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Jobs, Food and Greening: Exploring Implications of the Green Transition for Jobs in the Agri-food System

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Abstract

The agri-food system (AFS) employs about one third of the global workforce and contributes about one third of global greenhouse gas (GHG) emissions. This together with its large exposure to the effects of climate change and environmental degradation makes what happens in AFS central to the green transition and its implications for jobs and the structural transformation. Microeconomic evidence suggests that the adoption of climate smart agricultural practices will increase labor requirements, at least in the short run and at lower levels of incomes, when its mechanization is still limited. Econometric macro-model-based simulations suggest however that especially substantial investment in climate friendly agricultural R&D as well as soil and water preserving practices and market integration will more than offset the negative effects of climate change and even accelerate the structural transformation, especially in Sub Saharan Africa. Overall, the findings underscore the tremendous potential of increasing agricultural and climate friendly R&D investment for brokering an environmentally sustainable structural transformation. Repurposing of agriculture's current US$ 638 billion support package towards supporting more climate friendly practices, including to overcome the time lag between the moment of investment and the realization of the benefits, provides an important policy entry point.

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1 Introduction

The agri-food system (AFS) employs about one-third of the world's workforce. It also contributes more than one-third of global greenhouse gas (GHG) emissions each year and is heavily exposed to the effects of climate change and environmental degradation more broadly. The AFS's adverse impact and dependence on natural resources, coupled with the effects of climate change, amplify the pressing need for a 'green' transformation. This requires action along three dimensions: 1) enhancing the *resilience* of agriculture to evolving weather patterns via adaptation strategies, 2) *conserving* critical natural resources, including soil and water, and 3) reducing greenhouse gas (GHG) emissions through *mitigation* practices. Several practices exist already that can curtail GHG emissions and natural resource depletion and increase AFS's resilience to changing weather patterns. The impact of the adoption of such practices on jobs in agri-food, their number and quality, however, remains poorly understood. Given the continuing role of the AFS for employment and poverty reduction, sustainably scaling environmentally sustainable practices can only be done if their implications for AFS employment and the broader structural transformation are properly understood and considered.

To assess the implications of the green transition on AFS employment, the paper first examines how AFS employment will evolve under a business-as-usual scenario which assumes no changes in the current method of production and rapid climate change. To do so, it builds on the cereal yield outcomes predicted under the integrated climate-food model "IMPACT" by 2050 and the historical relationships between the evolution of the agricultural employment share and cereal yields, controlling for the stock of agricultural machinery. It then reviews the microeconomic evidence on the effects of sustainable agriculture on agricultural jobs and uses the findings from the same partial equilibrium multi-market economic model IMPACT to simulate long-term agricultural outputs and yields under accelerated investment in sustainable agricultural practices, to infer the effects on AFS jobs.

The remainder of the paper is structured as follows. Section 2 explores the evolution of AFS jobs throughout the process of structural transformation. This is followed by a review of the direct and indirect environmental externalities generated by on and off-farm segments of the AFS in Section 3. Section 4 discusses the initial insights on AFS job exposure to climate change under a business-as-usual scenario with climate change but without corrective interventions. Section 5 reviews the different measures that could be taken to foster a green transition, focused either on adaptation, conservation and/or mitigation. Section 6 assesses the implications of the green transition on AFS jobs and the process of structural transformation, using the insights from the micro-economic literature and the results from the macro-simulations. Section 7 reviews policy options when greening the sector to maximize the positive effects and mitigate the negative effects for AFS labor.

2 Jobs in the agri-food system

2.1 Agri-food – a major, but gradually declining source of employment

AFS employs a large, but declining share of the work force, as countries develop. Globally, almost 1.2 billion people are currently employed throughout the agri-food system (AFS), i.e., on the farm as well as off the farm along the agri-food value chains in input provision, and food processing, trading, and services[2]. This corresponds to 36.1 percent of global employment (3.25 billion people[3]), or about 1 in every 3 jobs worldwide (own calculations based on ILO data, 2022; see Appendix 1 for details). The majority of AFS employment is in low (LIC) and lower-middle income (LMIC) countries (733 million jobs in total, or about 61 percent of all AFS employment). In these countries, AFS is still the major sector of employment (64 percent of jobs in LICs and 48.4 percent in LMIC). The AFS share in employment declines to 30.4 percent in upper middle-income countries (UMICs) and 11.4 percent in high income countries (HICs) (Figure 1, Panel A).

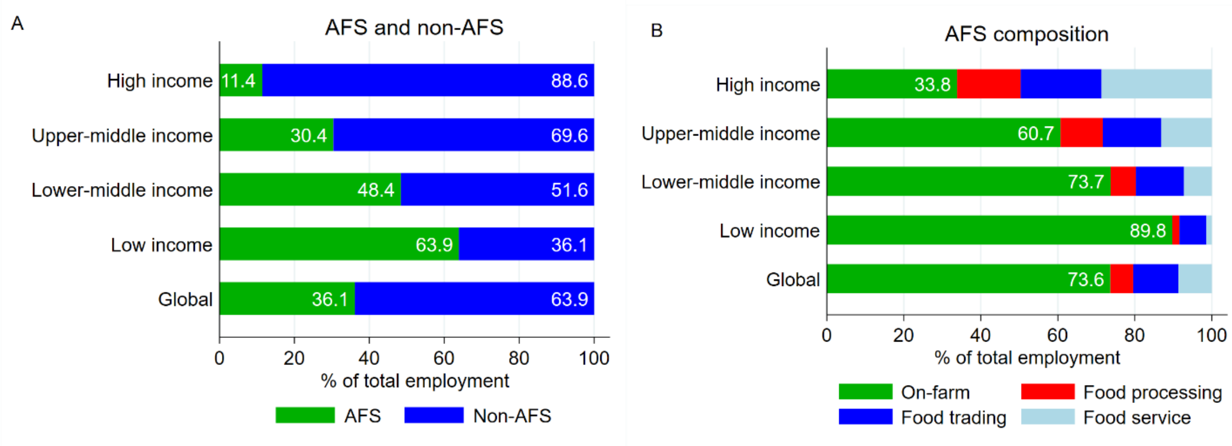
Despite its declining share over time, AFS employment and employment conditions remain central to the global jobs agenda. Not only is AFS still the main source of employment in lower income countries, the number of people employed in the AFS sector will also continue to increase for quite some time in many LICs (especially in Sub-Saharan Africa), even as the AFS share in total employment declines (Christiaensen, Rutledge and Taylor, 2021). This happens because of high population growth and underscores the centrality of the AFS for any poverty reduction, jobs, and green agenda. Furthermore, at 11.4 percent, even in HICs, the AFS share of employment is still nonnegligible, and sizeable for one

[2] Employment is classified as related to sectors of the agri-food systems based on definitions used in the International Classification of Economic Activity (ISIC). Using ILO data disaggregated by International Classification of Economic Activity (ISIC) activities, total estimates of employment in the agri-food system presented in this study includes: 1) employment in on-farm activities (crop, livestock, forestry, fisheries and aquaculture): 2) in food processing (manufacture of food and beverages), 4) food trading (wholesale and retail trade of food and food transportation); and 4) food services (food and beverage service activities). The estimates of employment in the agri-food system only include people who hold their main job in any industry of the agri-food system. The main job is that with the longest hours usually worked.

[3] According to ILO (2021), the share of people in working age (15+) corresponds to 74.5 % of the world population (7.9 billion people), down to 64.9% when we only include those aged 15-64. Globally, the employment-to-working age population ratio (15+) stood at 55.2% in 2021 (3.25 billion people 15 years and above who are employed out of 5.9 billion people in aged 15 years and above).

sector. In higher income countries, employment and employment conditions in the sector also often enjoy disproportionate public interest. This may follow from the essential, and increasingly also experiential nature of food, especially in HICs, and the role of agriculture as user and abuser of the world's natural and environmental resources (Meemken et al. 2023).

Figure 1 Share of employment in the AFS in 2022 (Panel A). Distribution of AFS employment across segments of the AFS in 2022 (Panel B).



Source: own calculation based on ILO data (2022).

2.2 Predominantly on-farm, but increasingly also off-farm, in the food chain

Within AFS, on farm jobs dominate, but with rising incomes, greater agricultural labor productivity, and urbanization, AFS jobs shift increasingly off the farm. Globally, on farm work still largely dominates AFS employment (866 million jobs globally), though the share declines as countries develop, from 89.8 and 73.7 percent in LICs and LMICs respectively, to 60.7 percent in UMICs and less than half (33.8 percent) in HICs (Figure 1, Panel B). While food processing is arguably the more widely known subsector of the off-farm AFS segment by the public, it is food trading that dominates (transport, wholesale, and retail of food products), followed by employment in food services (restaurants and mobile food and beverage service activities, event catering and other food and beverage service activities). Only in HICs does the latter surpasses the share of jobs in food trading. Food processing generates the least jobs.

The shift from on to off-farm work in the AFS system mirrors shifts in agricultural labor productivity and food consumption patterns. As agricultural labor productivity increases through better agronomic practices, modern input adoption and mechanization, the demand for labor in food production declines. At the same time, the demand for labor in the off farm AFS segment increases as the demand for purchased, processed and convenient food rises when countries urbanize and develop, and the food value chains elongate, downstream, but also upstream, through greater use of agricultural inputs and services in agricultural production (Agra, 2019; Roe and Nelson, 2022). Being more capital and skill intensive, off-farm AFS jobs also tend to be more remunerative. Yet, the numbers of jobs generated in the off-farm AFS segment as countries develop do not suffice to absorb everyone leaving the farms. It underscores the importance of the concomitant development of the non-AFS sectors. Overall, understanding the subsectoral AFS shifts as countries evolve is important to understand the implication of greening for AFS employment because the production technology (labor intensity) as well as the related environmental and labor externalities differ substantially by AFS subsector.

2.3 From underemployment to fully filled labor calendars

Especially on farms in lower income countries, underemployment is widespread. Despite its importance for job creation, underemployment on farms is widespread, especially in lower income countries (Table 1). In LICs the average number of hours worked per week in on farm activities is estimated at 33. This is 17.5 percent below a full work week (40 hours). As a result, while an estimated 144.5 million people are working on the farms in LICs (mostly self-employed), this yields only 120 million full time equivalent (FTE) jobs. This contrasts with work outside AFS, where workers tend to work even slightly more than 40 hours per week. The gap in the work week between on farm and non-AFS workers declines, however, as countries develop, but only converges at higher income levels. At that point, the average work week in non-AFS sectors also drops to 35 hours per week, from 41-43 hours per week on average in lower income settings.

Seasonality in agricultural production underpins on farm underemployment. The underutilization of the agricultural labor force in many low-income agricultural settings follows from the inherent seasonal character of agricultural production. This results in peaks (during the planting and harvest season) and troughs (outside the planting and harvest season) in the demand for agricultural labor. Importantly, this also means that underutilized labor on the farms is not readily available all year through, only during certain periods. Farming households and agricultural workers often fill these agricultural labor demand gaps through engagement in off-farm activities (within and outside the agri-food system) often low remunerative activities with low entry and exit barriers. As water control (irrigation), greenhouse cultivation and livestock rearing and aquaculture expands, the seasonal nature of agricultural production declines. This usually happens when countries develop.

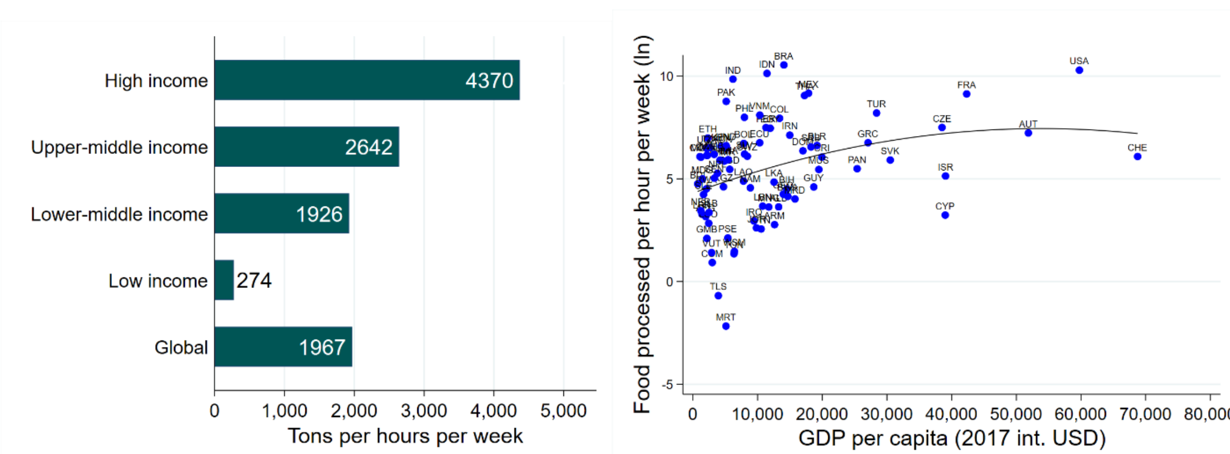
Table 1. Average number of hours worked in on-farm, off-farm and other non-AFS activities and total number of FT equivalent (assuming 40 hours per week).

	AFS				Non-AFS	
	On-farm		Off-farm		Other sectors	
Income group	**Average weekly hours**		**Average weekly hours**		**Average weekly hours**	
High income	37.0		34.5		35.0	
Upper-middle	36.4		43.5		41.2	
Lower-middle	38.0		44.8		43.6	
Low income	33.2		41.4		41.6	
Total	**36.6**		**40.8**		**40.0**	
Income group	**Employment (million)**	**FT equivalent (million)**	**Employment (million)**	**FT equivalent (million)**	**Employment (million)**	**FT equivalent (million)**
High income	16.1	14.9	50.1	43.2	514.8	450.5
Upper-middle income	258.6	235.2	118.3	128.7	863.0	888.7
Lower-middle income	447.1	424.6	128.1	143.4	613.7	669.3
Low income	144.5	120.1	13.6	14.1	89.4	93.0
Total	**866.3**	**794.7**	**310.0**	**329.4**	**2,080.9**	**2,101.5**

Source: own calculation based on ILO data (2022).

Unlike jobs on the farms, jobs in the off-farm AFS segment have fully filled, or even slightly over-filled calendars, just like jobs outside AFS. Given storage potential, the off-farm AFS segment is less subject to seasonality. More broadly, slight overemployment in off-farm AFS activities (and non AFS activities) in lower income countries (41-43 hours per week on average) may be linked to low productivity, and the need to work longer to make ends meet. On average, people employed in food processing activities in LICs work for example 17% more hours than their counterparts in HICs. Their labor productivity (tons of food processed per hour) is also 16 times lower (Figure 2).

Figure 2 Average food processed (in tons) per hours worked in food manufacturing across income groups



Note: hours worked in food manufacturing are obtained from ILOSTAT, the quantify of food processed from FAOSTAT

Source: ILOSTAT and FAOSTAT for the year 2021.

2.4 Less rural, more skilled and more wage based

As countries develop, sectoral reallocation of labor at national level (away from agri-food) goes hand in hand with a relocation and reorganization of work and workers. The conceptual framework underlying the process of economic transformation (Kuznets, 1977) suggests that as incomes increase, the labor market structure of a given country evolves along four complementary dimensions. First, as national income increases, economies experience a sectoral reallocation of labor from traditional, land-based agricultural sectors with underemployment (often focused on crops) to higher productivity sectors (per laborer, not necessarily per hour worked)[4] that can provide fuller employment and are not land-based, notably industry and services (the sectoral dimension).

Second, to benefit from agglomeration economies and/or proximity to consumers the latter sectors, which are much less land intensive, typically develop in more urban settings (towns and cities), inducing labor to move from rural to urban areas in search for jobs (spatial dimension). Third, and typically less discussed, as production processes become more capital intensive with greater task complexity, activities become increasingly organized in firms and organizational structures that reduce transaction costs and enable the capture of the economies of scale associated with the use of capital. Along also comes an increasing demand for higher skilled workers (the organizational dimension). Finally, capital accumulation fundamentally alters the organization of labor which becomes increasingly market oriented, specialized and wage employed, while the share of own-account and contributing family workers in non-marketed agriculture, as well as outside agriculture declines relatively to the share of paid employees (the occupational dimension).

Do jobs within AFS follow a similar pattern? The broad evolution to a less rural, more skilled, and more wage-oriented workforce at the national level as people move out of agriculture and countries develop (the so-called structural transformation) has been widely studied and described. To what extent this process is also observed within the sectors and to what extent it is driven by between as opposed to within sector changes is less clear. To begin to address this question, Figure 3 maps the AFS employment structure along the four dimensions of the structural transformation (sectoral, spatial, organizational, occupational) for four countries of the 4 income country groupings.[5] The analysis uses nationally

[4] Christiaensen and Maertens (2022).

[5] The choice of the 4 countries in each income category is partly driven by data availability and the countries are not representative of the countries in each income category as such. Yet, given the close association between the overall level of development and the state of transformation in each of the 4 dimensions, they provide a useful entry point to

representative microdata collected through labor force surveys in the USA (high income), Mexico (upper-middle income), India (lower-middle income) and Madagascar (low-income). This allows estimating the number of people employed in both on-farm and off-farm AFS activities and their respective subsectors (i.e. crop, livestock and fisheries; food manufacturing, food trading and food services respectively), whether people employed in the AFS live predominantly in urban or rural areas, whether their occupation (i.e. tasks and duties that characterize their jobs) requires low, medium or high skills, and whether they are paid employees or self-employment. Figure 3 presents the findings for the AFS sector as a whole (a disaggregated analysis for on-farm, off-farm AFS and non-AFS activities separately is in Annexes 2a-2c).

Within AFS, production shifts towards more protein and nutrient rich foods as well as a greater focus on food service provision in the off-farm segment. Nationally, the structural transformation is epitomized by the sectoral shift out of agriculture, reflecting the declining household food expenditure share as incomes increase (Engel's Law) (food expenditures in absolute value still increase). But, importantly, the AFS sector itself also changes as countries develop and urbanize. The shift towards more off-farm employment in the agri-food chains downstream in response to greater demand for processed, packaged, and prepared foods as well as the greater demand for inputs and agricultural services upstream has been highlighted above. Yet, household income growth also comes along with a higher demand for more protein- (meat, dairy, fish) and nutrient-rich food (fruits and vegetables) (Bennett's Law), increasing the share of employment in the on-farm livestock and fishery sector, away from crop production. In the United States, employment in livestock and fishery now makes up almost a third of total on-farm employment; in lower income countries, the share of both sectors is only a couple of percentage points (Annex 2a).

Within crops, the share of employment in fruit and vegetables further increases, at the expense of more land intensive grains and roots and tubers. It is often also met through migratory labor (Christiaensen, Rutledge and Taylor, 2021). The subsectoral employment shifts within on farm and crop production following the dietary shifts are further reinforced by the greater labor intensity of meat and fruit and vegetable production, which, until recently, have also been harder to mechanize (Annex 2a). Production of these higher value products and crops is also more remunerative, enabling farmers to keep up with raising wages outside the sector. In the off-farm segment, food services become ever more important, most likely reflecting a higher demand for meals and drinks consumed in restaurants, self-service, and

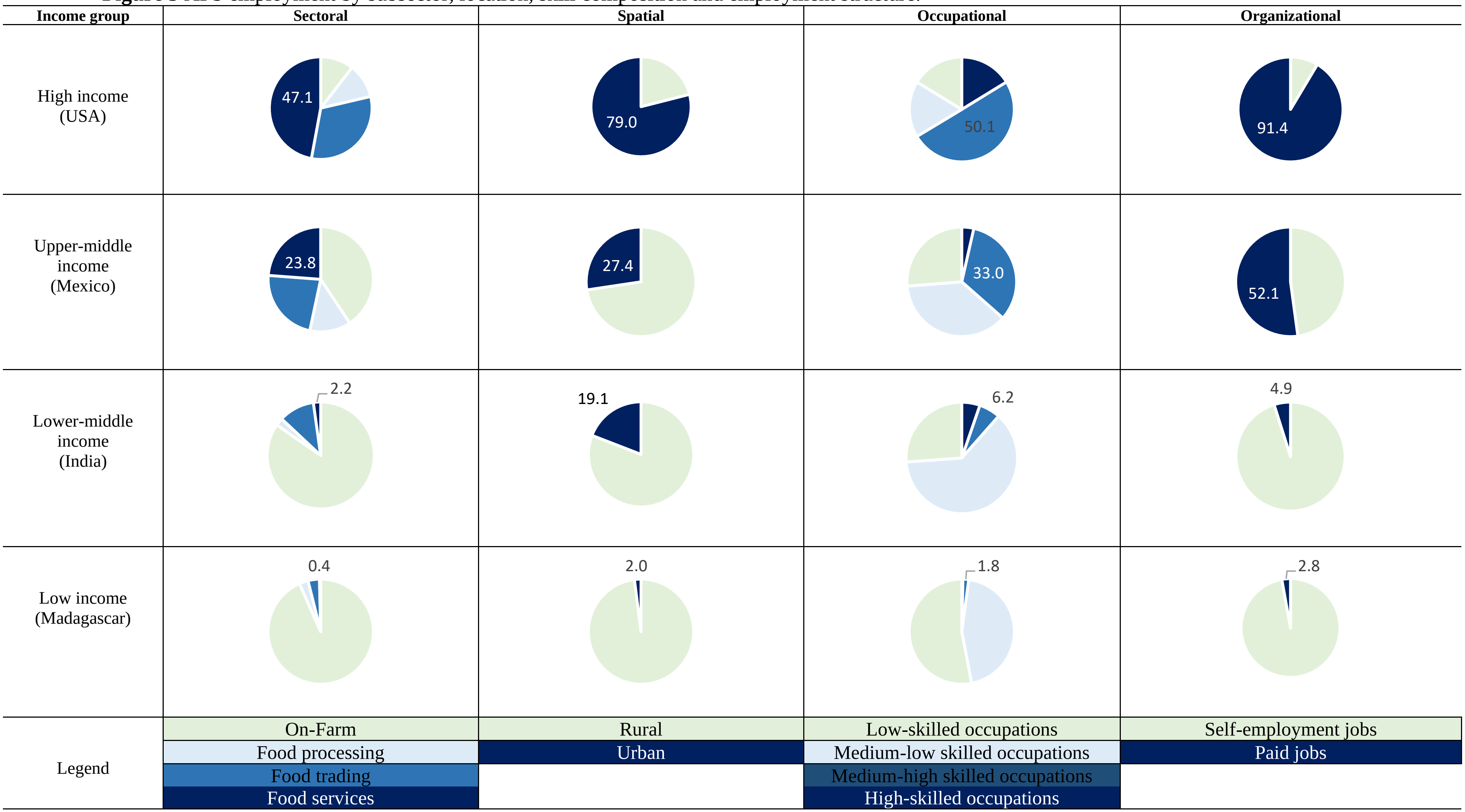
address the question whether job features within the AFS follow a similar pattern as has been observed across sectors.

take-away restaurants (raising from 5.8 percent of off-farm AFS employment in Madagascar to 52.6 percent in the United States) (Annex 2b).

AFS employment gradually urbanizes, largely driven by its off-farm segment, but in high income countries, even on-farm employment becomes partly urban. The urbanization of off-farm AFS activities as they become more capital and skill intensive and consolidate (AGRA, 2019), drives the gradual urbanization of AFS employment. Urban locations favor off-farm food trading and food service companies given agglomeration effects in towns and secondary cities and proximity to buyers and consumers. Nonetheless, slightly more than half of off-farm AFS jobs in India (LMIC) and Mexico (UMIC) are still rural. On farm employment remains mostly rural throughout[6], except in high income countries where part of it becomes urban.

[6] A nonnegligible share of the urban population in lower income countries, especially in Sub Saharan Africa, is also employed in agriculture (Christiaensen and Lozano-Gracia, 2020; Henderson and Kriticos, 2018). Yet, compared to rural on farm employment, the numbers are very small, so the vast majority of on-farm employment in lower and even upper middle-income countries remains rural.

Figure 3 AFS employment by subsector, location, skill composition and employment structure.



Source: own calculations based on microdata extracted from four household-based surveys: USA: Current Population Survey, 2018; Mexico: National Survey of Occupation and Employment (2018), India: Periodic Labor Force Survey (2018); Madagascar: Enquête Nationale sur l’Emploi et le Secteur Informel (2015).

Jobs in off-farm AFS are more skill intensive than those on-farm, but skill intensity increases for both as countries develop. While the majority of on-farm workers in low-income countries are low-skilled (55.8 % in Madagascar, Annex 2a), the vast majority of those working in the off-farm segment in Madagascar are already medium skilled (55.8 % medium low, 22.3% medium high in Madagascar, Annex 2a). Yet, as capital intensity increases and farming modernizes, farming becomes also more skill intensive, especially in high income countries, where farming today has become high-tech (e.g., precision agriculture, automation). In the United States, for example, almost half of on-farm workers are highly skilled today, even exceeding the share of high skilled workers in the off-farm AFS segment (Annexes 2a and 2b). With food services becoming more important in the off-farm AFS segment, which typically do not require higher education, this does not have to surprise.

