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ORIGINAL PAPER

The Contributions of Muscle and Machine Work to Land and Labor Productivity in World Agriculture Since 1800

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Abstract
Since 1800, there have been enormous changes in mechanical technologies farmers use and in the relative contributions of human and animal muscles and machines to farm work. We develop a database from 1800 to 2012 of on-farm physical work in world agriculture from muscles and machines. We do so to analyze how on-farm physical work has contributed to changes in land and human labor productivities. We find two distinct periods. First, from 1800 to around 1950, land productivity (measured as kcal food supply per hectare of cropland) was relatively stagnant at about 1.7 million kcal/ha, in part due to a scarcity of on-farm physical work. During this period, physical work was scarce because most of on-farm physical work (approximately 80% in 1950) was being powered by low power, low energy efficiency muscle work provided by humans and draft animals. From 1950 to 2012, land productivity nearly tripled as more machine-based work inputs became available. The additional machine-based work inputs have contributed to the growth in land and labor productivities, as they have enabled farmers to control more physical work enabling more irrigation and agrochemical applications. However, the tripling of land productivity has required a near 4.5-fold increase in physical work per hectare, suggesting diminishing returns. Farmers accomplished this extra work with less final energy because they transitioned from low-efficiency muscle work to high-efficiency machines which drove farm-wide energy conversion efficiency up fourfold from 1950 to 2012. By 1990, machine conversion efficiencies started to plateau. Given diminishing returns and plateauing efficiencies, we predict that fuel and electricity usage on farms will increase to continue raising land productivity.

Keywords Muscle work · Agriculture · Energy transitions · Energy history · Economic history

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Background

The Changing Role of Physical Work in Farm-Based Agriculture

All agricultural tasks in the field, such as sowing, irrigation, harvesting, and others, require physical work. The most important sources of physical work on farms from 1800 onwards were humans, animals, liquid fuels, and electricity. The relative importance of each of these energy sources has changed along with the evolution of mechanical technology.

According to Olmstead and Rhode (2018, p. 17), mechanization is defined as “replacing hand tools and human power with machinery driven by draft power (first from animals and later from liquid fuels and electricity).” Mechanization, in this definition, is the process by which new tools are used to do agricultural work once done exclusively by human hands. Those new tools may be powered by humans (better hand tools), draft animals (e.g., oxen-pulled plows),

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Fig. 1 Examples of different stages of mechanization. At left, a farmer uses an oxen's draft power to operate a plow. At right, a farmer uses energy from liquid fuels to power a harvester. (Open source images from clipground.com and Pixabay.com, respectively)

or machines powered by fossil fuels (e.g., tractors). Both Eastern and Western agricultural systems have been mechanizing in this way, even before 1800. (For China, see Perkins 2013. For Europe, see Smil 2017).

Although machines are now being used throughout the food supply chain (Roland-Holst 2020), we focus only on mechanization that happened directly on farms. We do not study mechanization done off the farm by food manufacturing plants, food vendors, or by others in the food supply chain.

On farms, tools are used primarily to do fieldwork (e.g., to hoe, plow, or irrigate fields), to bring crops in from the field (e.g., to bring in the harvest and haul manure), and to process crops (e.g., to thresh wheat, milk cows, etc.). We consider the mechanization of all tasks done on farms. Examples of how mechanization has affected the tasks farmers do are illustrated in Fig. 1.

The increase in productivity resulting from agriculture's mechanization has been well studied by economists (Ruttan 2002; Olmstead and Rhode 2018). We know that mechanization in the form of power irrigation was "one of the major underlying factors for the substantial productivity gains obtained during the Green Revolution in Asia in the 1960s and 1970s" (Bhattarai et al. 2002, p. 1). Furthermore, we know that most "mechanical technologies" have been labor saving, meaning they increase labor productivity (Ruttan 2002). Thus, agriculture's mechanization has been intimately associated with changes in land and human labor productivity.

Mechanization impacts labor and land productivity through the provision of physical work. However, the effects of mechanization on the amount, efficiency, and productivity of physical work and the impact of physical work on land and labor productivity have not yet been assessed.

Need, Aims, Contributions, and Structure

As described above, there have been considerable changes in the mechanical technologies farmers use, in the types and amounts of energy carriers consumed, and the efficiency of providing physical work over the past 200 years. There is a need to know how work has contributed to the growth of land and labor productivity on farms so that we can understand future demands for farm work and can predict how agricultural systems may evolve to enable a low carbon future.

Our *aim* is to describe, from a physical work perspective, the technologies used in field work. That description provides additional insights into the dramatic changes in land and labor productivity since 1800. To accomplish this, we built a world database[1] to collect and estimate the amount, efficiency, and productivity of physical work associated with humans, animals, fossil fuels, and electricity in agriculture from 1800 to 2012. Using this database and physical data on other agricultural inputs, we answer the following questions:

1. How has the efficiency of converting final energy into physical work evolved over time?
2. How have different final energy sources been used to power field work?
3. How did physical work contribute to land/labor productivity from 1800 to 2012?

