Agricultural mechanisation could reduce global labour requirements by hundreds of millions of agri-food workers

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Agricultural mechanisation could reduce global labour requirements by hundreds of millions of agri-food workers

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Abstract

The agricultural transition to more resilient and efficient farming is transforming food production systems in many regions globally. An important element of this global transition is exhibited through technological developments in farming practices. Their implications on the rural livelihoods employed in agriculture, however, have not been analysed at a global level. Here, we quantify the number of agricultural labourers that will be needed in agriculture following this agrarian transition. We focus on the potential labour reserves by simulating two what-if scenarios of incremental and very fast transition of mechanisation development in food systems and compare them to a baseline resembling the current state of agricultural employment. Presently, agriculture requires 286 million full-time equivalent workers (AWU) to reach the 2011-2015 production volumes of 21 major agricultural products. An incremental mechanisation development decreases the labour requirements to 74 million AWU while a very fast transition in mechanisation further reduces requirements to 19 million AWU. Given the significant implications of agricultural mechanisation on global labour requirements, our analysis demonstrates the need for forthcoming policies to consider the viability of rural groups led to exit agriculture in order to ensure a meaningful transition for the smallholders globally.

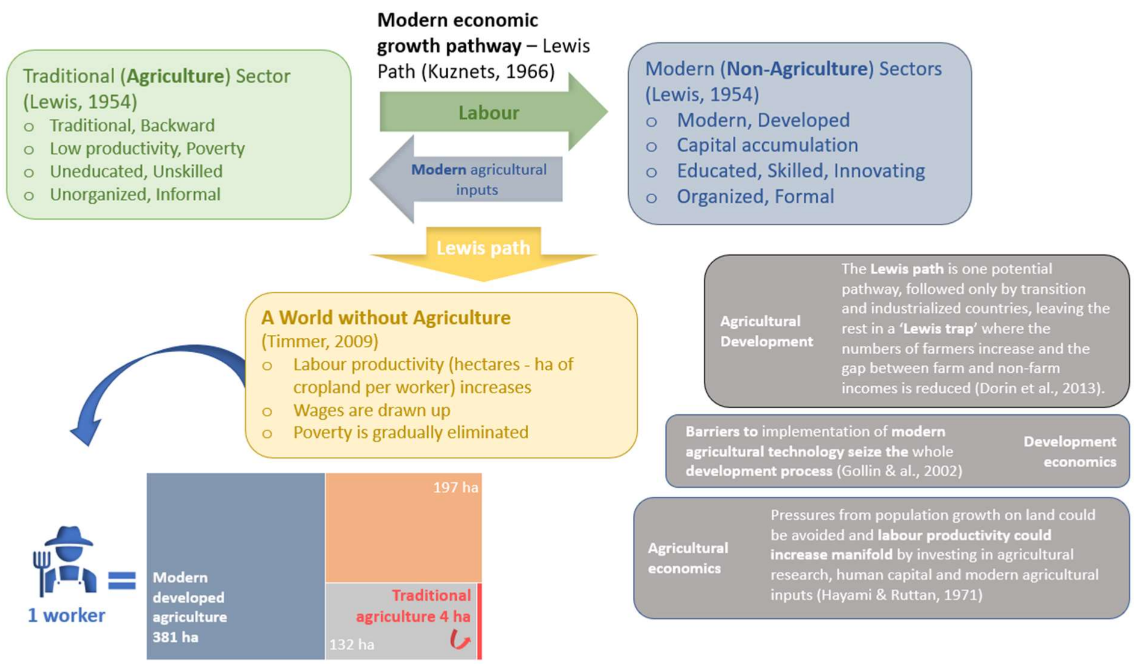
Main body

In developing countries, the agricultural sector is responsible for a large fraction of aggregate income and employment and plays a key role in economic development[1,2]. At the global level, mechanisation and the adoption of new technologies in agriculture have increased production efficiencies and resulted in a long-term decline in real food prices since about 1900[3]. The same process has also reduced labour requirements significantly[4]. A hundred years ago, agriculture employed 70% of the world's economically active population; by 1950 this share was reduced to 62% and in 2019 it had further decreased to 27% or 884 million people[5–7]. If current trends continue, agriculture will employ only a fraction of the people currently required globally. The consequences of this structural transformation are becoming clear in high-income countries where agriculture is increasingly resembling other sectors of the economy[8]. There are, however, specific socio-economic and cultural factors[9] that lead governments to treat the agricultural sector differently, and the close linkage of agriculture and the environment[10,11], and the increased salience of climate change and other environmental issues, may introduce novel considerations. These contingent factors make it difficult to predict accurately the pace and nature of agricultural development but it seems certain the sector will need a smaller workforce and hence lead to an increase in labour reserves.

The labour implications of more mechanised and efficient production systems have long attracted the interest of economists. Ricardo[12] suggested that the development of machinery would result in reduced employment and Marx[13] introduced the term "labour reserve armies" to describe such changes. Syrquin[14] characterised development as a structural transformation where a predominantly low income, agrarian rural economy becomes a chiefly industrial urban economy with significantly higher income per capita. Under this scenario, labour increasingly moves from "traditional" (agriculture) to "modern" (non-agriculture) sectors accompanied by a marked changed in the nature of work[15] (Fig. 1). Kuznets[16] described a "modern economic growth" pathway in which increased agricultural productivity supports industrialisation by increasing the supply of labour and producing low-cost food, and then industry in turn provides cheaper agricultural inputs that increase yields. As a result, labour productivity of the rural economy increases while wages rise and poverty is gradually eliminated, often called the Lewis path after the economist who introduced the dual-sector (subsistence/capitalist) model of development[17]. Timmer[18] goes further and argues that the falling share of agricultural employment will lead to a "world without agriculture" where there are almost no farmers left except for those that are required to operate highly sophisticated farm machinery[19]. This paradigm has been challenged by Dorin[17] and others who have suggested that in low-income countries continuing population growth, the absence of alternative employment, and limited opportunities for agricultural expansion will result in a "Lewis trap" where a labour surplus acts against investment in mechanisation and keeps wages low. However, there is an increasing realisation that future increases in food demand will need to be met from current (or reduced) agricultural lands to decrease pressures on natural ecosystems and limit greenhouse gas emissions associated with land conversion[20–27].