With better capitalized and market-oriented firms also comes a higher demand for paid employees and a corresponding decline in the share of own-account and contributing family workers, also on the farms. In lower income countries, farming remains dominated by family farms and the vast majority of working adults engaged in on-farm activities are self-employed (own account workers and/or contributing family members).[7] The share of paid or wage workers in the off-farm AFS segment is larger, but at lower income levels, even there, a majority still engages as own account workers. Wage employment dominates in the off-farm AFS segment in middle- and high-income countries. Similar employment patterns and orders of magnitude are reported by Dolislager et al. (2020, Table 4). Overall, these patterns reflect the consolidation of farms and agribusiness as activities become more capital intensive and skill intensive, increasing the optimal scale of operation and the complexity of tasks.

2.5 Disproportionate employment of youth first on-, then off-farm

When employed, youth (15–24-year-old) are disproportionately employed in AFS. Overall, across countries, youth (15–24-year-old) are about half as likely to be employed as adults (25+ year old) (Table 2). This does not surprise, as many youngsters are still in school and transitioning their way into the labor market. Controlling for the lower overall rate of employment, youth are disproportionately employed in AFS when compared to adults: overall, 45.4 percent of employed youth works in AFS, compared to 41.1 percent of employed adults (Table 2).

[7] Farm wage employment is particularly low in Africa 3 percent of total FTE employment compared to 6 and 9 percent in a selected set of Latin American and Asian countries respectively (Dolislager et al. 2020). Overall, given methodological challenges in capturing wage employment (cultural perception of work; casual and seasonal nature of wage employment), on-farm wage employment rates based on official surveys may also be somewhat underestimated (Oya, 2013).

At first, in low-income countries, disproportionate youth employment in AFS is driven by on farm employment; thereafter, in higher income countries, by a larger concentration in off-farm AFS. Looking within the AFS sector and across country income level, the larger share of youth employment in AFS is driven by the larger involvement in on farm employment in low-income countries: 64.7 percent of all employed youth works on the farm versus 59.2 percent of all employed adults (Table 2). As countries develop, youth stays disproportionately within the AFS system but shifts off the farm, towards off-farm AFS activities in the agricultural value chains (especially food trading and food services). In upper middle income and high-income countries 19.3 and 23.1 percent of employed youth works in off-farm AFS activities respectively, compared to 13.4 and 6.6 percent of employed adults. On farm youth employment shares are similar to those of adults. In lower-middle income countries, the overall AFS employment share of youth (both on and off the farm) drops briefly below the AFS employment share of adults (46.9 versus 51.1 percent). It rises above the adult share again in higher income countries (36.6 versus 30 percent in upper middle-income countries and 24.7 versus 9.1 percent in high-income countries).

Throughout the economic transformation, AFS plays a key role in youth employment. The findings are reminiscent of the much talked about exit of youth out of agriculture (Dolislager et al. 2020; IFAD,2019). Importantly, however, this only happens when becoming lower middle income, and with many finding new opportunities in the AFS chains. Unsurprisingly, with poverty concentrated in rural areas, poverty reduction has often been found to be faster when the off-farm segments of the AFS develop concurrently with labor productivity growth on farm (Christiaensen and Beegle, 2019).

Table 2. Youth and adult participation rate by economic activities, and youth and adult employment distribution across economic activities.

	AFS							AFS						
	On farm	Food processing	Food trading	Food services	Off farm	**Total AFS**	**Non AFS**	On farm	Food processing	Food trading	Food services	Off farm	**Total AFS**	**Non AFS**
	Youth participation rate (% of total youth 15-24)							Adult participation rate (% of total adult 25+)						
High income	0.7	0.7	2.2	7.5	10.3	**11.1**	**33.7**	1.5	0.9	0.9	2.2	3.9	**5.5**	**54.6**
Upper-middle income	6.3	1.3	3.0	2.8	7.1	**13.4**	**23.3**	9.8	1.6	3.4	2.9	7.9	**17.7**	**41.3**
Lower-middle income	9.6	0.6	2.3	0.8	3.7	**13.3**	**15.1**	22.3	1.2	5.6	1.4	8.2	**30.5**	**29.2**
Low income	25.4	0.6	2.2	0.3	3.1	**28.6**	**10.7**	40.3	1.1	4.5	0.5	6.2	**46.4**	**21.6**
Total	9.8	0.7	2.4	1.7	4.8	**14.6**	**17.6**	17.5	1.2	4.3	1.8	7.3	**24.7**	**35.4**
	Youth employment distribution (% of total youth employment 15-24)							Adult employment distribution (% of total adult employment 25+)						
High income	1.6	1.5	4.9	16.7	23.1	**24.7**	**75.3**	2.5	1.5	1.4	3.6	6.6	**9.1**	**90.9**
Upper-middle income	17.3	3.6	8.2	7.6	19.3	**36.6**	**63.4**	16.5	2.8	5.8	4.9	13.4	**30.0**	**70.0**
Lower-middle income	33.9	2.2	7.9	2.9	13.1	**46.9**	**53.1**	37.3	2.0	9.4	2.3	13.7	**51.1**	**48.9**
Low income	64.7	1.4	5.7	0.8	7.9	**72.7**	**27.3**	59.2	1.7	6.6	0.8	9.0	**68.2**	**31.8**
Total	30.6	2.3	7.3	5.2	14.8	**45.4**	**54.6**	29.0	2.0	7.2	2.9	12.1	**41.1**	**58.9**

Source: own calculations based on ILOSTAT data for 112 countries

2.6 Greater poverty reducing powers

At low-income levels, growth in agriculture is more poverty reducing. A multitude of empirical studies have highlighted the critical role of agriculture in poverty reduction, with growth in agriculture two to three times more effective at reducing poverty than an equivalent amount of growth generated outside agriculture (Christiaensen and Martin, 2018). It follows from the widespread involvement of the poor in agricultural production, the more direct rewards to their labor when agricultural productivity increases, as well as the job multiplier and welfare effects it induces in the nonagricultural sectors. The poorest typically benefit the most.

When the relative advantage of on-farm productivity growth for poverty reduction reduces as countries develop, jobs in the off-farm AFS segment become especially important for poverty reduction. The advantage of agriculture over non-agricultural disappears as countries become richer.[8] Agriculture becomes more capital and skill intensive and behaves more like any other business. It then becomes equally effective at reducing poverty. With spending on nonfood rising, off-farm employment opportunities become more important. When generated nearby, as in the secondary towns and cities, they are also more poverty reducing (Kanbur, Christiaensen, and De Weerdt, 2019; Rodriguez-Pose and Griffiths, 2021). Towns and secondary cities often act as conduits for agricultural inputs to the hinterlands and for agricultural outputs and food to consumers in the towns and cities. They are often also home to agro-processing plants, especially when agricultural produce is voluminous (e.g., sugar cane) or perishable (fruits and vegetables). As such, off-farm AFS businesses often concentrate in secondary towns and cities. In lower income countries, labor-intensive micro, small and medium enterprises employing lower-skilled workers dominate the AFS sector. It makes off-farm AFS businesses an important source of alternative employment for the poorer segments of the population, both in the towns and secondary cities, as well as their hinterlands.

In conclusion, this in-depth review of the employment patterns in AFS across country income categories, how they change as countries develop (by subsector, location, skill requirements and employment type—wage/self-employed) and how the poorer segments of the population are particularly affected by these changes (positively and/or negatively, depending on how they materialize), provides the first step in unpacking the implications of greening the sector for jobs in agri-food. The next step is to identify how current agri-food production, distribution and consumption processes affect the world's climate and its

[8] Ivanic and Martin (2018) situate the point of convergence around US$ 3,000-3,500 GDP/capita.

natural resources (land, water, biodiversity) and how exposed AFS jobs are to the changing climate and degrading natural resource base.

3 The agri-food – environmental nexus

The agri-food system interacts closely with the environment, which it affects, and by which it is affected. The negative (and positive) changes the AFS imparts on the world's environment can be divided into direct and indirect externalities (Table 3). Direct externalities are generated from primary agricultural activities (i.e., activities carried out on the farm as well as in fishery and forestry) that directly affect the availability and quality of the natural resources on which the AFS depends (land, water, biodiversity). Indirect externalities arise from both on-farm and off-farm AFS activities that induce climate change by raising GHG emissions (carbon dioxide (CO_2), but also methane (CH_4) and nitroxides (N_xO)). These change the weather patterns over time (temperature, rainfall, wind), thereby further affecting the conditions on which the agri-food system depends for its output and labor productivity (in addition to the changing availability and quality of land, water, and biodiversity).

On farm activities, and the associated land-use dynamics, contribute both directly and indirectly to environmental degradation. Key direct contributors eroding the natural resource base are, for example, deforestation with the associated loss of biodiversity and soil erosion, and excessive use of inorganic fertilizers and groundwater for irrigation with the associated water degradation. Indirect contributors include rice and beef production through GHG emissions (mainly methane). Sometimes the direct contributors also affect the GHG balance (e.g., through increased emission (forest fires) and/or reduced carbon absorption (deforestation)). The environmental externalities of off-farm AFS activities are largely indirect[9], mainly affecting climate change through GHG emissions from energy use during the pre- and post-production stages, such as food processing, storage, refrigeration, etc. (Mbow, 2019).

[9] Crippa et al. (2021) also consider GHG emissions from AFS related industrial wastewater such as from meat and poultry processing and raw sugar refining, but the overall share in AFS GHG emissions is small. Beyond their contributions to GHG emissions, agribusiness has thus far not been identified in the literature as a particularly excessive polluter of natural resources.

Both mitigation and adaptation measures can be taken to improve AFS's interaction with, and reduce its dependence on, the environment, with differential effects on the number, quality, and type of jobs. Measures can be taken to reduce the effects of AFS activities on the world's natural resource base and its climate ("mitigation" interventions in "climate change" parlance) or AFS production processes can adapt to the changing environment ("adaptation" interventions). Both strategies will affect the number, quality, and type of jobs in AFS differently. From this perspective, natural resource degradation and climate change as well as the related AFS job outcomes are endogenously determined by the technological and institutional innovations in the AFS (Barrett et al., 2021). This section explores the key channels of AFS related environmental degradation (directly and indirectly) and the exposure of AFS jobs to its effects. The subsequent sections then examine the job effects of current AFS practices (business as usual) using a multimarket model (section 4) as well as the implications for AFS jobs of a transition towards more sustainable approaches (section 6).

Table 3. Environmental degradation from on-farm and off-farm AFS activities.

Direct externalities/pollution (natural resource degradation)				**Indirect externalities/pollution** (AFS GHG emissions) (16.7 Gt-CO_2-eq in 2019 or 34% of total GHG emissions (49.8 GtCO_2-eq)										
On farm/agricultural land										**Off farm**				
				65.4% of AFS GtCO_2-eq.						34.6% of AFS GtCO_2-eq.				
Crop-driven Defores-tation	Intensification		Extensi-fication	Farm gate			Land use change		Other[a)]	Food waste disposal	Food distribution			Others[b)]
				Livestock (beef & dairy) (23.8%)	Rice (4.0%)	Synthetic Fertilizers (3.6%)	Net forest conversion (17.6%)	Drained organic soil (5.5%)	(10.8%)	(14.6%)	Food retail (5.6%)	Food transport (3.2%)	Food processing (3.1%)	(8.2%)
Biodiversity loss	Ground water depletion	Soil degradation	Depletion of soil nutrients	Enteric fermentation, manure management and manure left on pasture	CH_4 emission									

a) *Others on farm* include on-farm energy use (3.2%), fires in organic soils (2.7%), forest fires (1.3%), Savanna fires (1.3%), crop residues (1.1%), manure applied to soil (1.1%), and burning crop residues (0.2%).

b) *Others off farm include* electricity use (3.0%), fertilizer manufacturing (2.5%), food packaging (1.9%), other (0.9%)

Source: FAO. FAOSTAT database. Accessed on January, 2023. Available at: http://www.fao.org/faostat/en/#data.

3.1 Agri-food as direct polluter

Both intensification as well as extensification have been pursued to expand agricultural production. During 1990-2020, Asia's[10] cereal production increased by 64% from 826 million tons in 1991 to 1,354 million tons in 2020 (FAOSTAT and Annex 3). This happened mainly through Green Revolution type agricultural intensification, including the use of modern inputs (e.g. improved seeds, inorganic fertilizers, and pesticides), mechanization and better water control (irrigation), as well as better agronomic practices (Hazell, 2010). Total land area under cereal cultivation expanded by only 6.6 percent; it contributed only 10 percent of total cereal output expansion[11]; 90 percent followed from the increase in yields (cereal output/ha). Overall agricultural labor productivity (agricultural value added in constant 2015 USD/agricultural worker) grew by 2.7 percent per year.[12] In Sub Saharan Africa (SSA), agricultural output increased amidst continuing land expansion, with land expansion accounting for almost half (46 percent) of the increase in cereal output (75 out of the 164 percentage points increase). Land under cereal cultivation increased from 60.1 million hectares (ha) in 1990 to 105.5 million ha in 2020 (FAOSTAT and Annex 3). The use of modern inputs, mechanization and irrigation remained low (Sheahan and Barrett, 2017) and lower than expected (Binswanger and Savastano, 2017). During 1990-2020, agricultural labor productivity in SSA grew only at 1.7 percent per year, while the total number of jobs in agriculture still increased in absolute numbers.

Agricultural intensification and extensification have both come with natural resource degradation, albeit through different channels. While intensification of agricultural production preserved forests and wetlands, mismanagement and excessive use of agrochemical inputs and intensive use of irrigation (e.g., for rice cultivation) degraded soils (loss of organic matter, salinization) and depleted ground water tables (Molden, 2013; World Bank, 2008). Extensification of agriculture, on the other hand, as in SSA, causes degradation and loss of forests and wetlands for crop production. This in turn reduces the level of biodiversity and undermines the contribution of forests to pollination[13] and the natural regulation of water quality (IPBES, 2019) and climatic conditions (through carbon sequestration). Continuous cultivation of the soil without adequate soil nutrient replenishment[14] and encroachment into marginal lands further

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[10] Excluding Pacific countries and Central and Western Asian Countries.
[11] It contributed 6.6 percentage points out of the 64 percentage points increase in total production.
[12] This is faster than cereal output growth (1.6%), in part because yield increases following Green Revolution practices and mechanization also came along with a net worker exit out of agriculture in addition to the shift to higher value crops.
[13] For example, by eroding the ecosystem, crop-driven deforestation has led to the extinction of vulnerable species that contribute to pest control and pollination (Hendershot et al., 2020)
[14] While inorganic fertilizer use is wastefully high in some parts of the world where intensive agricultural practices are applied (e.g., Asia), it is much too low in most of Sub-Saharan Africa to keep up with soil nutrient depletion

induces soil erosion and a depletion of soil nutrients (including carbon), reducing crop yields and agricultural labor productivity. Through soil erosion and flooding downstream (given loss of water retention upstream) the effects of deforestation and soil erosion are felt well beyond the localities where they occur.

3.2 Agri-food as indirect polluter

The AFS is central to the global climate change mitigation efforts; it accounts for about a third of total anthropogenic GHG emissions. Indirect environmental externalities from the AFS include the emission (or reduced sequestration) of GHG gases (carbon dioxide (CO_2) and especially methane (CH_4)) generated through its on- and off-farm activities (Table 3). They indirectly affect output and labor productivity in the AFS through their effects on climate change. Globally, GHG emissions from the agri-food system account for about a third of the total anthropogenic GHG emissions (Table 3; Crippa et al., 2021). In 2019, they were estimated at about 16.7 gigatonnes (Gt) CO_2-equivalent emissions per year ($GtCO_2$-eq yr^{-1}) (FAOSTAT). Reducing GHG emissions in the AFS is central to the global climate change mitigation efforts. It is an important channel through which the world's green transition will affect AFS job outcomes.

On-farm land based AFS activities (including land use and land use change for agricultural purposes) account for the bulk of the AFS related GHG emissions (Table 3, Mbow et al., 2019; Crippa et al., 2021). Their share in total AFS related emissions is estimated at 65.4 percent. As a share of global anthropogenic emissions, crop and livestock activities within the farm gate and land use and land use change associated with agriculture (such as deforestation and the drainage and burning of organic soils, including peatlands) are estimated to contribute 15-28 percent (or about 10.8 CO_2-equivalent per year in 2019): 10–14 percent from agriculture[15] and 5-14 percent from land use change activities[16] (Mbow et al., 2019).

Three land-based AFS activities–-cattle rearing, land use change (deforestation and peatland degradation), and rice cultivation–-account for most on-farm gate and land use change related GHG emissions (Table 3)**.** Ranked by GHG emission shares, cattle rearing (for beef and dairy) is the most damaging (23.8 percent of AFS CO_2-equivalent emissions), followed by deforestation (17.6 percent), drainage and burning of organic soils (including peatlands) (5.5 percent), and rice cultivation (4

from regular crop cultivation and soil erosion. The average fertilizer application rate in Sub-Saharan Africa is 22 kilograms per hectare. This compares to a world average seven-times higher (146 kilograms per hectare). In some countries, such as China and Chile, fertilizer application rates are as high as 400 kilograms per hectare.

[15] According to FAO, in 2019 7.3 CO_2-equivalent per year comes from agriculture.

[16] According to FAO, in 2019 3.5 CO_2-equivalent per year comes from land use change.

percent). These activities are each concentrated in few continents (Figure 3), cattle in Asia and the Americas, deforestation (in Africa and Latin America), and rice in Asia (Annex 4a and 4b). Finally, the overall AFS GHG contribution share of synthetic fertilizer is 6.1 percent (3.6 percent points related to its use and 2.5 percent related to its manufacturing). There are important GHG gains from the reduction of inorganic fertilizer use, especially where there is excess application (Asia, Western Europe).[17] At the same time, its benefits for raising labor productivity in agriculture should not be ignored, especially where soil nutrient depletion is rampant as in SSA (Stewart et al. 2020). In much of SSA, substantial increases in N inputs could be absorbed (up to 100kg n per ha) and increase yields with little risk of increased N_2O emission (Richards, et al., 2016).

Emissions from livestock contribute the largest share of total AFS-related GHG emissions, estimated at 2–3.6 $GtCO_2$-eq yr^{-1} (Herrero et al., 2016). The highest contribution comes from the enteric fermentation from ruminant animals[18] (mostly cattle, for meat and dairy) through CH_4 emissions (16.9 percent of total AFS GHG emission), followed by manure deposited on pastures (4.6 percent), and manure management (2.3 percent). Adding indirect emissions from land use change, energy use, and transportation, the global contribution of the livestock sector to GHG emissions amounts to about 5.3 ±1.6 $GtCO_2$-eq yr–1 (Gerber et al., 2013) or about one-third of total AFS emissions. Across regions, 67.9 percent of the global GHG emissions from enteric fermentation of livestock production is generated in Asia (35.7 %) and the Americas (32.2 %). Sub-Saharan African countries generate less than 16 percent, mainly attributable to Ethiopia and Chad. Across lower-middle income countries, India and Pakistan are the largest contributors (13.8 and 4.5 percent, respectively), with Brazil, China, and Argentina the main contributing countries in the upper-middle income country category (Figure 3 and FAOSTAT).

Land use and land use change, in particular deforestation and degradation of organic soils (i.e., activities instrumental to preparing land for agricultural use), represent another major source. They add 4.9 ± 2.5 Gt CO_2-eq yr–1 (Mbow et al., 2019). Across tropical Regions, where many low and lower-middle income countries are located, approximately half of total forest loss during 2001-2015 was driven by agricultural extensification. In Africa and Latin America, agricultural extensification for smallholder agriculture accounts for an estimated 92 percent and 31 percent of total forest loss (Curtis et al., 2018). Together, Africa and the Americas are responsible for almost 83 percent of global emission

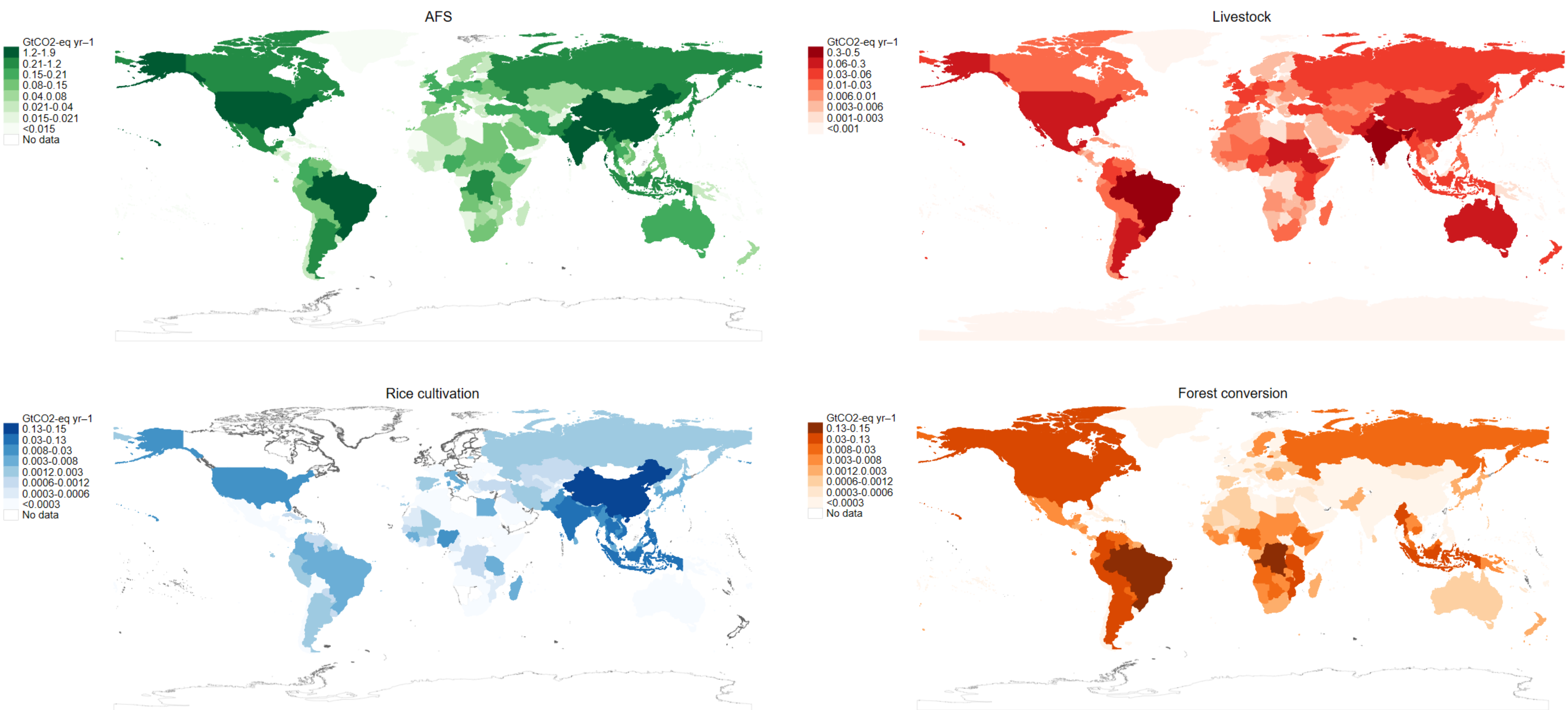
[17] Gao and Serrenho (2023) estimate that the production of nitrogen fertilizers accounts for about a third of their total GHG emissions, with the remaining two thirds released after their deployment in croplands, especially due to overuse. Increasing nitrogen-use efficiency is the most effective strategy to reduce emissions from nitrogen fertilizer.

[18] According to FAO data, GHG emissions from enteric fermentation accounts for 2.8 $GtCO_2$-eq yr–1, or 16.9 percent of total AFS GHG emissions.

from forest conversion, with 3 countries (Brazil, Congo DR and Indonesia) generating half of total emissions from forest conversion (FAOSTAT).

The third major source of "on farm" related GHG emission relates to methane emissions from lowland and irrigated rice cultivation. GHG emissions from rice cultivation are mainly linked to the emission of methane in flooded rice fields. Methane is generated during the anaerobic decomposition of organic material when paddy fields are flooded. It escapes to the atmosphere through diffusive transport through the rice plants during the growing season. Rainfed upland or rainfed, non-flooded lowland rice production systems, which dominate in Sub-Saharan Africa, do not produce significant quantities of methane (Table 2, Sass, and Yagi, 2000). Unsurprisingly, the majority of GHG emissions from rice cultivation is generated in Asia (86.5 percent of total GHG emissions from rice cultivation), followed by Africa (7.5 percent) and the Americas and Europe (4.4 percent and 1.5 percent). China, India, Indonesia, Thailand, Philippines, and Viet Nam account for the majority of the Asia's GHG contribution from rice (79.5 percent). Nigeria is the largest contributor in Africa, accounting for almost one-third of all rice related GHG emissions from Africa, but only 2 percent of the global GHG emissions from rice production (Figure 4 and Annex 5).

Figure 4. CO2-equivalent emissions in GT per year by country and most polluting agricultural activities.



Notes**:** Data are for 2019. Emissions from the livestock sector include 1) enteric fermentation, 2) manure left on pasture and 3) manure management.

