to be significantly lower, or avoided altogether (e.g., Challinor et al. 2014).

Early Canadian studies by Louise Arthur and her colleagues at the University of Manitoba (Arthur 1988; Arthur and Abizadeh 1988; Mooney and Arthur 1990; Arthur and van Kooten 1992) suggested that, even if farmers only adopted crops suitable to the changed climate, western Canadian farmers could benefit. For the United States, Adams (1989) and Adams et al. (1990) used crop simulation and economic models to conclude that climate change in that country could lead to an overall increase or decrease in wellbeing, but that such changes were generally small. Indeed, results depended on which of several climate models was employed, but the researchers were unambiguous in finding that the distributional impacts of climate change were the largest and most important aspect.

Despite many studies of the potential damages to agriculture from climate change, the subject remains little changed. The vast majority of economic studies have focused on North America and Europe, simply because of data availability. The detailed weather, crop yield, and land value data are only available for the United States and, to a lesser extent, Europe. This limits the use of land-rent regression models. While mathematical representations of land-use, crop-allocation decisions require less data, and can and have been developed for many more regions, the expertise required to build and use such models to analyse the future impact of climate change is still limited. Based on current knowledge, crop yield studies in artificial conditions suggest that crops might be quite resilient to climate change (see Appendix B). Regression models and MP studies suggest that agriculture might benefit from a rise in global mean temperature of a few degrees, but could be greatly harmed beyond this. Further, crop regions in the northern latitudes will benefit from global warming in terms of higher yields and the opportunity to plant more valuable crops, while farmers in the mid latitudes could experience a decline in incomes. What about global food security?

3. Climate Change and Food Security

Does climate change lead to greater food insecurity? This is a difficult question to answer. Food security might be compromised at the regional level, but not at the global level, or it might be compromised at both scales. Again, any analysis of this issue is plagued by uncertainty, with the discussion that follows to be considered suggestive at best.

Increasing concentrations of atmospheric CO_2 can improve agricultural productivity, enabling crops to better utilize nutrients, including water. Higher levels of CO_2 make crops less susceptible to drought. While droughts might increase in some regions of the globe, overall a warmer atmosphere holds more moisture leading to increased rainfall. Nonetheless, there remains a fear that, as temperatures continue to rise with increasing CO_2, the CO_2-fertilization effect will be offset by too much heat – that if the global mean atmospheric temperature rises by 2ºC above that experienced in pre-industrial times, crop yields will decline. Evidence from controlled experiments and information from crop and climate models suggest that crop yields may or may not be adversely affected by higher temperatures (see Appendix B). The majority of scientists believe that at higher temperatures, the adverse effect of heat on crop yields will eventually offset the benefits of CO_2 fertilization. However, the importance of technological change remains an unknown factor.

Brazil is a country that has become an agricultural superpower due to large investment in technology and farmland. As a result, this tropical country has become increasingly competitive with the United States in agricultural export markets. For countries that are vulnerable to climate change, Brazil's experience provides hope that food insecurity can be managed if there exists a political will and proper institutions (including agricultural research stations, extension programs, et cetera). First, one needs to recognize that Brazil is now the world's largest exporter of sugar, coffee, beef, and poultry; the second largest exporter of soybeans; the third largest exporter of corn; and the fourth largest exporter of cotton. It is also the largest producer of sugar and coffee, has the largest commercial cattle herd in the world, and is a leading grain producer as much grain is grown to feed livestock, particularly poultry. Second, can other tropical countries duplicate Brazil's success, or are Brazil's circumstances, political institutions, geography, and climate unique to preclude a similar rise in agricultural productivity? Finally, temperatures in tropical regions are projected to rise more slowly under climate change than temperatures in higher latitudes. What implication would this have for food security? Can Brazil's success be duplicated in other tropical countries?

Consider climate change and food security in the context of crop yields. For high-income countries at least, crop yields have continued to increase over the past several decades, or have stagnated or even declined. Consider trends in yields for four crops – maize, rice, wheat, and fresh vegetables – for selected large crop-producing regions in the developed and developing world. These trends are provided in Figures 5 through 8, respectively. The empirical evidence indicates that crop yields (t/ha) have increased steadily since the 1960s. Average global yields of maize have increased by 2.0% annually over the period 1961-2016, rice by 1.7%, wheat by 2.1%, fresh vegetables by about 1.0%, and those respectively of sorghum and soybeans (not shown in graphs) by 0.9% and 1.6% annually. For each of the four crops considered in the figures, trends in some countries stand out.

Throughout the period 1961-2016, the United States had the highest yields of maize, rice and, particularly, fresh vegetables, where U.S. yields exceeded those of any other region by a factor of four or more (which is why U.S. yields are plotted on a separate axis). For these three crops, European and Chinese yields are significantly greater than those in other countries while lower than those in the United States. When it comes to wheat, however, U.S. yields are close to the global average, and well below those of the European Union and China, and, perhaps surprisingly, Mexico. Wheat yields in those countries have risen strongly over the same period.

Although Canada is a major wheat producing and exporting country, its yields are well below those of the European Union, Mexico, and China (Figure 7). One reason is that Canada's farmers rely more on land inputs, whereas competitors rely more on fertilizer and other chemicals to increase output in response to rising prices. Meanwhile, it is difficult to compare yields of fresh vegetables across jurisdictions without further knowledge about the types of vegetables that are grown and the use of irrigation.

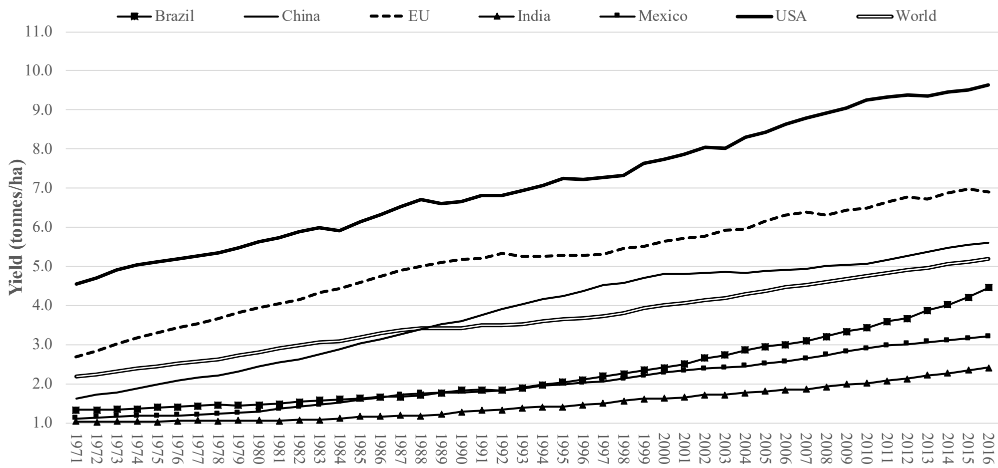

Figure 5: Ten-Year Moving Average of Maize Yields, Selected Countries/Regions, 1970-2016
Source: FAO http://www.fao.org/faostat/en/#data/QC

