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Smallholder Agriculture and Climate Change

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Abstract

Hundreds of millions of the world's poorest people directly depend on smallholder farming systems. These farmers now face a changing climate and associated societal responses. We use mapping and a literature review to juxtapose the climate fate of smallholder systems with that of other agricultural systems and population groups. Limited direct evidence contrasts climate impact risk in smallholder agricultural systems versus other farming systems, but proxy evidence suggests high smallholder vulnerability. Smallholders distinctively adapt to climate shocks and stressors. Their future adaptive capacity is uncertain and conditional upon the severity of climate change and socioeconomic changes from regional development. Smallholders present a greenhouse gas (GHG) mitigation paradox. They emit a small amount of CO_2 per capita and are poor, making GHG regulation unwarranted. But they produce GHG intensive food and emit disproportionate quantities of black carbon through traditional biomass energy. Effectively accounting for smallholders in mitigation and adaption policies is critical and will require innovative solutions to the transaction costs that enrolling smallholders often imposes. Together, our findings show smallholder farms to be a critical fulcrum between climate change and sustainable development.

Contents

1. INTRODUCTION

Smallholder farming systems provide livelihoods and food for hundreds of millions of the world's poorest households. Both climate change and the policies developed to react to it are transforming these systems. These impacts can be expected to continue and to intensify with potentially profound implications for economic development, human health, prosperity, natural resource management, security, and ultimately achievement of the Sustainable Development Goals (SDGs).

The scientific literature on smallholder agricultural systems in a changing climate has expanded sharply in the past decade. The purpose of this review is to synthesize this emerging literature to better understand the future of smallholder agriculture. The review contains sections on (*a*) climate change impacts, (*b*) smallholder adaptation strategies, and (*c*) greenhouse gas (GHG) emissions and mitigation. Previous works have addressed numerous dimensions of smallholders and climate change (1, 2). We aim to build on these efforts by exploring (*a*) the role of smallholders and smallholder farming systems in climate change impacts, adaptation, emissions, and mitigation as compared to other populations and other farming systems, and (*b*) the implications of smallholder farming systems for the study of climate change impacts, climate mitigation policies, and climate change adaptation policies.

Agriculture is a livelihood strategy for hundreds of millions of people, including for many people who have access to or who farm a limited amount of land. One recent study estimated that there are more than 475 million farms smaller than 2 ha globally, accounting for $\sim$80% of all farms, but operating on only $\sim$12% (289 million ha) of the world's 2.1 billion ha of agricultural land (3). These farms are distributed across the tropics but are particularly prevalent in South and Southeast Asia and sub-Saharan Africa (**Figure 1**). Smallholder farms vary dramatically in structure, function, and size within and between countries and regions (4). For example, small farms not only comprise the vast majority of all farms in Asia but smallholder-dense regions account for more than 90% of the food calories produced there (5). In sub-Saharan Africa, small farms also make up a large share of all farms and produce roughly half of food calories. In contrast, large farms dominate food calorie production in Latin America (5).

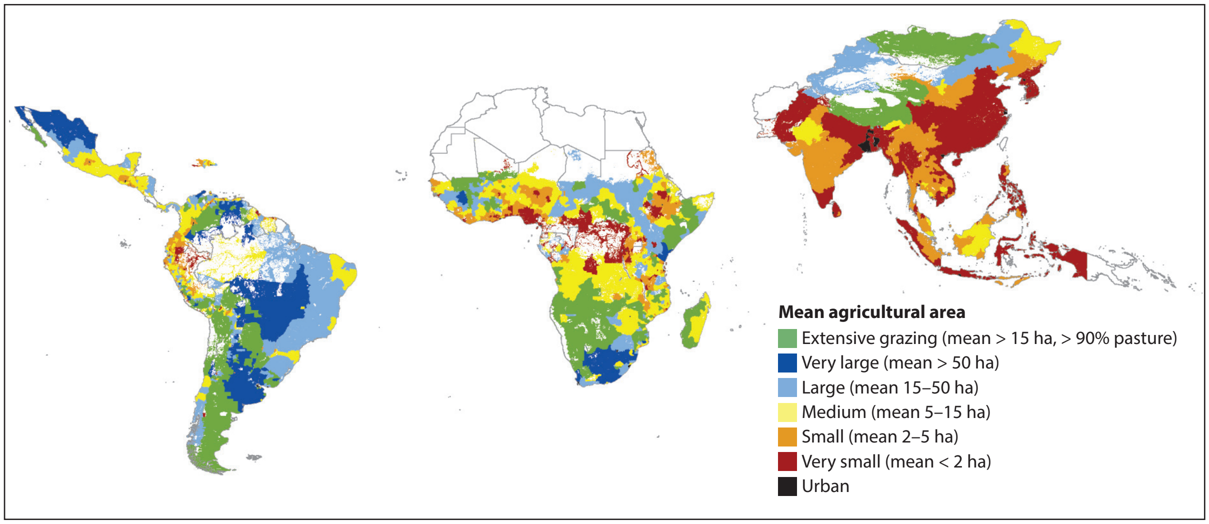

Figure 1

Map of mean agricultural area by subnational administrative unit in three global regions. The map incorporates 2,412 subnational units in 83 countries. Units are clipped to agricultural extent, incorporating both cropland and pastureland. Administrative units are defined the Integrated Public Use Microdata Series and/or the Database of Global Administrative Areas. Urban classification indicates mean population density greater than 1,000/km^2. Figure reproduced with permission of Samberg et al. (5).

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Many smallholders are vulnerable to climate change in ways that other farmers are not. The production risks posed by climate shocks may interact with other stressors, including infectious diseases, nutritional deficiencies, natural resource degradation, and insecure land tenure to compound risks to smallholder livelihoods. At the same time, smallholder farmers have myriad adaptive capacities, including knowledge, networks, and management practices that have long enabled smallholder systems to cope with both environmental and socioeconomic change under a changing climate. It is likely that these adaptive capacities will manifest differently from adaptive capacities employed in other farming systems.

Smallholders can also be expected to play an important role in GHG emissions and mitigation efforts. Per capita, CO_2 emissions arising from smallholder production and consumption are very low. However, small farms produce agricultural crops and livestock that frequently have high GHG intensities relative to other producers. Smallholder systems can also be in the position to mediate links between commodity markets and deforestation, and they emit a substantial share of the emissions of particulate matter known as black carbon—a potent, but short-lived climate forcer. Meanwhile, substantial barriers to enrolling smallholders in policy and to programmatic efforts to reduce GHG emissions may exist.

1.1. Definitions

There is no consensus or universal definition of the term smallholder (6). The term is commonly used to refer to farms less than 2 ha in size, although some authors use the term to refer to farms of up to 200 ha in size (7). Other authors do not define smallholder farm systems by land area, but instead base their definition on other identifiers. Some such identifiers include reliance on family labor [often using the term family farm (8)], percentage of production consumed on-farm, and quantity of economic output. Smallholder farms can also be distinguished from other farms by the economic size of their farm, a measure derived by scaling farm area by the revenue produced per unit of land, the cost of renting or selling land, or the amount of income derived from an area of land. Economic size can substantially diverge from physical size. In Brazil, the area of farmland presumed by the federal government to supply a given amount of farm income varies by a factor of 20 across the country (9). Finally, it is not always clear whether the very smallest of farms [referred to in some contexts as marginal farms (e.g., 10)] are included within estimates or definitions of smallholder farms.

In this review, we do not abide by a single definition of smallholder, given definitions vary among authors and small is a relative term that varies between contexts. Rather, we use the term as defined by each of the authors that we cite and, where appropriate, we flag ways in which definitions have influenced findings and debates in the germane literatures. Similarly, we interpret agriculture broadly, to incorporate crops and livestock, but also agroforestry, fisheries, aquaculture, hunting, and resource extraction, which frequently form part of diversified smallholder livelihoods.