Source: FAOSTAT (2022) for the year 2019. Available at https://www.fao.org/faostat/en/#data

Off-farm AFS activities are estimated to account for about 35 percent of total AFS GHG emissions. Food waste is estimated to account for almost 15% of total AFS emissions (Table 3), representing the largest contributor to total AFS emissions from downstream activities. Despite an overall reduction in GHG emissions from waste management from developed countries[19], in developing countries GHG emissions due to poor waste management continue to increase, more than offsetting the reductions in developed countries (Crippa et al., 2021). Emissions from food distribution are the second source (11.3 percent of total AFS GHG emissions). They are mainly linked to energy use in retail (refrigeration), transportation (road transport) and processing (packaging), and concentrated in industrialized countries (Crippa et al., 2021).[20]

These findings suggest that AFS job exposure to AFS GHG mitigation efforts is likely spatially concentrated and relatively limited as a share of overall AFS employment. AFS GHG emissions in developing countries are concentrated in three subsectors, livestock/cattle, deforestation and organic soil degradation, and rice cultivation, the importance of which varies greatly across continents and countries and with rice being particularly labor intensive. AFS employment in Asian countries, which house large populations of cattle and which depend greatly on domestically produced rice in flooded fields, are likely most affected, followed by a number of countries in Latin America such as Brazil (deforestation and cattle). Job exposure in SSA will more modest. It is mainly linked to efforts to reduce deforestation and organic soil degradation. Flooded rice production in SSA (irrigated and lowland) has so far remained limited. Similarly, the population of ruminants (cattle, sheep, and goats) remain relatively modest.

As countries develop, efforts to reduce GHG emissions will increasingly need to shift towards off-farm AFS activities, as their share in total AFS GHG emissions also increases.[21] Value chains elongate and packaging and refrigeration become more widely used, while post farm food waste increases. Similarly, the off-farm AFS share of employment also increases, though overall, relatively fewer people will be

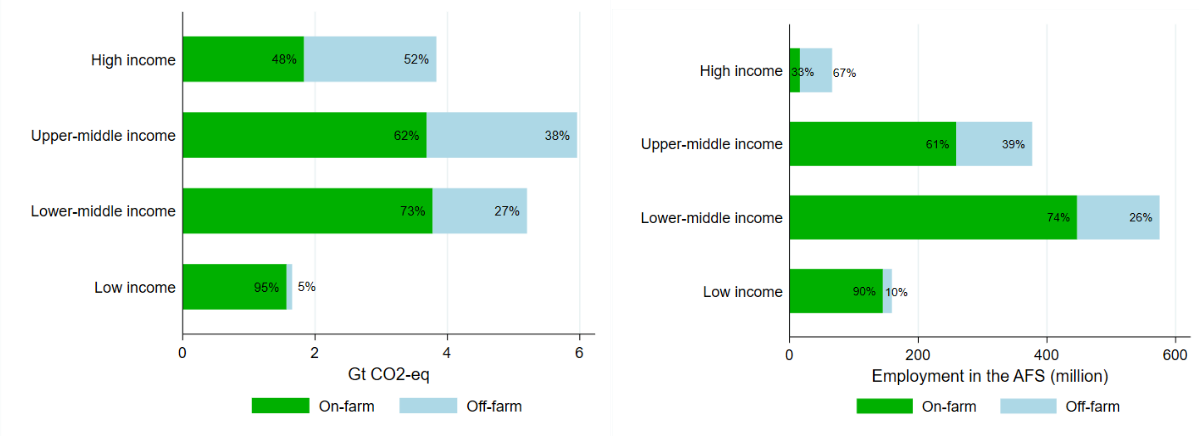
[19] This includes the energy use related to the treatment of solid waste (more particularly the organic biomass fraction of that waste) and organically degradable carbon in wastewater (Crippa et al. 2021).

[20] Food retail has the highest contribution (5.6% of total AFS GHG emissions) within the food distribution chain. The majority of total emissions from food retail comes from food refrigeration in industrialized countries, projected to rise worldwide given the expansion of cold chains and the rise of supermarkets in the food distribution across the world (Weatherspoon & Reardon, 2003). Local and regional food transport represents the second highest source of emissions within food distribution (3.2% of total AFS GHG emissions), mainly driven by road transport (81% of total food transport GHG emission) (Crippa et al., 2021). Finally, food processing represents the third source of contribution to total AFS GHG emissions within food distribution (3.1% of total AFS GHG emissions), mainly through packaging of beverages, fruits and vegetables (Crippa et al., 2021, Poore & Nemecek, 2018).

[21] In high income countries, the GHG emission per off-farm AFS worker also exceeds the GHG emission per on-farm AFS worker. To minimize the employment effect of GHG mitigation, reducing GHG emissions in the off-farm AFS segment becomes more efficient (i.e., maximizing GHG reduction per job affected).

affected by AFS mitigation efforts (on and off the farm) in high income countries, as the total number of AFS jobs decreases as a share of total employment as countries develop (Figure 5).

Figure 5 GHG emissions and employment per country income grouping



Source: own calculation based on ILOSTAT and FAOSTAT.

3.3 AFS job exposure to climate change

Climate change affects agriculture and jobs in AFS through three channels. The increasing concentration of GHGs in the atmosphere, partially released by the AFS, traps heat in the atmosphere, driving global warming and climate change. Climate change affects agriculture through 1)) greater frequency and intensity of *extreme* weather events (droughts, floods, heat waves, hurricanes), 2) gradually changing and more irregular weather patterns more broadly (temperature, rainfall patterns, onset and length of growing days) (Abbass et al., 2022) and 3) its effects on biodiversity. With most agriculture still rainfed, and thus fully exposed to the vagaries of the weather, the occurrence of extreme weather events and gradually changing weather patterns affect harvests and agricultural labor productivity directly. Over time, they also affect biodiversity as species migrate or become extinct, unable to withstand the changing weather patterns. This reduces the ecosystem services provided for example by pollinators and pest and pathogen predators, negatively affecting agricultural productivity.[22] Ortiz-Bobea et al. (2021) esimate that aanthropogenic climate change has already reduced global agricultural total factor

[22] For example, pollinating species provide higher quantity and quality of crops (Klein et. Al. 2007), in addition to preserving crop yield stability (Garibaldi et. Al. 2011). Pest controllers, instead, support crop productivity indirectly, by preserving crops from being affected by pests and pathogens.

productivity by about 21% since 1961, a slowdown equivalent to losing the last 7 years of productivity growth.

The effects of climate change on agricultural production will be particularly acute in Sub-Saharan Africa (Nhemachena et al., 2020). First, agricultural production systems in SSA are more weather dependent than in other continents (Africa has the lowest rate of irrigation) (Derbile et al., 2016). Moreover, mean precipitation is projected to decline further, while the surface temperature in Africa has already increased faster than the global average, exposing the continent to higher frequency and severity of heat waves and droughts (IPCC, 2021).

Climate change may further also affect the productivity of agricultural workers directly, in addition to its effects on crops and livestock production**.** It is estimated, for example, that the number of hours worked in agriculture is 40% lower in Africa during a heat wave compared to a normal week (Nico & Azzarri, 2022).[23] Further analysis shows that this does not only follow from lower crop output following heat (and drought) resulting in lower labor demand for crop planting, maintenance (weeding) or harvesting, but also from a decline in the intensity and number of hours worked due to the heat (Yengoh and Ardö, 2020).

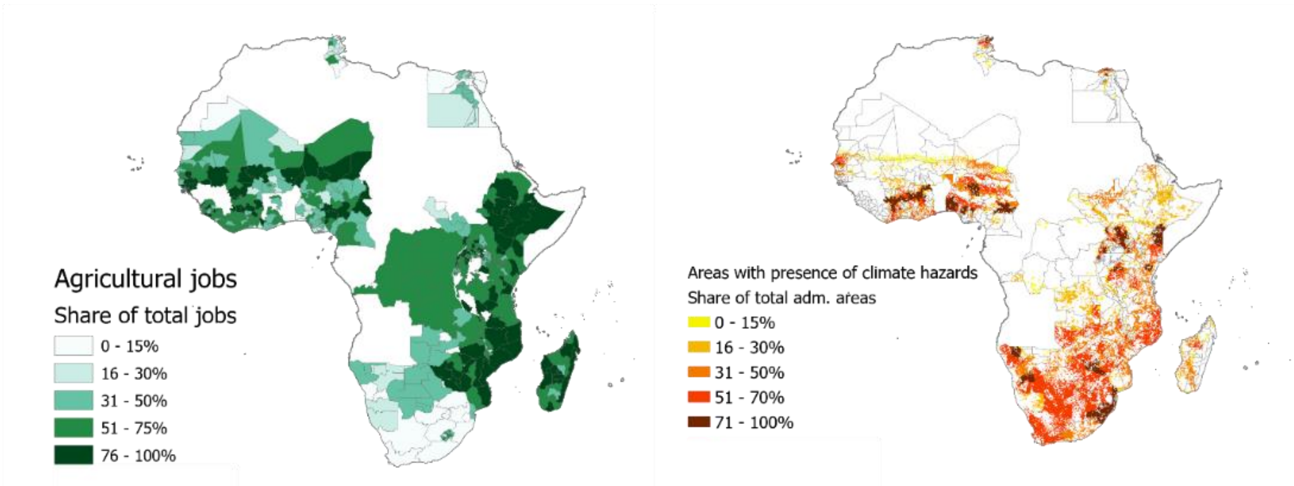
The number of on-farm jobs in Africa potentially affected by climate change is substantial. To further assess the exposure of AFS workers to climate change, the locations of past and predicted occurrence of extreme weather events (see Safavi et al. 2020 for detail) were overlaid with the spatial distribution of on-farm employment in 31 African countries (Box 1).[24] It shows that about a quarter of agricultural on-farm workers (self- employed and wage) in these countries live in areas where more than half of the area is exposed to climate hazards (now or in the future**),** corresponding to about 43.4 million jobs (Figure 6, Annex 6). Across African Regions, agricultural job exposure to climate change is particularly severe in the Southern and Western African Region, with an estimated 81 and 35 percent of agricultural workers living in regions or districts widely affected by climate hazards (Annex 6). Clearly, exposure of on-farm AFS jobs to climate hazards is substantial. This still ignores the widespread exposure to the gradual change in weather patterns, the second channel through which climate change affects AFS jobs, such as the changing onset and closure of the growing seasons, the more irregular, but more intense precipitation patterns, and the changing temperatures. This will affect a much larger set of farmers.

[23] The lower work intensity may result both from lower crop output as well as lower productivity of labor when temperatures are high (the direct effect), the effect one is really interested in in measuring.
[24] As the effects of climate hazards on AFS workers off the farm is more indirect, these are excluded.

Figure 6 On-farm AFS job exposure to climate hazards is substantial, especially in Southern and Western Africa

Panel A: Share of agricultural workers (jobs) by administrative areas.

Panel B: Share of total administrative areas with presence of climate hazards (drought, flood, climate, variability, future growing season contraction and high temperatures)



Note: estimates of agricultural workers based on data extrapolated from 31 African surveys. Labor force surveys conducted in Botswana, 2006; Egypt, 2017; Madagascar, 2015; Mauritania, 2017; Namibia, 2018; Rwanda, 2017; Sierra Leone, 2014; South Africa, 2017; Tunisia, 2014; Zambia, 2018; Zimbabwe, 2019; household income and expenditure surveys conducted in Burkina Faso, 2014; Cameroon, 2014; Chad, 2019; Congo, Democratic Republic of the, 2011; Côte ''Ivoire, 2008; Ethiopia, 2016; Gambia, 2016; Ghana., 2014; Kenya., 2015; Lesotho, 2003; Liberia, 2016; Malawi, 2016; Mali, 2018; Mozambique, 2015; Niger, 2014; Nigeria, 2013; Senegal, 2011; South Sudan, 2016; Tanzania, United Republic of, 2013; Uganda, 2016.
Estimates of areas with presence of climate hazards based on spatial data provide by Safavi, N.; Thornton, P.; and Wollenberg, E., 2020, "Global spatial data for agricultural GHG emissions and climate hazard”".

Source: Own calculations and Safavi, N.; Thornton, P.; and Wollenberg, E. (2020).

While inevitably coarse, the findings highlight how adoption of adaptation measures in African agriculture will be key to protect on-farm AFS jobs from the more frequent occurrence of climatic shocks as well as the gradually changing climatic patterns. How such a green transition may affect AFS jobs will be explored in more detail in sections 4 and 6.

Box 1: Estimating on farm AFS job exposure to climate hazards

To provide a first approximation of the potential effect of climate hazards on on-farm AFS jobs, representative non-georeferenced information at aggregated administrative levels on household occupation from 31 African countries is combined with georeferenced information on the past and future occurrence of climate hazards. In particular, data extracted from labor force and household income surveys of 31 African countries are used to generate subnational estimates of the total number of agricultural workers living in 545 administrative areas (first or second level of administration[25], as shown in Figure 3, panel A). Second, a raster dataset with information on the presence of climate hazards for agriculture–such as drought, flood, climate variability, future growing season contraction and high temperature (Safavi et. Al. 2020), was used to calculate the area size affected by the presence of climate hazards for agriculture, in each of the 578 administrative (Figure 3, panel B). While coarse, this statistical exercise confirms that climate hazards extend over a wide geographic area of Africa (27.1% of the total size area [26]), making the adoption of adaptation measures in agriculture key to protect oneself from the greater occurrence of climatic shocks as well as the changing climatic patterns.

4 AFS job prospects without corrective action

Environmental degradation will affect AFS jobs, but in the absence of agricultural models that explicitly incorporate the effects on labor, the prospects are hard to assess. Environmental degradation, both through climate change and the depletion of the natural resource base, substantially challenges the current food system (Abbass et al., 2022). Since the 1960s, an estimated 7 years of total factor productivity growth have already been lost globally due to climate change, most of it occurring since the 1980s (Ortiz-Bobea et al., 2021). For Africa, the State of Climate Change in Africa 2021 report indicates that increased temperature has contributed to a 34 percent reduction in agricultural productivity growth, more than in any other region (WMO, 2021). Slower agricultural productivity growth makes it more difficult to meet the world's increasing food demand without agricultural land expansion. It also slows down the structural transformation by decreasing the productive release of labor out of agriculture. In the absence of climate-informed agricultural models that explicitly incorporate the effects on

[25] The level at which subnational estimates of agricultural workers were calculated reflects the level of representativity of the survey (region, district, or village).
[26] Across the 545 administrative areas covering 31 African countries and expanding over an area of 18.3 million km^2, almost 5 million $km^2$is exposed to climate hazards.

employment in agri-food, the implications of environmental degradation for jobs in agri-food are hard to assess, however.[27]

Existing modeling outcomes of the effect of climate change on crop yields combined with estimates of the relationship between yields and agricultural employment offer a starting point. Different agricultural land use and integrated assessment models exist that project agricultural performance indicators across the globe, including crop yields and agricultural land use, under different climate change and socio-economic scenarios (van Zeist et al., 2020). The difference in the on-farm AFS employment share associated with the integrated assessment model projected cereal yield in 2050 under a particular climate change and socio-economic scenario (such as climate change without corrective action) and the projected 2050 cereal yield without climate change, then provides a first order estimate of the direction and magnitude of the expected on-farm AFS job effects of climate change. Given the central role of agricultural productivity for structural transformation (Gollin, Parente, and Rogerson, 2002; Alvarez-Cuadrado and Poschke, 2011; Ivanic and Martin, 2018), a tight (non-linear) relationship between the share of on-farm AFS employment and cereal yields is expected, especially in low- and lower middle-income countries, where the world's agri-food employment is concentrated (section 2.1). This relationship can be empirically estimated using the cross-country evolution over the past decades of on-farm agricultural employment and cereal yields. The effects on off-farm AFS jobs are not explicitly estimated. They are more indirect, with a slowdown/acceleration in agricultural labor productivity conjectured to slow down/accelerate the development of off-farm AFS employment.

In what follows, the SSP2/RCP8.5 scenario is considered the business-as-usual (BAU) scenario, run up to 2050 and representing the upper end of climate change without corrective action and middle of the road assumptions regarding population and economic growth. Climate change scenarios are ranked based on the underlying Representative Concentration Pathways (RCPs) (RCP1.9 – RCP8.5)[28],

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[27] One exception is found in the ILO report 'Greening with jobs' (ILO, 2018). The ILO report estimates the number of net jobs created across economic sectors in scenarios associated with a low-carbon and resource-efficient economy. It relies on multiregional input-output tables to map inter-industry flows of intermediate goods and services within an economy. The indirect effects on jobs are taken into account by considering how changes in inputs used by one industry (such as fertilizer use in agriculture) affect the output of other interconnected industries (e.g., fertilizer manufacturing). To estimate the indirect effects on jobs, the ILO considers two factors: the number of workers required to produce a particular input and the impact that reducing input use in other industries produces on workers across the supply chain. The model estimates a loss of 120 million jobs in agriculture, due to the transition from traditional to conservation agriculture in developing countries and organic agriculture in developed countries. The job losses in agriculture are largely due to lower labor requirements under conservation agriculture. However, the ILO model is static and does not consider future demographic trends or the potential effects of land extensification on job requirements in agriculture.

[28] Representative Concentration Pathways (RCPs) present different scenarios of GHG emissions for the 21st century, each leading to different global warming scenarios, with different projected temperature, precipitation, and sea level

while different Shared Socioeconomic Pathways (SSPs) (1-5) represent different assumptions on population expansion, urbanization, and economic growth[29] (Robinson et al., 2015). The RCP8.5 scenario anticipates a temperature increase between 3.2°C and 5.4°C by 2100 (relative to pre-industrial levels (1750)) (and by about 2°C by 2050)., The SSP2 scenario uses middle-of-the-road assumptions regarding population expansion and economic growth. The SSP2/RCP8.5 combination represents a scenario with little mitigation efforts, high CO_2-equivalent emissions, and substantial warming and sea level rises, thereby delineating the effects on agriculture of a more extreme climate scenario. The BAU scenario will further serve as a benchmark to assess the potential impact of accelerated investments in sustainable agricultural practices (section 6), i.e., the AFS jobs impact under a "green transition". The climate data (temperature, precipitation, sea level rise) are usually projected into 2100, with 2050 often an intermediate reference point. The focus here is on 2050, with uncertainty on yield predictions only increasing, the further out one predicts.

4.1 From integrated agricultural model to AFS jobs outcomes

Integrated agricultural models are used to estimate the impact of climate change on agricultural performance indicators by combining climate, biophysical, and economic models. These models assume that climate change leads to a reduction in biophysical crop yields, which ultimately results in lower agricultural production and increased prices. The climate and biophysical models evaluate the potential impact of environmental factors, such as temperature and rainfall patterns, on crop yields. The results from the climate and biophysical model are then incorporated into the economic model, which considers how farmers and consumers respond to changes in production and prices (Nelson et al., 2014). The economic model simulates long-term changes in agricultural performance indicators such as yields, crop area, food consumption, and crop prices.

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rise ranges. Four RCPs were considered for the fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPPC) in 2014. They are labelled according to the possible range of radiative forcing values in 2100 (2.6, 4.5, 6 and 8.5 W/m^2 respectively). They correspond to different CO_2 equivalent concentrations paths and end points and different changes in temperature, precipitation patterns and sea level rise, which are calculated by feeding the respective RCPs into Earth Simulation Models (ESMs) (formerly called Global Circulation Models (GCMs)). Overall, the larger is the radiative forcing, the larger is the Earth's warming. *[Pro memory, radiative forcing is the difference in energy that enters and leaves the Earth's atmosphere (expressed in W/m^2) (https://climate.mit.edu/explainers/radiative-forcing). When positive, for example because of an accumulation of greenhouse gases that prevent solar radiation absorbed as heat by the Earth from escaping the Earth's atmosphere into the colder surrounding space, the Earth's atmosphere warms up.]*

[29] Additional RCPs have been added since AR5 (RCP1.9, RCP 3.4 and RCP7) and the RCPs are now considered together with the Shared Socioeconomic Pathways (SSPs). The latter include different scenarios of socio-economic development, related to population, urbanization, and economic development, to provide a more joint-up, internally coherent socio-economic and climate narrative. The same SSP can come along with different RCPs depending on the mitigation/adaptation efforts (https://climatedata.ca/resource/understanding-shared-socio-economic-pathways-ssps/).

4.1.1 The effects of climate change on yields

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) version 3.1 is used here to generate projections on crop yields by region to 2050. At IMPACT's core is a global, partial equilibrium, multi-market, agriculture sector model (Robinson et al. 2017; Figure 7).[30] Climate models (Earth Simulation Models) further provide climate data (temperature and precipitation) as inputs to the crop and water simulation models based on the chosen RCP. These links are one way, from these models to the multimarket and water models. The crop models enable calculation of the expected crop yields under different climate scenarios.[31] The water models are dynamically linked to the multimarket model, with two-way flows of information over time. They balance the demand and supply of water (with the supply depending on the climate scenario) and each year optimally allocate water across competing nonagricultural and agricultural uses, including irrigation. Food supply is determined for 320 sub-national or national geographic units (Food Production Units (FPUs)) delineated according to intersections of administrative units (mainly countries) with major river basins. The macroeconomic trends affecting water and food demand reflect projections from demographic and economic growth models. Projected performance indicators by region include production, area, yields, food consumption, commodity prices, and trade.

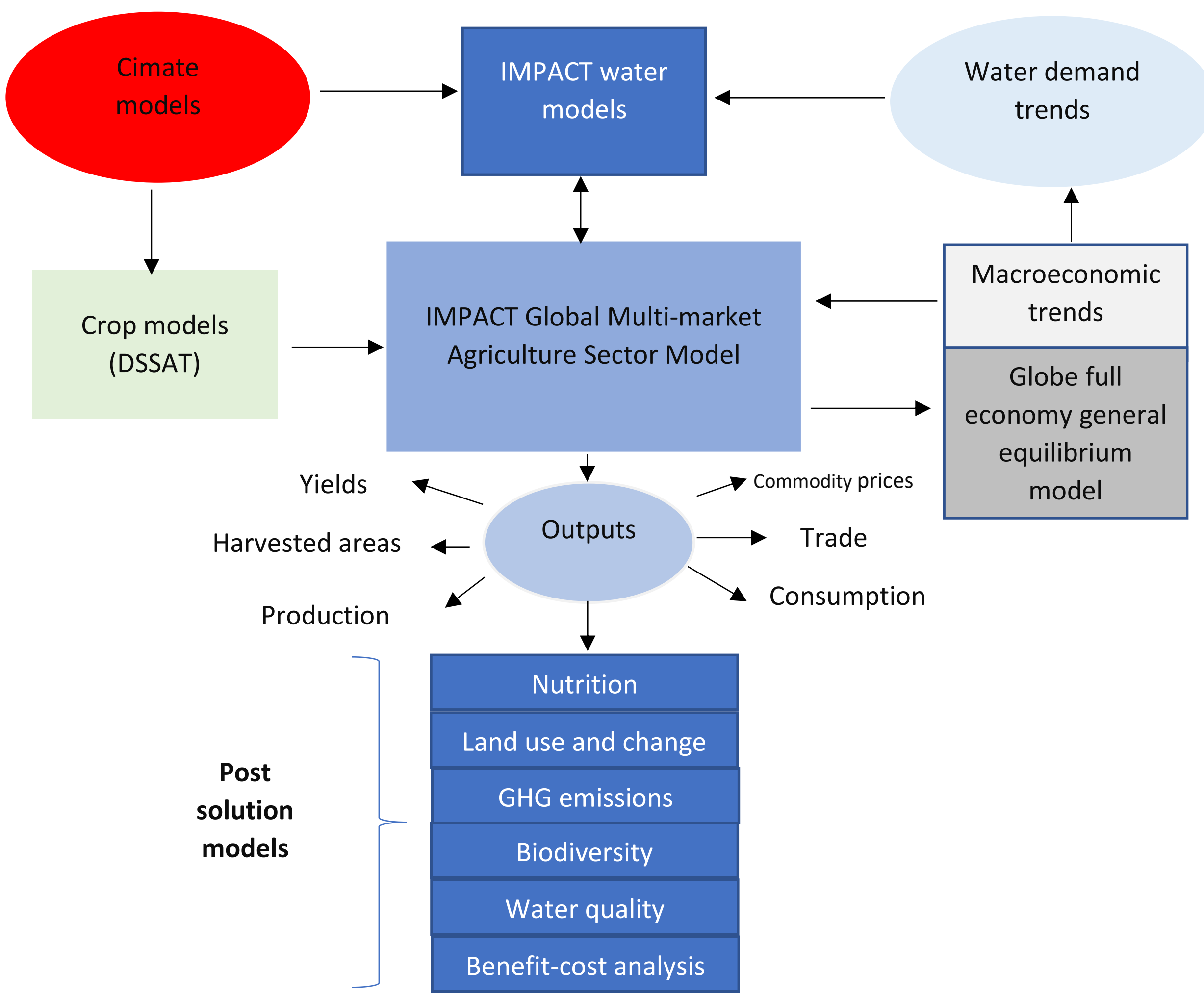
Irrigated and rainfed crop yield and area changes follow from both exogenous (yield trends and climate change) and endogenous (prices) sources. Exogenous sources include regional and crop-differentiated yield improvement trends (informed by public and private sector investment trends in agricultural research and development) as well as impacts from climate change (calculated using the DSSAT crop models). Endogenous sources include (annual) farmer responses to changing input and output prices (for example by adjusting fertilizer, chemical and labor use) as well as changing water availability (as calculated through the water model).