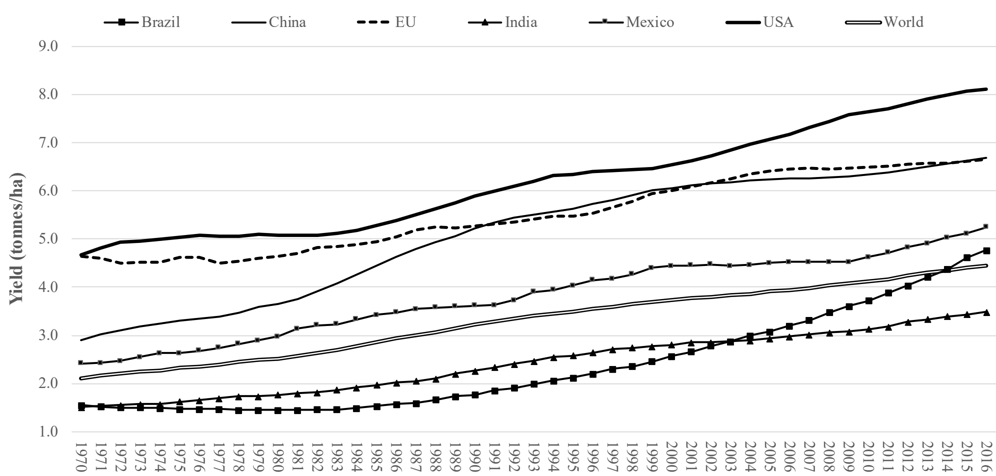

Figure 6: Ten-Year Moving Average of Rice Yields, Selected Countries/Regions, 1970-2016
Source: FAO http://www.fao.org/faostat/en/#data/QC

Although Canada is a major wheat producing and exporting country, its yields are well below those of the European Union, Mexico, and China (Figure 7). One reason is that Canada's farmers rely more on land inputs, whereas competitors rely more on fertilizer and other chemicals to increase output in response to rising prices. Meanwhile, it is difficult to compare yields of fresh vegetables across jurisdictions without further knowledge about the types of vegetables that are grown and the use of irrigation.

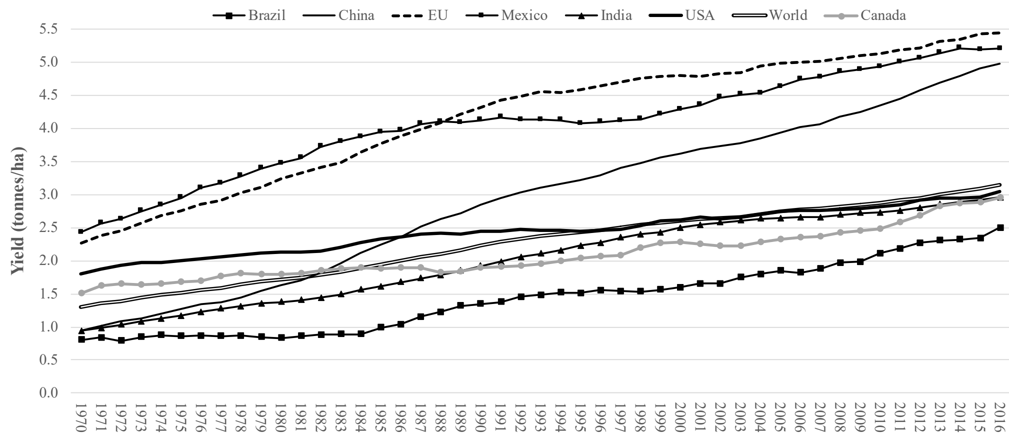

Figure 7: Ten-Year Moving Average of Wheat Yields, Selected Countries/Regions, 1970-2016
Source: FAO http://www.fao.org/faostat/en/#data/QC

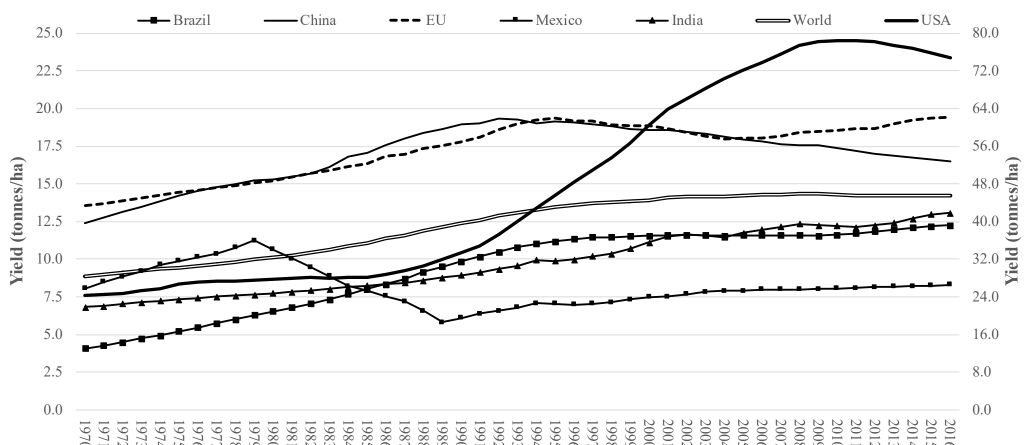

Figure 8: Ten-Year Moving Average of Fresh Vegetable Yields, Selected Countries/Regions, 1970-2016 (Note: U.S. yields are shown on the right vertical axis, the remainder on the left)
Source: FAO http://www.fao.org/faostat/en/#data/QC

In summary, when it comes to historical crop yields, it is difficult to find evidence to suggest that climate change would result in lower yields. Indeed, once adverse weather events are taken into account, which is done using a 10-year moving average of yields, it is easier to argue that technological improvements and, to a lesser degree, rising CO_2 levels (and potentially their interaction) have increased agricultural productivity.

Now consider what might happen with global warming. Agricultural productivity in tropical countries might be under greater threat than in temperate countries. Challinor et al. (2014) conducted a meta-analysis of 1048 observations from 66 studies to determine the separate impacts of adaptation, change in temperature, change in CO_2, and change in precipitation on crop yields in tropical and temperate regions (see also Appendix B). They concluded that, unless farmers adapted to the changed climate conditions, productivity would generally be adversely affected. With adaptation, wheat, maize, and rice yields in temperate regions would increase as a result of higher temperatures, all else remaining constant (ceteris paribus), but production of maize and wheat would be adversely affected by higher temperatures in the tropics. Importantly, however, the analysis showed that, while rice yields in the tropics would be unaffected by temperature increases between 0°C and 3°C, rice yields would increase by 10% or more if temperatures rose by upwards of 5°C, ceteris paribus. Indeed, temperature was the dominant explanatory factor explaining changes in crop yields, with precipitation and CO_2 fertilization playing a minor albeit yield-enhancing role (contributing less than 15% of the overall change in crop yields).

One problem for policy makers is that, whereas models might predict higher crop yields due to greater heat units (partly due to a longer growing season), precipitation is difficult to predict. If there is insufficient precipitation despite more heat for growing crops, agricultural production might well fall. Further, given that crop yields are projected to fall beyond temperature increases of 5°C or more from pre-industrial times, there is no way to determine which would be the case for the world's most important agricultural regions – it is only when the warming outcome occurs that the evidence becomes available.

As noted in section 2, crop yields are likely to continue increasing as the atmospheric concentration of CO_2 rises well above even 1,000 ppm, while temperatures may not be an impediment to yields over a wider range than indicated by climate modelers. Of course, precipitation has a significant role to play, but climate models are less able to project future precipitation than temperature. However, it may be possible to develop new crops using standard breeding techniques or, more likely, genetic engineering that can adapt to climate change (Ebert 2017). In addition, techniques related to the harvesting of water from fog in coastal desert areas,[11] innovative agricultural practices (such as increased use of drones), and new financial instruments (e.g., weather-index based insurance) will help society and farmers adapt to climate change.