2. METHODS

First, we conducted two novel, scene-setting analyses to provide an overview of contrasts in smallholder predominant agricultural regions versus other farming regions. The first analysis assessed how areas with high densities of smallholder farming over the period 1983–2011 differed from other agricultural areas across indicators of agriculture and climate. We overlaid a subnational map of smallholder agricultural dominance extending over 83 countries across Latin America, sub-Saharan Africa, and East and South Asia (5) with twelve other datasets (11–23). The methods and data are described in **Appendix S1** and **Table S1** (follow the **Supplemental Materials link** in the online version of this article or at **http://www.annualreviews.org/**); the results are described in the following section and are summarized in **Table 1**. The second analysis assessed the relationship between agricultural jobs and farm size. We estimated the numbers of agricultural jobs per unit agricultural production, circa 2013; **Figure S1** illustrates these results.

Second, we conducted an in-depth evaluation of the scholarly literature on the relationship between smallholders and the environment and resources, and examined the extent to which that literature informs the topic of smallholder agriculture and climate change. We identified key topics and explored evidence related to our three focal areas of climate change: impacts, adaptation, and emissions and mitigation. The review is not comprehensive; rather, for each topic, we focused on themes we considered most noteworthy.

3. MAPPING SMALLHOLDERS GLOBALLY

We found substantial variation in the agricultural and climate characteristics of farms, with respect to region and degree of smallholder predominance over the period 1983–2011, controlling for population density (**Figure 2*a***). We provide graphs of the relationship across a range of mean predominant farm sizes (**Figure 2*b*–2*j***) and across a set of farm size categories (**Table 1**) across sub-Saharan Africa, Asia, and Latin America.

3.1. Production

In all three regions, farm size is inversely correlated with population density (**Figure 2*a***). Because such density could confound our understanding of the relationship between farm size and other variables, we control for this and continent fixed effects in subsequent plots (**Figures 2*b*–2*j***). Across the globe, smallholder predominant regions allocated a greater proportion of the calories produced to products directly consumed as food, rather than conversion to feed or fuel (**Figure 2*b***). In smallholder areas, 70% of calories produced were available for consumption as food, compared to a mean of 66% nationally in the 83 countries in the sample and 55% globally (5). This pattern was most pronounced in Latin America, where more than 70% of calories were consumed as food in smallholder areas, compared to 49% in areas with the largest farm sizes (**Table 1**).

Similarly, the role of cattle in agricultural systems differed within and between regions with respect to the dominant farm size class. High cattle densities in smallholder-dominated units in Asia and sub-Saharan Africa demonstrate the importance of mixed crop-livestock systems in these regions, whereas relatively low cattle densities in equivalently smallholder-dominated areas of Latin America may reflect the extent to which livestock production in that region is part of frontier settlement processes (**Figure 2*c***).

3.2. Forest Loss, Carbon Storage, Fuelwood Balance, Greenhouse Gas Emissions

Smaller mean farm size was associated with a higher rate of forest loss per hectare of agricultural land across all three regions (**Figure 2*d***). Smallholder dense regions in both Latin America and sub-Saharan Africa were associated with greater levels of deforestation per hectare of agricultural land than the rest of the landscape (**Table 1**). Carbon storage showed similar patterns, with smallholder areas holding the most carbon per hectare (**Figure 2*e***). Areas dominated by smaller farms also had a negative fuelwood balance, but this is an artifact of high population density and no relationship was found between farm size and fuelwood availability once this was accounted for (**Figure 2*f***). Areas dominated by smaller farms also generated significantly greater GHG emissions per calorie

Table 1 Distribution of climate variables in relation to smallholder predominance by region

Region	Mean agricultural area	% Calories consumed as food	% Cropland in perennials	Cattle density (head/km^2)	% Change: heat events	% Change: annual CV precipitation	Maize yield variation explained by climate (categorical)	Water depletion (categorical)	Forest loss (ha loss/ha agricultural area)	Carbon (Mg/ha)	GHG intensity (Mg CO_2/Mkcal)	Fuelwood supply/demand balance (tons/year)
Asia	Large[a]	**53%**	16%	6.62	30.3%	−0.2%	2.16	2.33	0.02	100.38	0.20	−1.08
Asia	Medium	72%	46%	7.31	50.2%	−4.4%	1.47	1.53	0.21	181.81	0.52	74.88
Asia	Small[b]	70%	26%	15.90	**16.2%**	−4.6%	**2.29**	2.30	0.13	108.23	0.58	62.17
Asia	Very small	**76%**	22%	**24.92**	**9.7%**	1.0%	2.19	2.04	0.08	106.14	0.66	22.00
LA	Very large	**49%**	**11%**	**39.02**	0.5%	**15.9%**	**3.25**	1.27	0.04	**22.42**	0.04	39.25
LA	Large	64%	**30%**	25.62	18.6%	4.5%	2.58	1.94	0.04	**47.20**	0.15	43.77
LA	Medium	67%	38%	25.82	17.9%	1.0%	2.04	1.75	0.06	71.88	0.17	48.10
LA	Small	**71%**	**42%**	26.06	22.1%	**−8.9%**	**1.97**	1.58	**0.10**	**77.91**	**0.25**	**23.28**
LA	Very small	**72%**	**40%**	**10.54**	16.2%	**−8.9%**	2.12	1.78	**0.16**	**95.34**	**0.40**	**−6.70**
SSA	Very large	**70%**	17%	17.38	11.7%	13.8%	3.69	**2.76**	0.01	8.66	0.05	21.48
SSA	Large	79%	17%	15.14	24.7%	1.8%	2.36	**1.93**	0.02	30.47	0.12	35.00
SSA	Medium	80%	15%	15.01	23.2%	0.0%	2.53	1.61	0.02	24.83	0.11	28.80
SSA	Small	78%	**22%**	**22.71**	**38.0%**	2.1%	2.80	**1.48**	0.02	29.20	0.14	**−36.90**
SSA	Very small	77%	**27%**	19.99	**36.1%**	8.9%	2.49	**1.04**	**0.06**	**68.79**	0.12	**−77.68**

Abbreviations: GHG, greenhouse gas; LA, Latin America; SSA, sub-Saharan Africa.

[a] Large and/or very large percentages are indicated in bold when significantly different from medium, small, and very small in the same region.

[b] Small and/or very small percentages are indicated in bold when significantly different from large and very large in the same region.