There is thus likely to be greater emphasis on both closing yield gaps and advancing the production frontier, especially in countries with current low productivity. Such policies will have major effects on agriculture worker incomes and on labour markets in general, issues that are often not considered in studies of future agricultural scenarios.

Fig. 1 The structural transformation paradigm. The scematic representation of this study lists the agricultural and economic development theories prevailing today, linking the traditional (agriculture) and modern (non-agricultural) sectors under the modern economic pathway leading to a world without agriculture[6,15–18,28–30]. The implications of the economic growth pathway on labour productivity are graphically represented at a treemap demonstrating the size of land that a full-time agricultural worker is capable to cultivate, given current available agricultural technologies across agricultural systems that range from modern and developed to traditional subsistence farming.



Increasing contributions from labour or capital, the two classic factors of production, can lead to a rise in yields. Empirical studies and data show that capital-intensive mechanisation is most frequently responsible for higher yields and that this is accompanied by reduced labour inputs[31] or labour displacement[32]. In cross-country comparisons, current data from the International Labour Organization (ILOSTAT), OECD and the World Bank[6,33] demonstrate that fewer people are employed in agriculture in more prosperous economies and labour productivity increases as countries become richer. Dethier and Effenberger (2012)[1] indicated that technological adoption, affordability and access to production inputs are the factors that mainly drive the greater labour efficiencies. Martinelli et al.' (2010)[34] also found that increased capital investment in agriculture in Brazil has led to historically low agricultural employment, though still greater than in highly-industrialised countries like the U.S. and Canada. Jha et al. (2019)[35] investigated the development of automation in agriculture suggesting that it is a central policy subject that further improves productivity but also will trigger further decreases in labour demand patterns (further description of technological and labour productivity developments in Supplementary material, Text 1). Together, this suggests one possible future of an ever more efficient agricultural sector supporting a limited number of well-paid jobs but with a growing rural labour surplus[36]. This possibility raises issues of social and geographical equity and the viability of rural economies[37,38] underlining the importance of labour dynamics in agricultural and general development[39,40].

Understanding and quantifying the implications for labour of changing food production systems is critical to achieve simultaneous policy goals relating to food security, environmental sustainability and justice. However, direct measurements of the number of workers required to produce food at the global level, with crop and livestock-specific resolution, remain limited. Here we first estimate the number of agricultural workers needed globally to maintain the crop and livestock specific production volumes reported by the United Nations Food and Agriculture Organization (FAO) in the period 2011-2015[30]. We then explore labour requirements under two further scenarios assuming different rates of technological adoption: MDA_{INCRE} and MDA_{VFST} which refer to incremental and very fast Mechanisation Development in Agriculture that are based on different extrapolations of observed long-term trends in global agriculture and industrialisation[41] (see Methods for fuller description). We assume that agricultural productivity in low-income and middle-income countries begins to converge on that in high-income countries, though at least within the time frame of this study many countries in regions such as Africa and South Asia will not fully converge because of a variety of historical and institutional factors[17,42].

We compiled an inventory of agricultural labour input requirements for the production of 21 major food products: twelve plant-based and nine animal-based products in 178 countries. Data and other information were derived from agricultural censuses, open-source data platforms, grey literature and the scientific literature. Labour requirements include both external (hired) and own labour of the production systems and correspond to the full-time equivalent annual workers per annum (annual working units – AWU). The annual working units is the aggregate of seasonal, full and part-time workers to a full-time equivalent basis and naturally differs from the estimates of people employed in agriculture which are larger. The twelve crops we considered are: barley, groundnut, maize, millet, potato, rapeseed, rice, sugar beet, sunflower, sorghum, soybean and wheat. These twelve crops together provide 54% of total human calorie intake and 65% of plant-based human calorie intake (these figures and those below all refer to 2018)[30]; they account for 66% of total cropland. The livestock products include meat production from cattle, sheep, goats, pigs and poultry, milk production from cows, sheep and goats and egg production from poultry. These nine livestock products provide 17% of total human calorie intake and 92% of animal-based human calorie intake[30]. In total, the crop and livestock products considered in the present analysis provide 71% of the total direct human calorie intake, 76% of the total protein human intake and 72% of the total fat human intake.