In conclusion, it may well be true that unprecedented global warming will lead to large damages as envisioned by climate scientists, but dire warnings that climate change will lead to dangerous reductions in future crop yields and increasing incidence of famines are simply not warranted on the basis of currently available evidence. Overall, there remains uncertainty about the physical science, the validity of future climate projections, and estimates of the economic damages that might be forthcoming; most importantly, the potential for technological change is ignored or downplayed (see Box 2). While economists have thought about scenarios where the probability of damages from global warming are extremely high, the analyses of catastrophic situations is speculative at best – storylines that society needs to consider but not to fear.

[11] For example, see http://news.mit.edu/2014/harvesting-fresh-water-fog [accessed November 29, 2018].

Box 2. Climate Smart Agriculture

There is a great deal of concern that climate change could potentially lead to drastic declines in crop yields and increased famines. What is ignored in such prognostications is the role of technological change. As noted in the text, crop yields have not declined in recent years despite predictions to the contrary. The agricultural sector has seen major technological breakthroughs in the past several decades that have already altered the farming business in a positive way.

In developed countries, satellites coupled with computer technology can be used to determine globally what crops are being grown at any time and their prospective yields. This information aids in the creation of new weather-indexed insurance products that help farmers adapt to climate change (Kramer and Ceballos 2018). Global positioning satellites (GPS) can be used to guide equipment movement, while drones can be used to identify fungal and other pest invasions during the growing season, thereby enabling swift and effective targeting of chemical and fertilizer applications and optimal timing of harvests. New irrigation technologies that rely on swift and timely computer analyses, and water harvesting from early-morning fog (which occurs in some arid regions), are further examples of climate smart farming. These and other farm management technologies improve agricultural financial and environmental outcomes.

The same technologies might someday be employed in the developing countries. Improved technologies reduce spoilage during storage, while mobile telephony enables farmers to determine where and when to sell crops to maximize returns. Better stoves for heating and cooking reduce deforestation and the need for crop residues and manure that then improve soil quality. Higher yield crops currently grown in temperate latitudes are increasingly adapted to tropical conditions where hours of sunlight are shorter but temperatures higher.

The greatest potential of future technological changes will likely come from biology. Plant breeding and genetic engineering will lead to different crops and crop varieties that produce higher yields and are more resilient to weather extremes, such as droughts, and offer protection against pests, fungus, and disease. Likewise, research can be expected to provide chemicals or biological agents that target weeds and insect pests, while being more benign in their environmental impact. The same is true for food technologies that may lead to meat substitutes that will have a smaller imprint on the environment than do livestock.

While it is difficult to predict what the future might hold in store for agriculture, one can be optimistic that technological changes will greatly improve the ability of agricultural producers to adapt to climate change. Only when the scope for technological improvements is ignored might global warming lead to famines and starvation in the future.

4. The Role of Agriculture in Mitigating Climate Change

As a sector, agriculture is the third largest emitter of greenhouse gases after fossil fuel burning for electricity and heat, and transportation. Emissions of methane account for about half of total agricultural emissions, followed by nitrous oxides for 36% and CO_2 for 14%. While emissions from agriculture have been increasing, agricultural activities could contribute to a reduction in GHG emissions. By growing energy crops (viz., corn for ethanol), agriculture can reduce reliance on fossil fuels. Finally, by changing cropping practices, carbon can be stored in soils. These subjects are investigated in the next subsections. However, the contribution that the agricultural sector can make toward mitigation of CO_2 emissions is likely limited.

Although GHG emissions from agriculture have been rising, agricultural output has been increasing at a faster rate. Methane emissions are the result of primarily enteric fermentation, or the digestion of organic materials by livestock, predominantly beef cattle. Nitrous oxide emissions are associated with manure spread on fields as organic matter and as fertilizer. Both sources of GHG emissions are increasing as incomes grow and people demand more animal protein in their diets. Some progress has been made to reduce methane emissions through improved animal feed and capturing animal wastes, using the resultant methane gas and solid matter as fuel for use on and off the farm. More drastic measures include attempts to reduce demand for meat and develop substitute products.

One source of CO_2 emissions is fossil fuel burning associated with the operation of equipment (tractors, trucks, combines, et cetera) and for heating (e.g., reducing moisture levels in grain thereby improving its quality). But the main source of CO_2 emissions is deforestation for the purpose of agriculture. Land-use change may be incentivized, however, by climate change policies. Incentives to produce energy crops raise the price of farmland, which, in turn, causes forestland to be converted to agriculture or, in the tropics, to the production of palm oil, thereby releasing large amounts of CO_2. Governments sometimes devise incentives that encourage such changes in land use because landowners have lobbied or provided support for policies to promote biofuels. The point here is simply that one has to be careful in designing policies that affect land uses. For example, the European Union has incentivized the use of wood pellets (biomass energy) for power production, which has actually increased rather than decreased the degradation of old forests in eastern Europe and the southern United States. If crop yields decline (as some predict) and population continues to grow, it will be nearly impossible to shift farmland into forestry without subsidies; indeed, if food prices increase, the economics are likely to result in shifting land out of forestry into agriculture, which makes the production of electricity from biomass more expensive (see Johnston and van Kooten 2016). In essence, then, ethanol subsidies would partially offset subsidies to plant trees.

Rather than reducing emissions from agriculture, it is possible to remove carbon dioxide from the atmosphere and store it as soil carbon. This can be done by switching from conventional tillage (CT) to conservation tillage or zero-tillage, simply referred to as no-till (NT) agriculture (Benbrook 2012: Mortensen et al. 2012; Livingston et al. 2015). Estimates of carbon uptake by soils in the northern Great Plains as a result of going from CT to NT vary from 100 to 500 kg C/ha per year (West and Marland 2001). To this must be added the reduced emissions from employing less tillage operations, which saves some 30 kg C/ha per year. Assuming farmers do not go back to CT, the total savings in shifting from CT to NT will depend on the rate used to weight the future stream of carbon fluxes – that is, the rate used to discount physical carbon (see van Kooten 2018). This is provided in Table 2, where carbon has been converted to CO_2 (1 tC = 3.667 tCO_2). Total carbon uptake due to agricultural operations varies from about 14.7 tCO_2/ha to at most 45.8 tCO_2/ha. The amount of carbon that can potentially be prevented from entering the atmosphere via a dramatic change in agricultural practices is small compared to the carbon sequestered by forests.

Table 2: Expected Annual and Total Carbon Savings from Adopting Zero-Tillage Practices in Canada's Prairie Provinces (tonnes of CO_2 per ha)

Assumed annual carbon uptake in soil organic matter during first 20 years after adoption	2% Discount rate		4% Discount rate	
	Total	Annual	Total	Annual
200	21.8	0.4	15.3	0.6
300	29.8	0.6	21.5	0.8
400	37.9	0.8	27.7	1.1
500	45.9	0.9	33.9	1.4

Source: Authors' calculations using data from van Kooten and Folmer (2004)

Continuous cropping and NT may increase production costs (because more chemical inputs and/or greater investments in specialized equipment are required), but reduce yields (Lerohl and van Kooten 1995). However, high rates of adoption of NT indicate that the savings in tillage operations exceed the costs associated with increased use of chemicals and lower yields, if any. As a result, NT may be an inexpensive means for sequestering carbon. McCarl and Schneider (2000, pp.150-151) point out that, by reducing the intensity of tillage, soil organic matter will increase, resulting in an increase in carbon storage plus greater retention of moisture, which could result in a reduced need for irrigation. However, reduced tillage also has negative environmental impacts associated with greater use of pesticides for control of weeds, fungus, and insects. This may have negative spillover effects on ecological systems and water quality, which is why the use of some chemicals, especially inexpensive glyphosate, may potentially be banned (Marks 2018), thereby threatening carbon stored in soil organic matter.