This paper provides four major contributions to the literature on the energy history of farming. First, we developed the first long run, worldwide primary, final, and useful (WPFU) dataset of human and animal muscle work at a world regions resolution for the period 1800–2012. This dataset forms part of an overall ongoing WPFU database

[1] This is part of the long-run World Primary-Final-Useful (WPFU) exergy database that is being developed – see https://exergyeconomics.wordpress.com/database-projects/. Publication date is not yet confirmed. Resolution of human and animal muscle work will be at the level of world regions.

Table 1 Spatial resolution of regions in our datasets

World resolution	World regions (Our datasets)	World regions (UN M49 Regions)
World	South and East Asia (SEA)	Eastern Asia Oceania South-Eastern Asia Southern Asia
	West Asia (WA)	Western Asia
	Africa (AF)	Northern Africa Sub-Saharan Africa
	Western Europe (WE)	Northern Europe Southern Europe Western Europe
	Eastern Europe & Former USSR (EE)	Central Asia Eastern Europe
	North America (NA)	Northern America
	Latin America (LA)	Carribean Central America South America

World regions in our dataset are made up of one or more UN M49 World Regions (UN Statistics Division 2001). We list the abbreviation for the world regions in our datasets in parentheses

project, covering wider areas including electricity, industry, and transport sectors. Our database of human and animal energies at the primary, final, and useful stages is a valuable contribution to worldwide databases that have previously only presented such energy data at the primary energy stage (Fizaine and Court 2016; Malanima 2020). This contribution is described in section "Methods and Data" below and in Online Resource 1.

To write this paper, we isolated a more condensed dataset of farm-specific inputs, shown at a world regions resolution, and outputs, shown at a world resolution. The world regions included in our datasets are listed in Table 1. The datasets of farm-specific inputs are included as a Supplementary Material Spreadsheets (Online Resources 2–4). The dataset of farm-specific outputs is included as a Supplementary Material Spreadsheet (Online Resource 5).

Second, we propose a consistent energy accounting method for human and animal muscle work that addresses previous methodological inconsistencies (section "Primary Final Useful (PFU) Energy for Muscle Work").

Third, we are the first to present estimates on the evolution (1800–2012) of the world final-to-useful energy efficiency for physical work inputs to farms (Fig. 8). Other studies show the productivity of all final energy inputs to agriculture (Pellegrini and Fernandez 2018; Marshall and Brockway 2020), or the final-to-useful efficiency of working humans and draft animals (Serrenho et al. 2013). By calculating the efficiencies of final energy inputs to agriculture specifically, we are able to show how much useful energy has been required to maintain high agricultural productivity levels.

And fourth, we are the first to calculate the evolution (1800–2012) of worldwide work inputs per hectare of farmland (Fig. 11). Numerous studies have considered the life-cycle energetics of agricultural systems at the primary/final energy stage (Aguilera et al. 2015; Casado and De Molina 2017; Krausman 2004). However, we are the first to show the energetics of farms at the useful energy stage.

The remainder of this paper is *structured* as follows.

Section "Methods and Data" describes the methods, data, and assumptions we used to construct the portion of the WPFU database we used to answer questions 1–3 above. In section "How has the Efficiency of Converting Energy into Physical Work Evolved Over Time?", we answer research questions 1–3 from above. In section "Discussion", we discuss the significance of these answers. In section "Conclusion", we offer concluding remarks.

Methods and Data

Energy Conversion Chain Overview

Physical work is useful energy applied for mechanical end uses (Sousa et al. 2017). To show what is meant by physical work, Fig. 2 shows an energy conversion chain (ECC) diagram of the useful energy flowing to farms for mechanical end uses. Other authors have quantified the flow of useful work to all sectors and end uses (Haberl et al. 2019), but here, we focus specifically on the farming sector.

The ECC diagram shows how primary energy inputs from oil and gas wells, coal mines, and farms are converted into final energy inputs that power humans, animals, and machines. With the fuel they consume, humans, animals, and machines supply physical work to farms. Haberl (2001) had already proposed an energy conversion chain from biomass (primary energy) to food and feed (final energy) and muscle work by humans and animals (useful energy) similar to the one included in Fig. 2.

Our focus is the work done on farms, and our methods pick up changes in work done over time. Some work previously done on farms in 1800, such as grinding grain, has migrated to off-farm processing facilities (see Pimentel et al. 1973). Equally, there may be some processes that are now on-farm (e.g., milk chilling). Our data of work done on farms account for these types of changes.