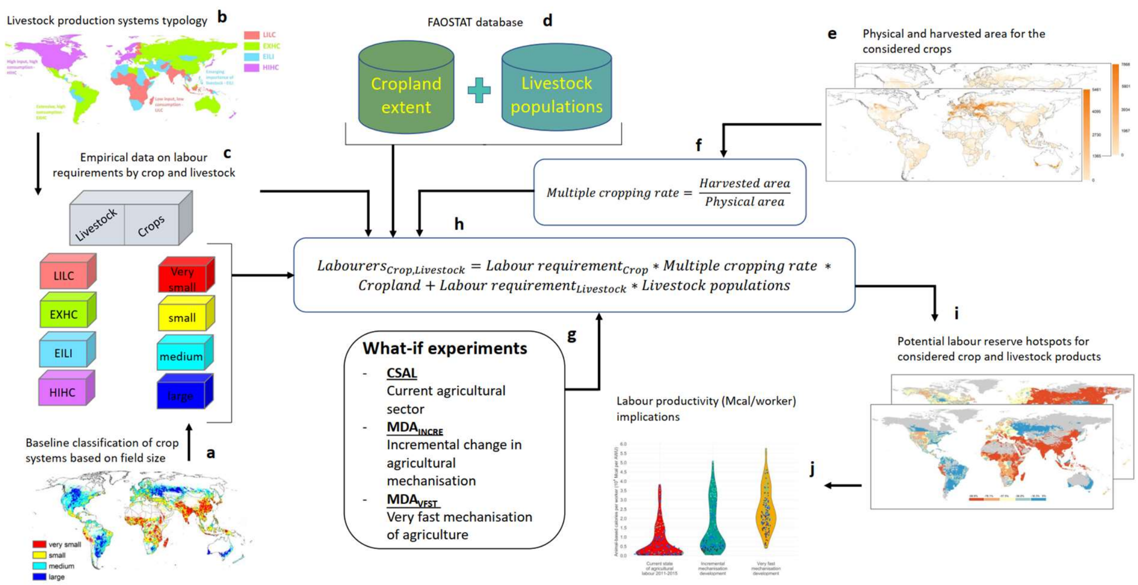
Methods

Baseline country classification

We developed a national-level agricultural (crop and livestock) labour inventory covering 178 countries (Fig. 2). The data inventory was compiled using information from data-rich countries on the number of people employed in the production of twelve major crops and nine livestock products. In countries where no or limited information was available, employment was estimated using a mechanisation proxy based on the global cropland field size index developed by Fritz et. al[43] to classify crop production systems. Through basic spatial analysis we determined the predominant field size class for each country and classified countries as having very small, small, medium or large typical field size. Field size is known to be correlated with the extent of technological adoption[26,44,45] and thus we assumed production practices and consequent labour inputs will be similar in countries within the same field size class. We tested this assumption by taking the number of tractors in use in each country (FAOSTAT[30]) as a different indicator of technological uptake, and found a positive correlation with field size class (Supplementary material Fig.1a). GDP per capita, an indicator of national wealth and ability to invest in capital factors, is also positively correlated with field size (Supplementary material Fig.1b). To further assess this assumption, we examined the number of agricultural workers per hectare of cropland (ILOSTAT[46] and FAOSTAT[30] respectively) and found an inverse relationship with field size class (Supplementary material Fig. 2) described by larger numbers of workers per hectare as field sizes decrease.

Livestock production systems were classified using a typology, developed by Herrero et al.[47], which describes typical livestock production practices across different regions, based on income, consumption of livestock products, local productivity, and the use of pasture versus cropland as livestock feed (Supplementary material, Fig. 3). Countries were assigned to one of four global livestock system clusters: (i) high income countries with high inputs of production and high levels of consumption (HIHC); (ii) low- and middle-income countries with low inputs of production and low levels of productivity and consumption (LILC); (iii) low-, middle- and high-income countries with higher livestock consumption and extensive grazing areas (EXHC); and (iv) low- and middle-income countries with varying livestock consumption and emerging importance of livestock (EILI). While these are groupings based on similarities of livestock systems, some outliers are identified. For example, Australia is in cluster EXHC instead of HIHC with other high-income countries, owing to the prevalence of extensive livestock systems[47]. As such, based on similarities we identified on labour productivity levels using empirical data for China, Australia and Brazil, we disaggregated the EXHC cluster in two sub-clusters $EXHC_{ASIA}$, which includes the parts of EXHC in Asia, and $EXHC_{PAC}$ which includes Australia and Latin America.

Fig. 2 Methodological design of the study. a-i, Field size classification[43] (**a**) and livestock systems typology[47] (**b**) are used to construct a baseline classification of countries, for crop and livestock systems respectively, based on which we compile the labour requirement data inventory (**c**) containing crop and livestock-specific labour inputs. Labour input requirements are combined with cropland and livestock populations data (**d**) from FAOSTAT[30] for the 2011-2015 period and information on multiple harvests (**e, f**) from SPAM 2010[48] in the agricultural labour model (**h**). The model calculates total labour input for current state of agriculture (CSAL) and two main what-if experiments of mechanisation development (**g**): (1) Incremental change of agricultural mechanisation (MDA_{INCRE} scenario) or (2) Very fast transition of mechanisation in the agricultural sector (MDA_{VFST} scenario). The estimation results in crop and livestock specific labour requirements under current state of agriculture and the two what-if experiments of mechanisation development which are compared to estimate potential labour reserves (**i**). Further implications (**j**) on labour productivity gains are quantified on the basis of food production (change in plant or animal-based Mcal produced per agricultural worker). Crop and livestock labour simulations were performed both at national scales and at a level of, globally, 120,000 simulation units that were aggregated from a size of 5′ × 5′ pixels (~ 8 × 8 km near the Equator) to a maximum of 30′ × 30′ (~ 50 × 50 km near the Equator) on the basis of physical heterogeneity and administrative boundaries.



‘What – if’ experiments

Here we explore three production scenarios to estimate how many agricultural workers will be needed if the current trends of increasing labour productivity continue under different paces of agricultural mechanisation. In the first scenario, the current state of agricultural labour (CSAL), we estimate the size of the labour force responsible for the production of current food volumes as reported by the United Nations Food and Agriculture Organization (FAO) for the average of the years 2011-2015[30]. In the next two scenarios (MDA_{INCRE} and optimistic MDA_{VFST}) we estimate the labour requirements to produce the same amount of food but assuming two different assumptions about increases in mechanisation and associated labour productivity.