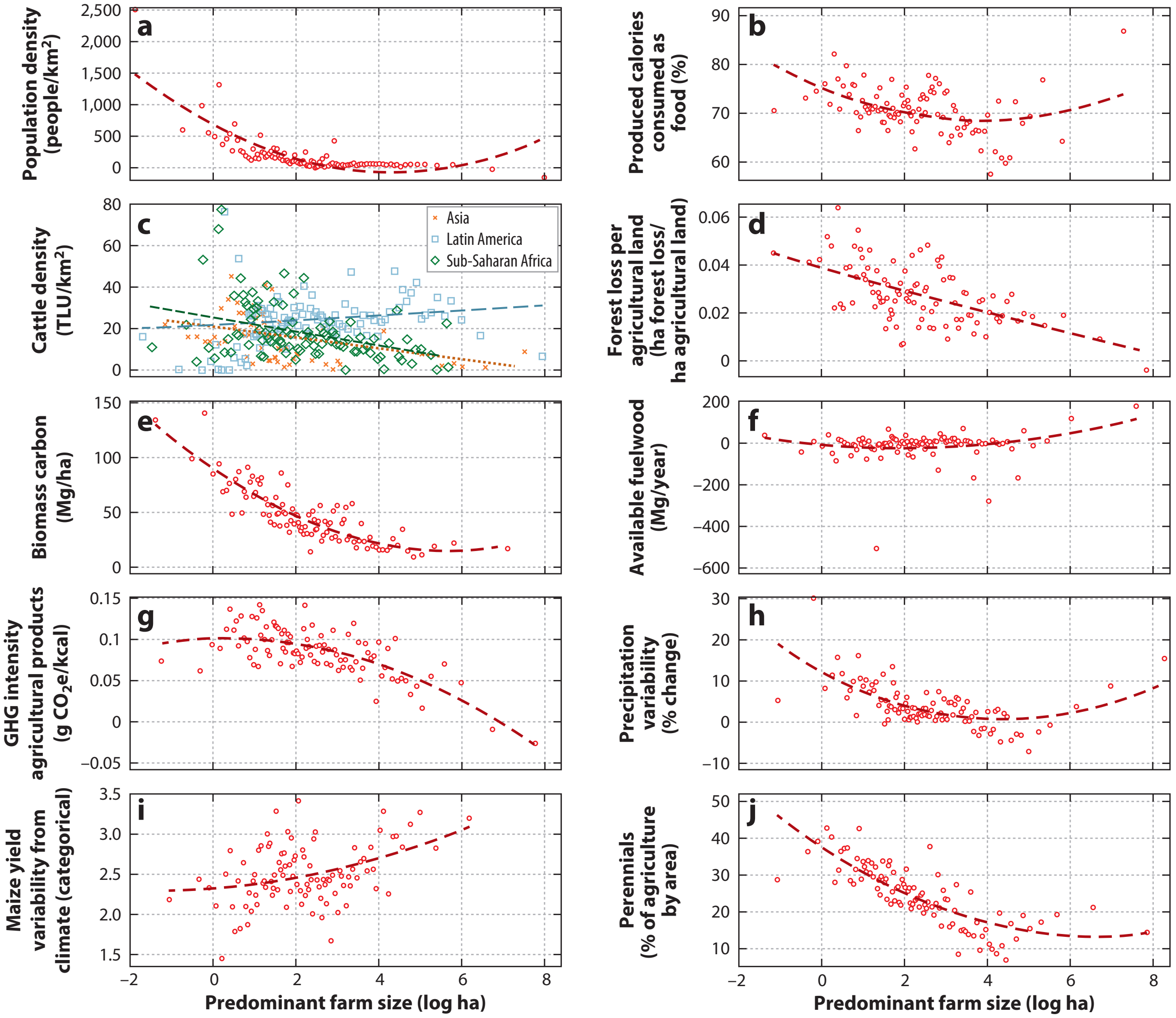

Figure 2

Relationship between climate and agricultural indices of interest and predominant farm size. This figure depicts the relationship between farm size and climate and agricultural indices germane for smallholders. Each panel is a visualization from the mapping exercise described in **Appendix S1** (follow the **Supplemental Materials link** in the online version of this article or at **http://www.annualreviews.org/**). Outcome variables by panel are (*a*) population density, (*b*) calories as food, (*c*) cattle density, (*d*) forest loss per unit of agricultural land, (*e*) biomass carbon per hectare, (*f*) available fuelwood, (*g*) GHG intensity of agricultural products, (*h*) precipitation variability, (*i*) maize yield variability, and (*j*) share of agriculture in perennial crops. The lines in each panel are quadratic lines of best fit estimated via regressions in which each the outcome variables of interest is regressed on predominant farm size controlling for continent fixed effects and population density. The data points show the results of a similar analysis showing the quantile-by-quantile relationship between residual variation in the variable of interest and the log of farm size after controlling for continent fixed effects and population density. The exceptions are panel *a*, in which population density is not included in the control variables, and panel *c*, which shows results by continent and thus does not include continent fixed effects. Each data point is located at *x* and *y* coordinates corresponding to the sum of the mean residual values for its quantile and the sample-wide mean. Negative values may occur when the quantile residual mean is more negative than the sample mean is positive. Apparent trends in the data points are a nonparametric form of interpreting the relationship between farm size and the variable of interest. We used global aggregate data only for relationships for which there were not strong regional distinctions in variable of interest–predominant farm size relationships. Abbreviations: CO_2e, carbon dioxide equivalent; GHG, greenhouse gas; TLU, Tropical Livestock Unit.

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produced than areas predominantly characterized by larger farms (**Figure 2*g***). The dataset used to calculate the comparison excludes emissions from land use change. Inclusion of land use change emissions was recently estimated to increase emissions intensities of both smallholder farming and largeholder farming by approximately 50% (24). However, attributing land use change to agricultural systems is not straightforward and much debated. Perhaps for this reason land use change emissions are frequently omitted from agricultural GHG emissions calculations used in regulatory settings.

3.3. Climate Trends

Increasing frequency of extreme heat events and increasing variability in rainfall are likely to affect agricultural production in many places. In sub-Saharan Africa, areas of smallholder-dense farming have seen a greater percent change in extreme heat events over the past 30 years, relative to other areas (**Table 1**). In contrast, areas in Asia with a higher density of small farms have seen smaller increases in extreme heat events than other areas. Latin America showed few noteworthy trends in this regard, although areas with the lowest density of farms have experienced the smallest increase in extreme heat events (**Table 1**). Latin America also showed a pronounced inverse correlation between farm size and precipitation variability, whereby smallholder-dense areas showed indications of increased interannual variability in precipitation, while regions with larger mean farm sizes experienced little to no change in variability (**Figure 2*h***).

3.4. Crop Yield and Climate

In the face of a changing climate, a primary concern for agriculture is the extent to which crop yields will decrease or destabilize. As an indicator of this phenomenon, we assessed the percentage of variability in maize yields (**Figure 2*i***) that can be attributed to climate variability. In Latin America and sub-Saharan Africa, a greater proportion of the variation in maize yields was associated with climate variability in areas with agricultural areas with large mean farm sizes (**Table 1**). This indicates that crop yields in smallholder-dense regions may be less vulnerable to climate variability than crop yields in other regions. However, we caution against drawing firm conclusions on this point. Research on climate impacts to agriculture has not commonly examined many of the crops of high importance for smallholders. We illustrate this issue by showing that a higher proportion of agricultural land was planted with perennial crops in areas dominated by smallholders (**Figure 2*j***).

3.5. Water Depletion

Only in sub-Saharan Africa did water depletion seem to be significantly associated with mean farm size (**Table 1**). Smallholder dense areas tended to have the smallest percentage of watershed area in states of high seasonal or permanent depletion, while areas with larger mean farm sizes were the most water stressed. In Latin America, regions with the lowest density of farming households had the lowest proportion of depleted watersheds.

3.6. Employment

Our second analysis, performed at the level of nations in the year 2013, revealed that smallholder predominant nations, many of which are less developed, had dramatically more agricultural jobs per unit of agricultural production than other nations (**Figure S1**). For example, greater than an order of magnitude more people were employed per unit of agricultural production in India than in the European Union.

3.7. Literature Review on Impacts and Adaptation

Climate change shocks, stressors, impacts, coping strategies, vulnerability, adaptation, resilience, and mitigation are a closely intertwined set of phenomena. For example, impacts are widely understood as loss and damage from climate change net of any adaptive measures undertaken in anticipation of and/or in response to climate change shock and stressors. Furthermore, we expect climate impacts and adaptation to alter GHG emissions through agricultural expansion, agricultural intensification, changing household consumption patterns, and migration both within rural areas and from rural areas to urban areas.

Scholarship on these climate change phenomena often focuses on the causes giving rise to individual phenomena of the set. For example, the literature on climate impacts both retrospectively and prospectively models the well-being of individuals, regions, or societies caused by climate shocks or stressors, net of adaptive capacity. By contrast, the literature on adaptive capacity (see Section 5) may also take both a retrospective and prospective approach but asks about the institutional, cultural, biophysical, and economic factors that give rise to adaptive capacity.