Manley et al. (2005) conducted two meta-regression analyses to determine the costs of sequestering carbon using NT. First, 52 studies examining the costs of conventional- versus zero-tillage (CT vs NT) were compared. The studies found that CT yielded higher net returns, except for the U.S. corn belt (corn and other crops) and Canadian prairies (wheat). A meta-regression analysis based on 24 studies was then used to determine the carbon-uptake benefits of employing NT. The results depended on the depth of measurement of the soil, because with CT organic matter is plowed under. Thus, soil organic carbon content is higher under NT than under CT if measurement is confined to the plow layer, but it is less under NT if measurements are made to a greater depth. Manley et al. (2005) also estimated the costs of sequestering carbon through changes in agricultural practices. These estimates are provided in Table 3 for zero- or no-till agriculture. The results indicate that costs of removing CO_2 from the atmosphere and storing it as soil carbon by changing tillage practices are unacceptably high, ranging from about \$47/tCO_2 to \$120/tCO_2.

Table 3: Net Costs of Carbon Sequestered under No-till Agriculture[a]

Region	Crop	Cost per tC at 25 cm	Cost per tC at 50 cm
Great Plains	Wheat	$95.48	***
	Other crop	$85.23	$120.15
Corn Belt	Wheat	$36.06	$47.28
	Other crop	$48.60	$49.95

[a] Costs in 2001 US dollars for crops harvested in 1986 (the sample mean) after 20 years of NT.
*** indicates that under those conditions, NT is not expected to result in net carbon sequestration compared to CT.
Source: Adapted from Manley et al. (2005).

Finally, the agricultural sector can aid in mitigating CO_2 emissions by producing energy crops that substitute for fossil fuels in transportation or production of electricity. Sugar beets, sugar cane, corn (maize), and sorghum can be used to produce ethanol, while soybeans and canola (rapeseed) are used to produce biodiesel (see Chapter 12). Farmland can also be used to produce hybrid poplar, with trees harvested within a short period (<10 years) and used as biomass for producing electricity; similarly, crop residues can be used to produce electricity in lieu of fossil fuels. The problem is that, when farmland is diverted to the production of energy crops, land and food prices increase, which can lead to deforestation (Searchinger et al. 2008). The rise in food prices harms the poorest in global society the most. Further, production of ethanol from corn (rather than sugar cane) and biodiesel from canola might actually increase rather than decrease GHG emissions, mainly because farmers apply chemicals to produce energy crops, just as they do with food crops, but the production and application of chemicals releases GHGs (Crutzen et al. 2008). The use of crop residues (or even wood residues from logging) reduces soil organic matter and the amount of carbon stored in the ecosystem. It also lowers nutrients available to the next crop, thereby requiring their replacement by fertilizers and other chemicals from offsite.

5. Is Bioenergy Carbon Neutral?

At the margin between agriculture and forestry, landowners transfer land from one use to the other depending on the expected returns to land (i.e., expected land rents). Climate policies affect such returns. For example, EU climate policies have increased the need for wood biomass in particular to achieve renewable energy targets (see Box 3). While capacity investments in wind and solar are expected to continue, their unreliability eventually limits their role – something known as the intermittency problem (energy output fluctuates with changes in wind and sunshine). Thus, investments in such intermittent capacity do not necessarily lead to greater relative growth in actual power consumption (van Kooten 2016; van Kooten et al. 2016). Countries increasingly look to one of the few sources of renewable energy, outside of hydropower, that can provide continuous reliable power, namely, biomass. Biomass energy is considered to be 'carbon neutral' – CO_2 emitted to the atmosphere is subsequently removed by terrestrial sinks, namely, growing forests (and other vegetation) and oceans. The question is: How carbon neutral is bioenergy?

Box 3. The Challenge of Renewable Energy

To meet their renewable energy goals, developed countries have invested heavily in wind and solar energy. Despite this, the proportion of total energy from these sources remains small. In 2016, 85.3% of total energy consumption in the United States came from fossil fuels (38.0% from petroleum, 31.5% from natural gas, and 15.8% from coal), 8.4% from nuclear power, 2.6% from hydro, and 3.7% from other renewables (2.3% from wind, 0.8% from biomass, and 0.6% from solar). In the same year, 75.3% of total energy consumption in the European Union came from fossil fuels (37.3% from oil, 23.5% natural gas, and 14.5% coal), with 11.6%, 4.8%, 4.1%, 2.6%, and 1.5% coming from nuclear, hydro, wind, biomass, and solar sources, respectively. The United States relies more on natural gas because of its low price due to fracking technology that is opposed in Europe, where gas prices are much higher. Ambitious targets and lucrative incentives for renewables in Europe have led to greater investment in wind, biomass, and solar energy. Yet fossil fuels dominate.

Europe has come further than any other jurisdiction in adopting renewables. In its 2009 Renewable Energy Directive, it adopted an aggressive '20-20-20' target to be met by 2020 – a minimum 20% reduction in CO_2 emissions from 1990 levels, a minimum 20% share of renewables in energy production, and a 20% improvement in energy efficiency. As a result, bioenergy was expected to more than double from 5.4% of final energy consumption in 2009 to 12.0% by 2020, with wood biomass contributing 36% of the 2020 target (Beurskens and Hekkenberg 2011). A more ambitious target – to reduce CO_2 emissions by at least 40% by 2030 compared to 1990 – was adopted at the Paris Conference. Thus, renewable energy is expected to account for 27% of the European Union's total energy production, with more than half coming from biomass sources, which are required because of their reliability compared to wind and solar sources.

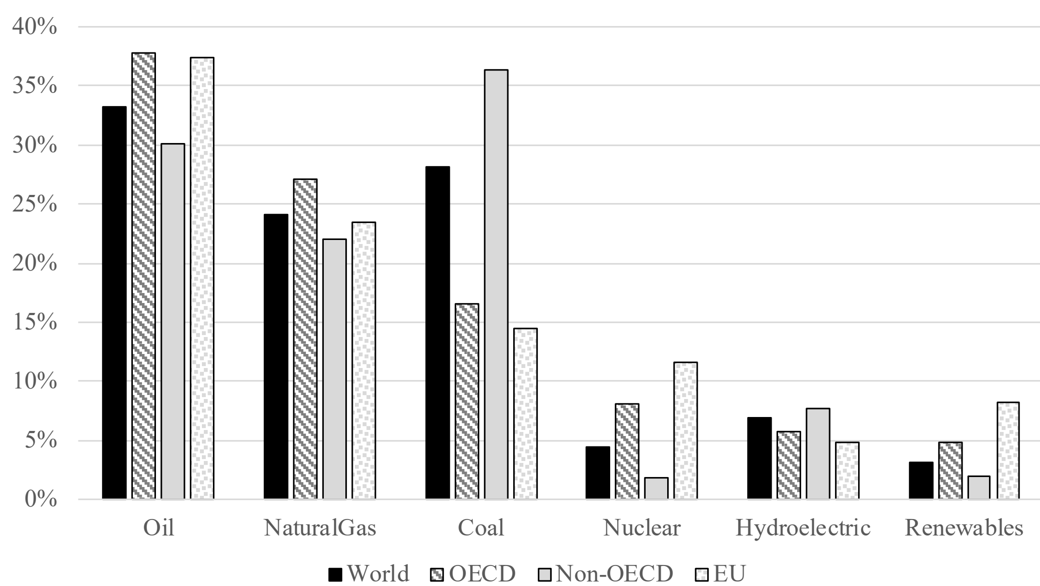

Figure 9: Energy Consumption by Fuel Type, Selected Regions, 2016 (Percentage)
Source: BP Statistical Review of World Energy June 2017