For croplands in the incremental change scenario (MDA_{INCRE}), we assume that technological adoption increases such that labour requirements in each of the baseline classes defined by field size becomes that of the next higher class (Supplementary material Table 1a). Thus a nation originally characterised by labour requirements associated with very small field sizes would now be described by small field size labour needs, and so on for larger field sizes (Supplementary material, Fig 5). In the very fast change scenario (MDA_{VFST}), all classes move to the labour requirements associated with the large field size class. In both scenarios the labour requirements of the large field size class do not change and hence we are not including the effects of future technologies. However, the agricultural sector is responsible for only a small share of labour in these countries and the effects of further technological adoption will be small.

For livestock production systems, we adopt a more geographic focus. In the incremental pathway (MDA_{INCRE}) we assume countries in Africa and South Asia with LILC labour requirements move to the EILI category (Supplementary material Table 1b). Similarly, HIHC countries in the Americas, Eurasia and Australia move to the EXHC category. In both cases, countries in the more mechanised category remain in the same class. For the very fast transition (MDA_{VFAST}) all countries move to the most labour productive systems globally, which is either $EXHC_{ASIA}$ or HICH, depending on the livestock product.

Labour requirement data and calculation

Information on crop and livestock-specific labour inputs was derived from agricultural censuses, open-source data platforms and the scientific literature. We obtained information on labour requirements for the production of crop and livestock food products from 30 sources (listed in Supplementary information, Table 2 and 3). All data sources include both external hired workers as well as the farmer and family workers. For cross-validation purposes, to test the validity of our estimates, country and crop/livestock product- specific information was derived from the Farm Accountancy Data Network (FADN) which is based on a statistical survey of farms in the EU and provides the most comprehensive data available for this purpose that here covers 5 agricultural products and 27 EU countries (for fuller description see Results).

Information on labour requirements was originally provided in three different formats: (i) person days per unit of key input (hectare – ha or head of livestock – head); (ii) hours per unit of key input; and (iii) cost per unit of key input. Person days represent the number of workers required per day (assuming 8 hours for normal labour at normal intensity) to perform production tasks per ha of cropland and per head of livestock. To estimate the number of full-time employees that are required per ha and per head we divide person days by the number of working days per year which we estimate to be 275. This number comprises a 5.29 day week (including overtime work) and 52 weeks' work (5.29 x 52 = 275)[49]. Requirements expressed in hours per ha and per head, are divided by the 8-hours worked per day to estimate person days. Requirements expressed as costs per ha and per head, are first divided by the average wage rate reported on ILOSTAT[50] (of the country from which the labour costs are derived) to obtain person days per ha and per head. This is then converted to number of workers per ha and per head using the method described above for crop and livestock production respectively.

The labour requirement is expressed as the number of full-time workers per annum. This measurement is defined as the Annual Working Unit (AWU)[51] and is smaller than the total number of people employed in agriculture which includes part-time, casual or seasonal workers[1].

Livestock numbers, cropland extent and successive cropping

We calculated the labour required to produce the global amounts of the different crop and livestock products in the period 2011-2015[30]. The extent of cropland and numbers of livestock associated with these volumes of the 2011-2015 period were derived from the FAOSTAT[30] database which is broken down by country. Within-country prevalence of crop and livestock production systems displays spatial variability and thus, the respective within-country labour requirements and implications would be driven by these spatial patterns. Thus, to assess the labour reserves at local scales our method downscaled the national-level crop and livestock production information to sub-national grid cells of varying sizes from ~ 9.26 km × ~ 9.26 km to ~ 55.56 km × ~ 55.56 km (5' x 5' to 30' x 30' arc minutes at the equator). This grid reference is a result of EPIC-IIASA integrating the process-based agronomic model 'Environmental Policy Integrated Climate' (EPIC)[53,54] to a global data structure that is referenced at a 5' x 5' spatial resolution. The 5 arcmin grid cells belong to the same topography classes, have identical soil texture and are based within the same 30' x 30' climate grid and administrative region cells which are then combined to simulations units. This results in approximately 120,000 simulation units of sizes that vary from ~ 69 to ~ 2500 km^2 near the equator conditional to input data heterogeneity.

Cropland area was derived from the FAOSTAT[30] database which provides crop-specific information on physical area in cultivation. In some areas, multiple crops per year are grown on the same land and hence require additional labour. We accounted for this using data in SPAM 2010 v2[48] which gives the total harvested area per year allowing a multiple cropping rate to be calculated (Eq. 1).

$$Multiple\ cropping\ rate = \frac{Harvested\ area}{Physical\ area} \tag{1}$$

The number of full-time-equivalent workers required for the production of each crop per hectare ($Labour_{Req}$) was estimated by multiplying the crop labour requirements per ha ($Labour_{Req/ha}$) with the cropland extent (ha) for each of the crops and add labour requirements per head of livestock ($Labour_{Req/head}$) multiplied by the number of each of the livestock types (Eq. 2). $Labour_{Req}$ was then adjusted using the multiple cropping rate (estimated in Eq. 1) to reflect the actual extent of production and the subsequent actual requirements in labour ($Labour_{Act}$) using the basic formula in Eq. 3.