4. CLIMATE CHANGE IMPACTS TO SMALLHOLDER FARMING

This section reviews evidence on sensitivity of agricultural production to climate change and variability in smallholder agricultural systems as compared to other agricultural systems. Agricultural climate impacts research has long played an important role in climate policy analysis, including as a key component of efforts to model the costs and benefits of climate action versus inaction (25). Nevertheless, this research has seldom differentiated between sensitivity of smallholder systems and other farming systems, has often neglected entirely livestock and fisheries, and seldom explores components of agricultural supply chains beyond farms (26).

Crop simulation modeling (27) and statistical modeling of crop-climate relationships (28) are the two primary methods used to research climate impacts on agriculture. The distinction is not clear cut—many parameters of crop simulation models are based on statistical modeling, and variables used in statistical modeling often employ some sort of simulation modeling (29). We reviewed studies using both types of methods. Outcome variables of interest included the oft-investigated crop yield, as well as cropping frequency per growing-season area (30–32), and cropping extent (1). In the case of statistical modeling, we focused on the subset of models that (*a*) directly investigated the influence of farm size on climate impacts or (*b*) used methods that enable causal inference of the influence of climate on crop production (33).

Statistical analyses are often retrospective investigations of climate impacts to agricultural systems. They examine crop productivity metrics conditional on climate change and a set of changes in the agricultural system that climate triggers. These changes can come in the form of changes in crop health, farmer decisions to alter management, and feedbacks between the two. These farmer decisions are often cryptic to datasets used to research climate impacts and are, by definition, adaptive measures. Thus, the empirical study of climate change impacts to agriculture should be understood as an effort to quantify climate impacts net of adaptation.

4.1. Direct Comparison of Climate Impact in Smallholder Versus Other Farming Systems

Few studies have directly examined the influence of farm size or smallholder status on the climate sensitivity of agricultural production. Reidsma et al. (34) provided one exception, a study that uses aggregations of farm-level data collected across Europe over the period 1990–2003 to investigate the relationship between the economic size of farms and the sensitivity of farm productivity to growing season climate (34). The findings were mixed. In Greece, Spain, and Germany, smaller economic farm size was associated with less sensitivity to mean growing season temperature and precipitation. However, in Italy, France, Benelux, the United Kingdom, and Scandinavia, smaller size was associated with greater temperature sensitivity. The findings of Reidsma et al. (34) are not causal. Rather, the study examined cross-sectional variation alone, therefore likely suffering from bias from the omission of variables correlated with production variability, mean temperature, and/or economic size of farms.

A contrasting finding comes from Troost & Berger (30), who used agent-based modeling derived from farm surveys in Southwestern Germany to explore climate change adaptation. The authors found farm size might be expected to reduce the climate sensitivity of farm income. The finding is particularly notable as it suggests that economies of scale in the adoption of less climate-vulnerable technologies favoring larger producers have the potential to exceed existing policies favoring smaller producers. However, the study cannot be compared directly with Reidsma et al. (34) because it defines farm size differently, examines different climate shocks, controls for more sources of variation in farm production functions, and examines a small geographic area for which Reidsma et al. (34) does not report findings.

4.2. Smallholder Versus Other Farming Systems by Association

Many studies do not directly investigate the climate responsiveness of smallholder versus other farming systems, but enable exploration of the relationship between climate responsiveness and variables associated with smallholder predominance. Compared to other farming systems, smallholder systems (*a*) predominate in the low latitudes [see **Figure 1** and Samberg et al. (5)] on marginal soils (2), (*b*) are primarily rainfed (35), (*c*) employ diversified farming systems (36), (*d*) are often subsistence households, and (*e*) are part of food systems with different supply chain configurations than other farming systems (37). The following section reviews studies that provide insights into smallholder versus other farming systems on the basis of one or more of these five possible proxies for farm size.

Numerous studies have demonstrated that crop production responses to changes and variability in mean and extreme temperatures vary with latitude. Broadly, crops grown in both the tropics and in other latitudes have been found to be more sensitive to climate change and variability in the tropics. For example, the Agricultural Model Intercomparison Project, a multi-model, multi-crop crop simulation modeling activity, revealed heightened climate sensitivity in the tropics compared to other latitudes. Maize, wheat, and soy all performed more poorly in low latitudes than in the middle to high latitudes under a changing climate, perhaps because tropical climates are already near the heat threshold for these crops (38). No association between rice yields and warming was found from 0 to 2°C of warming, but with greater than 2°C of warming, low-latitude rice performed worse than mid- to high-latitude rice (38).

Additionally, both crop simulation modeling and statistical modeling approaches found greater declines in maize yields under higher temperatures in Tanzania than in Iowa or France (29). The similarity of the response in crop simulation modeling suggests a dominant biophysical impact mechanism, as these efforts hold management factors constant. That the statistical modeling is also similar is further evidence of this similarity. Greater declines in wheat yields in response to higher temperatures were observed in India than in Kansas (29).

Cross-region, within-crop-type comparative studies should not necessarily be extrapolated. The designated focus on only crops grown in both temperate and tropical regions is a form of selection bias with ambiguous implications. Crops originating from temperate regions are often at bio-geophysical margins in the tropics. Additionally, tropical staple crops of high importance for smallholders are omitted from such comparisons.

Beyond yield, changing temperatures may also affect food quality and postharvest characteristics of smallholder food systems. Stathers et al. (37) speculate that warming temperatures may increase postharvest losses in smallholder systems from crop fires, heat stress on labor, and insect pest reproduction. Extreme temperatures can reduce nutrient content of certain crops; for example, the protein content of wheat has been found to fall with exposure to temperatures above certain thresholds (39). Many smallholders rely on short rather than long supply chains, where households are subsistence-based and/or most of their food comes from highly localized markets, as opposed to consumers in urban areas and the global North who typically depend on more globalized markets. Climate shocks and stressors to smallholders' production systems can hence directly affect food availability in short, nonredundant food supply chains (40). Nevertheless, limited evidence can be found on differential impacts of climate on smallholders versus nonsmallholders after crop harvest.

As with temperature, smallholder farming systems may be exposed to stronger impacts from changing precipitation regimes than other farming systems due to their prevalence in the tropics. Globally, precipitation patterns, anomalies, and distributions are already being affected by climate change in many smallholder-dominant regions (41). A study involving explicit linkage of gridded crop and hydrological modeling found end-of-century water deficiency under Representative Concentration Pathway 8.5 watts m^{-2}, the highest greenhouse gas emissions scenario commonly investigated, which was heavily concentrated in regions of smallholder predominance (42). Relatedly, median potential yield loss and change in output due to future water shortage under climate change were found to be focused in smallholder-predominant regions (42).

By contrast, an emerging evidence base shows that mixed, integrated, and diversified farming practices, a hallmark of smallholder systems, suffer lesser climate impacts than more specialized systems. A recent review found that, of those papers that investigate the relationship between agricultural diversification and climate impacts, the vast majority focused on the tropics. Nearly all empirical papers focused on smallholders, whereas several modeling papers focused on ambiguously sized farms or largeholders (43). Thus, the literature is not well suited for a comparison of smallholders versus largeholders except by proxy measure.

Off-farm income diversification can also reduce climate vulnerability of livelihoods. Such income is more common in smallholder systems than other farming systems (44). However, such income is unevenly distributed among smallholders. Wealthier smallholders often have a larger share of nonfarm income (45).

Changes in crop growing seasons and shifts in agro-ecological zones have been widely observed, and they affect rainfed agriculture (46). For example, in the Indus River Plain, a shortened and increasingly variable rainy season both prevents full crop maturation in rainfed systems and decreases groundwater recharge rates in already overdrawn aquifers (35). Although many smallholders are reliant on rainfed systems, the smallholder sector is diverse and in some arid regions may depend on boreholes or other simple irrigation technology (47).