Climate change affects yields through two channels. First, it affects crop yield outcomes for rainfed and irrigated crops as calculated from the solution of the DSSAT crop models given the differing temperature and precipitation patterns associated with the different climate scenarios. Second, it also

[30] For a review of different agricultural land-use and integrated assessment models, see the Agricultural Model Intercomparison Project (AgMIP) (https://agmip.org/).
[31] Crop models are mechanical biophysical models that calculate expected crop yields based on genetic (crop variety, length of growing period), climate (temperature, rainfall,) and environmental (soil) inputs. The Decision Support System for Agrotechnology Transfer (DSSAT) Crop System model used by IMPACT further allows for examining the effects of crop management (e.g., soil management, fertilizer use). DSSAT is a widely used crop model to explore the effect of climate change (Gunawat et al. 2022), but, as other crop models, it does not contain economic factors, such as farmers' behavioral responses to input/output price changes. These responses are accounted for through the partial equilibrium multi-market model.

affects the water availability for agriculture (including for irrigation) under different climate scenarios as calculated through the water model. As the different climate scenarios generate gradually changing temperature and precipitation patterns, the IMPACT model does, however, not consider the effects of climate variability or extreme events such as droughts or shocks. Given the one-way direction from the climate model to the multi-market model (via crop and water models), the effects of climate change mitigation (including through endogenously determined land use change) are also not accounted for beyond what is implicitly assumed in the chosen RCP.

Figure 7. Schematic presentation of the IMPACT model



Source: Rosegrant et al. 2017.

Core assumptions of the model. "Middle-of-the-road" assumptions about population and per capita GDP growth, as defined under IPCC Shared Socio-Economic Pathway 2 (SSP2), are used to project future food demand (Table 4). They are the exogenous drivers of food demand and are the same under all scenarios that will be considered (but differ by country/region).[32] Food demand is further endogenously determined by changing prices. As indicated above, an exogenously determined trend growth in agricultural TFP is also imposed. This is motivated and informed by the historical and projected trend investments in agricultural R&D, which translate with a lag into productivity growth. Agricultural R&D is hereby generically defined, including extension. Water resource management and allocation across sectors (agriculture, livestock, domestic and industrial use) is modeled endogenously by linking the partial equilibrium agricultural model to a suite of water models the parameters of which are also informed by the climate scenarios. The climate change scenario considered is RCP8.5.

Table 4. Exogenous assumptions in the IMPACT model.

Exogenous assumption	Projection to 2050	Source
Global population growth	9.2 billion	IPCC's Shared Socio-Economic Pathway 2
GDP growth	GDP US$(PPP) 230 trillion. Global average of US$(PPP) 25,000 per person by 2050; huge regional variation remains; GDP/capita in developing countries still less than half this in developed countries, with wider regional differences remaining	IPCC's Shared Socio-Economic Pathway 2
Rapid climate change	RCP 8.5 pathway predicts a temperature increase by about 4.3˚C by 2100 (between +3.2 and +5.4 °C) relative to pre-industrial temperatures (1750) and by about 2˚C by 2050 (between +1.4 and +2.6 °C).	Representative Concentration Pathway 8.5 (RCP8.5), as modeled by the HadGEM general circulation model (GCM)

Source: Rosegrant et al. 2017.

Three climate change scenarios are considered: 1) no climate change; 2) business as usual (RCP 8.5); and 3) BAU with climate corrective investments. A first scenario assumes *no climate change*. Strictly speaking, this is a scenario with no climate change from 2005 onwards, which is in fact similar to the RCP2.6 scenario (+0.6-1.6°C by 2050). In what follows, this will be referred to as the 'no climate change' scenario. A second scenario considers the effects of *rapid climate change* (as defined under Representative Concentration Pathway 8.5 (RCP 8.5), which corresponds to a 2°C increase by 2050, and a 3.2-5.4 °C increase by 2100). As in Rosegrant et al. (2021), the second scenario is taken here as the

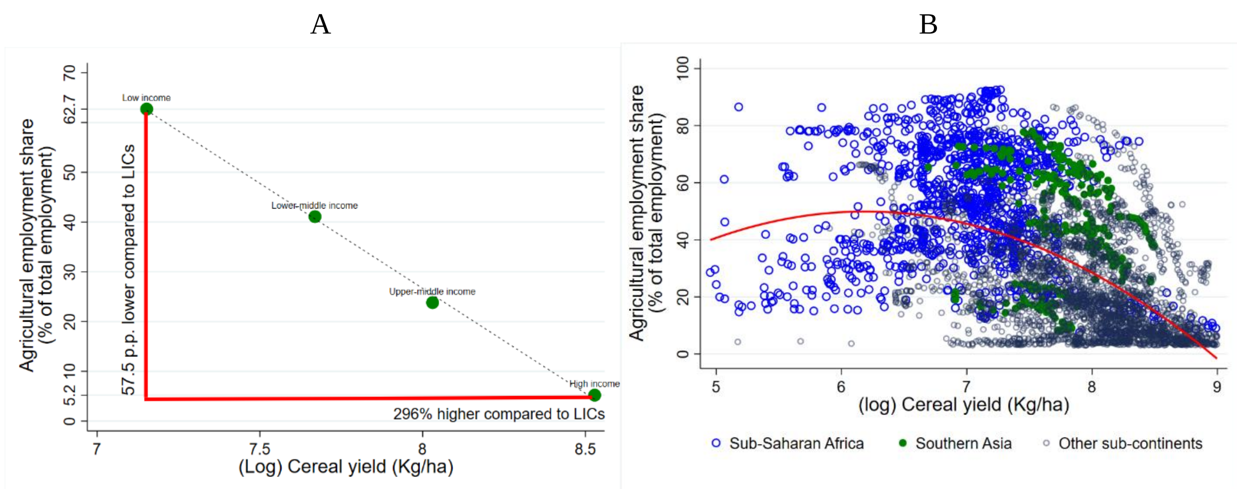
[32] Annual GDP growth for Sub-Saharan Africa, for example, is faster than the global average (5.4 vs 3.13 percent per year, or 3.49 vs 2.38 percent in per capita terms)), reflecting catch up growth. Nonetheless, GDP per capita in SSA remains still only a third of the global average in 2050 (US$ppp 8,000 vs 25,000 respectively).

reference or business-as-usual (BAU) scenario. Under both scenarios, investment in agricultural research and development (R&D) continues as usual (with SSP2 assumptions on population and economic growth), while no corrective actions to mitigate the effects of climate change are considered. The third scenario consists of BAU with a host of climate smart agricultural investments. IMPACT based yield projections under the first two scenarios are compared in the remainder of this section to tease out the expected effect of climate change by 2050 on yields (section 4.2) and AFS employment (section 4.3). IMPACT based yield projections under the third scenario will form the basis for discussing the effects of a green transition on AFS jobs (section 6).

4.1.2 From yield changes to AFS job impacts

Agricultural productivity drives structural transformation. As discussed in section 2.1, the share of employment in agriculture declines as countries develop (GDP/capita raises). This is typically mediated through an increase in agricultural productivity, especially of staple crop productivity and more pronounced in lower income settings where subsistence requirements are still important (Emran and Shilpi, 2018; Gollin, Parente, and Rogerson, 2002; McArthur and McCord, 2017)). A common and widely available measure of agricultural productivity is land productivity or yield (output/ha), particularly cereal yields. The strength of the empirical regularity between both variables is illustrated in Figure 8, Panel A. It displays a virtually perfect fit between the average agricultural employment share by country income level (LIC, LMIC, UMIC, and HIC) and the cereal yield level (expressed in logarithmic terms).

Figure 8. Observed relationship between yield growth and the share of agricultural employment



Source: Own calculations using ILOSTAT (share of agricultural employment) and FAOSTAT (cereal yields).

Instrumental variable estimation lends credence to the notion of cereal yields as causal driver of agricultural employment shares. The close correlation between rising cereal yields, GDP growth, and a declining employment share in agriculture (structural transformation) was also conceptually elaborated and econometrically established through 1960-2000 cross-country regression analysis by McArthur and McCord (2017). They estimate that a 0.5 ton increase in cereal yields is associated with a 1.65 percentage points lower share of the labor force in agriculture 5 years later, when using country fixed effect estimation, and a nearly 5 percentage point decrease when also instrumenting yields to control for confounding factors that are both correlated with the agricultural employment shared and yields[33]. Through the instrumentation, they also establish that cereal yield increases causally drive the structural transformation, especially in lower income countries and settings. The estimated magnitudes of the effect of yields are similar when controlling for a host of other macro-economic factors such as government investment, inflation, government consumption, total fertility rate. Cereal exporters experience a lower decline in the agricultural labor share when yields increase, consistent with the predictions of Matsuyama (1992) that increased productivity in open economies with a comparative advantage in agriculture (e.g., Argentina, Thailand, South Africa) may lead to specialization in agriculture and a slowdown (or even reversal) in the agricultural labor exit. Finally, they show that the contemporaneous and lagged effects of yields on agricultural labor shares are similar for the first 8 years after which the effects dissipate. In their estimations, they use a 5-year lag.

Quantification of the relationship between cereal yields and agricultural employment shares can thus in principle help estimate the effects of climate change and climate corrective investments on AFS jobs. Doing so, requires some additional assumptions, including that the estimated relationship is accurate, that it remains stable over time as countries develop, and that it retains its relevance as technology changes (for example through a shift to more climate smart agricultural practices that tend to be more labor intensive). The extent to which these assumptions hold will be assessed. To obtain the total number of AFS jobs lost or gained under the different climate scenarios, the population growth assumptions of SSP2 are taken. As longitudinal data on AFS (as opposed to on-farm AFS) employment shares are not available for most countries, the empirical application focuses on agricultural (or on farm AFS) employment as dependent variable.

In particular, the following equation is estimated using Ordinary Least Squares. Longitudinal annual data from 11 sub-continents, spanning 1990 to 2020, are used to estimate the relationship between the share of agricultural employment (i.e., on farm AFS employment) and cereal yields. The link is specified

[33] The interaction of the global fertilizer price with the cost adjusted distance to the nearest nitrogen production site is used as instrumental variable.

as a quadratic relationship to allow for non-linear (decelerating) exits out of agriculture as yields increase. The specification further controls for the level of mechanization in the country (expressed in metric horsepower)[34] and subcontinental differences. This helps control for the degree of capital/labor substitution:

$$Share\_Emp\_agr_{r,t} = \alpha + \beta_1\left(Log\_yield_{r,t}\right) + \beta_2(Log\_yield_{r,t})\text{^}2 + \beta_3\left(Log\_mech_{r,t}\right) + \beta_4(D_r) + u_{r,t} \quad [1]$$

$Share\_Emp\_agr_{r,t}$ is the share of agricultural employment in total employment for each sub-continent r at any given year t between 1990 to 2020. The equation further uses the average cereal yield per hectare of cultivated land ($Log\_yield_{r,t}$), expressed in natural logarithms, and its quadratic transformation (($Log\_yield_{r,t}$)^2), as independent variables. $Log\_mech_{r,t}$ represents the total agricultural machinery stock (in 1000 metric horsepower), expressed in natural logarithms, as a proxy for agricultural mechanization Finally, a sub-continent dummy variable, D_r, is also included to control for subcontinental differences (observed and unobserved) that may affect the relationship between yields and the agricultural employment share.

The estimated results predict the 2020 employment shares quite well, providing confidence in the model. Estimation results[35] confirm a quadratic relationship as suggested in Figure 8, panel B using country observations.[36] Using the 2020 yield data, the estimated model predicts the 2020 agricultural employment shares for the different subcontinents quite well [37], especially for SSA and South Asia. This provides confidence in the (within sample) predictive power or accuracy of the estimated model. How climate change affects jobs in AFS on both continents is of particular interest given the global concentration of poverty in both continents, the continuing concentration of employment in AFS in both continents, and the critical role AFS jobs will play in determining the future poverty reduction trajectories.

From employment shares to number of employees. To obtain the total number of people employed in on farm agriculture under the different scenarios, the total number of people entering the labor market in

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[34] Data on the quantity of agricultural capital stock at the country level from 1961 to 2020 have been obtained from the U.S. department of agriculture (USDA) and are accessible at https://www.ers.usda.gov/data-products/international-agricultural-productivity/.

[35] $Estimated\ coefficients:\ Share\_Agr\_emp_{r,t} = -14.3 + 4.2\left(Log\_yield_{r,t}\right) - 0.32(Log\_yield_{r,t})\text{^}2 - 0.14(Log\_mech_{r,t})\ u_{r,t}$

[36] The yield turning point at the country level ($level\ of\ yield = exp(-\beta_1/(2{*}\beta_2)$)), beyond which the agricultural employment share declines, is estimated at approximately 815 kg/ha.

[37] Equation (1) was also estimated using country level data, yielding similar coefficient estimates. Yet the IMPACT model provides yield estimates at the subcontinental level and the 2020 predicted agricultural employment shares using 2020 observed yields and continent based coefficient estimates provided a closer fit with the actual agricultural employment shares.

2050 is obtained and multiplied by the projected 2050 agricultural employment share under the different climate/investment scenarios. Total employment in 2050 is predicted using the estimated coefficients from a simple linear model regressing total employment in each subcontinent on the working-age population using 1991-2021 cross-continent data and the UN population projections of the working-age population into 2050. The analysis was conducted at the subcontinent level.

The 2050-2010 change in the agricultural employment share (and total agricultural employment) under the different climate scenarios is obtained as follows:

$$Change_{{sh_{agr}}_{r,s}}(2050-2010) = \beta_1 * (\Delta Log\_yield_{r,s}) + 2 * \beta_2 * (\Delta Log\_yield_{r,s})^\wedge 2 + \beta_3 * (\Delta Log\_mech_r) \quad [2]$$

$Change_{{sh_{agr}}_{r,s}}(2050\_2010)$ measures the difference in the share of agriculture employment between 2050 and 2010 for different climate/investment scenarios, with *r* and *s* denoting the respective regions/subcontinent and climate/investment scenarios. $\Delta Log\_yield_{r,s}$ is the difference between the projected (log) cereal yield in 2050 and the observed (log) cereal yield in 2010 under the different climate/investment scenarios for each region "r". In a similar vein, $(\Delta Log\_yield_{r,s})^\wedge 2$ is the difference between the quadratic transformation of the projected (2050) and the observed (2010) (log) cereal yield. Finally, ΔLog_mech_r is the sub-continent difference between the mean (log) agricultural machinery stock projected in 2050[38] and the mean (log) agricultural machinery stock observed in 2010.

Equation [2] enables assessing how the agricultural employment shares—and by extension the structural transformation—change under the different climate/investment scenarios.

Given the stability and relevance assumptions, caution remains warranted when interpreting the projected changes in agricultural employment shares and agricultural employment. First, when comparing the AFS employment outcomes of climate change without corrective action, i.e., BAU, with the AFS employment outcomes effects under the no climate change scenario (section 4.3), the reliability of the projections depends on the temporal stability of the estimated relationship between agricultural employment shares and yields. Given the profound impact of climate change on the amount of agricultural production and the geographic location of that production, the occurrence of climate induced migration as well as the long period considered, this is a strong assumption. On the upside, with climate

[38] The mean sub-continental agricultural machinery stock in 2050 was estimated using a simple linear regression model. The model regressed the agricultural machinery stock on a time trend variable, using cross-country data from 1991-2021 and adding country fixed effects. Using the estimated coefficients from the model, the stock of agricultural machinery in 2050 was predicted at the country level and then averaged at the sub-continental level.

change already affecting agriculture over the past decades, some of the effects are arguably already reflected in the current coefficient estimates and climate induced migration is expected to be mostly internal or intra-continental. Second, the relevance of the estimated coefficients to examine the employment effects of climate corrective action is also not automatic. For example, climate smart agricultural practices may be more labor intensive, keeping more people into agriculture to produce similar amounts of food. Equation 2 would then overestimate the decline (or underestimate the increase) in the agricultural employment share. Yet, as will be shown in section 6.1, whether climate smart agricultural practices are indeed more labor intensive depends on the degree to which they are mechanized and as the adoption of CSA practices spreads, mechanization of CSA practices will likely increase. By controlling for mechanization in the estimation of the agricultural employment share – yield relationship and allowing for trend mechanization, such concerns are alleviated.

4.2 Agricultural performance without correcting the climate course

Under BAU, i.e. climate change without corrective action, the IMPACT model predicts agricultural production to be 8.7 percentage points lower than it would have been without climate change (55.4 versus 64.1 percent higher than in 2010 respectively).[39] Total output across the 6 major food groups would reduce by 469 million tons (Table 5), with cereals accounting for 51.8 percent of the decline or 243 million tonnes (-7.3 percent less than without climate change). Central and West Africa (-9.4 percent) and South Asia (-8.9 percent) stand to experience the largest declines in cereal production, after North America (-28.1 percent). In addition, climate change will have a considerable impact on fruit and vegetable production, as well as roots and tubers across all sub-Saharan African regions, resulting in an expected reduction of 11.8% and 8.2%, respectively.

Table 5. Projected food losses in 2050 (in million tons) of six major food group under the BAU scenario with climate change (relative to the BAU with no climate change)

Region	Meats	Cereals	Fruits and vegetables	Oils	Pulses	Roots & Tubers	**Total losses**
				Tons (million)			
Central & West Asia & North Africa	0	-8	-4	-1	-2	0	**-15**
East Asia & Pacific	-1	-5	5	0	0	0	**-1**
East & Southern Africa	0	2	-17	0	0	-16	**-31**
Europe	-1	5	-29	-2	-1	-13	**-41**
Former Soviet Union	0	28	-6	1	0	-41	**-18**
Latin America & Caribbean	-1	-28	-26	-9	-1	2	**-63**
North America	-1	-200	2	-11	3	-5	**-212**

[39] Note that under both the no climate and climate change scenario, yields are projected to increase substantially. Concerning the former, Van Zeist et al. (2020) assess the yield predictions of six of integrated agricultural models (including IMPACT) in the absence of climate change and find them to be below the attainable yields and realistic. This provides confidence in the no climate change benchmark. Data available at https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/DVOY7B/. Note

South Asia	-1	-40	-50	-5	-1	17	**-80**
Southeast Asia	-1	15	43	-1	0	-3	**53**
West & Central Africa	0	-12	-17	-7	-1	-24	**-61**
World	**-6**	**-243**	**-99**	**-35**	**-3**	**-83**	**-469**

Source: Own calculation based on IMPACT datasets (https://dataverse.harvard.edu/dataverse/impact)

Food production losses will be driven by a decline in crop yield growth under climate change. In LICs, global average crop yields are estimated to fall between 6 and 9 percent by 2050 (Rosegrant et al., 2021). By 2050, maize yields are estimated to be 23% lower compared to the 'no climate change' scenario. In Sub-Saharan Africa, maize yields will be 11% lower, while wheat yields will be at least 15.5% lower. A few crops, however, appear to benefit from climate change. For example, in the MENA region, rice and millet yields are projected to increase. Climate change will also result in longer growing season in norther latitudes and thus benefit yield growth of many cereal crops, e.g., barley in North America and Europe. In Central Asia and Eastern Europe, cereal yields are projected to grow under climate change compared to the no climate change scenario, except for maize (Table 3.2 in Rosegrant et al., 2017).

Slower yield growth, coupled with the increasing demand for food, will drive food commodity prices higher. Average crop prices are projected to be 1.59 times higher[40] than the 2010 prices, and between 12% and 18% higher compared to the 2050 scenario with no climate change (Rosegrant et al., 2021). When compared to a hypothetical scenario without climate change, global prices for crops such as maize, groundnuts, potatoes, and soybeans are expected to rise significantly, with increases of 54%, 48.4%, 37%, and 32.6%, respectively (Table 3.4 in Rosegrant et al., 2017).

Increasing food demand and higher food prices puts upward pressure on cultivated land expansion which is predicted to expand by 18-20 percent compared to 2010. Under the BAU scenario with exogenous food demand (driven by exogenous income and population growth)—albeit for cheaper calories given higher food prices—and declining yields following climate change, producers will respond by increasing the acreage of land for less expensive crops or intensifying farm-management practices (Nelson et al., 2014). Overall, the harvested area for all crops is expected to increase by 18-20% between 2010 and 2050, or a net increase of 200 million harvested hectares (Rosegrant et al., 2017). Cereal production acreage will primarily expand in Sub-Saharan Africa, where the harvested area for the six main cereal crops is projected to increase by 41%, from 86.9 million hectares (FAOSTAT data) to 122

[40] https://www.foodsecurityportal.org/tools/impacts-of-alternative-investment-scenarios.

million hectares relative to 2010[41]. In South Asia, the area harvested for six cereal crops is projected to expand by only 4% under the BAU scenario. It will increase the demand for mechanization. Given the magnitude of the additional land taken in cultivation, it would likely also entail an increase in the demand for agricultural labor (compared with no climate change).

The decline in crop yields will cause a slowdown in global GDP growth. As agricultural productivity has multiplier and welfare effects that extend to non-agricultural sectors through consumption and production linkages (Christiaensen et al., 2011; McArthur and McCord 2017), climate change's impact on yield growth will also affect non-agricultural sectors. The slowdown in per-capita GDP growth is anticipated to be more significant in Sub-Saharan Africa and South Asia, where agriculture still has a massive economic presence. Projections for 2050 suggest a per-capita income reduction of 4.4% and 3.7%, respectively. In contrast, GDP per capita reduction in the developed world will be less than -0.3% (Rosegrant et al., 2017).

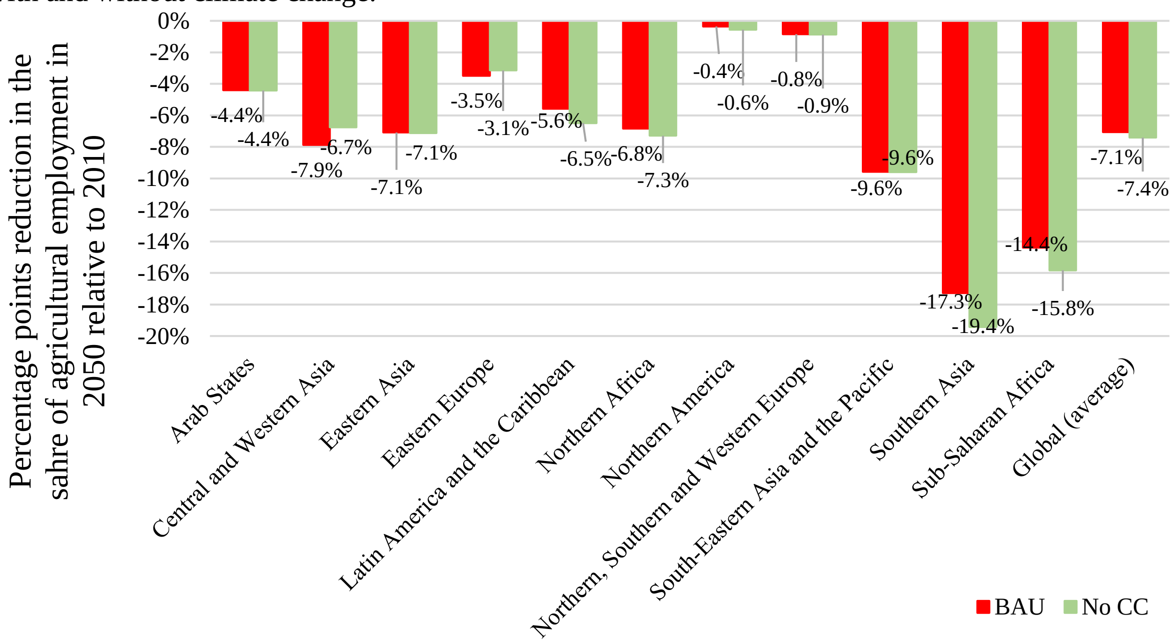
In conclusion, while climate change is clearly predicted to exert a negative effect on yields, GDP and welfare, the overall decline in crop yields is on average not as large as might have been expected. This follows partly from the widely divergent effects on crop yields across locations, with yields even increasing in some locations.[42] Overall, the underlying exogenous productivity trend reflecting lagging payoffs of agricultural R&D remains a very potent force carrying yield growth forward. While substantial, these projected yields without climate change have been shown to be realistic (i.e., consistent with attainable yields (van Zeist et al., 2020)) and the effects of climate change as calculated through the DSSAT crop models (and the water model) in IMPACT under RCP8.5 do not appear to change this course of yield growth too much, at least not on average across the globe. The fact that IMPACT does not account for GHG emission feedback loops should not change this picture much. RCP8.5 is already considered the more extreme GHG emission scenario with no mitigation action, and the increase in GHG emissions for example from the agricultural land expansion predicted by IMPACT under SSP2/RCP8.5, should thus in principle be largely accounted for already (even though not explicitly modeled as such). On the other hand, the IMPACT model does not account for the more erratic weather patterns (and extremes) that come along with climate change (it only estimates the effects of the average change in the weather parameters). More erratic weather may reduce farmer investment and reduce yields.