[1] According to ILO[52], "the international definition of employment calls for inclusion of all persons who worked for at least one hour during the reference period".

$$Labour_{Req} = Labour_{Req/ha} * Cropland_{ha} + Labour_{Req/head} * Heads \quad (2)$$

$$Labour_{Act} = Labour_{Req} * Multiple\ cropping\ rate \quad (3)$$

Results

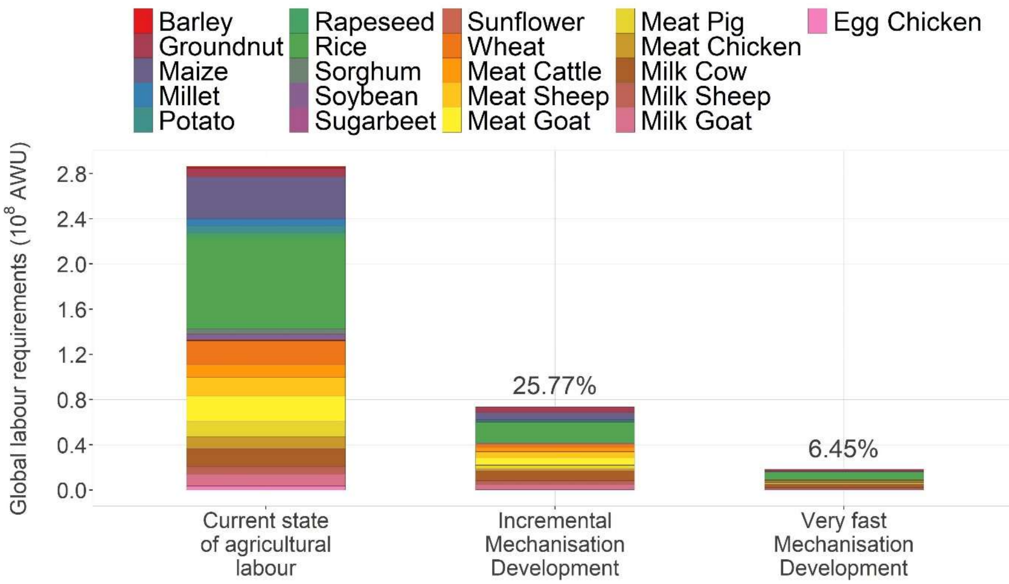
Global labour reserves and spatial patterns

Today, a global labour force of 286.3 million full-time equivalent workers (AWU) is required to produce the total amounts of the 21 agricultural products we consider here. Our analysis suggests that moderate technological development of agricultural production systems under the MDA_{INCRE} scenario will decrease the labour requirement to 73.8 million AWU, approximately a quarter of the current requirements. Crop production will require 20.7% the current workforce, and livestock production 33.8% (Fig. 3 and Supplementary material Fig. 6). Were technological adoption to proceed as in the MDA_{VFST} scenario, our analysis suggests labour requirements would decline to 18.5 million AWU, just 6.5% of the baseline (6% for crops and 7% for livestock production).

In the current state of agricultural labour, the largest shares of employment across crop production systems are estimated in rice (80.6 million AWU), maize (37.2 million AWU) and wheat (21.6 million AWU) production (which translate to 28%, 13% and 8% of the total labour respectively) while for the livestock production systems the largest shares correspond to goat meat (22.2 million AWU), sheep meat (16.9 million AWU) and dairy cows (16.1 million AWU) production (the equivalent of 8%, 6% and 6% of total labour respectively).

There is a larger drop in labour requirements from the current state to MDA_{INCRE} than from MDA_{INCRE} to MDA_{VFAST}. The reason for this is that labour productivity increases particularly strongly which is associated with the transition from very small field size to small field size. More technological adoption leads to further increases in productivity but these are proportionately less as the major inefficiencies have been removed. Crop production currently accounts for 61.4% of the agricultural labour which decreases to 49.3% in MDA_{INCRE} but only to 56.4% in MDA_{VFST}. This is a result of the different trends of change between crop and livestock production systems where the corresponding rate of change for crops, is larger in MDA_{INCRE} but decreases in MDA_{VFST} (Supplementary material Fig. 7).

Fig. 3 Total labour requirements (AWU) in the current and future agricultural mechanisation scenarios.