The impacts of extreme events and natural disasters on smallholder agricultural systems is mixed. A global analysis of the influence of natural disasters and extreme weather impacts on crop production found that lower-income countries, home to the vast majority of the world's smallholders, have lower disaster-driven yield deviations than higher income areas (48). However, another study focusing specifically on the influence of cyclones on GDP found little correlation between smallholder dominance and recovery of agricultural GDP (49). The agricultural GDP of Small Island Developing States, a set of nations where smallholders predominate, recovered more rapidly than that of all other countries, but the agricultural GDP in Asian countries, home to the vast majority of all the world's smallholders, recovered more slowly than other countries.

Sea-level rise represents another potential climate impact, as many smallholders are found in low-lying coastal plains, especially in South and Southeast Asia, and are among the populations most vulnerable to sea level rise (41, 48). In these regions, a large proportion of the most productive agricultural area is situated in low lying, highly populated deltas (50). Sea level rise can be expected to reduce arable land area and increase the salinity of freshwater and crop fields, reducing crop yields. Rao et al. (50) found that a 1 m rise would cause a loss of 4,040 km^2 of land in Andhra Pradesh, India, including 1,593 km^2 of agricultural land. The rise would displace approximately 1.67 million inhabitants, 70% of whom would be smallholders that farm less than 2 ha (50).

4.3. Short-Lived Pollutants

Short-lived climate pollutants (SLCP) have been found to affect crop yield through direct and indirect mechanisms. The top five Atmospheric Brown Cloud (ABC) hotspots are located in areas with high smallholder prevalence: East Asia, the Indo-Gangetic Plain in South Asia, Southeast Asia, Southern Africa, and the Amazon Basin (51). SLCPs are mainly derived from localized pollution, such as soot (e.g., black carbon from coal furnaces and transportation), smog [e.g., tropospheric ozone (O_3) from atmospheric reactions of methane (CH_4), nitrogen oxides (NOx), volatile organic compounds (VOC), carbon monoxide (CO)], CH_4 (e.g., CH_4 from oil and gas production, and agricultural processes), and refrigerants [hydrofluorocarbons (HFC)]. Burney et al. (52) found direct yield reductions of up to 36% from smog and soot on wheat in India over the period 1980 to 2010, perhaps due to decreased radiation from atmospheric scattering that reduces the plants' ability to absorb carbon. In some populous states, losses reached 50%. The authors also investigated rice loss, and found it to have a similar magnitude but to lack statistical significance. Additionally, black carbon deposition on ice and snow in the Western Himalayas accelerates snowmelt and has been associated with severe downstream flooding in the Ganges-Brahmaputra basin (spanning Tibet, Nepal, India, and Bangladesh), an area which accounts for nearly 28% of global rice production (53).

4.4. Conflict

Smallholder farmers in developing regions around the world, and in sub-Saharan Africa in particular, face a sort of double jeopardy, not just from climate change, but also from conflict that may arise in response to it (54–56). The climate-conflict literature assesses conflict at all scales and of all types, interpersonal, civil, political, cultural, or religiously motivated, such as dowry killing in India and witch killing in Tanzania. Few studies, however, have been conducted subnationally, and thus few have distinguished between rural farming populations and the ever-growing urban populations of Africa (57). This is problematic, as we would expect food producers and food consumers to respond differently, and possibly in opposition, to food price shocks. In a recent study, McGuirk & Burke (57) addressed this problem by studying the influence of climate on conflicts over food versus conflict over land across net-producing and net-consuming regions. The authors found that increased food prices were associated with reduced conflicts over food in net-producing regions, but with increased conflicts in consuming regions. The most likely mechanism is that under rising food prices, net-consuming regions may seek increased purchasing power through conflict. The key implication of this finding is that the presence of significant and countervailing trends in climate-conflict relationships within countries may downward bias estimates of the influence of climate on conflict. In addition, some members of society are disproportionally affected by conflict. Women, for example, are both a key component of smallholder farming systems and vulnerable to climate-related conflict (58).

5. CLIMATE CHANGE ADAPTATION AMONG SMALLHOLDER FARMERS

In response to, and in preparation for, climate change and climate variability described in the previous section, farmers, businesses, and governments are adjusting their plans, practices, and behaviors in a set of processes collectively known as adaptation. The IPCC defines adaptation as, "…the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities" (59, p. 118). More broadly, adaptation can be understood as the decision-making process and set of actions undertaken to maintain or build the capacity to deal with current or future projected change (60, 61). Adaptation can involve technological, ecological, social, or governance approaches (62–65). Many adaptive measures have long been implemented in response or preparation to past or contemporary climate stressors. Those that have improved the well-being of adopters are known as adaptive strategies; those that worsened the outlook of adopters are known as mal-adaptive.

The central research challenge regarding adaptation is to understand the potential for future adaptation before the world experiences climate change at full force. Climate change will likely worsen in velocity and magnitude. Thus, the results of many adaptive measures will be known only once they are tested under future climates. Adaptation research has sought to gain insight into potential future adaptation through the study of past adaptation efforts. Researchers have examined the causes and potential of adaptive capacity, defined as the "pre-conditions that enable any adaptation" to climate change (66). The literature examines whether past adaptation strategies are predictive of future adaptation strategies due to the underlying adaptive capacity of actors, and whether such capacity will be sufficient to meet the increasing speed and scale of climate change (67–70).

We reviewed the evidence based on the differences in the types, origins, strength, and future potential adaptive strategies and adaptive capacity in smallholder farming systems compared to other farming systems. We first discuss on-farm adaptation strategies, then discuss off-farm adaptation strategies, and close with cross-cutting insights.

5.1. Agricultural Adaptation Strategies

A number of agricultural adaptation strategies have been adopted by smallholders in order to cope with the stresses of a changing climate. These include on-farm diversification, adoption of water technologies and management, introduction of new crop varieties, and strategies to spread risks across space or time. The availability or suitability of each of these options will differ for individual smallholder depending on regional, local, and farm-level context.

5.1.1. On-farm diversification. A hallmark of smallholder systems is agricultural diversity at the landscape, species, and genetic scales. But to what extent is this diversity an adaptive response and to what extent does it confer adaptive benefits? A strong evidence base shows that in some cases a substantial share of diversity of production in farming systems has arisen through adaptive responses (71, 72). Evidence is limited on the extent of diversification response for smallholders compared to largeholders. However, within smallholders, some evidence shows larger smallholders to be more likely to adapt through on-farm diversification than smaller smallholders (73, 74). This evidence is consistent with theories suggesting that underlying adaptive capacities can scale with the size of agricultural holdings (30).

5.1.2. Water technologies and management. Water technologies and management are particularly critical for adaptation for smallholder farmers, who are primarily dependent on rainfed agriculture. If water resources become less predictable, water management and irrigation will become increasingly important. Improvements in the efficiency of existing irrigation systems will be needed. Promising avenues include efficiency gains from technologies such as laser leveling, sprinklers, and drip irrigation. For nonirrigated agriculture, water conservation, water harvesting, and storage techniques will serve as critical adaptation strategies (75–77). Conservation agriculture can also help both irrigated and rainfed systems to increase the organic matter in soil, improving moisture retention and water-use efficiency (78).

5.1.3. New crop varieties. New crop varieties can confer adaptive benefits. Traits of potential benefits to smallholders include drought resistance, heat tolerance, salinity tolerance, and fast-maturing varieties bred to adapt to shorter growing seasons (75, 79). The suitability of new crops as an adaptation strategy for smallholders has been the subject of some debate, with critiques that crop-based research has focused on the needs of temperate agricultural systems, annual crops, and mono-cropped systems. Concerns have also been raised about the costs associated with new varieties, particularly for hybrid seeds or biotechnology, which may be prohibitively expensive for many smallholders (80).