We choose the term physical work, rather than mechanical work, as mechanical work is most often associated with machines, whereas in this case, there are humans and animals doing farm work too. Physical work can be derived from three sources: humans and animals (also known as

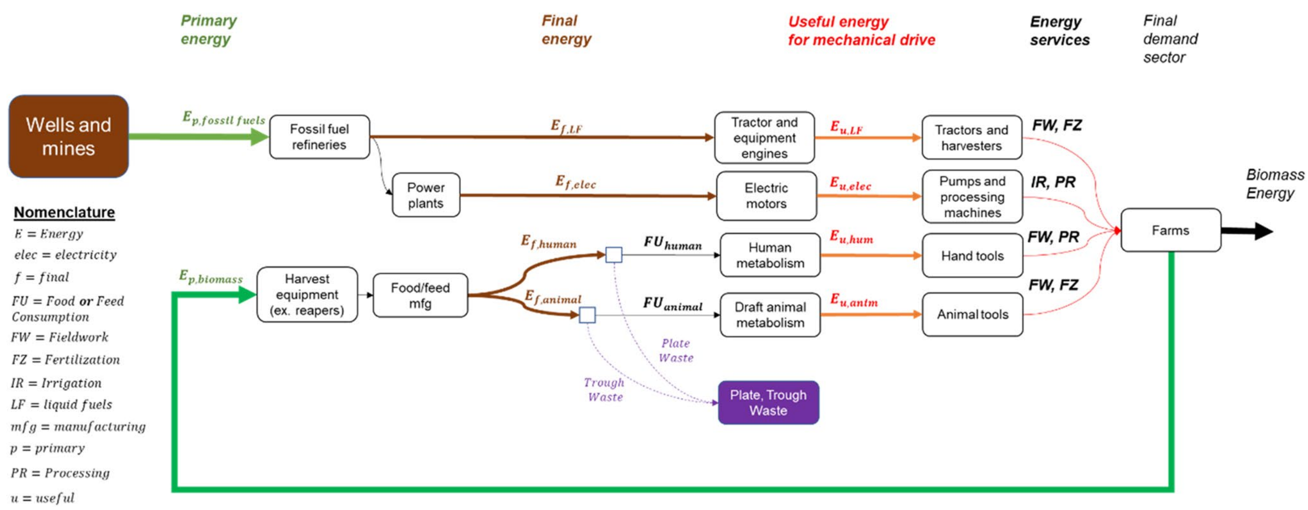

Fig. 2 Energy conversion chain of energy flows to farms. Each box shown in the diagram represents users in the energy conversion chain. Users take one form of energy and convert that energy into a more useful form of energy until ultimately energy services for farms are produced. The arrows represent the flows of energy from extraction/harvest through each energy user and on into energy services. The labels above arrows represent the stage of energy (e.g., Primary, Final, or Useful) flowing between users

Table 2 Nomenclature

Variable	Sample unit	Description
$\%A1$	%	Percentage of countries categorized as Annex I
Cropland	ha	Area of land used to grow crops in a given year
η_{F-U}	–	Energy conversion efficiency
E_p	MJ/y	Primary energy
E_f	MJ/y	Final energy
E_u	MJ/y	Useful energy
Foodsupply	Kcal/y	Food supply for humans in a given year
FU	Kcal/y	Food/feed use or consumption
P	kW	Working power output
$\%PW$	%	Percentage of electricity used for physical work end uses
PlateWaste	–	Proportion of food wasted off the plate
t	Hours	Time spent working
TroughWaste	–	Proportion of feed wasted in the trough

"muscle work") and machines (powered by liquid fuels or electricity).

Methods

We aggregated info from different world regions in our dataset to present results at the world resolution. In the Supplementary Material spreadsheets that contain all of our input data (Online Resources 2–4), we present data at the resolution of those world regions (in our datasets) shown in Table 1.

In the remainder of this section, we describe methods for calculating muscle work and machine work. For each calculation, we describe how we estimated final energy and then advance to describe our methodology for calculating physical work ("useful energy"), final-to-useful conversion efficiencies, and the productivity of land, human labor, and physical work inputs.

In this section, we introduce the variables and equations we use. Table 2 lists our nomenclature. Table 3 gives the nomenclature for subscripts we use.

Table 3 Subscript nomenclature

Subscript	Description	Example value
a	Animal type	"Donkey"
d	Development category	"Annex I"
i	Industry	"Primary industry"
r	Region	"Africa"
t	Year	"1998"

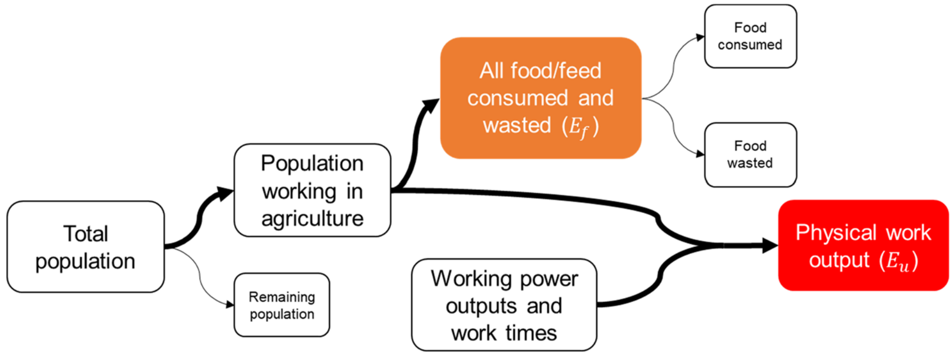

Fig. 3 Human and animal final and useful energy calculations. The colors of boxes correspond to the box colors in detailed flowcharts that show all model inputs, shown in Figs. S5 and S6 in Online Resource 1