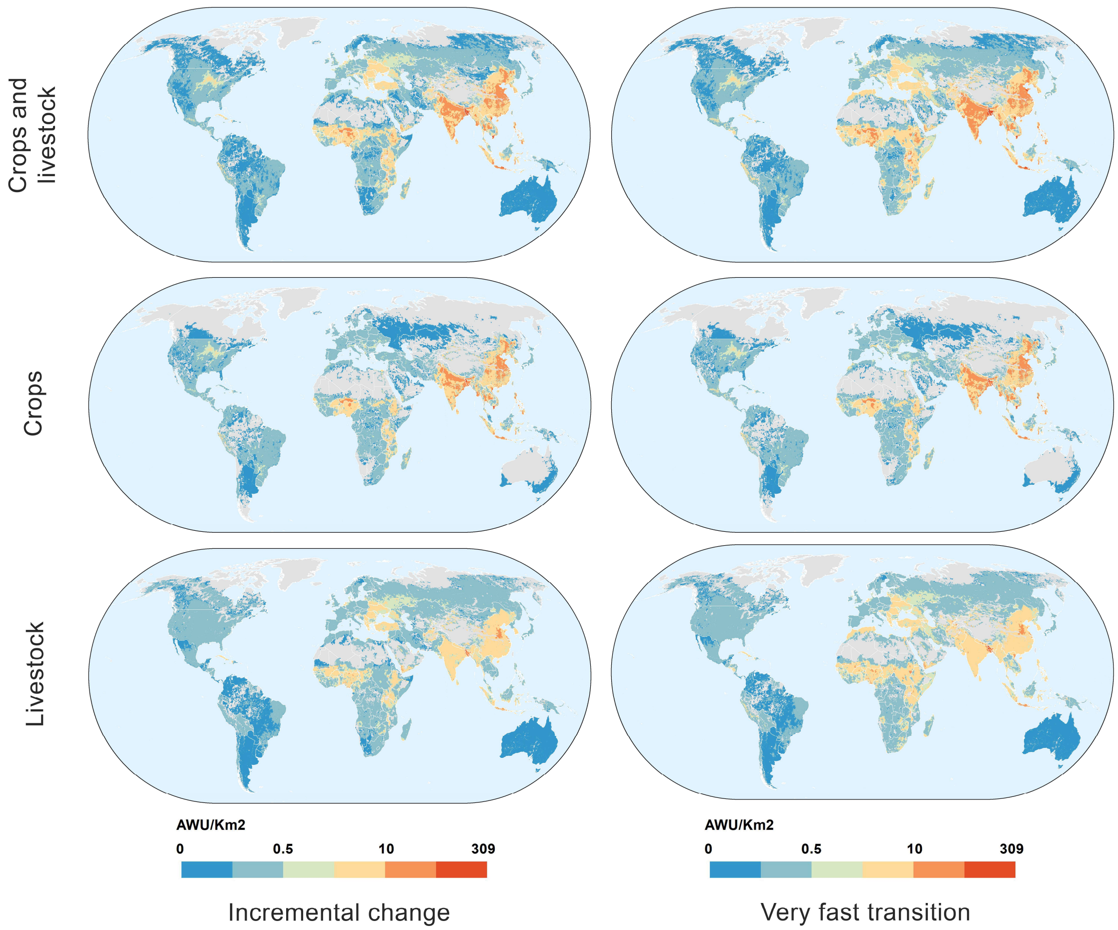


The largest movements of labour out of agriculture under MDA_{INCRE} occur in south and east Asia and the drier areas of equatorial Africa (Fig. 4 and Supplementary material Fig. 8). In some regions, reductions in labour differ noticeably between crop and livestock production. Thus in parts of Central Asia (chiefly southern Russia) labour levels in crop production remain roughly the same while those in livestock production see a significant decrease (between 0.5 and 10 AWU/km^2). The discrepancies result from within-country differences between the crop and livestock systems and the associated labour productivity levels. Russia, in example, is in the top of the labour productivity levels for crops (due to large field size for crop systems) but has low and mid-range labour productivity for livestock production (as it belongs to the $EXHC_{ASIA}$ cluster) (for fuller description of labour requirements across clusters see Supplementary material, fig. 4). There is also considerably spatial heterogeneity in demand for labour. Across Africa, labour requirements for crop production typically decreases by 1 – 10 AWU/km^2 though there are a few hotspots where the figures are 10 and 50 AWU/km^2. Patterns for livestock systems in Africa are similar except there are some regions where very little labour is released. Hot spot effects are more profound in the areas that appear to have more dense agricultural activity but also lower current labour productivity and thus an increase in mechanisation result in a spatial aggregation of labour reserves.

The same general geographic patterns are seen under MDA_{VFST} but are accentuated, with countries in Southeast Asia (India, Bangladesh, Indonesia, Vietnam and Philippines) in particular seeing large drops in the agricultural labour force (10 – 50 AWU/km^2). The largest drops in crop production systems (1 – 10 AWU/km^2) are chiefly in South Asia and Central Africa while for livestock production there are hotspots in North Africa and East Europe. The labour reductions are similar spatially because agricultural production is simulated to remain the same under the mechanisation scenarios. However, their effects are larger under MDA_{VFST}

as in this scenario the labour requirements of each system move to highest labour productivity levels which triggers further reductions globally in comparison to MDA_{INCRE}.

Fig. 4 Potential release of labour per square kilometre (AWU / Km^2).