5.1.4. Risk-spreading strategies. Many farmers of all sizes employ risk spreading strategies across time and space. Weather insurance products are widely used by large-scale farmers. However, these often cannot be employed by smallholders due to high transaction costs as a share of total costs and the potential for adverse selection and moral hazard stemming from imperfect information about climate risk to crop production (81). Smallholders often turn to informal risk-sharing strategies that depend on close sociocultural ties and familiarity (82). Such schemes work best in tackling idiosyncratic risk faced by a subset of participants in a network. To combat wider-spread pervasive covariate risk, smallholders are increasingly turning to index insurance, an approach that ties payments to regional agricultural outcomes rather than direct measurements of production losses on participants (75, 83). Index insurance faces several challenges as it continues to scale. Schemes may have intolerably high uncertainty about risk where climate data are scarce (75) and where crop-climate sensitivity is poorly researched. In addition, adverse selection could arise where participants can gain or derive seasonal weather forecast information.

5.2. Smallholder Nonagricultural Adaptation

Adaptation options can also extend beyond the agricultural sector, recognizing that smallholder farmers are not necessarily bound to an agriculturally based livelihood. Indeed, livelihood diversification is widely employed by smallholders, including as an adaptation strategy. Many smallholder households already rely on diverse income sources, particularly in areas where agriculture is marginal. Livelihood diversification helps to increase household income, reduce income vulnerability, and act as an insurance mechanism against agricultural failure (84, 85). Not all smallholders can afford to diversify. Diversification is more common among wealthier smallholders than poorer or more vulnerable farmers (2, 44). Evidence is mixed on the relationship between farm size and propensity to diversify livelihoods among smallholders: Studies have variously found farm size to be positively associated, to be negatively associated, or to have no effect on diversity of production (74, 86).

The use of migration and livelihood transitions as adaptation strategies is an emerging area of interest (87–89). Migration can be temporary (e.g., seasonal) or permanent, and can involve farming of alternative areas, agricultural labor in other regions, and migration, often to urban areas for nonfarm work.[1] Migration is an enormously important channel through which climate can be expected to influence political order, and is a difficult topic of study. One limitation is migration statistics, which suffer from difficulty tracking the movement of people both within and across political boundaries. Another challenge is the dual influence of sending and receiving regions on migratory patterns.

Little evidence is available on differential migration behavior in smallholders versus other groups. One exception is Hidalgo et al. (92). The study analyzes the influence of drought on "land invasions," a common form of local migration in Brazil due to a constitutional pathway to obtain land tenure through occupation of idle private lands. Drought increased land invasions in Brazil, particularly in regions where a larger share of rural households were fixed contract agricultural renters and not land owners. However, the study was not designed to disentangle the role of renter predominance versus other factors, such as climatologically dry regions, in explaining heightened migration. The results suggest that regions with better natural resource endowments (in this case in the form of more productive land) and concomitant higher well-being can be expected to send fewer migrants than poorer regions.

However, Gray's (93) findings sharply question the universality of the poverty-migration nexus. Drawing on evidence from Ecuador, Gray (93) shows that landholders are more likely to be international migrants than land renters. Interestingly, Gray also finds local migration to be more sensitive to climate than international migration. The findings of Gray are important for showing that studies such as Hidalgo et al.'s (92) may supply limited insight for comparing climate-driven migration in smallholder versus non-landowning rural populations. Taken together, these two studies are but one more reminder of the subtle distinctions between well-being and poverty, adaptive capacity, and the lack of it.

Migration is a component of structural transformation, i.e., the change in the economic makeup of societies from agricultural to industrial economies. Do climate impacts speed structural transformation? In many parts of the world, climatic conditions unfavorable to agriculture are seen to prompt both livelihood transitions and urban migration. A recent study in India found that casual laborers shift from agriculture into manufacturing in years of low agricultural productivity and when the climate is less suited to agricultural production (94). Similarly, Henderson & Storeygaard (95) show that increased aridity in sub-Saharan Africa increases rates of urbanization, provided that regional cities have sufficient nonagricultural industrial activity. This effect is strongest in arid subregions of sub-Saharan Africa.

5.3. Barriers and Limits to Adaptation for Smallholders

Smallholders face many barriers to adaptation, including limited economic and financial resources, lack of access to usable information, unavailability of appropriate technologies for different users, credit constraints, lower socioeconomic and educational status of users, and limited access to social networks (96–100). These constraints can lead smallholders to have lower levels of risk tolerance compared to other farmers, which also influences adoption (100, 101). The uncertainty associated with future climate changes also poses a barrier for the adoption of adaptation measures (102, 103). Policies and programs can help overcome these barriers and offer incentives for adoption of adaptation strategies, but need to account for the specific needs and constraints of smallholders.

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[1] Migration can be classified as an adaptive measure, a climate impact, or a hybrid of the two, depending on the volition of migrants (see, e.g., 90, 91).

6. GREENHOUSE GAS EMISSIONS AND MITIGATION

As in other systems, smallholder agricultural practices and associated livelihood activities generate GHG emissions that contribute to climate change. These emissions are generated through activities that include, but are not limited to (*a*) land-use change, such as deforestation to create new agricultural land, including shifting cultivation (104) and slash and burn systems (105); (*b*) agricultural practices, particularly from livestock and rice production; and (*c*) household energy use, including the use of firewood as a fuel source.

Opportunities for mitigating GHG emissions in smallholder agriculture fall into three broad categories (106, 107). First, mitigation can occur through emissions reductions, particularly from (*a*) reduced rates of land-use change—for example, from reduced deforestation—and (*b*) improving the efficiency (i.e., greater output per unit area) of low production agricultural systems (108, 109)—for example, through practices that deliver added nitrogen more efficiently to crops, and through livestock management that makes most efficient use of feeds. Second, farms can move toward removals enhancement, increasing rates of carbon sequestration—for example, practices that maintain or enhance the storage of carbon in the soil or in belowground or aboveground biomass, and those that remove methane from the atmosphere through oxidation on agricultural lands. Third, household dependence on firewood as a primary fuel source can be reduced—for example, through adoption of cookstoves that burn alternative fuels.

In this section, we summarize the literature that discusses whether and how smallholder agriculture contributes to climate change, and the extent to which smallholders are the target of policies and programs to mitigate climate change, in relation to the three key themes identified above.

6.1. Land-Use Change

Smallholders clear forested land both in slash-and-burn and shifting agriculture systems, and as part of a strategy to claim land for longer-term tenure. Land is cleared to harvest timber products, and for the production of agricultural and livestock products for subsistence or sale. Smallholders have in many instances been pushed to settle on marginal lands in forest-agriculture frontier areas, as a consequence of either political marginalization or rising land rents that result from the growth and development of agricultural centers (110–112). This pattern, which often repeats as agricultural regions develop, may increase the likelihood of deforestation by this demographic. However, the proportion of forest clearance that is attributable to smallholders varies across space and time, and in many places smallholders account for a much smaller proportion of deforestation than do larger landholders. For example, in Brazilian Amazonia between 2004 and 2011, smallholders (defined as <100 ha) accounted for just 12% of deforestation, although this proportion increased during that period (113). In a separate study, most smallholders (defined as <200 ha) in Brazilian Amazonia maintained more than half of their land as forest (7).

Commodity agriculture is associated with a majority of deforestation globally: The production of beef, soybeans, palm oil, and wood products alone are associated with an estimated 40% of global forest loss (114). Commodity agricultural supply chains often include smallholders, who—for example—engage in palm oil production in Indonesia (115), dominate cocoa production in West Africa (116), and operate calving ranches that supply animals to larger cattle farms in Brazil (117). Thus, although large-scale producers of commodity crops are responsible for a substantial share of the demand for forest frontier lands, smallholders play an integral role in supply chains that threaten tropical forests.

6.1.1. Policies and programs aim to mitigate climate change by altering smallholder land-use behavior. Governments and other actors are working to develop policies and programs to mediate the land-use change behavior of smallholder farmers, with a particular focus on reducing conversion of forests, via both regulations and incentives. Regulations designed to reduce deforestation include land-use policies (e.g., Brazil's Forest Code), and the creation of protected areas. Some protected areas have successfully reduced deforestation (118). In the Brazilian Amazon, strictly protected areas, legally inhabited sustainable development reserves, and indigenous territories have had demonstrably reduced deforestation (119) and have at least in part protected the livelihoods of smallholder agro-extractivists living within sustainable development reserves from the pressures of encroaching cattle, mining, and timber industries (120).