Several issues need to be considered. First, the harvest, collection, transportation, and processing of wood and agricultural residuals releases CO_2. Compared to the fossil fuels they replace, more CO_2 is released per unit of heat produced in these activities than in the production and use of fossil fuels. The main reason relates to the size of the landscape required to produce timber. Second, as noted above, fertilizers and chemicals are used to grow energy crops (landowners even use fertilizers when growing short-rotation trees meant for burning), and their production and spread releases greenhouse gases. Finally, the release of CO_2 to the atmosphere when biomass is burned is a concern because, in the case of forest biomass, the carbon might otherwise have been stored for a long period in the living ecosystem (growing trees) or in post-harvest wood products or, in the case of crops, carbon stored in the consumer's body.

The other problem relates to the timing of CO_2 fluxes. When biomass is burned to produce electricity, whether in the form of wood biomass or biofuels, more CO_2 is released to the atmosphere than if that same energy were produced using coal, natural gas, or petroleum – bioenergy produces less heat per unit of mass than fossil fuels. The only difference is that the CO_2 released by burning a bioenergy crop can be recovered from the atmosphere by vegetation, growing new trees, or the ocean, but it takes time to recover this CO_2 (Johnston and van Kooten 2015; van Kooten and Johnston 2016). The recovery of carbon from the atmosphere is much shorter for energy crops and logging residues, for example, compared to the use of whole trees (which would, alternatively, be made into lumber thereby storing carbon).

The importance of the timing of carbon fluxes is illustrated with the aid of Figure 10. Suppose that electricity is generated by a coal-fired power plant. In that case, an amount 0F of CO_2 enters the atmosphere and remains there indefinitely as indicated by the horizontal dashed line. Suppose instead that the power was generated by burning wood biomass rather than coal. In that case, an amount $0K > 0F$ of CO_2 enters the atmosphere at time 0, thereby creating a carbon deficit equal to FK. If trees are planted at $t=0$, the trees will begin to remove CO_2 from the atmosphere and store it in wood biomass, with the cumulative amount of CO_2 removed determined by the growth function as indicated by the S-shaped curve in Figure 10. At $t=M$, the amount of CO_2 left in the atmosphere as a result of burning wood biomass at $t=0$ equals the amount that would have been in the atmosphere if coal had been burned instead. Then, at $t=N$, the CO_2 that had been released by burning biomass will have been completely removed. Between $t=M$ and $t=N$, the biomass option has resulted in a carbon dividend or benefit relative to the coal option. This is generally what is meant when biomass burning is declared to be carbon neutral.

When it comes to biomass energy, the time that incremental carbon is in the atmosphere may be on the order of decades, in which case it contributes to climate forcing. Thus, if there is some urgency to remove CO_2 from the atmosphere to avoid such climate forcing, the timing of emissions and removals of carbon are important, with current emissions of CO_2 and removals from the atmosphere by sinks more important than later ones. This implies that carbon fluxes need to be weighted as to when they occur, with future fluxes discounted relative to current ones.

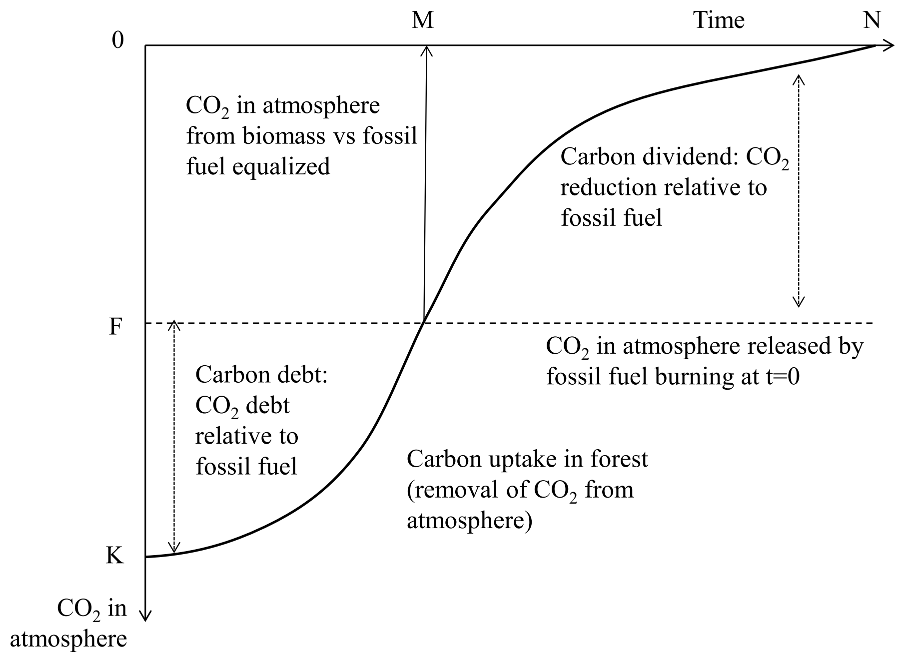

Figure 10: Carbon Flux Profile for Biomass Energy Versus Business-As-Usual Fossil Fuel Energy [Source: Johnston and van Kooten (2015)]

The rate used to weight or discount future carbon fluxes can be used in the policy arena to put into practice the urgency of the need to address climate change. Clearly, if global warming is not considered a problem, the economist might use a zero discount rate, in which case it really does not matter if biomass growth removes CO_2 from the atmosphere today, 50 years, or even thousands or millions of years from now – it only matters that the CO_2 is eventually removed. In that case, coal and biomass are on a similar footing and, since coal is more energy efficient, it would be preferred to biomass (to avoid the carbon debt given by FK in Figure 10).

Suppose, on the other hand, that global warming is already widespread and consequential and that the once distant concern is now a pressing one as future climate change is largely determined by today's choices regarding fossil fuel use. Then we want to weight current reductions in emissions and removals of CO_2 from the atmosphere much higher than those in future years. This is the same as discounting future uptake of CO_2, with higher discount rates suggesting greater urgency in dealing with global warming. Figure 11 depicts such urgency, but for a level of urgency where discount rates are sufficiently high that burning of biomass for energy never leads to carbon neutrality. Indeed, if one were to accept that climate change is a more urgent matter (a relatively high discount rate), substituting biomass for fossil fuels may actually lead to a net increase in atmospheric CO_2 emissions, which can occur when carbon fluxes are discounted at rates as low as 2.5% (Johnston and van Kooten 2015, p.190). In Figure 11, forest carbon uptake is discounted to such an extent that carbon uptake in the more distant future is of little value today. As a result, the discounted future uptake of CO_2 from the atmosphere (regardless of the sink) is too small to offset the additional increase in CO_2 emissions (the carbon debt) when biomass substitutes for fossil fuels in power production.