[41] Own calculation based on FAOSTAT data on area harvested for cereal production in 2010 (https://www.fao.org/faostat/en/#data/QCL) and IMPACT projection of area harvested in 2050 under climate change (https://www.foodsecurityportal.org/tools/impacts-of-alternative-investment-scenarios).
[42] The IMPACT model also accounts for the positive effects on yields of CO_2 fertilization.

4.3 The implication of climate change for AFS jobs

Climate change under the BAU scenario (SSP2/RCP8.5) is predicted to slow down the exit out of agriculture by 1.4 percentage points in SSA. Whilst yields for major cereal crops continues to increase between 2010 and 2050, progress decelerates under the BAU scenario.[43] In SSA, climate change is predicted to reduce cereal yield growth by approximately 5 percentage points compared to the no-climate-change scenario. This is predicted to slow down the decline in the share of agricultural employment by 1.4 percentage points (-14.4 percentage points under climate change without corrective action versus -15.8 percentage points without climate change) (Figure 9). In Southern Asia, the slowdown is even larger—2.1 percentage points. Though globally, the slowdown in the decline of the structural transformation (as captured by the decline in the agricultural employment share) is more limited—0.3 percentage points (7.4 percentage points decline without climate change and 7.1 percentage points decline under BAU). In Central and Western Asia, it even accelerates.

Figure 9. Percentage reduction in the share of agricultural employment in 2050 under the BAU scenario with and without climate change.

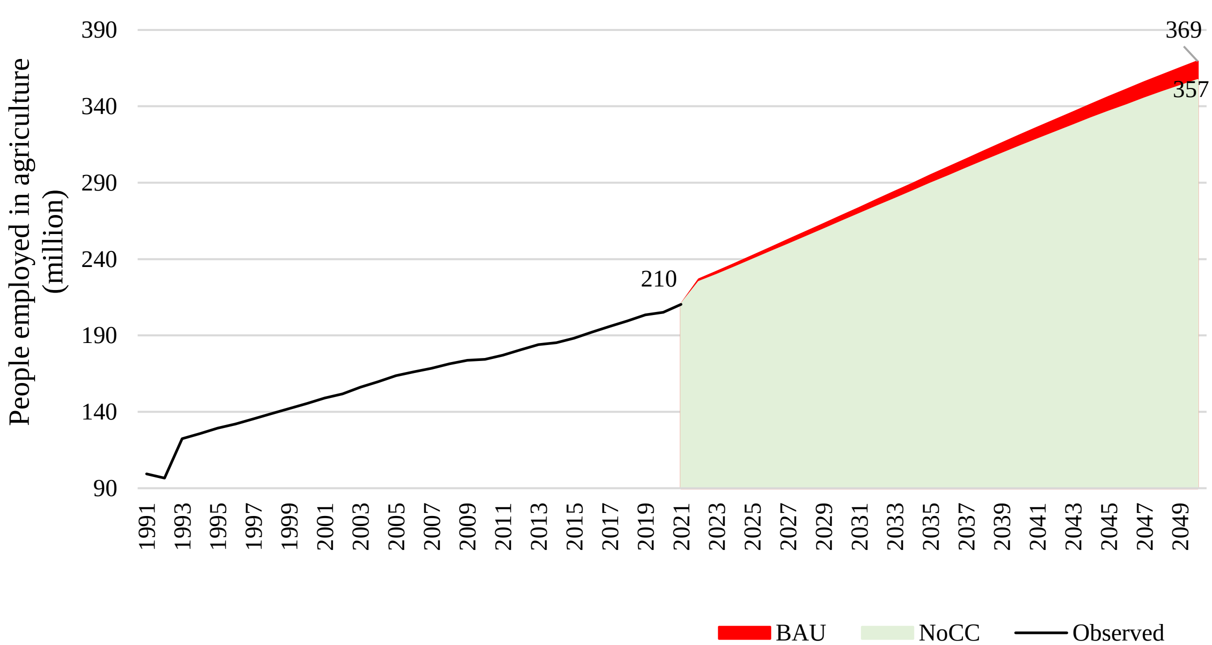


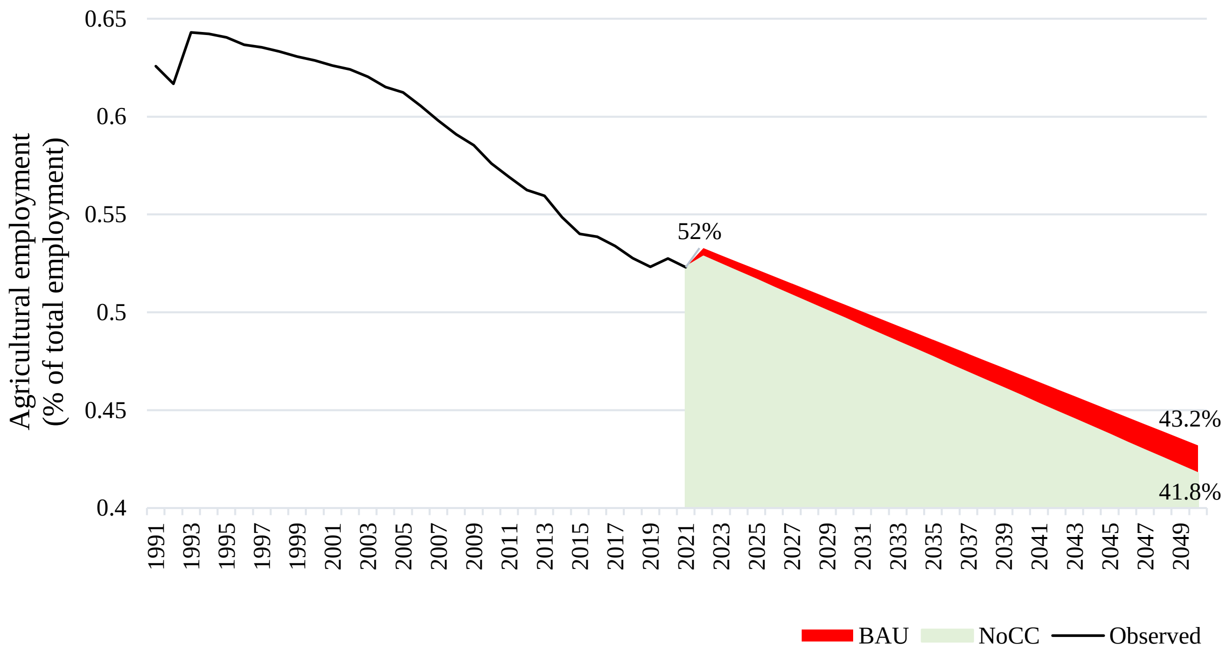
[43] In this study, the difference in cereal yield growth in 2050 between the BAU and the scenario without climate change was calculated based on Table 3.2 in Rosegrant et al. (2017). The table shows the percentage change in yield growth in 2050 for six cereal crops under BAU compared to no climate change (i.e., no climate change since 2005). Using this data, we calculated the weighted change in cereal yield growth due to climate change. Weights for each cereal crop were based on the 2050 share of the harvested area for each cereal crop (in the total harvested area for the six cereal crops), in each sub-continent. To estimate the harvested land share for the six main cereal crops in 2050, projections from the IMPACT model on the percentage change in harvested areas between 2010 and 2050 were used. These projections were then applied to the 2010 FAO data on the hectares of harvested land for the same six cereal crops.

Source: own calculation based on IFPRI data on future cereal yield growth, FAOSTAT data on cereal yields (Kg/Ha) and ILOSTAT data on employment in agriculture.

Despite a decline in the share of agricultural employment, the number of people working in SSA agriculture is still projected to increase, however, regardless of the impact of climate change, due to fast population growth. In fact, under BAU, the number of people employed in agriculture in SSA is projected to increase faster than without climate change (consistent with the slower decline in the agricultural employment share). There will 12.3 million more agricultural workers compared to the no climate change scenario trends (Figure 10). Consequently, the sub-continent's share of agricultural employment under the BAU scenario with climate change is expected to be 43.2% in 2050, instead of 41.8 percent (without climate change), which is still very high and reflective of the historically low yields and low yield trend growth in SSA given low agricultural investment (Christiaensen and Vandercasteelen 2019). Cereal yields in SSA are predicted to increase from 1501 kg per ha in 2010 to 2313 kg per ha in 2050 (without climate change) or 2195 kg per ha (with significant climate change/BAU).

Figure 10. Observed and projected number of people employed in agriculture in Sub-Saharan Africa (upper panel). Share of agricultural employment (in total employment) in Sub-Saharan Africa (bottom panel).





Source: own calculation based on employment data from ILOSTAT.

Anticipated implications for the different dimensions of the economic transformation. The rise in food commodity prices and the fall in incomes under climate change is likely to cause a shift in the employment distribution along the AFS, increasing on-farm and decreasing off-farm AFS employment (relative to no climate change). Consumers are likely to alter their consumption patterns, opting for more affordable calories, i.e., staples (Bennett's Law) and auto-consumption and away from processed and convenient foods which would in turn reduce demand for off-farm AFS labor. Lower income growth may also slow down the pace of productive urbanization, which is typically supported by enhanced labor productivity in the agricultural sector enabling lower nominal urban wages (cheaper food), while potentially accelerating unproductive urbanization as a result of distress migration. Finally, climate change and extreme weather conditions will likely require agricultural workers to be retrained to better adapt to the changing climate, which is not to be confounded by an increase in the demand for high-skilled workers, unless the projected land expansion needed to keep up with food demand is met by rapid mechanization and large-scale farm expansion, in which case, the share of agricultural waged labor also stands to increase.

5 Greening the AFS – entry points

Brokering a more sustainable AFS happens through a combination of adaptation, conservation and mitigation measures, their relative importance depending on the context. A multitude of agricultural technologies and agronomic practices are pursued to green the agri-food system (see Segnon et al., 2022 for a review). They go under the broad heading of climate smart agricultural practices[44] and include technologies and practices focused on 1) increasing the resilience of agriculture to changing weather patterns (adaptation strategies), 2) conserving natural resources (soil and water) and 3) reducing GHG emissions (mitigation strategies). The appropriate mix of measures will differ across contexts**.** Mitigation strategies aimed at limiting methane emissions for rice production are for example likely better suited for lower- and upper-middle income countries in Southern and South-Eastern Asia. In Africa, a focus on adaptation, conservation, and regenerative practices may be more appropriate, to enhance AFS resilience to climate change and mitigate natural resource degradation. Measures often also contribute to more than one aspect at once. Agro-forestry, for example, helps protect crops from heat and drought (adaptation), increases soil fertility (conservation) and sequesters carbon (mitigation).

5.1 Adaptation

Adaptation strategies consist of measures focused on adapting the AFS to the increasing frequency and intensity of extreme events (droughts, flooding, heat waves) as well as adapting it to longer term gradually warming and drying as the climate changes. Agrometeorological forecasts, crop diversification, and erosion control as well as the development of comprehensive early warning systems are some of the more frequently used, proven measures to help farmers reduce the effects of short-term extreme weather events. Timely seasonal forecasts, for example, reduced crop failure and losses through better timing of planting and harvesting in East and West Africa (CIAT et al., 2020a; Agyekum et al., 2022). Shifts in the timing of planting and harvesting also prove to be an important adaptation strategy in Asia (Gunawat et al., 2022).

The adoption of drought-tolerant seeds, intercropping, and improved water infrastructure also help farmers adapt to long-term warming and drying. In Zimbabwe, the use of drought-tolerant seeds and small-scale irrigation has proven to be a successful country-specific adaptation strategy (CIAT & World Bank, 2017). Drought-tolerant seeds have been found to be particularly effective as they are more

[44] Giller et al. (2015) provide insights into the many shapes of sustainable agricultural practices, including conservation agriculture, climate smart agriculture (CSA), sustainable intensification and mitigation strategies. They discuss the principles and practices associated with each term. They also offer a thought-provoking debate on the need to move beyond a limited set of principles associated with conservation agriculture. Finally, they argue for a toolbox and methods that allow for informed decision-making regarding technology choices tailored to local conditions while considering the trade-offs associated with technology choice in the short and long term.

resilient to temperature and rainfall variability, leading to faster increases in crop yield compared to traditional seeds. Similarly, micro-dosing, improved seed varieties, and intercropping have been used to improve resilience to climate stressors in Nigeria (FAO & ICRISAT, 2019). Water management practices like contour stone bunds and weirs have also shown potential in improving crop resilience during periods of drought, while fodder crops and crop residues can mitigate the impact of a changing climate on animal feed availability (CIAT et al., 2020b). Furthermore, solar-powered irrigation has been identified as a promising solution to meet increasing water demands in semi-arid areas of Sub-Saharan Africa while reducing emissions from agriculture (Schmitter et al., 2018).

5.2 Conservation

Natural resource conservation can be achieved through conservation agriculture, agroforestry, and land rehabilitation. Conservation agriculture, for instance, involves sustainable alternatives to traditional agricultural intensification practices that negatively impact natural resources such as soil and water and associated ecosystem services. By adopting minimum or no tillage, permanent soil cover, and crop diversification in sequence, conservation agriculture can not only conserve natural resources but also reverse the process of land degradation and enhance soil productivity (Kassam et al., 2019).

The preservation of forests, afforestation, and reforestation is effective in conserving natural resources, reversing land degradation, and limiting deforestation's impact on biodiversity loss (Mackey, 2019). Furthermore, agroforestry systems contribute to enhanced biodiversity by conserving forests' biodiversity and restoring natural functions while reducing the rate of agricultural-driven deforestation (Hendershot et al., 2020). In addition to environmental benefits, land restoration and conservation in Africa are projected to increase agricultural productivity by up to 26 times more than the cost of inaction (FAO, 2022). Additionally, alley cropping agroforestry has the potential to sequester CO_2 from the atmosphere, thus mitigating climate change and improving the livelihoods of smallholder farmers (Mbow et al., 2014).

5.3 Mitigation

Both supply/production and demand/consumption options are pursued to mitigate GHG emissions in AFS. The supply-side options aim to reduce GHG emissions during production such as the retention and sequestration of organic material (carbon) through agroforestry (Henders, 2018) or improved management of crop (zero-tillage) and grazing lands (animal rotation). Demand-side options, on the other hand, focus on changing consumption patterns, through promotion of healthy and sustainable diets and the reduction of food waste and loss. This reduces the amount of GHG produced, while continuing to meet demand (Herrero et al., 2015; Dora et al., 2020).

Adjustment of traditional flooded rice cultivation practices such as through the System of Rice Intensification (SRI) can substantially reduce global GHG emissions. Flooded rice production contributes significantly to GHG emissions (Islam et al., 2020) (section 3.2). The adverse environmental impacts of flooded rice production systems are further compounded in semi-arid regions where irrigation is often powered by fossil fuels (Reddy et al., 2013). The use of synthetic nitrogen fertilizers adds further to the already significant greenhouse gas emissions from rice production (Reddy et al., 2013). However, it is possible to minimize the environmental impact of rice cultivation and increase its production by implementing effective agronomic strategies. These include three practices applied in the System of Rice Intensification (SRI): 1) better water management through reduced irrigation water application, such as by using furrow or intermittent irrigation when growing lowland rice (Karki et al., 2021); 2) transplantation of seedlings less than 15 days old and using a single seedling per hill to reduce seed and labor input and minimize environmental impact compared to conventional transplanting; and 3) using mechanical weeders for weeding, which can also serve as green manure to enrich both the crop and soil (Reddy et al., 2013). Other practices such as non-puddling reduced-tillage land establishment can save water and reduce labor inputs.

In mitigating greenhouse gas emissions from the livestock sector, both demand and supply-side strategies can be employed. Supply-side options include the use of methane inhibitors such as 3-Nitrooxypropanol (NOP), which has been shown to effectively reduce enteric methane emissions from beef and dairy cattle (Dijkstra et al., 2018). Additional options are improving feed quality through processed crop residues or better forages, as well as using anaerobic digesters to treat liquid manure (Prasad et al., 2020). The balance between grass availability and grazing can also be optimized, which can positively affect forage production, animal productivity, and soil carbon sequestration (Mottet et al., 2017). GHG emissions can further be reduced by reducing meat consumption, especially in industrialized countries. Beef is the most GHG-intensive meat, particularly when imported, as long-distance transportation significantly increases food miles (Westhoek et al., 2011). Import tariffs, coupled with lower import shares and higher meat prices, can discourage meat consumption and stimulate local production of protein-rich plant foods, leading to import substitution effects.

6 Implications of the green transition for jobs in AFS

Understanding the direct and indirect effects of mitigation and adaptation practices on AFS employment is crucial to evaluate the implications on the broader economic transformation. Direct effects include changes in AFS labor requirements and labor productivity, while indirect effects involve related job reallocation across sectors and space (rural/urban), organizational structures (self-employed/wage) and tasks (skills). To begin to assess the implications of the green transition for AFS jobs[45], this section reviews the direct effects of mitigation and adaption strategies for AFS labor use and productivity as emerging from the limited number of microeconomic studies (section 6.1) and explores the projected evolution of the share of agricultural employment under different investments in climate-smart agriculture, irrigation expansion, water use efficiency, soil water holding capacity, and improved market infrastructure based on the IMPACT model and the historically observed link between the evolution of yields and agricultural employment shares (section 6.2). The section primarily focuses on sub-Saharan African countries, but also includes rice production systems in Asia.

6.1 Microeconomic results

Whilst the implementation of adaption, conservation, and mitigation strategies are crucial to sustain the African food system, few studies have methodically evaluated the impact of such strategies on labor requirements.

6.1.1 Sustainable agricultural practices demand more labor

The limited number of existing studies using non-experimental designs suggest that conservation strategies in agriculture are associated with increased labor requirements per hectare (Table 6)**.** Research by Montt and Luu (2020) reveals that adopting conservation strategies in Sub-Saharan African countries results in an additional 55 days of labor per hectare per year, primarily during the harvesting and threshing stages. This finding is further supported by observational data from Malawi and Zimbabwe, which indicates that maize fields under conservation agriculture require 45 percent more labor time compared to traditional agriculture (Corbeels et al., 2013). Similarly, adopting conservation strategies in rural Ethiopia was found to necessitate more labor days per hectare, with women contributing 10.1 labor days and men contributing 5 labor days (Teklewold et al., 2013). Labor availability was identified as a significant factor influencing the adoption of conservation strategies in rural Ethiopia. Finally, Hörner and Wollni (2022) examined the impact of the adoption of integrated soil fertility management practices (use of organic fertilizers, inorganic fertilizers, and improved seeds) on labor demand. Their research revealed that all these practices are linked with increased labor requirements, and their combined use leads to a rise in persons-days per hectare by 20.5 compared to non-adopters.

[45] The literature of the direct implications for farm labor of the adoption of climate smart agricultural practices is incipient, and models that fully incorporate the implications of the green transition for AFS labor are not yet available (with good micro-econometric evidence to inform them also still missing).

Quasi experimental evidence from Malawi also points to greater labor use in conservation agriculture. Additional insights on labor requirements under sustainable agriculture practices were provided by quasi-experimental data collected by the International Food Policy Research Institute (IFPRI). IFPRI conducted two rounds of household panel survey data in Malawi in 2013 and 2019 to evaluate the impact of sustainable intensification practices on labor requirements[46], among other socio-economic indicators. The analysis, based on a difference-in-difference model with propensity score matching, revealed that households that adopted at least one sustainable intensification practice experienced a higher labor demand compared to non-adopters, with a difference of 17 person-days per hectare per year between the baseline and follow-up surveys. However, it is worth noting that this difference was not statistically significant[47].

The impact of conservation agriculture on labor requirements remains difficult to disentangle as it often depends on the specific strategies implemented, as well as whether conservation practices are adopted alone or in combination with other practices. For example, adopting minimum tillage alone can reduce labor requirements during land preparation. Montt and Luu (2020) reported that minimum tillage reduced labor input during land preparation by 9 labor days per ha compared to traditional tillage. Minimum tillage adopters in Kenya used 50 fewer person-days per hectare compared to non-adopters (Jena, 2019). Yet, Teklewold et al. (2013) found that implementing conservation tillage with system diversification did not have a noteworthy impact on labor use, possibly because pesticide application was reduced. Labor requirements were only found to increase when all practices were adopted together.

Using technologies to enhance water usage efficiency from rainfall is anticipated to result in higher labor requirements. For example, Abdulai and Huffman (2014) found that adopters of water conservation technologies for rice cultivation in northern Ghana used significantly more labor (+14.2 person-days per hectare) compared to non-adopters due to the construction of earthen bunds or small ridges [48]. Moreover, constructing and maintaining contour ridges for water conservation may require more labor, with men typically favored over women due to the physical demands of the task. This is supported

[46] The first group of households consisted of non-randomly selected households identified as program beneficiaries at the time of the baseline survey. The second group included a random sample of households in program communities that did not participate in the program at baseline but some of group 2 households benefit from the program as it expanded through the years. The final groups of households (group 3) consisted of a random sample of non-beneficiary households in randomly selected (control) communities not targeted by the program.
[47] The lack of control for the specific type of sustainable practice adopted by farmers and the variation in labor requirements across different stages of production (such as land preparation, harvesting, etc.) could potentially account for the observed result.
[48] Estimated using and endogenous switching regression on cross-sectional data of 342 rice farmers in northern Ghana

by in-depth interviews and focus group discussions with smallholder farmers in Zimbabwe (Dube et. Al, 2018)

SRI is a rice production system that reduces methane emissions by minimizing water use and alternating wet and dry conditions. Compared to traditional rice cultivation systems, SRI has been found to offer several environmental benefits such as lower GHG emissions per hectare (-40%) and fossil energy (-74%), as well as reduced water use (-60%) (Gathorne-Hardy et al., 2016). Duvvuru & Motkuri (2013) estimated that GHG emissions per hectare (in CO_2-equivalent per year) were substantially reduced (-26.8%) compared to traditional rice systems.

The labor requirements of the SRI, however, exhibit variability across different continents. In West Africa, SRI tends to be more labor-intensive compared to traditional systems due to higher labor requirements during sowing and planting (+9 day per hectare). For example, in the Oti region of Ghana, transplanting half a hectare of land using SRI takes 3 people 4 days, while the same land area can be sown through broadcasting under traditional rice systems by just one person (Graf and Oya, 2021). However, in India, SRI farms use 29.5% less labor hours than traditional rice farms mainly due to less transplanting and mechanical weeding (954 hours per hectare per year in SRI; 1355 hours in traditional rice systems (Gathorne-Hardy et al. 2016). Duvvuru & Motkuri (2013) found that labor requirements per hectare per year under SRI were substantially reduced. In India, lower labor requirements under SRI are mainly due to reduced labor demand for weeding (-63%) and transplanting (-55%) compared to traditional rice systems. In contrast, in West Africa, higher labor requirements are driven by manual weeding and scattered transplanting.

The observed difference in the labor requirements between Asian and African countries indicate that the degree of farming system mechanization has a significant impact on labor requirements under conservation agriculture. This can be particularly relevant in sub-Saharan Africa, where agricultural activities heavily depend on manual labor due to the low rates of mechanization (Sheahan and Barret, 2017)

Table 6. Labor requirements under conservation agriculture.

	Author (year)	Country(s)	Strategy (or production stage)	Average effect on labor requirements compared to non-adopters: Labor demand	Unit of measurement	Statistical significance
Soil conservation	Montt and Luu (2020)	Ethiopia, Kenya, Malawi, Mozambique, and Tanzania	Intercropping	13	Person-day/Ha/year	Yes
			Residue retention	21	Person-day/Ha/year	Yes
			Minimum tillage	103	Person-day/Ha/year	No
			Intercropping and residue retention	16	Person-day/Ha/year	Yes
			Intercropping and minimum tillage	15	Person-day/Ha/year	No
			Residue retention and minimum tillage	7	Person-day/Ha/year	No
			Full package	55	Person-day/Ha/year	Yes
	Teklewold et. Al (2013)	Rural Ethiopia	Crop diversification	-4	labor-day per Ha	Yes
			Improved maize variety	4.8	labor-day per Ha	Yes
			Minimum (conservation) tillage	6.1	labor-day per Ha	Yes
			Crop diversification and improved maize variety and minimum (conservation) tillage	15.1	labor-day per Ha	Yes
	Corbeels et. Al (2013)	Malawi and Zimbabwe	Crop rotation (intercropping), no tillage and organic soil cover using crop residues	45%	Labor days Ha	N.A.
	Hörner and Wollni (2022)	Ethiopia	Organic fertilizers	5.3	Labor-days/ha	No
			Inorganic fertilizers	8.4	Labor-days/ha	Yes
			Organic fertilizers and inorganic fertilizers	18.2	Labor-days/ha	Yes
			Organic fertilizer sand improved seeds	6.9	Labor-days/ha	No
			Inorganic fertilizers and improved seeds	20.7	Labor-days/ha	Yes
			Organic fertilizers and inorganic fertilizers and improved seeds	20.5	Labor-days/ha	Yes
	IFPRI (2022)	Malawi	Any or combinations of the following practices: 1) crop rotation, 2) crop residues on the field, 3) applied manure, 4) maize-legume intercropping, 5) use of inorganic fertilizer	17	Person-day per Ha	No
	Jena (2019)	Kenya	Minimum tillage	-50	Person-day Ha	Yes
Resource-use efficiency	Abdulai and Huffman (2019)	Northern Ghana	Water conservation technologies	14.2	Person-day per Ha	Yes
SRI	Graf and Oya (2021)	Benin, Ghana and Mali	Land preparation	-1.5	Days/Ha	No
			Sowing/ planting	6.9	Days/Ha	Yes
			Weeding	3.2	Days/Ha	No
	Gathorne-Hardy et al, (2016)	India		-401	Hours/Ha	Yes

6.1.2 Labor related performance indicators

Studies focusing on SRI in Asian countries consistently show higher rice yields and labor productivity compared to traditional systems. Across Asian countries, SRI increases rice yields ranging from 324 kg/ha in rural Bangladesh (Barrett et Al.,2016) to 810 Kg/ha in Indonesia (Takahashi and Barrett, 2014) and 2,775 kg/ha in India (Gathorne-Hardy et al, 2016). Higher yields are associated with increased rice labor productivity 11.8 more kg per day in Indonesia (Takahashi and Barrett, 2014)) and 5.1 more kg per labor hour compared to non-adopters in India (Gathorne-Hardy et al, 2016), and, resulting in higher agricultural income gains, 260 international USD per hectare in rural Bangladesh (Barrett et Al.,2016), + 499.3 international USD per rice season in Indonesia (Takahashi and Barrett, 2014) and 2,217 international USD per hectare in India (Gathorne-Hardy et al, 2016)[49]. In West Africa, SRI also brings higher crop yields and labor productivity, leading to higher net income from rice production (Table 7). Unlike in Asia, where the benefits of SRI come at the expense of landless workers (Gathorne-Hardy et al, 2016), SRI in West Africa can generate better jobs, as a result of higher labor requirements and increased labor productivity (Graf and Oya, 2021).