Incentive programs designed to reduce deforestation include supply-chain governance (e.g., third-party certification programs), and reducing emissions from deforestation and forest degradation (REDD+) initiatives, which in many cases address agriculturally driven land-use change. Certification programs and payments for environmental services-type programs have been critiqued as tending to disproportionately benefit larger landholders (121) and can be difficult to implement among smallholder populations (122), especially where land tenure is unclear (123). REDD+ policies that promote land-use transitions, for example from swidden systems to plantations, may reduce GHG emissions but may also undermine livelihoods (124). In contrast, some certification programs have been relatively successful in including smallholders, especially when mechanisms that lower the barriers to entry are included in their design (125).

6.2. Agricultural Practices

Smallholders tend to be capital-poor, and often depend on low-efficiency agricultural practices. As such, the emissions per unit food produced by smallholders can be relatively high. Additionally, many smallholders keep ruminant livestock, which are high emitters of methane through enteric fermentation (126). Livestock systems in the developing world, where the majority of smallholders are found, are frequently characterized by low productivity, low feed availability, and poor quality of feed resources (127). As such, opportunities for smallholders to reduce emissions might come from higher input use efficiency (128), better soil and livestock management through land-use strategies such as conservation tillage, mulching, improved manure and pasture utilization, and composting (122).

6.2.1. Altering smallholder agricultural practices. There are a wide range of opportunities for reducing GHG emissions by promoting improved agricultural practices. Many of these can help to promote the intensification of food production on existing agricultural land, both increasing yields and reducing deforestation pressure, with adaptation co-benefits as well. Others can help to sequester and store carbon on farmland. Intensification may be achieved through greater inputs (e.g., fertilizers, pesticides), improved (e.g., drought-resistant) crop varieties, better agricultural practices (e.g., improved pasture management), and new technologies (129). Here, we consider integrated crop-livestock-forestry systems and conservation agriculture as two options among many that offer particular promise for reducing GHG emissions by smallholders.

Government agencies and NGOs globally are recognizing the potential of maintaining or restoring trees and forests on farmland to deliver environmental and livelihood benefits. As an alternative to both slash-and-burn agriculture and more conventional homogeneous farming systems, integrated crop-livestock-forestry systems offer significant potential for carbon sequestration and reduced emissions, and may confer adaptation and resilience benefits (43, 130).

Conservation agriculture (CA) is an approach that can alter land use and reduce GHG emissions. CA frequently involves no till practices, the use of cover crops, and crop rotation, each of which confer different degrees of benefits in terms of GHG emissions mitigation (78). In sub-Saharan Africa, one study reported that although avoided deforestation brought the most benefits—in terms of reductions in tons $CO_2{}^{e}$ ha^{-1} $year^{-1}$—the establishment of living fences, fire prevention, crop rotation and improved fallows, conservation tillage, reduced energy use, and substitution for mineral nitrogen fertilizer also conferred mitigation benefits at the plot and landscape level in CA systems (78).

However, rates of adoption of CA among smallholders have been low, in part because yields may be reduced in the initial transition years (131). Furthermore, it is not clear that the adoption of CA will necessarily or always mitigate climate change (78). The capacity to retain crop residues for mulch is a precondition of CA, but mulch is in many cases fed to livestock; successful implementation of CA systems thus requires mechanisms to meet the demands of both soils and livestock (132).

6.3. Household Energy Use

An estimated 2.7 billion people, including a majority of smallholders, rely on solid biomass fuels such as wood, crop residues, dung, charcoal, and coal as their primary domestic fuel source for cooking, lighting, and heating (133). Solid fuel use is most prevalent in Africa and Southeast Asia, where more than 60% of households and more than 94% of rural households cook with solid fuels (133, 134). The incomplete combustion of biomass, such as through the use of traditional stoves, contributes to climate change primarily through the emission of black carbon, a potent, but short-lived cause of climate change. Incomplete biomass combustion also causes substantial human health problems: Particulate matter from burning biomass inside people's homes results in an estimated 3.9 million deaths per year (21) and may cause an estimated 9.8 million premature deaths in Africa alone by 2030 (135). Another substantial source of emissions from household energy use is the land-use change associated with the collection of woodfuel. An estimated third of woodfuel harvest in 2009 was unsustainable; i.e., it contributed to loss of native ecosystems (21).

6.3.1. Policies and programs aim to mitigate climate change by altering smallholder energy use. Advanced wood burning and biogas stoves can reduce biomass fuel consumption by 60% or more (136), and can decrease black carbon and CO_2 emissions by up to 90% (137). Multiple projects and programs have therefore distributed and/or promoted such cookstoves, as a relatively cheap means to both reduce pressure on limited fuelwood resources and reduce the human health costs associated with smoke inhalation (138). However, cookstove adoption rates have in many places been significantly lower than expected. In a study in Bangladesh, low adoption rates were associated with a combination of factors that include unwillingness to pay for new technologies and misperception of the health risks from air pollution (139).

6.4. Barriers to Mitigation

Estimating mitigation potential in agriculture can pose technical hurdles, particularly in smallholder systems. For instance, the avoidance of emissions displacement also involve challenges related to indirect land-use change effects (140, 141), leakage (142, 143), definition of counterfactual scenarios (144, 145), and the attribution of land use to different events in general. Specifically addressing integrated assessment models (IAMs), Hertel & Lobell (146) argue that remarkably little has been done to represent the rural poor given their relevance for emissions and potential mitigation. Moreover, IPCC emission factors—often used in modeling exercises aimed at calculating the climate change mitigation potential of agriculture—are often unrealistic or have limited geographic representativeness (147, 148)

Enrolling smallholders in traceable supply chains has become a stumbling block in efforts to curb commodity-driven tropical deforestation. Just as transaction costs can shield smallholders from deforestation enforcement efforts and undermine deforestation free supply chains, they can also limit the participation of smallholders in schemes to pay for mitigation on smallholder properties through take up of lower emissions agricultural technologies or avoided deforestation. Both emissions inventories and monitoring and evaluation efforts can be sufficiently costly as to prohibit smallholder participation in incentives-based GHG mitigation schemes. Standardized emissions factors are focused on the agriculture of developed countries. This is problematic given the potentially unjust nature of several alternatives—imposing punitive measures that mitigate smallholder GHG emissions in ways that undermine their livelihoods.

7. CONCLUSIONS

The shocks and stressors of climate change pose an uncertain future for the hundreds of millions of the world's poor who earn their livelihoods and feed their families from smallholder agricultural systems. Whether they remain on the landscape or migrate away, whether they continue to farm traditionally or adopt new practices, the future of smallholders is a fulcrum between climate change and the SDGs. Our review compared smallholder systems with other farming systems in a changing climate, and established both bright contrasts and ambiguous terrain.

Smallholder adaptation is indeed a pressing priority. We found that smallholders are inherently vulnerable to the impacts of climate change, due to their location in tropical latitudes, dependence on natural resources, lack of access to markets or financial networks, and political marginalization. However, there is very limited evidence to suggest that small farms are more vulnerable to climate change than other agricultural systems.

If smallholder systems do suffer greater climate impacts than other agricultural systems, it would be problematic on multiple levels. Small reductions in agricultural output could push smallholders into greater poverty, trap them there, cause hunger, and trigger civil conflict and migration to rural and urban regions that each offer even poorer prospects. Meanwhile, due to the labor-intensive nature of smallholder agricultural production, many more people (at least on the production side of agriculture) can be expected to be affected by each unit of lost agricultural output from climate change. We can expect sharp distinctions in the nature and geography of indirect effects of smallholder versus largeholder climate vulnerability.