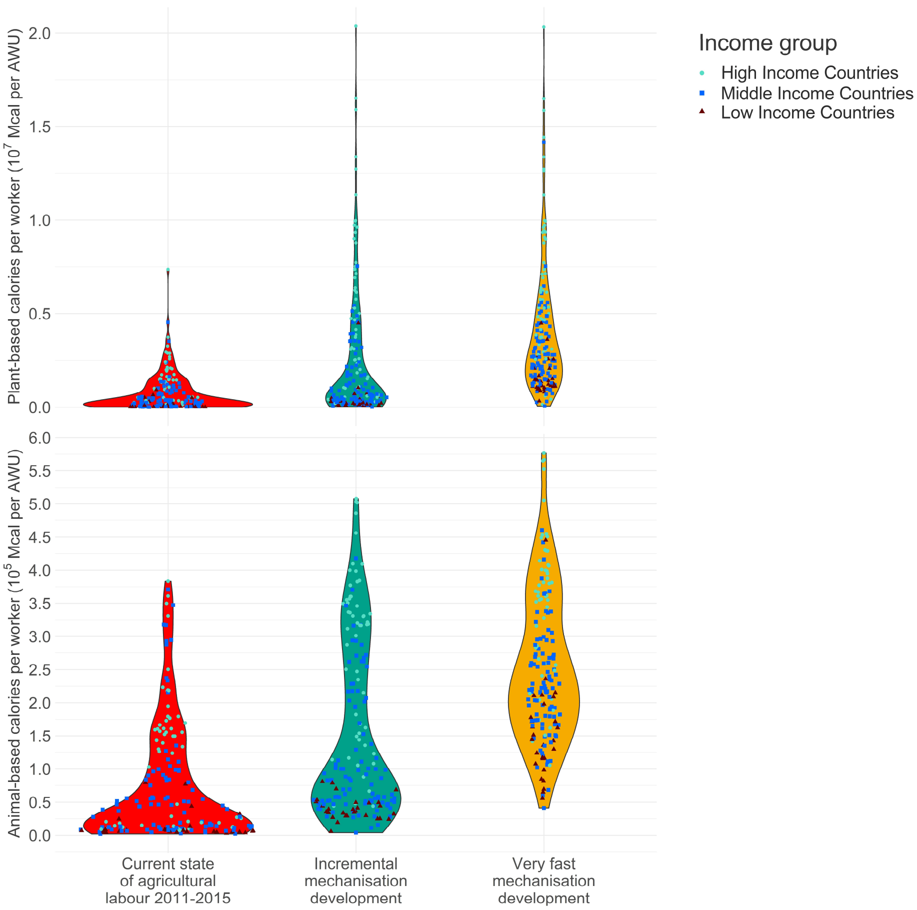


Agricultural development is estimated to increase significantly labour productivity, as measured by calories produced per agricultural worker (Mcal per AWU) (Fig. 5 and Supplementary material Fig. 9). Plant-based calorie production per worker increases on average from 0.71×10^7 Mcal in CSAL to 2.44×10^7 Mcal and 3.87×10^7 Mcal under MDA_{INCRE} and MDA_{VSFT} respectively. Under current conditions the calories produced per worker increases with economic development from 0.14×10^7 Mcal in low-income countries through 0.51×10^7 Mcal in middle-income countries to 1.49×10^7 Mcal in high-income countries. In our technological adoption scenarios, the productivity of low-income countries gradually increases (MDA_{INCRE}) and eventually becomes similar to that of the most economically developed countries (MDA_{VFST}). The latter occurs as we simulate mechanisation development in agriculture without quantifying the associated economic and income developments – which are modelled as constants here. The result is this intimate mixture of high, middle- and low-income countries across the whole range of labour productivity levels. In livestock systems, animal-based calories per worker, increases on average from 0.66×10^5 Mcal in CSAL to 1.45×10^5 Mcal and 2.43×10^5 Mcal under MDA_{INCRE} and MDA_{VSFT}. High-income countries tend to be the most efficient though today there are a few relatively rich countries, mainly in west Asia (countries in the Arabic peninsula) and Eastern Europe, which for historical reasons have anomalously low productivity. Production of animal-based calories, in all scenarios, requires significantly larger amounts of labour inputs compared to plant-based calories. A typical full-time worker today produces 0.071×10^7 plant-based Mcal per year but just 0.007×10^7 animal-based Mcal. Though productivity increases under the two development scenarios the ~10:1 crop:livestock efficiency ratio remains roughly the same. When measured by protein produced per AWU, agricultural productivity is increased at similar rates (Supplementary Material, Fig. 10). Production of protein per AWU from plant-based sources increase on average from 16×10^3 tonnes of protein in CSAL to 50×10^3 tonnes and 84×10^3 tonnes under MDA_{INCRE} and MDA_{VSFT} respectively. Animal-sourced protein productivity per full-time worker increases on average from 6×10^3 tonnes in CSAL to 12×10^3 tonnes and 20×10^3 tonnes under MDA_{INCRE} and MDA_{VSFT}. Similarly to calories, production of protein requires larger amounts of labour inputs for animal-sourced protein in comparison to the plant-sourced. However, due to the high protein content of animal products, the ~3.7:1 plant:animal efficiency ratio appears more balanced though remains in favour of plant-sourced protein production.

Evaluation of labour requirement estimations

We explored the accuracy of our estimated labour requirements by comparing them with figures on labour input provided by the FADN[55–58]. FADN information on production for most agricultural products is presented as aggregate farm types in the EU Farm Economy Focus datasets. For some livestock products (meat cattle and cow's milk), product and country specific information is available. The respective information for crops, was available only for cereal and grains (barley, wheat and maize) and we obtained it from EU farm reports, that also use FADN data. As such, we compared three crops (barley, maize and wheat) and two livestock products (cattle meat, cow milk) across 27 EU countries (Supplementary Material, Fig. 11 – Fig. 13). To allow comparison we took FADN data on country-specific total labour input per farm, measured in AWU, and converted it to AWU per hectare for crops and per head for livestock. This was then multiplied by either cropland extent and number of livestock (using 2011-2015 FAOSTAT[30] figures) to obtain AWU in agriculture for each product-country combination. In general there was a good match between our estimates and the FADN data though with some exceptions. For example, the production of some crops, such as barley in Italy and Denmark requires significantly more labour than we estimated as did beef production in Austria, Germany and Spain. Some other countries (Poland, Hungary and Romania) had even larger differences and thus, their extrapolated labour requirements were replaced with the reported from FADN. Despite these discrepancies, our predictions provide an approximation of the number of full-time workers required in agriculture, that is used to compare implications from different agricultural trends that will emerge in the future (incremental and very fast transition) and the location-specific absolute estimation of labourers required is out of scope in the current approach. Lastly, we examined the estimated global AWU in reference to the total number of people working in agriculture worldwide as reported by FAO. We estimate that currently 286 million AWU is required in agriculture and FAO reports 884 million people employed in agriculture, a ~1:4 AWU:people employed in agriculture. This compares reasonably well in the context of EU countries where the FADN-reported actual number of people who obtain some income from agricultural work can be up to four times larger than the reported corresponding AWU[2].