Sustainable agricultural practices also hold the promise of enhancing crop yields and net returns to land, but it remains unclear whether these suffice to increase returns to (family) labor (Table 7)**.** Research from Ethiopia suggests that the net value of maize per hectare is higher under conservation agriculture (Teklewold et al., 2013). Similarly, improved water use-efficiency technologies for rice cultivation in Ghana increase crop yields (+432 kg/ha), and net returns to land (+36.5 Int. USD/ha). While this holds the potential that the higher returns to land also translate into higher returns to labor, i.e., that the higher returns to land suffice to compensate for the higher labor input, returns to labor are not reported in the these and most other studies and cannot be ascertained from the reported results. As such, the findings remain inconclusive.

While conservation agriculture is generally believed to enhance agricultural productivity, a few studies also point in the opposite direction. For instance, Montt and Luu (2020) found that implementing conservation agriculture in SSA may not necessarily result in increased crop yields. Potential negative effects of conservation agriculture on crop yields is further underscored by Corbeels et. Al. (2020). They found that average yields under full adoption of conservation agriculture in 16 sub-Saharan African countries are only slightly higher than those of conventional tillage systems. Specifically, the increase is about 3.4% on average for cotton, cowpea, maize, rice, sorghum, and soybean. Additionally, maize yields under no- or reduced tillage alone are not significantly different from yields under conventional tillage. This is reinforced by a meta-analysis study based on 5463 paired yield observations from 610 studies, indicating that no-till alone results in a yield penalty of approximately 10% (Pittelkow et al., 2015).

The economic benefits from sustainable agricultural practices amplify when multiple practices are implemented in conjunction. While some adaptation options, such as conservation tillage, may not

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[49] To ensure comparability across different studies, the reported values in the studies were converted to international dollars using the purchasing power parity (PPP) conversion factor that corresponded to the year of the study.

effectively increase crop yields on their own (Kichamu-Wachira et al., 2021), reduced tillage and mulching have been shown to have a slightly positive effect on maize yields in sub-Saharan African countries, with an increase of 3.9% (Corbeels et al., 2020). However, when intercropping is also adopted, crop yield gains can more than double, with an increase of 8.4%. Despite these potential benefits, implementing sustainable practices as a full package can be challenging due to the knowledge-intensive methods and investment required in appropriate machinery (Montt & Luu, 2020; Moser & Barrett, 2006). The effects often also take some time to materialize.

Even when multiple sustainable practices are implemented, crop yield increases may not be immediately observable due to the time required for improved soil quality. Studies have shown that improved soil quality under sustainable practices requires a waiting period before yield improvements can be seen (Maggio et al., 2022; Corbeels et al., 2020). For example, based on household survey data from Uganda, Maggio et al. (2022) estimated that one year of additional adoption of organic fertilizers and maize-legume intercropping increases crop production value by 30% and 23%, respectively. Corbeels et al. (2020) conducted a meta-analysis based on 933 observations from 79 studies conducted in 16 different countries in sub-Saharan Africa. They found that crop yield performance (% change in yield) improves over time due to gradually improved soil quality under conservation agriculture.

And higher farm income may also lead to reduced time for off-farm productive activities, which may result in lower overall return to labor and lower overall household income. The availability of labor is an important factor in the adoption of sustainable agriculture, as shown by recent studies (Ngoma et al., 2021). The effectiveness of sustainable agriculture in creating productive jobs depends not only on higher crop yields but also on how these labor requirements are met. If laborers are hired in, they add to job creation (locally or through migration); if largely met by family labor, the return should suffice to offset any potential decline in off-farm income and human capital formation building. This is not always the case as shown for SRI in Indonesia (Takahashi & Barrett, 2014) and for conservation agriculture in SSA (Montt & Luu, 2020; Teklewold et al., 2013). Overall, evidence suggests that the higher labor requirements of sustainable agriculture are typically met by household labor, with the workload change often higher for women and children than for men, highlighting the need for careful examination of the effect of sustainable intensification practices on total household income and human capital formation (childcare, nutrition, schooling).

Overall, the evidence on the returns to labor of conservation agriculture is still unclear and more experimental micro-econometric evidence on the effectiveness of conservation agriculture in

improving crop yields, labor productivity and farm income is needed. This would imply comparing the crop yields, income, labor productivty and overall income of farmers who have adopted conservation agriculture with similar farmers in similar settings who have not over longer periods of time and a wide variety of contexts. However, there is currently a dearth of experimental data and evaluation studies on conservation agriculture to do so. As a result, our current understanding of the impact of conservation agriculture for AFS jobs outcomes remains inconclusive.

Table 7. Difference in agricultural labor productivity, yield and agricultural income between adopters and non-adopters of different sustainable agricultural strategies

Background information			Impact compared to non-adopters:					
Study, author(s) and Year	**Geographic area (Country(s))**	**Strategy or production stage**	**Agricultural labor productivity**		**Crop yields**		**Agricultural income**	
				Type of crop		**Type of crop**		**Type of income**
Montt and Luu (2020)	Ethiopia, Kenya, Malawi, Mozambique, and Tanzania	Intercropping			75.32 *** (kg/ha)	Maize	32.3*** (USD 2010/ year)	wage income per person
		Residue retention			-169.25 *** (kg/ha)	Maize	2.7*** (USD 2010/ year)	wage income per person
		Minimum tillage			-359.63 (kg/ha)	Maize	-6.9 (USD 2010/ year)	wage income per person
		Intercropping + residue retention			-165.99 *** (kg/ha)	Maize	5.5*** (USD 2010/ year)	wage income per person
		Intercropping + minimum tillage			-176.72 (kg/ha)	Maize	22.7 (USD 2010/ year)	wage income per person
		Residue retention + minimum tillage			-761.05*** (kg/ha)	Maize	33.2*** (USD 2010/ year)	wage income per person
		Full package			-496.31*** (kg/ha)	Maize	72.5*** (USD 2010/ year)	wage income per person
Teklewold et. Al (2013)	Rural Ethiopia	Crop rotation (intercropping)			267.3*** (int.USD/ha)	Maize		
		Improved maize variety			398.7*** (int.USD/ha)\	Maize		
		Minimum (conservation) tillage			331.9*** (int.USD/ha)	Maize		
		Crop rotation + improved maize variety + minimum (conservation) tillage			788.1*** (int.USD/ha)	Maize		
IFPRI (2020)	Malawi	Any or combinations of the following 1. Crop rotation 2. Applied manure 3. Left crop residues on the field 4. Maize-legume intercropping	2.1*** (int.USD/person day)					

Background information			Impact compared to non-adopters:					
Study, author(s) and Year	Geographic area (Country(s))	Strategy or production stage	Agricultural labor productivity		Crop yields		Agricultural income	
				Type of crop		Type of crop		Type of income
Corbeels et al	Sub-Saharan Africa (16 countries)	Minimum tillage			0% (change in yield (%). Kg/ha)	Maize		
		Minimum tillage+ Mulching			3.9% (change in yield (%). Kg/ha)	Maize		
		Full package			8.4% (change in yield (%). Kg/ha)	Maize		
		Any or combinations of the above			4.0% (change in yield (%). Kg/ha)	Maize		
		Any or combinations of the above			3.4% (change in yield (%). Kg/ha)	Six crops		
Jena (2019)	Kenya	Minimum tillage			36.7 (kg/ha)	Maize	161.4* (int. USD/ha)	Net income from maize production per ha
Abdulai and Huffman (2019)	Northern Ghana	Earthen bunds			432.14*** (kg/ha)	Rice	36.5*** (int. USD/ha)	Net returns from rice production per ha
Graf and Oya (2021)	Benin, Ghana and Mali	System of rice intensification (early transplanting of single plants/hill, aerobic soils and wide spacing between hills)	96.2* (kg/day worked)	Rice	666.2** (kg/ha)	Rice	296.4** (USD/ha)	Gross margin on rice production without cost of family labor
Gathorne-Hardy et al, (2016)	Andhra Pradesh, India	See Graf and Oya (2021)	5.1*** (kg/hour worked)	Rice	2,775*** (kg/ha)	Rice	2217.1***(int. USD/ha)	Net income from rice production
Duvvuru al, (2013)	Andhra Pradesh, India	See Graf and Oya (2021)	4.2 (kg/hours worked)	Rice		Rice		
Takahashi and Barrett (2014)	Kelara Karalloe, Indonesia	See Graf and Oya (2021)	11.8*** (kg/person-day)	Rice	810*(Kg/ha)	Rice	499.3* (int. USD per rice season)	Net income from rice production
Barrett et al. (2016)	Rural Bangladesh	See Graf and Oya (2021)			3.24 kg*** (Kg/decimal land)	Rice	2.6*** (int USD per decimal land)	Net income from rice production

Note: To facilitate comprehension, the values reported in local currency units in the reviewed studies have been converted using the PPP conversion factor that corresponds to the year of the study.
1 decimal land=0.004046 ha
***p<0.01, **p<0.05, ***p<0. 1

6.2 Macroeconomic results

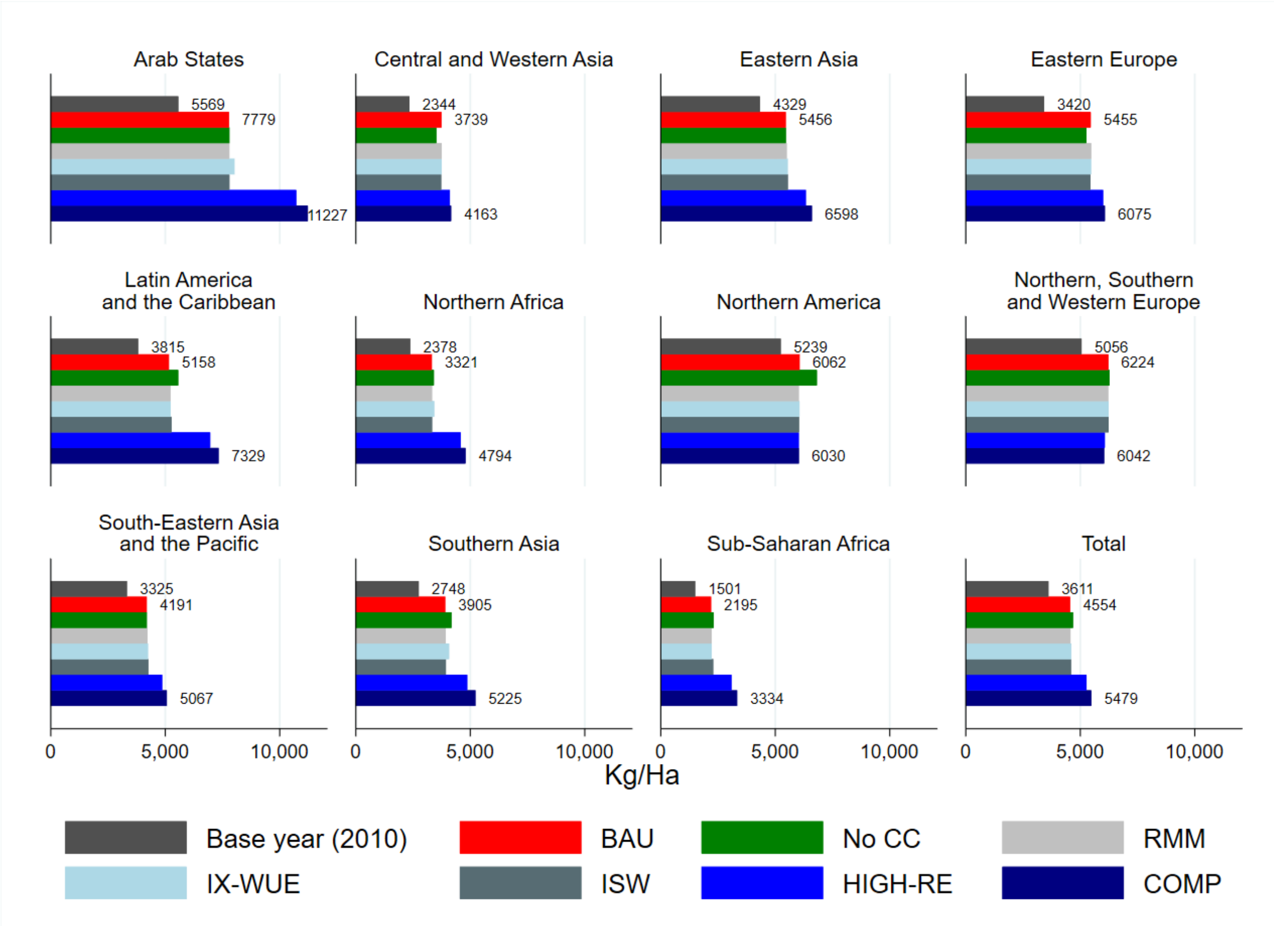
The IMPACT model examines the effectiveness of a series of climate related investments on agriculture's performance in the face of the SSP2/RCP8.5 climate path (i.e., BAU). The effect of the following interventions is investigated: 1) increased investments in agricultural R&D (generically defined) to boost agricultural productivity (yields);[50] 2) irrigation expansion and increased water use efficiency; 3) investments to increase soil water holding capacity (e.g., no-till agriculture);[51] and 4) investments in infrastructure to improve market efficiency through the reduction of transportation costs and marketing margins. The effects of each of these interventions on cereal yields (and the other agricultural performance indicators) is modeled separately as well as a package. Here the focus is on the effects of the comprehensive package (compared with BAU). The five alternative investment scenarios are described in detail in Annex 7 (including the associated additional costs) (Rosegrant et al., 2017).

A comprehensive intervention package of climate related investments would raise global agricultural production in 2050 by 11.5 percent relative to the BAU scenario and by 25 percent in SSA, much of it driven by gains in yields. For SSA, cereal yields would more than double between 2010 and 2050, albeit from a low base (from 1501 kg/ha in 2010 to 3334 kg/ha in 2050) (Figure 11). This vastly surpasses the projected yields under BAU with climate change (2195 kg/ha) and more than compensates for the projected loss from climate change (118 kg/ha) (the projected cereal yield in 2050 under no climate change is 2310 kg/ha). The projected large increases in crop production and yields are expected to lead to a decrease in the average crop prices by 21 percent; cereal prices will decrease, on average, by 28.4 percent. Higher incomes will also follow, with an anticipated increase at global level of 6 percent, by 9.1 percent in South Asia and by 7.1 percent in SSA.

[50] It includes investments in CSA technologies and practices such as drought- and/or heat-tolerant crop varieties, but also investments that enhance the uptake of well-researched existing agricultural technologies, such as investment in agricultural extension.

[51] Irrigation expansion or investment in soil water holding capacity may not be feasible in some geographic areas. Irrigation expansion may also result in temporal trade-offs if water use surpasses recharge rates. Accounting for such and other limitations to the scope for improving water management across regions, improvements in water retention capacity for agriculture are phased in over time and vary across regions in the IMPACT model, with a maximum increase of 5-15 percent in effective precipitation by 2045. Improvements in water retention capacity are modeled by adjusting the parameter for effective precipitation in the water module (see Rosegrant et al 2017 for more detail).

Figure 11. Projected average cereal yields in 2050 under different investment scenarios



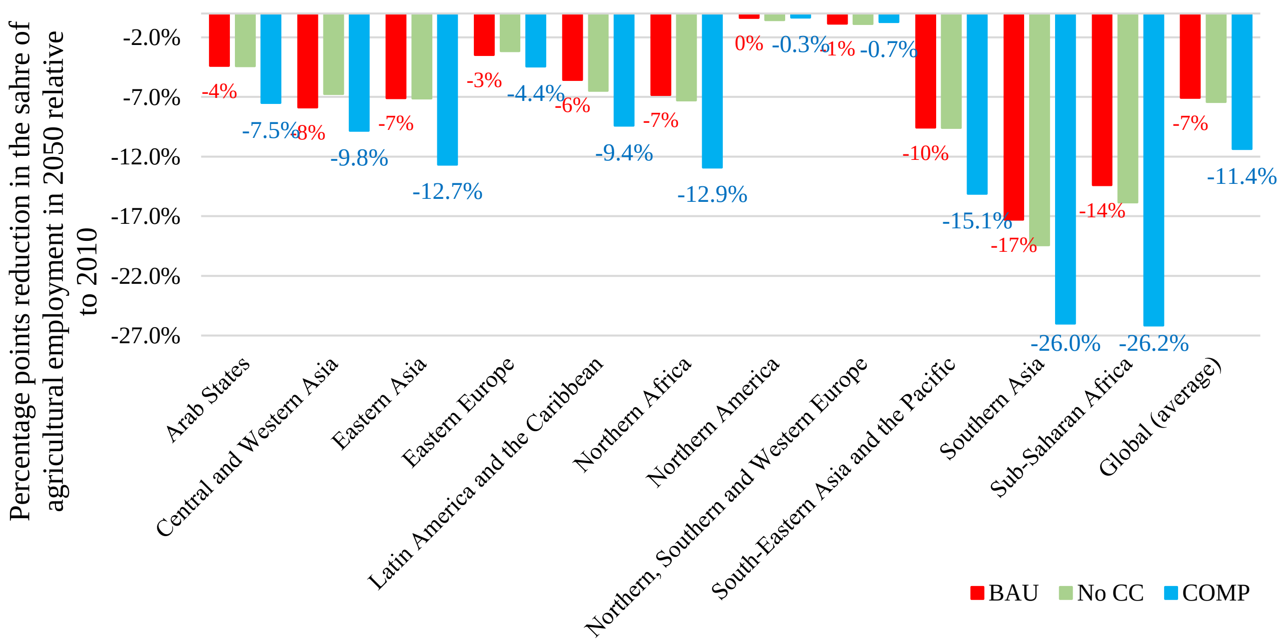
Note: "**base year 2010**" indicates average cereal yield in 2010 (FAOSTAT data). "**BAU with CC"** indicates the business-as-usual scenario with climate change factored in; "**BAU with no CC"** indicates the business-as-usual scenario without climate change. **RMM** indicates the scenario with investments in infrastructure improvements. **IX-WUE** indicates the scenario with investments in irrigation expansion and water use efficiency. **ISW** indicates the scenario with increased soil water holding capacity. **HIGH-RE** indicates the scenario with increase in R&D plus increased in research efficiency. **COMP** indicates investment under the comprehensive scenario (**RMM+ IX-WUE+ ISW+ HIGH-RE).**

Source: The source of data for the average cereal yields in 2010 is FAOSTAT. Cereal yield projections to 2050 are based on IMPACT results. These projections have been made for different investment scenarios.

Yield gains are largely driven by the productivity enhancements following R&D investment (including in climate smart agricultural practices), as well as some synergies from combining different interventions. Under the comprehensive package, cereal yields in SSA would increase from 1501 to 3334 kg/ha (during 2010-2050), or by 1139 kg/ha compared to BAU with climate change. Investment in agriculture and CSA related R&D alone, would increase yields by 893kg/ha (compared to BAU with climate change) explaining 78.4 percent of the yield gain (=893/1139), while investment in improved transport infrastructure (27 kg/ha) and water (30 kg/ha) and soil management (94 kg/ha) would together add another 151 kg/ha (or 13.3 percent of the yield gain). This brings the projected total gain from the 4 interventions to 1043 kg/ha (compared to BAU with climate change) when implemented separately. Synergies from combining the interventions yield another 96 kg/ha (=1139-1043 kg/ha), accounting for 8.4 percentage points of the yield gain.

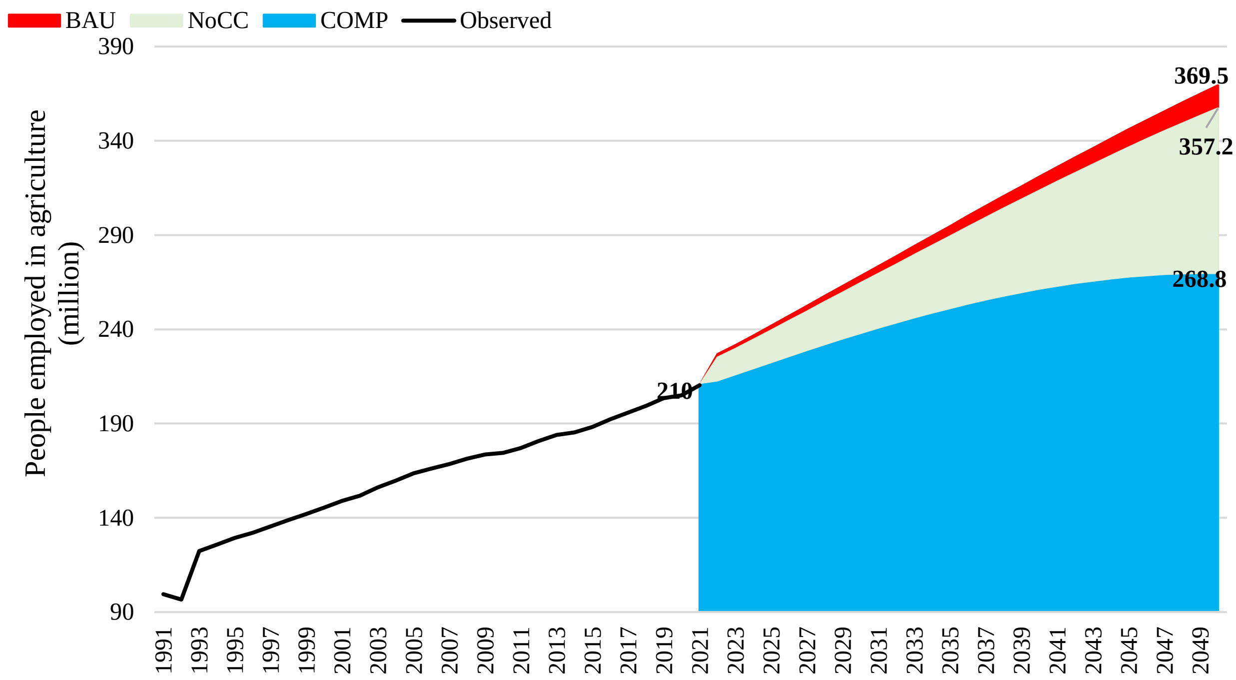
An accelerated shift of labor out of agriculture would ensue, fueling the structural transformation. The change in the agricultural employment share between the comprehensive intervention package and BAU with climate change is calculated using equation (2) as before. Globally, the agricultural employment share would be 4.3 percent lower under the comprehensive package, suggesting a substantial acceleration of the structural transformation compared to BAU. In Sub-Saharan Africa, the decline in the share of agricultural employment be almost twice as fast as under BAU (by 26.2 versus 14 percent respectively). When converted into agricultural workers, almost 101 million fewer people would be working in on farm AFS compared to the BAU with climate change (Figure 13). With incomes higher and given the proper accompanying investments in agricultural value chain development, some of these workers will be absorbed in the off-farm AFS labor force, so that the decline in the overall AFS labor force will be smaller.

Figure 12. Percentage points reduction in the share of agricultural employment in 2050 (relative to 2010) under the comprehensive scenario and the BAU scenario with and without climate change.



Source: own calculation based on IFPRI data on future cereal yield growth, FAOSTAT data on cereal yields (Kg/Ha) and ILOSTAT data on employment in agriculture.