To address the economics of mitigating climate change through land-use activities requires a systems-oriented approach that assesses various carbon fluxes over time, as well as the opportunity costs of options not chosen (or perhaps not even considered). How would the economist balance costs of climate change mitigation against potential benefits, even if these are not known with certainty? What are the obstacles from a policy perspective?

First, prices and opportunity costs are considerations of importance to economists. If coal is replaced by biomass in the production of electricity, the price of coal will inevitably fall, thereby causing a decision maker elsewhere to increase the capacity of coal-fired power plants. For example, if coal is no longer used to generate electricity in the United States or the United Kingdom, its price will fall; as a result, India might expand its production of electricity using coal. We already see this in Japan and Germany, where decisions to eliminate or reduce reliance on nuclear power have led to greater use of coal generation because coal provides reliable generating capacity at a lower cost than natural gas (as natural gas prices are higher in these countries than in North America). This represents a leakage associated with bioenergy that needs to be taken into account.

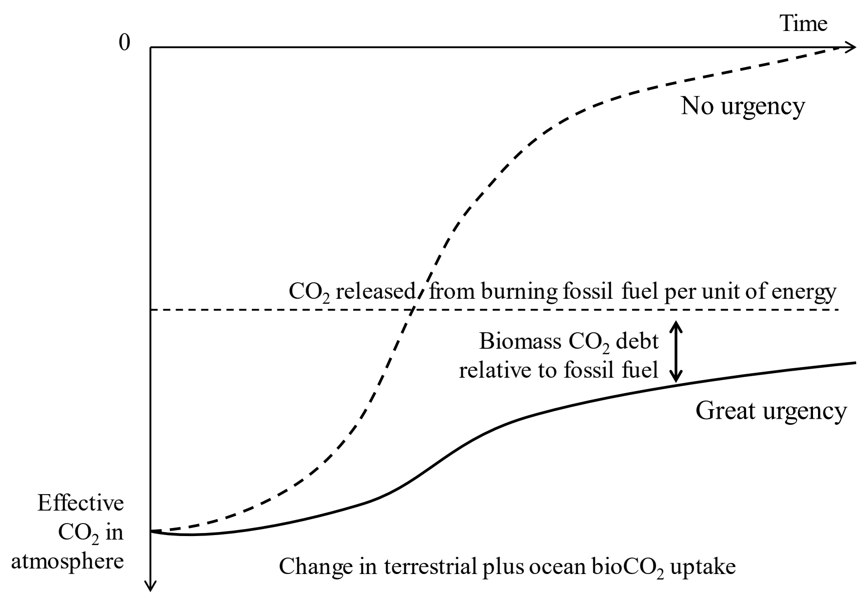

Figure 11: Carbon Flux Associated with Fossil Fuel and Biomass Energy Production over Time: Comparing Lesser and Greater Urgency to Address Climate Change

Second, the largest impacts of using bioenergy relate to land-use changes. Because land is the most important input into the production of bioenergy, incentives to produce energy crops distort land use by converting cropland from food production into bioenergy crops, including wood biomass (viz., fast-growing hybrid poplar plantations), and thereby raising food prices. It is likely that CO_2 emissions are increased rather than reduced as a result of distorting land use, especially once increased use of chemicals (especially fertilizer) is included, while technologies to produce electricity from wood pellets (or liquid fuels from ethanol) get locked in.

Third, with the exception of the U.S. South and a few other places where plantation forests and private industrial ownership dominate, and where land shifts more easily between forestry and other uses, the opportunity costs of producing energy products can be high. In most circumstances, bioenergy is the marginal demander of fiber so that any factor that causes the price of non-energy products, which require wood or plant fiber as an input, to increase could cause bioenergy processors to drop out of the market. Only direct subsidies can offset uncertainty regarding prices of products that compete for fiber, enabling producers of bioenergy to remain competitive.

Finally, policies that incentivize production of bioenergy have international consequences, and it is necessary to examine the economic impacts of renewable energy policies in an international context. For example, the diversion of cropland to the production of energy crops has increased food prices. While fuelwood is used principally in developing countries for subsistence, the recent rise in bioenergy demand is a rich-country phenomenon that is currently met by residuals from the manufacture of wood products, much of which is converted to wood pellets for generating electricity. Research that takes this into account finds that prices of lumber decline because more logs are harvested for lumber as sawmill residues have higher value. Prices of products that compete with pellets increase because the prices of residues are higher and less residues are directed at these products, reducing their global supply (Johnston and van Kooten 2016).

Overall, one has to be careful in promoting energy crops. The unexpected and unintentional consequences often hurt those in poor countries the most. Given that concern for citizens of developing countries is a primary reason for pursuing climate mitigation activities, it is important to be mindful to avoid mitigation policies that do them more harm than good.

6. Conclusions

An important question regarding climate change that has yet to be satisfactorily answered pertains to the primary sectors. There appears to be consensus that climate change will have a negative effect on agriculture – that crop yields will decline. As a result, forestlands and wildlife habitat are also expected to decrease as well because forests will be converted to crop production and/or grazing area for livestock, unless subsidies for biomass substitution of fossil fuels in the generation of electricity prevent this. These conclusions are fraught with uncertainty, partly because they ignore the potential for increased crop and timber yields due to a CO_2-fertilization effect, but primarily because it neglects technological improvements related to machinery and management methods, including greater use of irrigation and financial instruments, such as weather-indexed insurance, that protect farmers against harmful vagaries in temperatures and precipitation. In addition, investments in crop breeding (including genetic engineering) could lead to tree and crop varieties that withstand drought; grow better in a more concentrated CO_2 atmosphere; and protect against pests, diseases, and even wildfires.

What is most surprising is that policy makers appear more confident that technological advances in wind turbines, solar photovoltaics, and batteries will take place than that technical changes should come in the primary sectors. The main difference is that technological improvements in agriculture are related to adaptation, whereas those in the energy sector are more oriented towards the mitigation of climate change. It is unclear why advances in one field are more likely than those in another, nor why government should promote the one and neglect the other.

When it comes to agriculture, one wonders why climate change mitigation policies that are questionable in terms of their ability to forestall global warming (e.g., subsidies to biofuels and wood biomass power generation) are preferred to 'adaptation' policies, such as genetic engineering, water harvesting, new management methods, and financial innovations that would ensure adequate food supplies in the future. The reasons surely have to do with institutions and governance, and which groups are better able to lobby for their preferred solutions. It is all about who can capture the most government largesse at the expense of taxpayers and consumers.

It is also unclear why policies are implemented to encourage planting of energy crops for transportation (ethanol, biodiesel) and use of biomass for generating electricity. Both promote environmental damage by bringing wild spaces into commercial production (expanding cultivation at the extensive margin) and deepening crop production through greater use of chemicals at the intensive margin. These policies increase land prices and divert land away from growing food toward energy production, thereby increasing food costs that harm the least well off in the global society. Yet, these policies do very little if anything to reduce the concentration of CO_2 in the atmosphere, and may even increase it.

Incentives to increase production of energy crops has one major benefit: it reduces the costs to the Treasury of farm program payments because prices are higher. Once these added benefits are capitalized in land values, however, the farm sector will again clamor for agricultural programs that protect it from production and price shocks.