Smallholders have long coped with a variable climate in ways wholly distinct from larger producers, and these strategies may position smallholders to be more resilient to climate change than their larger counterparts. In addition, novel adaptive measures suitable for smallholders should not be discounted. Progress in water harvesting, crop breeding, climate information services, and index insurance suggests a multitude of new avenues for smallholders to cope with a variable and changing climate (79, 149).

At the same time, numerous factors leave smallholders at a disadvantage in coping with climate change. First, relative to other farmers, smallholders are heavily concentrated in places at the extreme edge of suitability for the crops that they grow. Second, population and landscape changes triggered by development, climate, and other factors disproportionately affect smallholder landscapes. Forced and volitional migration, civil conflict, and natural resource degradation and depletion can all be expected to undermine coping strategies.

Traditional and novel approaches may combine in conflictual or synergistic ways. For example, improved integration in market economies has been shown to simultaneously enhance coping and undermine it by limiting collective action that smallholders use in more isolated places to distribute risk (150). By contrast, new evidence suggests that index insurance can enhance informal coping strategies (151). Further confounding matters, smallholders are themselves an enormously heterogeneous group; among smallholder farms, economic size may reduce vulnerability by increasing access to costlier adaptation strategies (44).

The contribution of smallholders to GHG emissions greatly varies by emissions metric. As both producers and consumers, smallholders emit very little CO_2 per capita—just a tiny fraction of the per capita emissions of the urban middle class in the same countries and elsewhere. But smallholder use of traditional biomass for energy causes a substantial share of the world's black carbon emissions, a potent short-lived climate forcer. In addition, crop and livestock products of smallholder farming systems are often GHG-intensive relative to other production systems. Finally, smallholders play an important but largely cryptic role in emissions from land-use change. Large-scale producers of commodity crops are responsible for a substantial share of the demand for forest frontier lands, but smallholders are often closely associated with deforestation processes, especially for some commodities, such as cattle products. The influence of smallholders on land-use change can be magnified by regulations against deforestation that, due to transaction costs of enforcement, may fail to enable, or to provide incentives for, small farms to reduce land clearing.

Smallholders can be expected to have an important but delicate role in mitigation of emissions from land use, land-use change, and forestry. Low per capita emissions, even greater discrepancy of historical emissions of smallholders versus other groups, and the precarious nature of smallholder livelihoods together suggest that it would be unjust to target mitigation in smallholder systems alone. Thus, the comparative GHG intensity of smallholder food products is concerning in the context of growth of European policies to adopt GHG intensity standards for food products (152, 153). However, by contrast, mitigation of emissions from smallholder household energy use might benefit smallholders through co-benefits from reducing the crippling disease burden from local air pollution. Finally, many mitigation technologies may be "no regrets" opportunities, reducing GHGs while strengthening livelihoods (including through adaptation) (69, 70, 154).

8. RECOMMENDATIONS FOR RESEARCH AND POLICY

Our review has multiple practical implications for research and policy, including by identifying knowledge gaps and leverage points for addressing the challenges facing smallholders. Here, we outline some of these implications in the hope that they may aid researchers and decision makers.

8.1. Impacts

Rapid progress in the estimation of climate impacts to agriculture is underway. Such analyses must extend to crops that smallholders favor, such as tropical staples and perennials. They must also seek to contrast the differential vulnerability of farming practices, groups, and contexts by identifying past differential crop responses to climate. Modeling climate variability as a proxy for climate change will play an important role in such research. Other creative avenues may be to employ as test cases regions that have experienced rapid climate change in the past—for example, high latitudes, mountainous regions, and regions that have undergone substantial biogeophysical climate change from land conversion. Such work will benefit by continuing to leverage the proliferation and fusion of geospatial data from sensors, cell phones, satellites, and household surveys. These data are being transformed into information on crop yields, household well-being, regional poverty, climate variability, and regional resource endowments predictive of vulnerability. A critical challenge facing the field is scaling these reduced form estimates (be they at the level of household or political unit modeled as a stylized household) to the planetary scale. A common means for scaling crop climate vulnerability estimates has been IAMs. Thus, we urge work using new data on heterogeneous climate vulnerability of agriculture to inform parameterization of climate agriculture relationships depicted in IAMs. At the same time, the ability of IAMs to model adaptive measures such as trade can help to contextualize the reduced form analyses (155), by, for example, projecting the fungible nature of diets, agricultural livelihood strategies, inputs to agricultural production, and the importance of risk spreading to limit impacts.

8.2. Adaptation

Novel risk-spreading strategies appropriate for smallholders, such as index-based insurance products, are proliferating. These products should be improved with better climate data, better climate-crop sensitivity data (particularly for crops of importance for smallholders), and better representation of local and tele-connected covariate risk to production. In addition, adaptive measures should go beyond reducing vulnerability, and should rather aim to enable smallholders to escape and evade poverty traps, by creating pathways to well-being. It will be important to understand how these measures will interact with the traditional coping strategies that smallholders often employ. Interventions to promote well-being should be developed to recognize smallholders as a dynamic group with potential future livelihoods on their own farms, in other rural sectors, and in cities near and far.

8.3. Mitigation

Terrestrial GHG mitigation is an urgent priority and forms a central component of many of the Nationally Determined Contributions (NDCs) stipulated under the Paris Agreement (153). Research is needed on which components of these NDCs are working, which are not, why, and the potential for synergies and integration with adaptation and development policies. Reducing emissions will be a great deal more difficult without the participation of smallholders, particularly with respect to reducing emissions from land-use change and black carbon emissions. Interventions targeting terrestrial GHG reductions must be designed to do no harm to the livelihoods of smallholders. However, mitigation efforts should also not neglect smallholders, not least because mitigation efforts and mitigation finance have the potential to vitally improve rural livelihoods.

SUMMARY POINTS

1. Understanding the role of smallholder agricultural systems in a changing climate is fundamental for confronting climate change in a manner that does not undermine the Sustainable Development Goals.
2. We mapped spatial variation in a suite of climate and agriculture characteristics with respect to categories of farm size predominance. Our results revealed profound differences within regions by farm size, and within farm size but across regions.
3. Little direct evidence contrasts the influence of climate on smallholders versus other systems. Indirect evidence is mixed—the regions where smallholders predominate are at higher risk of climate change, whereas the technologies that smallholders employ may be more resilient.

4. When smallholder systems suffer climate impacts to production this may trigger a cascade of problems including poverty, hunger, civil conflict, migration, and a disproportionately high amount of lost work.
5. Smallholders cope with a changing climate in ways that are distinct from other farmers. Environmental and social outcomes depend on how these coping strategies evolve under both development and climate change.
6. Smallholders present a greenhouse gas emissions paradox. They emit a small amount of CO_2 per capita and are poor, making GHG regulation unwarranted. At the same time, they produce relatively GHG-intensive food and emit disproportionate quantities of black carbon through the use of traditional biomass.
7. Targeting smallholders may be important for many climate mitigation and adaptation policies. Doing so effectively will depend on innovative solutions to the transaction costs that enrolling smallholders often impose.
8. Substantial progress has been made in understanding risks that climate change poses to smallholders, and opportunities to limit the problem; however, a great deal of uncertainty remains concerning most of the dimensions that we reviewed.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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AUTHOR CONTRIBUTIONS

A.S.C. and P.N. are equal first authors; J.D.B.G., L.K., L.S., and V.R. are equal second authors; and J.R.M. and S.N. are equal third authors. A.S.C., P.N., and J.D.B.G. conceived of the review; A.S.C., P.N., J.D.B.G., L.K., V.R., J.R.M., and S.N. wrote background papers; A.S.C. and P.N. wrote and edited the review; J.D.B.G., L.K., L.S., V.R., and J.R.M. commented on an earlier draft; and A.S.C. and L.S. conceived of and created the figures.

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