Fig. 5 Calorie production per agricultural worker (Mcal per AWU) in the current state of agricultural sector (CSAL) and the two what-if scenarios of mechanisation development (MDA_{INCRE} and MDA_{VFST}). The violin plots present the labour productivity in calorie produced per worker in the current and the two potential pathways of mechanisation development in agriculture. Points represent countries, which are classified by income groups (World Bank Income group aggregates[59]). Greater point density is denoted by larger widths in the violin plots which are being gradually lifted as the agricultural sector shifts from the current state (CSAL) to the potential paths of mechanisation development (MDA_{INCRE} and MDA_{VFST}, from the left to the right-hand side).



[2] Based on Eurostat empirical data on agricultural labour inputs measured in both persons-basis and AWU. Access to data, https://ec.europa.eu/eurostat/databrowser/view/ef_lf_size/default/table?lang=en

Discussion

Our analyses are in agreement with a number of earlier studies that have explored the relationship between agricultural productivity, labour requirements by food production systems and levels of economic development[60–62]. These studies have found that agricultural productivity growth is primarily constrained by lack of access to inputs and to modern technology, and this in turn is constrained by limited economic and human capital. To tackle this barrier, governments have brought in policies aimed at enhancing the adoption of modern technologies by smallholder farmers[62]. Earlier studies have contested this pathway of structural convergence, particularly for developing (Asian) and transitioning (Latin American and African) countries suggesting that it would not necessarily lead to economic growth but rather, lead to a trap where neither productivity per worker nor the agricultural incomes and food security increase[17]. The latter is based on evidence showing increasing levels of active population in agriculture which led to decreased levels of available land per farmer in those countries. As such, the way to increase farm labour productivity, when land per farmer is shrinking, has so far included attempts to increase yield per unit of land, achieved through mono-cropping and intensive use of agrochemical inputs – practices that result in a decline of marginal productivity and an increase in costs. However, the importance of agricultural mechanisation in advancing agricultural productivity and eliminating hunger in developing countries, put pressures on global agriculture inexorably leading to pressure on technology adoption[32,63].

If agricultural productivity continues to increase, along either of these scenarios explored here, then inevitably a large number of people will leave the agricultural work force and enter the labour reserve. In this study we estimate that a moderate agricultural mechanisation pathway could reduce the current global labour requirements (286 million AWU) by ~74% which, in terms of number of people obtaining income from agriculture, would mean that 654 million agri-food workers would be led to exit agriculture. This exit will be greatest in those countries that are currently the farthest from the productivity and technology frontier, typically but not exclusively those in the lower-income bracket[61].

The composition but also the productivity of labour in a calorie basis varies significantly between the production of plant (12 crop products) and animal (9 livestock products) – based calories. Globally, 40% of agricultural workers (AWU) are involved in the production of the total animal-based calories however, this is not indicative of the amount of animal calories consumed per capita. This is attributed to the fact that production of animal-based calories is significantly more labour-demanding compared to the plant-based –the same amount of labour input can produce either 1 animal–based calorie or 10 plant–based calories. In monetary terms, we estimate that the gross production value per agricultural worker is ~15,000 Int. $ (international dollars) for crops and ~12,000 Int. $ for livestock products. As such, while a given working unit can produce a lot more crop than animal-based calories, the significantly higher value of production of the latter (on a per unit of output basis), results in approximately similar levels of financial returns per worker. This finding is in line with previous empirical studies suggesting that time expenditure for the production of livestock products is larger than that of crop products and requirements can differ considerably, even within the same type of product, on the basis of mechanisation level[64,65]. Furthermore, shifts towards sustainable diets may reduce demand for animal-sourced calories[66–68] which will have major implications for workers in the livestock sector. Though demand for plant-sourced calories will increase and require a greater workforce, this will absorb only a small fraction of the surplus labour, the exact fraction depending on the adoption of new technology, risking increased rural unemployment.

In the current paper we provide an evidence-based approximation of the labour requirements for the production of 21 agricultural products. We present a method to quantify the potential implications of agricultural mechanisation on the number of people required for the production of current food volumes. The empirical data utilised in the present analysis reflect actual hours needed per hectare in order for all production processes to take place. Thus, our estimates correspond to the requirement for full-time agricultural workers (AWU) which, for reasons to do with the high proportion of seasonal and part-time work in agriculture, is most appropriate to assess labour inputs[69]. The actual number of people who obtain some income from agricultural work can be up to four times larger than AWU in EU countries[3], an estimate with significant heterogeneity across countries and with the ratio that is becoming higher in low-income countries[70]. Estimates of the effects of technological change on AWU may thus underestimate the welfare consequences for society. A further limitation of our approach is the extrapolation of labour inputs based on a baseline classification of countries in representative aggregate classes[26,43,47]. While these classes are constructed to reflect similarities in production systems, there still remains considerable within-class heterogeneity which was responsible for the differences we observed between our estimates and data on AWU in the EU. Owing to these limitations, our method to quantify labour changes from agricultural mechanisation is not intended to be used as a tool to estimate absolute product- and location-specific labour requirements but rather, is a framework allowing comparisons of potential labour discharges from agriculture, across different development pathways at a global scale.

The confluence of growing agricultural technological development and labour productivity gains means that there is a necessity to design strategies within the agricultural sector to simultaneously support efficiency in food production systems and secure a meaningful transition for the farmers that will become a labour-surplus in a future more efficient agricultural sector. Integrating socioeconomic goals, food security objectives and environmental targets will be critical in achieving the sustainable development of agriculture. This study demonstrates the significance of addressing these needs, quantifies the potential labour reserves of the global crop and livestock production systems and utilises available local-scale knowledge of agricultural technologies and corresponding labour input requirements.

[3] Based on Eurostat empirical data on agricultural labour inputs measured in both persons-basis and AWU. Access to data, https://ec.europa.eu/eurostat/databrowser/view/ef_lf_size/default/table?lang=en

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