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APPENDIX A: Models Employ in Evaluating the Economics of Climate Change

Economists employ a variety of different models to study the economics of climate change. Global scale models inform national-level policy formation, but generally provide insufficient detail to guide policy specific to a particular sector, such as agriculture. Because such models integrate carbon-climate modules into an economic growth model, they are generally referred to as integrated assessment models (IAMs). To obtain sector specific and/or input specific (viz., land) detail requires the use of regional-level farm management models, or land-use models that examine the allocation of land across crops and between agriculture and forestry. These tend to be mathematical programming (MP) models, which, like IAMs, tend to be normative in nature although rooted in economic theory and able to provide useful insights. Integrated assessment and MP models are discussed in the next subsections, followed by regression models.

Integrated Assessment Models

Economists use integrated assessment models (IAMs) to investigate the economic impact of projected climate change at a regional and global level. Two of the most well-known models are Nobel laureate William Nordhaus' DICE model (Nordhaus 2013) and Richard Tol's FUND model (Tol 2014), both of which are open source (FUND at http://www.fund-model.org/source-code and DICE at https://sites.google.com/site/williamdnordhaus/dice-rice). The objective in these models is to maximize the present value of the utility that people get from consumption, subject to various economic, biophysical and climate constraints. Since utility from consumption accrues to people over a period of 100 or more years, the issue is an intergenerational one and sensitive to the choice of discount rate. IAMs link a carbon-climate component to a damage function that then affects the economy. Damages are a function of temperature; they reduce GDP and require society to make investments to mitigate CO_2 emissions and to adapt to the higher temperatures. In the DICE model (version 2016R2-083017), the equation for damages is $D_t = \text{GDP}_t \times (a\, \overline{T_t} + b\, \overline{T_t}^c)$, where D_t and GDP_t are damages and gross domestic product at time t; a, b , and c are (somewhat arbitrary) parameters; and $\overline{T_t}$ is the mean average global temperature at time t.

While DICE and FUND provide estimates of the social cost of carbon that policy makers use to guide decisions about carbon taxes, such IAMs have been criticized by both economists and climate scientists. For example, Robert Pindyck (2013, 2017) finds the models to be too ad hoc, with outcomes highly sensitive to assumed parameter values. Nicholas Lewis (2018) finds that the parameterization of the carbon-climate component of the DICE model, in particular, is faulty (see also Lewis and Curry 2015). Despite such criticism, IAMs offer one of the only ways that economists can provide policy advice that is informed by the findings of the climate models and the Shared Socioeconomic Pathways (SSPs), or storylines, that are used to determine future CO_2 emissions; see https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about (Riahi et al. 2017).

Other Mathematical Programming Models

Mathematical programming (MP) models of the agricultural and/or forest sectors are similar to IAMs as they both seek to optimize an economic objective function subject to biophysical, political, and economic constraints. The main differences relate primarily to detail – MP models are detailed sector-level models that initially replicate observed crop allocations, input usage, land uses, or other primary sector activities. Models are then used to investigate the impacts of exogenous price shocks, introduction of a carbon tax, changes in crop/livestock insurance schemes, entry of new crops or crop varieties (e.g., resulting from genetic engineering), et cetera. MP models seek to optimize gross margins (gross returns minus certain variable costs); land value; the utility of a representative landowner; or some other relevant economic variable subject to various economic, social, climate, biophysical, and technical constraints. The constraints represent the crop production technology, but somewhere (usually in the production constraints) climate factors are a driver. Parameters in these models are often based on information from other studies. Since MP models can focus solely on agriculture or land use, they can provide detailed information about how climate change affects the agricultural sector. To determine the costs (or benefits) associated with climate change, the calibrated model is solved with the current climate conditions, and subsequently re-solved with the projected future climate conditions. Differences between the base-case objective function and the future scenario (or counter factual) constitute an estimate of the costs or benefits of climate change.

Most numerical constrained optimization models are static, while others are dynamic in the sense that current activities (the land uses chosen today) affect the state of nature in the next period (future possibilities), and thus the choices one can make in the future. This is the idea behind integrated assessment models. Most models of land use in agriculture and forestry are static, although the Forest and Agricultural Sector Optimization Model (FASOM) is an exception (Adams et al. 1995). It optimizes the discounted sum of producers' and consumers' surpluses across forestry and agriculture, determines optimal harvest times of commercial timber, permits reallocation of land between the agricultural and forest sectors over time, and takes into account carbon uptake and release. To keep things manageable, it employs a 10-year time step. The impact of climate change is not modeled, per se, as FASOM is primarily used for policy to determine how carbon penalties and subsidies might affect the allocation of land use within and between the two primary sectors – climate change is exogenous in these models.

One variant of static numerical optimization models is the computable general equilibrium model (CGE). A CGE model maximizes a social welfare function subject to equality constraints. Each sector in an economy is somehow represented in the constraint set (even if subsumed within a larger sector) and sometimes in the objective function. The extent to which sector detail is modeled depends on the question to be addressed (purpose of the study) and the extent to which detailed macroeconomic level data are available. Early work employing CGE models in agriculture was done at the Economic Research Service of the U.S. Department of Agriculture (Darwin et al. 1995; Schimmelpfenning et al. 1996). Stevenson et al. (2013) linked a CGE model and a global, spatially-explicit database on land use to investigate the relationship between CO_2, plants and climate – the GTAP-AEZ (Global Trade Analysis Project Agro-Ecological Zone), multi-commodity, multi-regional CGE and agro-ecological zone database.

Regression Models

Observed land values reflect the fact that land rents diverge as a result of different growing conditions, soil characteristics, nearness to shipping points, and so on. Assuming that agricultural producers face the same output prices, a regression model estimates farmland values as a function of one or more climate variables (e.g., growing degree days, temperatures at various times during the growing season) and various control variables (soil quality, latitude, nearness to an urban area or population density, nearby open spaces, presence of irrigation, et cetera). The land-rent regression model has the following general functional form (e.g., Schlenker and Roberts 2009):

$$z_{it} = \hat{a}_{1,it}\,\Delta h_{1,it} + \hat{a}_{2,it}\,\Delta h_{2,it} + \ldots + \hat{a}_{n,it}\,\Delta h_{n,it} + \hat{b}_{1,it}\,k_{1,it} + \hat{b}_{2,it}\,k_{2,it} + \ldots + \hat{b}_{m,it}\,k_{m,it} + \varepsilon_{it},$$

where z_{it} is the dependent variable. The dependent variable might consist of actual sales data, yield data (which is multiplied by price to obtain value), assessed values (used for tax purposes), or even self-reported land values (e.g., value of land in crop *i* in year *t*).

The explanatory variables on the right-hand side of the above equation are heat units *h* and control variables *k*. Heat units are measured as the amount of time (say, hours) during the crop-growing season in year *t* that crop *i* is exposed to temperatures that fall within a small interval *j* denoted $\Delta h_{j,it}$. There are *n* such *j* intervals, where the initial *j* interval, Δh_1, might be the number of hours that the crop is exposed to temperatures <1ºC; the second interval, Δh_2, would be the hours the crop is exposed to temperatures from 1ºC to 2ºC; and so on. The control variables might include county-level precipitation, longitude and latitude, distance to a city, et cetera. An important variable such as precipitation may be ignored in such models because rainfall can vary greatly even between neighboring farms, so instrumental variables such as average regional precipitation or a drought index might be used instead. Finally, ε_{it} represents the error term, which is often assumed to be normally distributed.