Primary-Final-Useful (PFU) Energy for Muscle Work

Our methodology lends clarity on how to accurately and consistently quantify final and useful energy inputs from humans and animals.

The methods that have previously been used to estimate muscle work at the primary, final, and useful energy stages have inconsistently labeled what is to be included in primary, final, and useful energy (Heun and Brockway 2019; Brockway et al. 2014; Serrenho 2016). The inconsistent labeling of energy stages has produced final-to-useful (F–U) efficiency estimations that vary widely, from 1.4 to 13% (see Online Resource 1: Table S1 for more detail). Efficiency estimates in previous studies are varied relative to ours, because authors have made different choices regarding (1) the population involved in muscle work, (2) the amount of food consumption that is allocated for work, (3) what to label as the final energy stage in the energy conversion chain (Fig. 2), and (4) the conversion of final energy into physical work. We describe the choices other authors have made and the inconsistencies that have arisen from these choices in Section S2 of Online Resource 1.

In response, we offer a consistent methodology based on the data that we had available, detailed by the flow chart in Fig. 3.

In our method for humans and animals, (1) only the population working in agriculture are included in muscle work calculations, (2) all food/feed consumed and wasted by that population is included in final energy, (3) the final energy stage is where the working population obtains the food which they then either waste or consume, and (4) the amount of consumed energy converted to physical work is based on working power output and working time (Fig. 3).

It is important to note, both here and in Online Resource 1 that the efficiency we calculate for humans is lower than expected because we judge that all food humans consume and waste should be allocated for work. In this paper, we judge that all of a human laborer's daily food consumption should be allocated for work to remain consistent with our methodology for animals. If we judged that only food consumption during work hours should be allocated for efficiency calculations, we would see efficiencies rise roughly three fold, which in 1800 would have been an increase from ~ 10 to ~ 30% efficiency. Serrenho takes something like this approach for animals when he judges that work allocation is only the feed consumption during an animal's eight hours of work (2013).

The physical work outputs we calculate are independent of these final-to-useful efficiencies so how we allocate consumption has no effect on the values shown in Figs. 10, 11 and 12.

In Online Resource 1, we describe the process of creating a WPFU database for muscle work using our consistent methodology.[2]

We take and isolate farm-specific data from the WPFU muscle work database to estimate the final energy and physical work inputs to farms. The WPFU database does not quantify the Primary-Final-Useful (PFU) energy consumption on farms, but the database does quantify PFU energy for animals doing "mechanical" work (as opposed to transport work to move goods around off the farm) and workers in primary industries. We assume that animals used for "mechanical work" are all used on farms. We assume that these animals that plow and harvest are the same animals used to move crops the distance from field to farmstead. We take all data for farm animal energy directly from the WPFU database, specifically the animal energy for "mechanical work" section. We share this farm-specific data at the world level in the Supplementary Material spreadsheets (Online Resources 2–5). We describe how we isolate the farm-specific dataset in the following paragraphs.

For humans, the data from the WPFU database quantify the PFU energy consumption for primary industry workers, which includes workers in agriculture and forestry (AF). AF workers make up some proportion of all primary industry (PI) workers. We assume that AF workers

[2] See https://exergyeconomics.wordpress.com/database-projects/ for more information on the WPFU database.

work the same number of hours and have the same power outputs as primary industry workers. In section "How Have Different Energy Sources Been Used to Power Field Work?", we compare the power outputs of AF workers, draft animals working in agriculture, and tractors to show how small human worker power output is compared to both animals and tractors. By assuming that AF workers have the same work characteristics as primary industry workers, we can calculate the proportion of the final and useful energy used for physical work on farms based on the percentage of PI workers in a region that work in AF, as in Eq. 1:

$$E_{f,human,r,t} = \frac{Workers_{r,i=AF,t}}{Workers_{r,i=primary\ industry,t}} E_{f,i=primary\ industry} \quad (1)$$

To find the number of workers in AF ($Workers_{AF}$) we subtracted non-AF workers from primary industry workers to reach the total number of AF workers, as in Eq. 2:

$$Workers_{AF} = \sum_{r} \left(Workers_{r,i=primaryindustry,t}\right)\left(1 - Miners_{r,t} - Fishermen_{r,t}\right) \quad (2)$$

In Eq. (2, $Workers_{r,i=primaryindustry,t}$ refers to the population of primary industry workers in a given region. $Miners_{r,t}$ and $Fishermen_{r,t}$ refer to the proportion of primary industry workers made up by miners and fishermen respectively. Miner population data were taken from Mitchell (1998), who lists miner populations by country from 1820 to 2012. Fishermen data were only available from 1995–2012, so we took the average of percentages over just this time period. Fishermen equals the calculated percentage of primary industry workers in fishery occupations by region, both male and female. Fisher population data for these calculations was taken from the FAO (2020). At the world level, fishermen ranged from only 3–5% of total AF workers.