Figure 13. Observed and projected number of people employed in agriculture in Sub-Saharan Africa



Source: own calculation

In conclusion, the evidence suggests that an acceleration of the structural transformation is still feasible under BAU climate change, given the appropriate package of interventions. The macro-simulations building on the IMPACT model and the historically observed relation between the evolution of yield increases and on farm labor use thus suggest that an acceleration of the structural transformation is still feasible, given appropriate investments, especially in agriculture and CSA-related R&D. Arguably, these findings may not fully account for CSA's larger labor intensity highlighted by the micro-econometric evidence.[52] Yet, explicit control for machinery use in estimating the labor share/yield relation, ensuing mechanization of CSA as labor costs increase[53], and the very large decline in on farm employment with the comprehensive package[54] help reconcile the micro-econometric finding of increased labor intensity in CSA with the macro predictions of a substantial decline in on-farm labor use following the comprehensive investment package.

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[52] The estimated relationship between yields and agricultural labor use reflects historical agronomic practices during 1990-2020 when CSA is still incipient.
[53] Increased labor intensity when switching to CSA likely only applies in the short run. CSA likely mechanizes as it spreads and the cost of labor increases, as observed in SRI (more mechanized in Asia (which is further in the structural transformation) than in Africa).
[54] Larger (short run) labor intensity in CSA is unlikely to offset the dramatic decline in on farm labor use under the comprehensive intervention package.

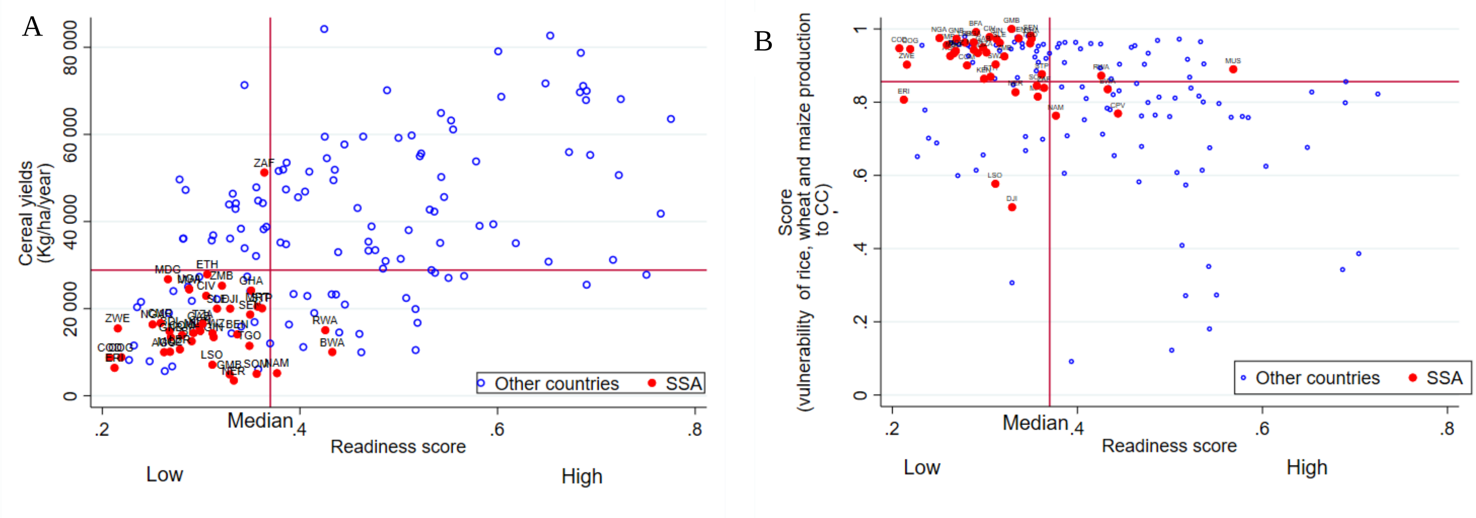
Nonetheless, important caveats remain and further modeling work, that endogenizes labor and more explicitly examines the AFS labor implications of climate change mitigation and more extreme weather events, is called for. First, instead of examining the effects of environmental degradation on AFS labor ex post, based on historically observed relationships between AFS labor and agricultural performance indicators generated by the integrated agricultural models, it would be worthwhile to build a labor module into the in integrated agricultural assessment models, to directly explore the effects, with the labor related parameters informed by solid micro-evidence, including those related to CSA practices. Second, the modeled mechanisms in IMPACT show a substantial reduction in food commodity prices under a comprehensive package of agricultural investments. However, the model does fully account for all mitigation policies, such as forest conservation (and to some extent biofuel production).[55] These are likely to divert land from food production and push up food prices, thereby reducing the employment multipliers in the non-farm economy. Thirdly, the increasing frequency and intensity of extreme weather events will not only increase uncertainty, dampening investment in the sector, it may also cause irreparable damage, putting production systems on a low agricultural growth path. Neither is explicitly accounted for in the current models.

7 Policies to foster the green transition in agriculture

To transition to a greener AFS, policies and programs must create enabling conditions for the adoption of adaptation and mitigation strategies. This will be especially needed in SSA, where cereal yields are still low and highly vulnerable (especially for maize and rice, two key staples) with limited capacity still to adjust (Figure 13). However, the rate of adoption among small-scale farmers in sub-Saharan African countries remains low due to structural barriers such as limited access to economic resources, knowledge gaps and risk aversion (Ignaciuk et al., 2022; Scognamillo & Sitko, 2021)Policy options to foster the transition towards a greener food system can be broadly organized around three mutually interdependent pillars to 1) incentivize, 2) inform, and 3) invest in the transition towards a greener food system. They are discussed in turn.

[55] Liquid biofuels for transport derived from primary agricultural feedstocks are included in the IMPACT model, but they are largely driven by exogenous demand (mainly government mandates). Other biofuels are not accounted for.

Figure 14. Cereal yields level (Kg/ha/year) and adaptation readiness score (Panel A). Projected change of major cereal yields (average score for rice, wheat, and maize) and adaptation readiness score (Panel B).



Source: Notre Dame Global Adaptation Initiative for adaptation readiness score and score of the projected change of major cereal yields; FAOSTAT data for cereal yields

Repurposing agricultural support and expanding social protection can help incentivize the transition to a more resource-efficient and resilient food production system. Net public transfers to agricultural production during 2016-2018 totaled US$ 638 billion per year (Gautam et al. 2022). Yet, much of this support supports unsustainable farming practices and is misaligned with the climate goals. Direct support to agricultural production accounted for 70% of the total disposable net transfer and 70% of this was allocated to direct support for output, inputs, or production factors and market price supports. Only 17% was allocated to public goods and services like research and irrigation, and just 5% was used for 'green subsidies' (subsidies to achieve better environmental outcomes). Redirecting some public spending towards agricultural R&D and incentivizing the development and adoption of climate-smart agricultural practices, can raise productivity and lower GHG emissions (by 40 percent between 2020 and 2040). An important area of attention is to help farmers overcome the time lag before the benefits from CSA materialize. More broadly, studies have shown that households in social protection programs are more likely to adopt green practices (Maggio et al., 2022; Scognamillo & Sitko, 2021). Passive labor market policies financed through public funding can help workers who are transitioning between jobs, such as unemployment benefits or income support programs.

Early warning systems and skill development can help build capacity. By providing accurate and timely information on climate risks early warning systems help farmers and communities take the necessary precautions and adapt to changing climatic conditions. Early warning system policies focus on the development of analysis, monitoring, and forecast tools for early warning and strengthening farmers' capabilities to interpret and act upon this information. Extension systems can train farmers in climate adaptive and conservation agricultural practices more broadly, which has been proven to enhance agricultural performance and effectively reduce weather variability and climate change impacts on agricultural output (Azzarri & Nico, 2022). Active labor market policies can further up- and re-skill off-farm AFS workers. Support mechanisms to the private sector to help re/upskill their workers include tax incentives and matching funds as well as the development of sector-specific training programs that can benefit multiple employers.

The third pillar involves supporting countries to meet their investment needs to transition to a greener economy. Technology transfers, for example, are critical for the dissemination of sustainable technologies and practices in the AFS of developing countries. In Tanzania, the use of solar-powered irrigation systems has helped smallholder farmers harness solar energy to power their irrigation systems, reduce their vulnerability to climate change and raise their crop yields and incomes[56]. Matching grants can be used to leverage the private sector to transfer such climate friendly technology or projects. State and local governments can be supported to fund local research institutions to develop new technologies or demonstration projects that showcase the benefits of sustainable agricultural practices or other adaptation or mitigation practices. Additionally, they can provide funding for supporting infrastructure.

[56] https://elicofoundation.org/solar-powered-irrigation-systems-transforming-smallholders-farming-practices-in-rural-tanzania/

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Annex 1. Defining and operationalizing employment in the agri-food system.

Employed population. Concepts for employment were defined by the 13th International Conference of Labor Statisticians (ICLS, 1982)[57] as all persons of working age who, during a short reference period, were engaged in any activity performed by persons of any sex in working-age, to produce goods or to provide services for use by others or for own use.

Employment includes persons "at work," i.e., who worked in a job for at least one hour during the reference period and persons "not at work" due to temporary absence from a job, or to working-time arrangements (such as shifts in work, flextime, and compensatory leave for overtime).

Employment or own-use production work? Data used for the calculation of employment in the agri-food system does not allow distinguishing between persons employed and persons who engage in activities to produce goods or provide services mainly for the final consumption of their households. This suggests that subsistence foodstuff producers, also referred as persons in own-use production work, constitute an important subgroup of the total number of people 'employed' in the agri-food system, especially in low and lower-middle income countries[58].

Employment in the agri-food system. In this study, employment in the agri-food system is defined as the total number of employed persons who perform their main job[59] in each of the segment of the AFS value chain. The segments of the AFS value chain include on-farm activities (crop, livestock, forestry, fishery, and aquaculture) and off-farm activities (food and beverage processing activities, food trading and food services).

Operationalizing employment in the agri-food system. Employment in the agri-food system is classified as related to the agri-food system based on definitions used in the International Classification of Economic

[57] See https://www.ilo.org/wcmsp5/groups/public/---dgreports/---stat/documents/normativeinstrument/wcms_087481.pdf

[58] The latest ICLS resolution concerning 'statistics of work, employment and labor underutilization' (2013) sets the statistical criteria to further distinguish between persons employed and persons who engage in own-use production work. As a results, the concept of employment only refers to persons who work "for pay or profit" and it implies activities undertaken in exchange for remuneration in the form of wages or salaries, or in the form of profits derived from the goods and services produced through market transactions (including remuneration in cash or in kind, whether received or not, and may also comprise additional components of cash or in-kind income). This contrast with the concept of own-use production work which only refers to persons who, during a short reference period, performed any activity to produce goods or provide services for own final use. See https://www.ilo.org/wcmsp5/groups/public/---dgreports/---stat/documents/normativeinstrument/wcms_230304.pdf

[59] The term job is used in reference to employment while the term work activity is used with reference to subsistence foodstuff producers. Since ILO data do not disaggregate between employment and subsistence foodstuff producers, the term job is applied indistinctly to both persons employed and persons who engage in the agri-food system mainly to produce food for the final consumption of the household.

Activity (ISIC) standards agreed for use by UN member states (UN, 2015) as a standard by which measures of economic activity can be compared (in the System of National Accounts[60]).

Persons employed in the agri-food system are classified by different codes for a number of activities related to the pre- and post-harvest stages of production, as indicated in Table 6 below.

Table 8. ISIC industries used to classify employment in the agri-food system.

Stage of Production		ISIC industry	ISIC Code
On-farm:	**Agriculture, forestry, and fishing** (Exploitation of vegetal and animal natural resources, comprising the activities of growing of crops, raising, and breeding of animals, harvesting of timber and other plants, animals or animal products from a farm or their natural habitats)	Crop and animal production, hunting and related service activities	01
		Forestry and logging	02
		Fishing and aquaculture	03
Off-farm	**Food processing**	Manufacture of food products	10
		Manufacture of beverages	11
	Food trading	Wholesale of food, beverages, and tobacco	463
		Retail sale of food, beverages, and tobacco in specialized stores	472
		Freight rail transport	4912
		Freight transport by road	4923
		Sea and coastal freight water transport	5012
		Inland freight water transport	5022
		Freight air transport	5120
	Food services	Food and beverage service activities	56

Data sources and data manipulation. Country-level employment data were sourced from the ILO database (ILOSTAT) which serves as the foundation for global estimates of employment in the agri-food system, for the year 2021[61].

The ILO database provide**s** direct country-level estimates of employment job by industry. The total number of persons employed by industry are available in the ILO database at the ISIC 2-digit level.

The ILO database provides direct estimates of the total number of people employed in on-farm activities (that is crop and animal production, forestry and logging, and fishing and aquaculture), in the manufacture of food products and beverages, as well as in the food services sector of the agri-food system. However, persons employed in the wholesale and retail sale of food, and in the transport of food-related products are not directly observable but accounted for in the broad trading and transport sectors. These two broad sectors also include persons employed in the trading and transportation of non-food products (Table 7).

[60] https://unstats.un.org/unsd/nationalaccount/sna.asp

[61] https://ilostat.ilo.org/data/

Table 9. Employment in food trading and food transportation and corresponding categories available in the ILO database.

Stage of Production			ISIC industry	ISIC Code	Aggregate ISIC industry available in ILOSTAT	Corresponding ISIC code in ILOSTAT
Off-farm	**Food trading**	**Trading**	Wholesale of food, beverages, and tobacco	463	Wholesale trade, except of motor vehicles and motorcycles	46
			Retail sale of food, beverages, and tobacco in specialized stores	472	Retail trade, except of motor vehicles and motorcycles	47
		Transport	Freight rail transport	4912	Land transport and transport via pipelines	49
			Freight transport by road	4923		
			Sea and coastal freight water transport	5012	Water transport	50
			Inland freight water transport	5022		
			Freight air transport	5120	Air transport	51

To avoid overestimates, employment in trading and transportation related specifically to the agri-food system was estimated following recommendations in Davis et al. (2023).

Specifically, we used a two-step calculation to estimate the total number of persons employed in the wholesale and retail sale of food, and in the transport of food-related products, as follows.

First, for each country we calculated the share of agri-food system employment (% of total employment) but we excluded total employment in trade and transportation, as per formula [1] below.

$$Share\_AFS_c = \frac{(onfarm_c + Food\ processing\ _c + Food\ services_c)}{total\_EMP_c} \qquad [1]$$

Where $Share\_AFS_c$ measures the share of employment in the agri-food system in country c. In [1], the numerator of the ratio includes the total number of persons employed in on-farm activities, food processing and food services (that is $onfarm_c + Food\ processing\ _c + Food\ services_c$). The term $total\_EMP_c$ measures the total number of persons employed in country c, but it excludes persons employed in trading and transportation.

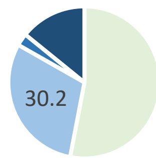
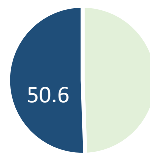
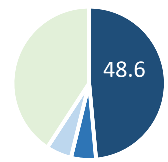
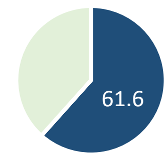
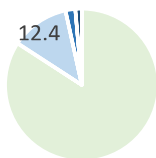
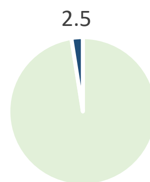
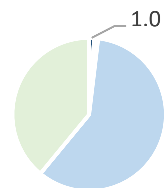
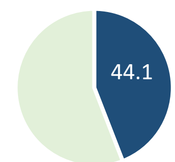
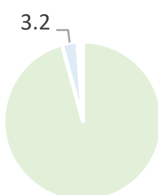
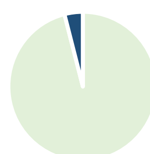
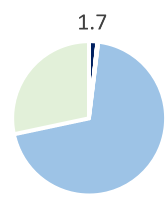
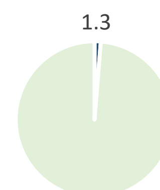
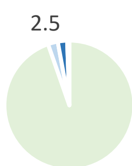
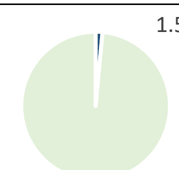
Second, we multiplied the share of agri-food system employment ($Share\_AFS$) by the total number of persons employed in the wholesale and retail sale, and in the transport of food and non-food products (that is the broad sectors in ILOSTAT), as follows.

$$tot\_emp\_food\_trading\_food\_trans_c = Share\_AFS_c * tot\_emp\_trading\_transpor_c \qquad [2]$$

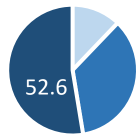
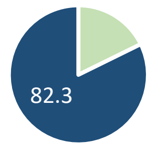
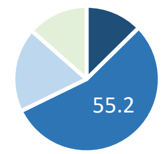
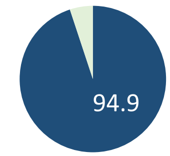
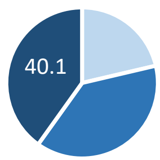
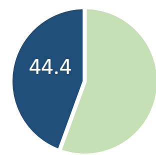
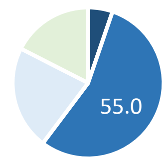
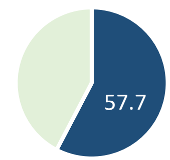
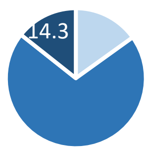
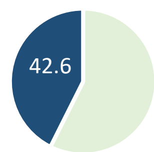
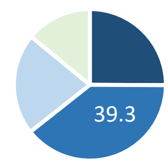
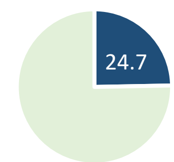
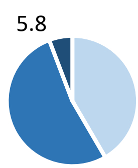
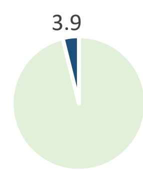
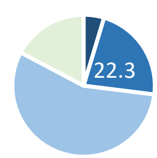
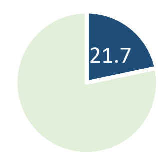
In [2], $tot\_emp\_food\_trading\_food\_trans_c$ is the estimated number of persons employed in food trading and food transportation; $Share\_AFS_c$ measures the share of employment in the agri-food system in country c (which goes from 0 to 1); $tot\_emp\_trading\_transpor_c$ is the observed number of persons employed in the wholesale and retail sale, and in the transportation of food and non-food products.

The underlying assumption is that: given total employment in trading and transportation, the total number of persons employed in the wholesale and retail sale of food, and in the transport of food-related products increases proportionally to the importance of the agri-food system in the total economy $Share\_AFS_c$.

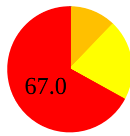
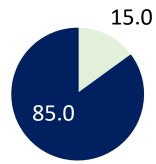
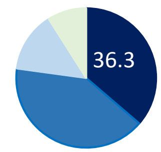
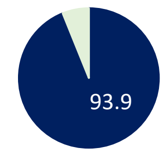
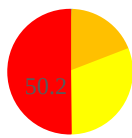
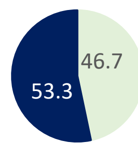
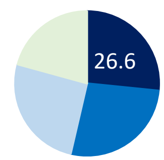
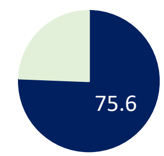
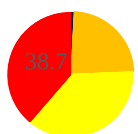
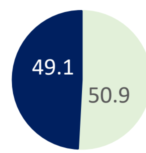
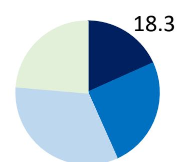
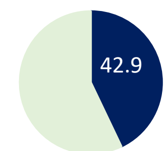
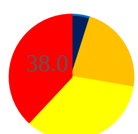
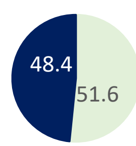
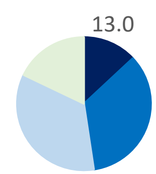
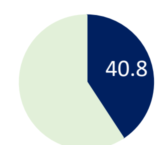
Annex 2a. Employment in on-farm AFS along the four dimensions of structural transformation

Income group	Sectoral	Spatial	Occupational	Organizational
High income (USA)				
Upper-middle income (Mexico)				
Lower-middle income (India)				
Low income (Madagascar)				
Legend	Crop Livestock Fisheries Other on-farm activities	Rural Urban	Low-skilled occupations Medium-low skilled occupations Medium-high skilled occupations High-skilled occupations	Self-employment jobs Paid jobs

Annex 2b. Employment in off-farm AFS along the four dimensions of structural transformation

Income group	Sectoral	Spatial	Occupational	Organizational
High income (USA)				
Upper-middle income (Mexico)				
Lower-middle income (India)				
Low income (Madagascar)				
Legend	Food processing Food trading Food services	Rural Urban	Low-skilled occupations Medium-low skilled occupations Medium-high skilled occupations High-skilled occupations	Self-employment jobs Paid jobs

Annex 2c. Employment in the non-AFS along the four dimensions of structural transformation

Income group	Sectoral	Spatial	Occupational	Organizational
High income (USA)				
Upper-middle income (Mexico)				
Lower-middle income (India)				
Low income (Madagascar)				
Legend	Mining and quarrying	Rural	Low-skilled occupations	Self-employment jobs
	Manufacture	Urban	Medium-low skilled occupations	Paid jobs
	Construction and wholesale/retail trade		Medium-high skilled occupations	
	Other services		High-skilled occupations	

Annex 3. Macroeconomic, labor market and land indicators under extensification agriculture in Sub-Saharan Africa and intensification agriculture in Asia

	Indicator		Sub-Saharan Africa				Asia			
			1990-1999	2000-2009	2010-2020	1990-2020	1990-1999	2000-2009	2010-2020	1990-2020
Macro context	GDP per capita (constant 2015 US$)	Average annual growth	1.3%	2.0%	1.0%	1.4%	2.9%	4.2%	3.0%	3.4%
	Agriculture, forestry, and fishing, value added per worker	Average annual growth	1.5%	1.3%	2.1%	1.7%	1.2%	2.9%	3.4%	2.7%
	Agriculture, forestry, and fishing, value added per worker	Constant 2015 US$	1,639.4	1,787.5	2,117.0	1,876.3	7,035.5	9,418.1	10,827.7	9,335.8
Cereal production and productivity	Cereal yields	Kg/Ha	1,168.8	1,335.0	1,475.5	1,338.1	2,653.6	3,059.1	3,636.7	3,149.3
	Cereal production	Start year	**1990**	**2000**	**2010**	**1990**	**1990**	**2000**	**2010**	**1990**
		Metric tons (million)	65.2	83.5	131.8	65.2	826.3	934.7	1,148.0	826.3
		End year	**1999**	**2009**	**2020**	**2020**	**1999**	**2009**	**2020**	**2020**
		Metric tons (million)	83.3	131.8	172.6	172.6	974.1	1,148.0	1,354.7	1,354.7
	Ratio (end-to-start year)		1.3	1.6	1.3	2.6	1.2	1.2	1.2	1.6
	Land under cereal cultivation	Start year	**1990**	**2000**	**2010**	**1990**	**1990**	**2000**	**2010**	**1990**
		Ha (million)	60.1	70.6	91.4	60.1	284.1	282.8	295.2	284.1
		End year	**1999**	**2009**	**2020**	**2020**	**1999**	**2009**	**2020**	**2020**
		Ha (million)	70.7	91.4	105.5	105.5	289.3	295.2	302.8	302.8
	Ratio (end-to-start year)		1.2	1.3	1.2	1.8	1.0	1.0	1.0	1.1
Labor market	Number of people employed (million)									
	Agriculture, forestry, and fishing	Start year	**1990**	**2000**	**2010**	**1990**	**1990**	**2000**	**2010**	**1990**
		People (million)	117	147	177	117	765	778	696	765
		End year	**1999**	**2009**	**2020**	**2020**	**1999**	**2009**	**2020**	**2020**
		People (million)	144	176	205	205	765	708	556	556
		Net jobs created	**27**	**29**	**29**	**88**	**0**	**-71**	**-140**	**-208**
	Industry	Start year	**1990**	**2000**	**2010**	**1990**	**1990**	**2000**	**2010**	**1990**
		People (million)	18	23	30	18	266	318	428	266
		End year	**1999**	**2009**	**2020**	**2020**	**1999**	**2009**	**2020**	**2020**
		People (million)	22	29	44	44	315	415	461	461
		Net jobs created	**4**	**7**	**14**	**26**	**49**	**97**	**33**	**195**
	Services	Start year	**1990**	**2000**	**2010**	**1990**	**1990**	**2000**	**2010**	**1990**
		People (million)	47	64	100	47	331	475	625	331
		End year	**1999**	**2009**	**2020**	**2020**	**1999**	**2009**	**2020**	**2020**
		People (million)	62	95	140	140	462	613	806	806
		Net jobs created	**15**	**31**	**40**	**93**	**131**	**138**	**181**	**475**

Source: ILOSTAT (2022) and WDI (2022).

Annex 4a. Activity share of GHG emissions by activity, in total GHG in the Region.