Once the parameters of the model ($a_1, \ldots, a_n, b_1, \ldots, b_m$) are estimated, as indicated by the hats (^) on the parameters (in which case the ε_{it} should not really be shown), it is possible to forecast the impact of changes in the Δh_j on the dependent variable. The changes in Δh_j are derived from climate forecasts that provide the future pattern of temperatures. If future climate affects one of the *k* variables, it too will need to be changed to derive a forecast of z_i.

As an example, assume the dependent variable in the above equation is farmland value. Then, once the model parameters have been estimated for a sample of farms, the results are used first to predict the farmland values across an entire study region or country. Then the climate variables are changed to reflect the projected change in climate, with the same model parameters now used to predict farmland values for that region or country under global warming. The model implicitly assumes that, if landowners face different climate conditions, they will choose the agricultural land use (crop and technique) that maximizes their net returns. The differences between farmland values in the current climate state and the projected future climate regime constitute the costs (if overall farmland values fall) or benefits (if values rise) of climate change.

There is no reason to suppose that the estimated parameters will continue to hold under a changed climate regime, however. They are unlikely to hold, for example, if growing conditions under a future climate regime are outside the observed range of values used to estimate the model. Model results might hold for temperature increases of 0ºC to 5.0ºC, but not for projections that fall outside the range of data used to estimate the model parameters – such projections are simply unreliable. Likewise, the estimated parameters may no longer apply if technology has changed over time.

APPENDIX B: Effect of Climate Change on Plants and Crops

An increase in average global temperatures does not affect all crops in the same way, nor does it impact different crop regions in the same way. At the region level, greater humidity and precipitation could be offset by the negative impacts of higher temperatures. Although higher CO_2 in the atmosphere makes plants more drought tolerable, there are limits; crops simply do better in higher temperatures if they also have adequate water.

The most prevalent food crops are C3 plants, which include wheat, rice, barley, oats, many vegetables, and even important tree crops (e.g., apples). C3 crops are expected to do better under projected climate change than C4 crops, the primary ones of which are maize, sorghum, and sugar cane – crops that are also best suited to produce biofuels (Arunanondchai et al. 2019). Yet, Xie et al. (2018) found that maize yields increased by an average of 27% when the CO_2 concentration of the atmosphere was increased by 300 ppm over the ambient level (400 ppm).

There are proportionally more C4 plants among perennial weeds, which implies that they do less well under climate change than C3 plants; for example, C3 weeds would develop herbicide resistance more easily than C4 weeds as CO_2 increases. As an adaptation strategy to greater weed infestations (if any), genetic engineering can be used to increase the ability of crops to compete with weeds, whereas biological and chemical research can lead to improved herbicides and other agronomic practices for combatting weeds. Since crops are mainly C3 and many weeds are C4, C3 crops might outcompete weeds for valuable nutrients as CO_2 levels rise, with genetic engineering potentially able to provide food crops with an additional advantage over weeds. While keeping these adaptation options open, there is evidence that crop yields will increase as atmospheric CO_2 levels and temperatures increase.

Before considering the effect of climate change on crop yields, it is important to note that too little atmospheric CO_2 could lead to starvation: photosynthesis would shut down if the atmospheric concentration of CO_2 fell to some 150 to 200 ppm. As the concentration of atmospheric CO_2 increases, crop production (yield and biomass) can be expected to increase. Indeed, evidence indicates that the 20th Century increase in atmospheric CO_2 has contributed to about a 16% increase in cereal crop yields (Idso 2001), and may have been responsible for upwards of one-fifth of the yield increases associated with the Green Revolution (Stevenson et al. 2013; Idso et al. 2014). Levitt and Dubner (2009, p.185) indicate that there could be a 70% increase in plant growth with a double CO_2 atmosphere. Clearly, crop yields are positively correlated with CO_2 levels, which explains why Dutch farmers will grow crops in greenhouses with an atmosphere of 1,000 ppm CO_2 (Idso 2001) and hydroponic operations often run at 1,400 ppm (Levitt and Dubner 2009, p.185).

What is the implication for the future? This is both unclear and controversial. One can find numerous studies that conclude that crop yields will increase with global warming because higher CO_2 reduces leaf stomatal pores that take in CO_2 and release water vapor (Idso 2001), enabling plants to better withstand drought, higher temperatures, and even noxious air pollutants (e.g., Morgan et al. 2011). A number of studies have linked higher levels of atmospheric CO_2 to increased crop yields even if precipitation is lower (e.g., Long 1991; Bettarini et al. 1998; Gifford 2004; Long et al. 2004; Goklany 2015). Andresen et al. (2018) attributed rising CO_2 between 2006 and 2014 to a 15% increase in biomass productivity in European pasturelands. Prakash et al. (2017) found that wheat yields increased by 44% to 52% (depending on variety) when CO_2 concentrations went from 335 ppm to 477 ppm, while the same increase in CO_2 accompanied by a 1°C increase in the average growing season temperature still resulted in an 8% to 38% increase in yields. Pandey et al. (2018) found that biomass in wheat increased by 73% to 145% in going from 330 ppm to 700 ppm CO_2, despite limited phosphorous in both situations. Earlier studies by Wittwer (1995) found that yields of rice, wheat, barley, oats, and rye could increase by upwards of 64%; potatoes and sweet potatoes by as much as 75%; and legumes (including peas, beans, and soybeans) by 46% at higher levels of CO_2. Indeed, "results from 3,586 separate experimental conditions conducted on 549 plant species reveal nearly all plants will experience increases in dry weight or biomass in response to atmospheric CO_2 enrichment" (Idso et al. 2014, p.13).

In addition to yields, other factors are also important. In a meta-analysis of 57 studies that examined the effect of enriched CO_2 growing conditions on the nutritional value of vegetables, Dong et al. (2018) found that plant nutritional enhancements outweighed any CO_2-induced, plant nutritional declines. Evidence also indicates that there is no CO_2-induced change in the relationship between a predator-herbivore and prey-plant (Boullis et al. 2018).

The website www.co2science.org provides an inventory of studies that find positive impacts of global warming on crop production, along with critiques of those that find the opposite. In contrast, the Intergovernmental Panel on Climate Change (IPCC) provides summaries of studies that find an overall reduction in crop yields. The IPCC's Fifth Assessment Report (2014) reviewed 782 studies, finding an overall median reduction in crop yields of 4.8% and average change of −5.9%; indeed, "the grand mean of the five [Assessment Reports] (–4.0%) and the overall median (−0.92%) show a worrying change in food production for a range of scenarios of climate change, locations, crops, and levels of adaptation" (Porter et al. 2017).

To add to the confusion, the U.S. National Climate Assessment report (USGCRP 2018) projects mid-century (2036–2065) yields of commodity crops to decline by "5% to over 25% below extrapolated trends broadly across the region for corn, and more than 25% for soybeans in the southern half of the region." Notice that the report does not suggest that crop yields will fall; rather, U.S. crop yields are expected to continue trending upwards, but productivity growth will be below what it would be in the absence of climate change.

One can only conclude that the evidence regarding the impact of climate change on agriculture is a matter of interpretation, dependent on which studies are chosen to support one's viewpoint and how the evidence is presented.