Final Energy Consumption by Animals and Humans

In this paper, we treat working draft animals as "machines" that convert some amount of final energy into useful energy. Therefore, we say that final energy consumption (see Fig. 3) for animals working in agriculture is all the feed that they consume or waste including feed energy that is not digestible. Feed can be wasted in the process of transporting it and giving it to the animals (Fig. 3). We calculated regional final energy data for different animal types, for each region and year:

$$E_{f,animal,r,t} = \frac{FU_{animal,a,r,t}}{(1 - TroughWaste)} \quad (3)$$

Consumed feed is also estimated for each type of animal in each region and for each year. Further details for the estimation of final animal energy is provided in Online Resource 1: Sects. S3.3.3–S3.3.4.

For the sake of consistency, final energy consumption for humans includes all food energy that is consumed or wasted by human agricultural workers including food energy that is not digestible. We calculated the final energy consumed by humans for different regions each year:

$$E_{f,human,r,t} = \frac{FU_{r,t}}{1 - PlateWaste_{r,t}} \quad (4)$$

Consumed food is estimated for agricultural workers in each region and for each year. Further details for the estimation of consumed food and final energy are provided in Online Resource 1: Sects. S3.2.3–S3.2.5.

Physical Work Done by Animals and Humans

Muscle work, or "physical work" done by animals and humans, is estimated by multiplying human/animal power output by the time they spent working at that power output:

$$Physical\ Work = Pt. \quad (5)$$

Physical work is estimated for agricultural workers in each region and for each year, and then summed to estimate worldwide physical work. It is important to note here that, unlike in other studies (Brockway et al. 2014; Ayres and Warr 2010), we calculate physical work independently from final energy.

Further details for the estimation of physical work and the data used are provided in Online Resource 1: Sects. S3.2.6 and S3.3.4.

Final Energy of Liquid Fuels and Electricity

We define final energy consumption for machines in the same way as Sousa et al. (2017). Final energy consumption for machines is energy that is purchased for use in a machine, often in the form of a processed fuel, like gasoline or electricity.

Table 4 Data sources

Data	Source	Description
Animal final and useful energies	Mitchell (2013) Kander and Warde (2011) FAOSTAT (2020)	See Online Resource 1: Section S3.2 and S3.3 for details
Cropland	Klein et al. (2017)	Same as FAO's 'arable land and permanent crops' category
Efficiency	Electric motors (Serrenho et al. 2016) Tractors (Aguilera 2015, Table 6.7)	Tractor "specific fuel consumption" under field conditions
Electricity inputs	Pinto et al. (2022) WPFU electricity database (1925–1960) FAOSTAT (2021) Energy use from electricity (1961–2012)	FAOSTAT category is "Electricity"
Food supply	Malanima (2020) Supporting information, "The Series (Excel File)"	Converted from food supply per capita, using Maddison (2018) time series
Food supply, animal products	FAOSTAT (2013)	"Food Supply—Livestock and Fish Primary Equivalent", Animal Products
Human final and useful energies	See Online Resource 1: Section S3.2	
Liquid fuel inputs	FAOSTAT (2021)	"Energy for "transport fuel used in agriculture (excl. fishery)"
Nitrogen fertilizer inputs	Smil (2001)	Appendix L in the Smil source shows N totals from 1850 to 1910 Appendix F shows N totals from 1910–2000
Physical work % (electricity) % of electricity work for irrigation	California (California Department of Food and Agriculture 2009) Japan (Sasamori 1957), South Africa (South Africa DOE 2012), UK (Warwick HRI 2007), US (Schurr et al 1990)	See model in (Figs. 4, 5)
Quantity of tractors	Federico (2005, Table 4.11)	

Final energy inputs from liquid fuels from 1961 to 2015 were taken from FAOSTAT's aggregated series of energy for "transport fuel used in agriculture (excl. fishery)" (Table 4). This "transport fuel" includes all motor gasoline and gas-diesel oils used on farms, which are the primary fuels of large equipment, especially equipment for field work. The aggregated "transport fuel used in agriculture" time series excludes data for other fossil fuels used to do primarily non-physical work task. Those fuels not used primarily for physical work tasks are natural gas (including LNG), fuel oil, liquefied petroleum gas (LPG), and coal. The primary uses for these "other" fossil fuels were either for space heating or food drying (natural gas, LPG) or for production of electricity (coal/natural gas).