GHG emissions by activity, in total Region GHG emissions (within regions)														
Activity share (column %) of GHG emissions by region			Arab States	Central and Western Asia	Eastern Asia	Eastern Europe	Latin America and the Caribbean	Northern Africa	Northern America	Northern, Southern and Western Europe	South-Eastern Asia and the Pacific	Southern Asia	Sub-Saharan Africa	**World**
Agricultural land	**Land use change**	Fires in organic soil	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	19.6%	0.0%	0.0%	**2.7%**
		fires forest	0.0%	0.0%	0.0%	0.6%	1.1%	0.0%	0.2%	0.0%	1.9%	0.2%	5.0%	**1.3%**
		Net forest conversion	0.3%	0.2%	0.4%	4.4%	39.3%	6.9%	10.0%	3.0%	17.6%	0.4%	44.7%	**17.6%**
	Farm gate	Drained organic soil	0.0%	0.0%	1.7%	17.1%	0.8%	0.0%	6.5%	12.8%	14.3%	1.3%	2.5%	**5.5%**
		Synthetic fertilizers	0.8%	4.9%	7.2%	3.4%	1.9%	3.0%	5.0%	3.8%	2.2%	6.7%	0.5%	**3.6%**
		Crop residues	0.4%	1.2%	1.6%	1.7%	0.9%	0.9%	1.9%	1.1%	0.7%	1.6%	0.4%	**1.1%**
		Manure left on pasture	3.6%	7.5%	3.0%	0.7%	6.5%	11.2%	2.5%	1.8%	2.6%	5.0%	8.2%	**4.6%**
		Manure applied to soil	0.2%	1.2%	1.4%	1.4%	0.7%	0.4%	1.0%	2.2%	0.7%	1.2%	0.3%	**1.0%**
		Manure management	0.4%	2.6%	2.9%	2.6%	1.0%	1.1%	4.0%	5.6%	2.1%	2.8%	1.0%	**2.3%**
		Enteric fermentation	6.5%	22.8%	10.3%	8.6%	24.8%	23.8%	12.3%	15.3%	8.3%	29.0%	17.9%	**16.9%**
		Savanna fires	0.3%	1.1%	0.0%	0.5%	0.8%	0.9%	0.1%	0.0%	1.6%	0.0%	5.6%	**1.3%**
		Burning crop residues	0.0%	0.3%	0.3%	0.3%	0.2%	0.1%	0.3%	0.1%	0.2%	0.3%	0.2%	**0.2%**
		Rice cultivation	0.3%	0.8%	7.7%	0.2%	0.7%	1.4%	0.6%	0.5%	10.3%	8.9%	1.8%	**4.0%**
		on-farm energy use	7.2%	5.0%	6.9%	4.7%	2.5%	3.4%	4.6%	4.9%	1.5%	1.3%	0.9%	**3.2%**
Total on-farm		Total on farm	20.2%	47.6%	43.6%	46.1%	81.1%	53.1%	49.0%	51.1%	83.6%	58.8%	89.2%	**65.4%**
pre and post production		Electricity use	3.3%	6.7%	5.7%	1.4%	0.6%	2.7%	1.9%	1.7%	0.3%	11.4%	0.3%	**3.0%**
		Fertilizers manufacturing	7.6%	2.7%	6.6%	7.2%	0.8%	6.0%	3.3%	1.6%	0.5%	1.8%	0.0%	**2.5%**
		Food packaging	1.1%	1.8%	6.6%	2.4%	0.5%	0.9%	2.0%	5.2%	0.6%	0.3%	0.3%	**1.9%**
		Food processing	18.7%	5.7%	2.1%	5.4%	1.0%	4.5%	7.7%	7.4%	1.8%	1.5%	0.4%	**3.1%**
		Food transport	10.3%	3.8%	4.1%	2.8%	2.4%	5.4%	4.8%	7.0%	2.2%	2.6%	0.8%	**3.2%**
		Food retail	6.2%	7.0%	5.2%	19.2%	0.9%	1.6%	20.1%	13.2%	1.6%	1.0%	0.4%	**5.6%**
		Food waste disposal	32.7%	24.7%	26.2%	15.5%	12.7%	25.8%	11.2%	12.8%	9.3%	15.6%	8.6%	**14.6%**
		Other	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	7.0%	0.0%	**0.9%**
Total off-farm			79.8%	52.4%	56.4%	53.9%	18.9%	46.9%	51.0%	48.9%	16.4%	41.2%	10.8%	**34.6%**
Total AFS			**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

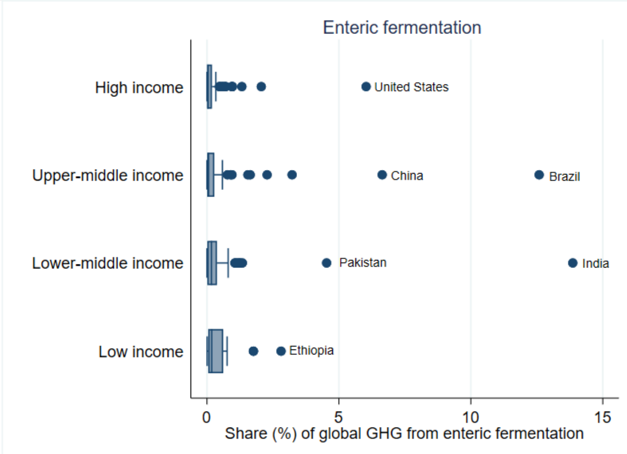
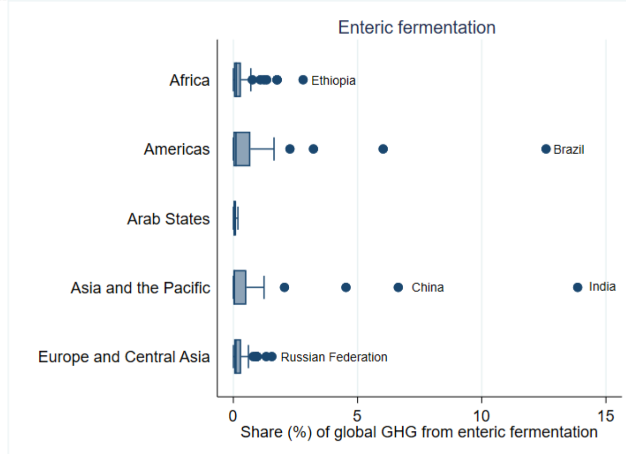
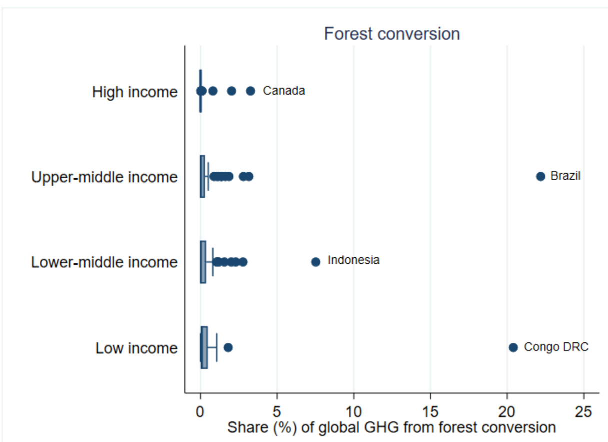
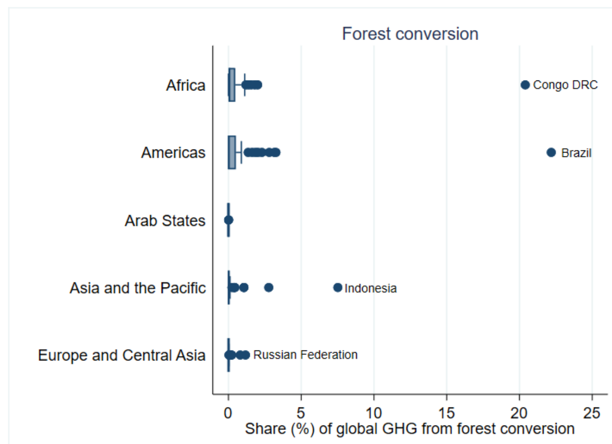
Source: own calculation based on FAOSTAT data. Domain: climate change. Available at https://www.fao.org/faostat/en/#data/GT

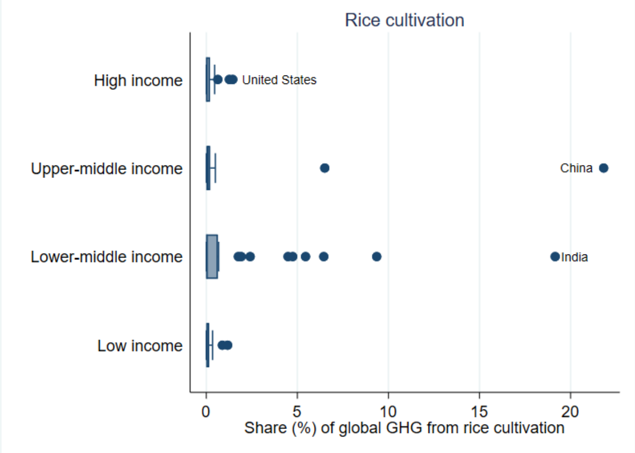
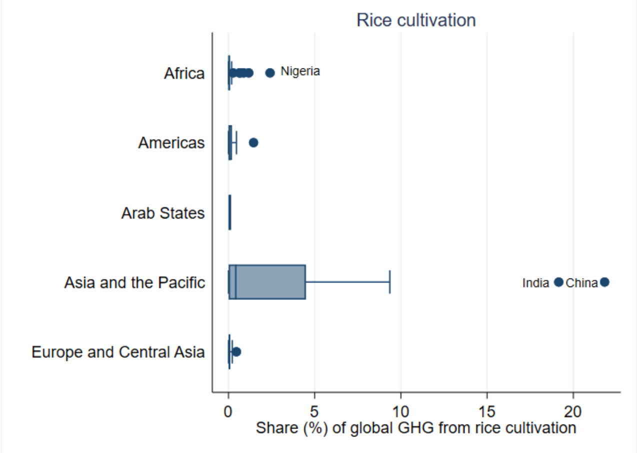
Annex 4b. Share of GHG emissions by activity, in global GHG by activity.

			GHG emissions by activity in the region in global GHG emissions by activity (between region)											
Regional share of GHG emissions (row%) by activity			Arab States	Central and Western Asia	Eastern Asia	Eastern Europe	Latin America and the Caribbean	Northern Africa	Northern America	Northern, Southern and Western Europe	South-Eastern Asia and the Pacific	Southern Asia	Sub-Saharan Africa	**World**
Agricultural land	**Land use change**	Fires in organic soil	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	**100%**
		fires forest	0.0%	0.0%	0.4%	2.8%	15.3%	0.0%	1.2%	0.1%	19.9%	2.4%	57.9%	**100%**
		Net forest conversion	0.0%	0.0%	0.3%	1.5%	38.8%	0.7%	5.3%	1.3%	13.8%	0.3%	38.0%	**100%**
	Farm gate	Drained organic soil	0.0%	0.0%	4.0%	19.4%	2.4%	0.0%	11.0%	17.4%	36.0%	3.0%	6.9%	**100%**
		Synthetic fertilizers	0.4%	3.0%	25.5%	5.9%	9.1%	1.6%	13.1%	8.0%	8.4%	22.9%	2.2%	**100%**
		Crop residues	0.6%	2.4%	18.4%	9.6%	13.5%	1.5%	15.2%	7.4%	8.6%	16.9%	5.9%	**100%**
		Manure left on pasture	1.4%	3.7%	8.4%	1.0%	24.6%	4.6%	5.1%	3.0%	7.8%	13.5%	26.8%	**100%**
		Manure applied to soil	0.3%	2.8%	18.1%	8.9%	13.1%	0.7%	9.9%	16.7%	9.7%	14.6%	5.1%	**100%**
		Manure management	0.3%	2.4%	15.4%	6.8%	7.3%	0.9%	16.0%	17.7%	12.2%	14.5%	6.4%	**100%**
		Enteric fermentation	0.7%	3.0%	7.8%	3.2%	25.5%	2.7%	6.7%	6.8%	6.8%	21.1%	15.9%	**100%**
		Savanna fires	0.4%	1.9%	0.2%	2.5%	10.6%	1.3%	0.7%	0.0%	17.6%	0.2%	64.6%	**100%**
		Burning crop residues	0.4%	2.6%	18.1%	7.9%	13.4%	1.2%	11.6%	3.3%	10.4%	17.9%	13.1%	**100%**
		Rice cultivation	0.1%	0.4%	24.3%	0.3%	2.9%	0.7%	1.5%	0.8%	35.0%	27.2%	6.8%	**100%**
		on-farm energy use	4.0%	3.5%	27.2%	9.1%	13.6%	2.0%	13.4%	11.4%	6.5%	5.1%	4.1%	**100%**
Total on-farm		Total on farm	0.5%	1.6%	8.4%	4.4%	21.6%	1.5%	7.0%	5.8%	17.6%	11.0%	20.4%	**100%**
Pre- and post- production		Electricity use	2.0%	5.0%	24.4%	3.0%	3.5%	1.7%	6.1%	4.3%	1.5%	47.0%	1.4%	**100%**
		Fertilizers manufacturing	5.5%	2.5%	33.9%	18.3%	5.7%	4.6%	12.5%	4.9%	2.8%	9.2%	0.0%	**100%**
		Food packaging	1.1%	2.1%	44.1%	8.1%	4.5%	0.9%	9.7%	20.4%	4.5%	2.1%	2.6%	**100%**
		Food processing	10.7%	4.1%	8.5%	11.0%	5.9%	2.8%	23.2%	18.0%	8.1%	5.8%	1.8%	**100%**
		Food transport	5.7%	2.6%	16.1%	5.5%	12.9%	3.2%	14.1%	16.4%	9.6%	10.1%	3.9%	**100%**
		Food retail	2.0%	2.8%	11.9%	21.4%	2.8%	0.5%	33.5%	17.6%	4.1%	2.3%	1.2%	**100%**
		Food waste disposal	4.0%	3.8%	22.7%	6.6%	15.2%	3.4%	7.1%	6.5%	8.8%	13.1%	8.8%	**100%**
		Other	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	**100%**
Total off-farm			4.1%	3.4%	20.7%	9.7%	9.5%	2.6%	13.7%	10.5%	6.6%	14.6%	4.7%	**100%**
Total AFS			**1.8%**	**2.2%**	**12.7%**	**6.2%**	**17.4%**	**1.9%**	**9.3%**	**7.5%**	**13.8%**	**12.3%**	**15.0%**	**100%**

Source: own calculation based on FAOSTAT data. Domain: climate change. Available at https://www.fao.org/faostat/en/#data/GT

Annex 5. Countries mainly responsible for GHG emissions from agriculture and land use change

GHG emissions from on-farm direct and indirect activities		Most polluting countries and areas
		Across space, enteric fermentation from lower- and upper-middle income countries contribute to an estimated 69.1 percent of global enteric GHG emissions. These emissions are mainly attributable to India, Brazil, and China which account for roughly one-third of global emissions from enteric fermentation. In Africa, Ethiopia shows the highest GHG emission from enteric fermentation of livestock production.
		65.2 percent of global emissions from forest conversion come from upper-middle- and low-income-income countries. Brazil, Congo DRC, and Indonesia are responsible for 50.1 percent of total emissions from forest conversion. In Africa, Congo DRC shows the highest contribution of GHG emissions from forest conversion, on the same scale as Brazil.

GHG emissions from on-farm direct and indirect activities	Most polluting countries and areas
 	Methane emissions from paddy rice cultivation are mainly concentrated in lower-middle income countries which account for 59.6 percent of global emissions from rice cultivation. Eight Asian countries (China, India, Indonesia, Philippines, Thailand, Viet Nam, Bangladesh, and Myanmar) account for 78 percent of the global emissions from rice cultivation In Africa, Nigeria shows the highest GHG emission from rice production (32 percent of total emissions from Africa).

Source: own calculation based on FAOSTAT data. Domain: climate change. Available at https://www.fao.org/faostat/en/#data/GT

Annex 6. Number and share of jobs in sub-Saharan Africa exposed to current and future climate hazards in agriculture

Share of the administrative area affected by climate hazards	Region (Number of countries)	Estimates **Number of agricultural workers**	[95% conf. interval] **Lower bound**	**Upper bound**	**Agricultural workers (percent of total country's workers)**	Estimates **Total number of agricultural and non-agricultural jobs**
Not affected (0 %)	Central Africa (2)	-	-	-	-	
	Eastern Africa (11)	3,193,702	3,066,322	3,321,083	44.7	7,140,704
	Northern Africa (2)	181,394	158,740	204,047	23.4	774,252
	Southern Africa (4)	-	-	-	-	
	Western Africa (12)	2,103,935	2,025,469	2,182,401	39.8	5,280,443
	Total	**5,479,031**	**5,250,531**	**5,707,531**	**41.5**	**13,195,399**
>0-15%	Central Africa (2)	14,400,000	14,100,000	14,600,000	68.6	21,000,000
	Eastern Africa (11)	14,500,000	14,100,000	15,000,000	69.7	20,800,000
	Northern Africa (2)	1,937,044	1,877,315	1,996,772	19.2	10,100,000
	Southern Africa (4)	34,833	31,551	38,115	38.3	91,019
	Western Africa (12)	9,141,432	8,838,093	9,444,771	51.7	17,700,000
	Total	**40,013,309**	**38,946,959**	**41,079,658**	**57.4**	**69,691,019**
15-30%	Central Africa (2)	7,223,467	7,041,236	7,405,698	57.3	12,600,000
	Eastern Africa (11)	35,600,000	34,600,000	36,500,000	68.7	51,800,000
	Northern Africa (2)	1,806,652	1,754,458	1,858,846	31.7	5,699,324
	Southern Africa (4)	32,693	29,781	35,605	29.4	111,181
	Western Africa (12)	10,100,000	9,730,227	10,400,000	56.1	18,000,000
	Total	**54,762,812**	**53,155,702**	**56,200,149**	**62.1**	**88,210,505**
30-50%	Central Africa (2)	-	-	-	-	-
	Eastern Africa (11)	18,200,000	17,800,000	18,500,000	65.7	27,700,000
	Northern Africa (2)	1,415,726	1,359,359	1,472,094	28.2	5,014,551
	Southern Africa (4)	197,664	186,200	209,128	10.5	1,868,132
	Western Africa (12)	14,700,000	14,300,000	15,100,000	55.4	26,500,000
	Total	**34,513,390**	**33,645,559**	**35,281,222**	**56.5**	**61,082,683**
50-75%	Central Africa (2)	885,950	840,797	931,103	80.1	1,106,774
	Eastern Africa (11)	14,000,000	13,800,000	14,300,000	70.4	19,900,000
	Northern Africa (2)	1,162,528	1,113,188	1,211,867	21.3	5,447,325
	Southern Africa (4)	810,627	786,222	835,032	6.2	12,900,000
	Western Africa (12)	15,200,000	14,600,000	15,700,000	43.9	34,600,000
	Total	**32,059,105**	**31,140,207**	**32,978,002**	**43.4**	**73,954,099**
75-100%	Central Africa (2)	170,867	152,072	189,662	46.6	366,464
	Eastern Africa (11)	6,159,738	5,933,997	6,385,479	61	10,100,000
	Northern Africa (2)	459,522	433,112	485,932	32.9	1,395,585
	Southern Africa (4)	336,479	322,169	350,790	10.2	3,293,343
	Western Africa (12)	4,271,729	3,976,632	4,566,827	35.3	12,100,000
	Total	**11,398,335**	**10,817,982**	**11,978,689**	**41.8**	**27,255,392**

Source: estimates of agricultural employment based on data extrapolated from 31 African surveys. Labor force surveys conducted in Botswana, 2006; Egypt, 2017; Madagascar, 2015; Mauritania, 2017; Namibia, 2018; Rwanda, 2017; Sierra Leone, 2014; South Africa, 2017; Tunisia, 2014; Zambia, 2018; Zimbabwe, 2019; household income and expenditure surveys conducted in Burkina Faso, 2014; Cameroon, 2014; Chad, 2019; Congo, Democratic Republic of the, 2011; Côte d'Ivoire, 2008; Ethiopia, 2016; Gambia, 2016; Ghana., 2014; Kenya., 2015; Lesotho, 2003; Liberia, 2016; Malawi, 2016; Mali, 2018; Mozambique, 2015; Niger, 2014; Nigeria, 2013; Senegal, 2011; South Sudan, 2016; Tanzania, United Republic of, 2013; Uganda, 2016. Estimates of areas with presence of climate hazards based on raster data provide by Safavi, N.; Thornton, P.; and Wollenberg, E., 2020, "Global spatial data for agricultural GHG emissions and climate hazards".

Annex 7. Investment scenarios included in the IMPACT model

Scenario	Type of investment (acronym)	Description	Propagated effects via investments	Additional costs compared to the reference scenario
Baseline scenario	REF_HGEM	Reference scenario with climate change		
	REF_NoCC	Reference with no climate change (constant 2005 climate)		
Productivity enhancement	1. HIGH+RE	High increase in R&D investment across the CGIAR portfolio plus increased research efficiency	Investment priorities include improved high-yielding and stress resistant crop varieties, livestock and fish breeds and husbandry practices, support of climate-smart agriculture practice	**Marginal increase from + $0.9 billion to $6.7 billion per year during 2015-2050.**
Improved infrastructure	2. RMM	Infrastructure improvements to improve market efficiency through the reduction of transportation costs and marketing margins	Improvements to transportation infrastructure--road building, road maintenance, and railroad--and increased electrification	**+25.94 billion per year to improve road, rail, and electric networks. This**
Improved Water and soil resource management	3. IX+WUE	Improving irrigation efficiency while conserving more water	e.g., no-till agriculture and water harvesting that increase the water holding capacity of soil or otherwise make precipitation more readily available to plants.	**+$8.33 billion per year in additional investments across developing countries**
	4. ISW	Investments to increase soil water holding capacity	No-till agriculture and water harvesting that increase the water holding capacity of soil or otherwise make precipitation more readily available to plants	**+$4.96 billion/year**
Comprehensive scenario	COMP	Comprehensive scenario is a combination of 4 scenarios: HIGH+RE; IX+WUE; ISW; and RMM		

Annex 8. Percentage points change in the share of agricultural employment to 2050 under different investment scenarios

	Cereal yield (Kg/ha)				Employment 2010 (thousand)			Agricultural machinery stock (1000 horsepower)		Coefficient (Dependent variable: share of agricultural employment in total employment)					% point change in the share of agricultural employment in 2050 comparing the scenario with 2010		
Region	Observed	Scenarios			Observed			Observed	Estimated	Constant	log cereal yields	(log cereal yields) ^2	log (mech)	country FE	Scenarios		
	2010	BAU	No CC	COMP	Agr	Total	%	2010	2050		b1	b2	b3	b4	BAU	No CC	COMP
Arab States	5,569	7,779	7,801	11,227	4,575	39,488	11.6	769	1,360	-14.3	4.26	-0.32	-0.14		-4.4	-4.4	-7.5
Central and Western Asia	2,344	3,739	3,520	4,164	16,051	59,288	27.1	5,309	10,240	-14.3	4.26	-0.32	-0.14	0.38	-7.9	-6.7	-9.8
Eastern Asia	4,330	5,457	5,464	6,598	289,137	872,447	33.1	229,109	318,518	-14.3	4.26	-0.32	-0.14	1.58	-7.1	-7.1	-12.7
Eastern Europe	3,421	5,456	5,267	6,075	15,198	136,046	11.2	12,260	24,832	-14.3	4.26	-0.32	-0.14	0.00	-3.5	-3.1	-4.4
Latin America and the Caribbean	3,815	5,158	5,566	7,329	40,478	251,132	16.1	2,720	5,019	-14.3	4.26	-0.32	-0.14	0.03	-5.6	-6.5	-9.4
Northern Africa	2,378	3,322	3,411	4,794	13,355	50,426	26.5	3,008	4,876	-14.3	4.26	-0.32	-0.14	0.19	-6.8	-7.3	-12.9
Northern America	5,240	6,062	6,816	6,031	2,784	159,379	1.7	105,829	194,882	-14.3	4.26	-0.32	-0.14	-1.29	-0.4	-0.6	-0.3
Northern, Southern and Western Europe	5,057	6,224	6,272	6,043	7,610	193,594	3.9	10,150	20,370	-14.3	4.26	-0.32	-0.14	-0.77	-0.8	-0.9	-0.7
South-Eastern Asia and the Pacific	3,325	4,191	4,195	5,068	115,669	297,063	38.9	6,787	10,312	-14.3	4.26	-0.32	-0.14	0.92	-9.6	-9.6	-15.1
Southern Asia	2,749	3,905	4,179	5,226	292,392	592,533	49.3	33,981	46,521	-14.3	4.26	-0.32	-0.14	1.15	-17.3	-19.4	-26.0
Sub-Saharan Africa	1,501	2,195	2,313	3,334	174,413	302,814	57.6	230	426	-14.3	4.26	-0.32	-0.14	0.33	-14.4	-15.8	-26.2
Total	**3,612**	**4,554**	**4,685**	**5,479**	**88,333**	**268,564**	**25.2**	**37,287**	**57,941**	**-14.3**	**4.26**	**-0.32**	**-0.14**		**-7**	**-7**	**-11**

Source: the percentage point change in the share of agricultural employment is calculated under different scenarios based on equation [1]. Baseline data (2010) for cereal yields are obtained from FAOSTAT, while cereal projections (to 2050) under different scenarios are based on FAOSTAT baseline data (2010) and IMPACT projections of cereal yields in 2050 under different scenarios. Note that BAU stands for the business-as-usual scenario, NoCC stands for the no climate change scenario, and COMP stands for the comprehensive scenario.

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