Energy inputs from liquid fuels were quantified by indexing inputs to the total quantity of tractors in the world. World tractor quantities were compiled by Federico from 1920 to 1961 (2005, Table 4.11). We extrapolate energy inputs back further to 1900 based on the index trend.

Between 1925 and 1961, electricity data for world agriculture came from the electricity data collected for the World Primary-Final-Useful (WPFU) database.[3]

Allocations of electricity for physical work varied by region after 1960, especially from those regions defined as Annex I (A1) vs Annex I (NA1) by the FAO. After 1961, electricity consumption data ($E_{f,D}$) was obtained for both A1 regions and non-A1 regions. The proportion of electricity consumption in A1 countries (A1) after 1960 was obtained with

$$E_{f,A1} = A1\left(E_f\right), \tag{6}$$

where $A1$ = the proportion of total on-farm electricity (E_f) consumed in A1 regions. FAOSTAT publishes $E_{f,A1}$ and $E_{f,NA1}$ for 1961–2012. Before 1961, we extrapolated $A1$ from FAOSTAT data. By 1950, $A1$ was > 0.999, as nearly all on-farm electricity is consumed in Annex I (A1) regions.

Physical Work Done by Machines

The total amount of liquid fuel powered work is obtained from the final energy consumption of machines and their energy efficiency:

[3] Electricity data for all end uses will be included in the future WPFU exergy dataset. Farm-specific data can be found in the Supplementary Material Spreadsheets.

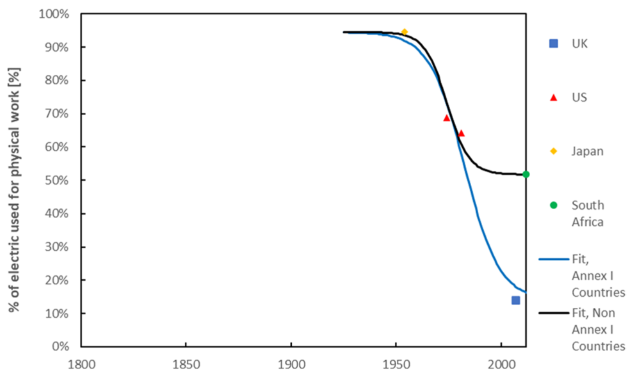

Fig. 4 Evolution in the proportion of on-farm electricity used to do physical work (%PW) in Annex I Countries and Non-Annex I Countries. Sources: see Table 4

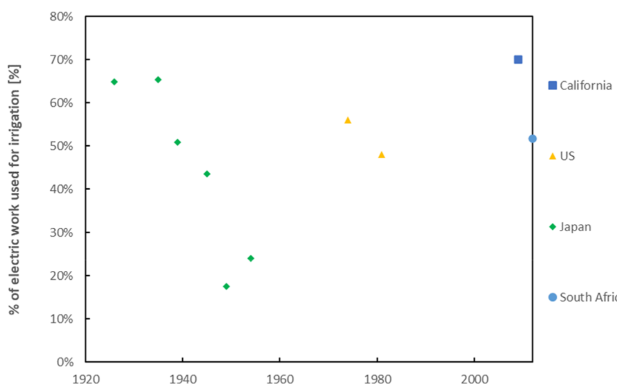

Fig. 5 Regional variation in the % of electric powered work on farms used for irrigation purposes. In three of the four regions shown, more than 50% of electric powered work has been used for irrigation. Source: Table 4

$$Physical\ Work = E_f \eta_{F-U}. \tag{7}$$

The total amount of electricity-powered work is obtained with the electricity consumption, the percentage of electricity consumed to fuel physical work, and the final-to-useful electric efficiency:

$$Physical\ Work = E_{f,D}\left(\%PW_D\right)\eta_{F-U}. \tag{8}$$

The subscript D refers to the development level of a group of countries, (e.g., whether it was in the Annex I group or Non-Annex I group, as defined by the FAO).

The percentage of electricity consumed to fuel physical work has changed over time. As farms have become more mechanized, the number of devices doing auxiliary fieldwork and processing tasks like spreading fertilizer or threshing grain has increased (Binswanger 1986, Tables 8–9). The proportion of electricity used to produce physical work has decreased since 1950, as farmers have developed their systems to do new tasks like lighting and refrigeration (Fig. 4).

Historically, more than half of the physical work on farms powered by electricity was used for irrigation purposes. This turns out to be very different by region, with California having the highest portion of work being used for irrigation (Fig. 5).

Energy Efficiencies

The energy conversion efficiency referred to in this paper is for the conversion from the final-to-useful energy stage. The efficiency of human, animal, or machine x ($\eta_{F-U,x}$) is the ratio of useful energy produced to final energy consumed, as in Eq. (9):

$$\eta_{F-U,x} = \frac{E_{u,x}}{E_{f,x}}. \tag{9}$$

The energy conversion efficiency for all the humans, animals, and machines in the agriculture industry is the useful energy outputs from all prime movers divided by the final energy outputs from the same:

$$\eta_{F-U,x} = \frac{\Sigma_x E_{u,x}}{\Sigma_x E_{f,x}}. \tag{10}$$

With so many different machines used in agriculture, it would have been difficult to track all efficiencies over time. Instead, tractor efficiencies were used as a proxy for all FF-powered machines, as most machines used for on-farm work are powered by diesel/gas engines, just as tractors are. Electric motor efficiency, rather than pump efficiency, was used to calculate work from electricity.

Land and Labor Productivity

Land Productivity (kcal/ha) We define land productivity as food supply per hectare:

$$Land\ Productivity = \frac{Food\ supply\ [\text{kcal}]}{Crop\ land\ [\text{ha}]} \tag{11}$$

The numerator is food *supply* for humans; food supply does not include feed for animals (e.g., corn grown for feedstock) or energy from other crop products (e.g., cotton). Food supply represents all animal and plant-based foods that are consumed or wasted by the general human population. The food supply is measured in terms of kcal of digestible energy. A more typical measure of land productivity would be calculated using crop output as in the equation $\frac{Crop\ output\ [kcal]}{Cropland\ [ha]}$.

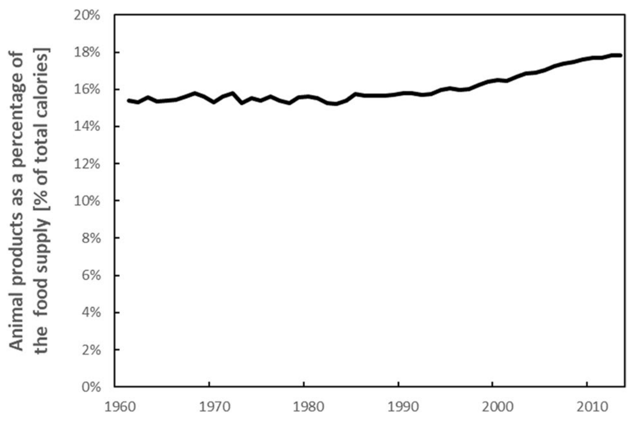

Fig. 6 Animal product calories as a percentage of the overall food supply. Source: FAOSTAT (2013)

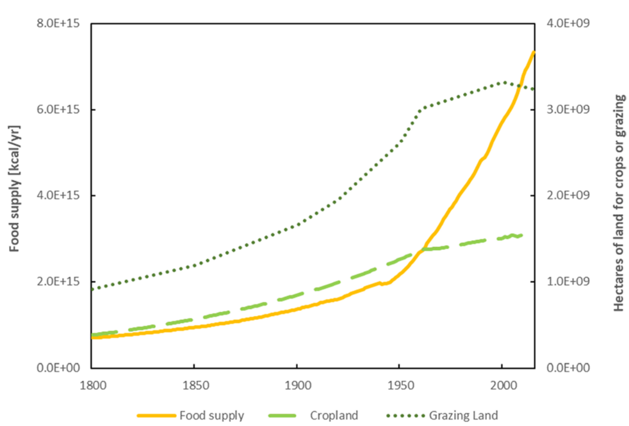

Fig. 7 World food supply (converted from per capita food supply, source: Malanima 2020) and world cropland and grazing land estimates (source: Klein et al. 2017). Food supply growth accelerated after 1950 despite a slowdown in agricultural expansion for both cropland and grazing land

Structural changes in food supply and how that supply is produced could have confounding effects on our metric for land productivity. For example, if consumers started consuming more milk and meat, which have a higher land cost per calorie than grains, we would expect our metric for land productivity to fall. Humans are in fact consuming more meat per capita since 1961; roughly 80% more by weight, largely in the form of pigmeat and poultry, and not the more land-intensive beef according to FAO Food Balance Sheets (2013). However, they are also consuming more calories per capita, roughly 30% more according to the same FAO source. As the world's food supply per capita increases, the world is eating more of both animal and non-animal-based products. The world as a whole is consuming roughly the same ratio of animal product calories to other calories. To see this more clearly, we show the consumption of land-intensive animal calories (including milk, meat, and eggs) as a share of total calorie consumption. Although we are now eating more meat than ever before, the share of animal products in the total diet has changed less than 3% since 1961. To date, the relative composition of animals to crops in our diet has changed little, as shown in Fig. 6. Thus, while there has certainly been an increase in meat consumption in the form of poultry and pigmeat, we see no reason to believe there have been structural changes that would have major confounding effects on our productivity metric.

Our productivity metric is impacted by structural changes in what animals are fed, whether crops or roughage found on pastureland. In the United States, a structural change has occurred such that more animals are now being raised on crops than on pasture, meaning that less pasture is required. Although less pasture and more cropland is required in the US, our world-level data show growth in pasture land keeping pace with growth in cropland (Fig. 7). Cropland and pastureland requirements for each calorie of animal products are themselves a result of variables such as pastureland intensification and cropland productivity growth. Thus, while our data suggest that there have not been structural changes in land use, we cannot be fully confident in this. Therefore, we cannot say with certainty that a structural change has not impacted our productivity metric.

Physical Work Productivity (kcal/J) We define physical work productivity as the supply of food calories available to society per the amount of physical work used to grow the food, measured in joules:

$$\textit{Physical work productivity} = \frac{\textit{Food supply}[\mathrm{kcal}]}{\textit{Physical work}\left[\mathrm{joule}\right]} \qquad (12)$$

Food supply [kcal] is defined as above for land productivity and does not include feed for animals or other crop products.

By measuring work inputs in joules (J), we make a consistent comparison between labor (humans and animals) and capital (machines). Rather than relating hours of work or capital services, we compare work, which accounts for differences in the power, speed, and usage of humans, animals, and machines for farm work.

Human Labor Productivity (kcal/J) The FAO states that labor productivity is volume of (food) output divided by units of labor to produce that output (Mechri et al. 2017, p. 31). The FAO recommends that the units of labor is the number of workers or amount of time (e.g., hours worked). In 2001, the OECD suggested units of labor usage to be measured in time worked.

We extend this approach and quantify labor usage in joules (J), an energy unit that is based, in part, on the time laborers worked and their power outputs. Joules of labor usage is directly proportional to the number of hours laborers spent working; the suggested metric of the OECD. Joules

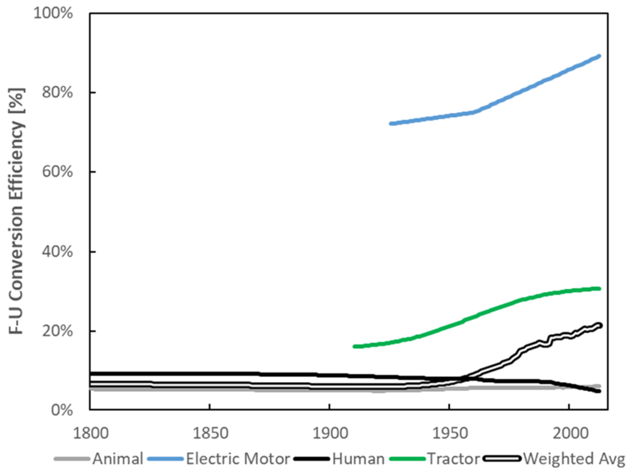

Fig. 8 Efficiency of energy conversion for each power source 1800–2012, world average. Weighted average final-to-useful (F–U) efficiency since 1950 has more than doubled, meaning that for the same fuel inputs, twice the work can now be produced. We use a means of allocating calories for animal and human efficiencies that is used broadly in the literature. This allocation has a large impact on the value of efficiencies shown here. If this allocation was changed, efficiencies could appear to roughly triple for any year (from ~ 8–10% to 24–30%). In contrast, the allocation we make has no effect on the quantities of physical work we calculated to find physical work productivities, meaning no matter what allocation is used for efficiency with our data, the physical work productivity shown in Fig. 12 would stay the same. See Sect. 2.2.1 for more detail on efficiencies and Section S2 of Online Resource 1 for a review of the literature on how calories are allocated for efficiency calculations

of labor usage also vary ± 8% based on which region the human power output comes from (shown in Appendix Fig. S11). The conversion from Joules to hours, assuming an 85 W power output, is roughly 30,600 J/h (30.6 kJ/h).

The volume of output we measured in terms of food supply for humans [kcal], as we did for land productivity. This is the same food supply as was used for land productivity, and it also does not include animal feed or other non-food crop products (e.g., Cotton or hemp).

In summary then, we calculate human labor productivity as follows:

$$\mathit{Human\,Labor\,productivity} = \frac{\mathit{Food\ supply}\,[\mathrm{kcal}]}{\mathit{Human\,muscle\,work}\,[\mathrm{joule}]}. \tag{13}$$

Data

The data sources used to create this database are shown in Table 4.

Our Nitrogen fertilizer data come from Smil (2001) (see Table 1). Smil lists "other" Nitrogen (N) fertilizer inputs from 1850 to 1910, including Guano and Chilean Nitrate, Ammonium Sulfate, Cyanamide, and Calcium Nitrate. After 1910, Smil includes fertilizer inputs from these "other" sources as well as inputs of fertilizer produced by the Haber Bosch process. Data on world food supply and cropland are shown in Fig. 7.

Results

Each subsection below provides an answer to the research questions raised in section "Need, Aims, Contributions and Structure" which describe the effects of mechanization. To repeat, the questions are as follows:

1. How has the efficiency of converting final energy into physical work evolved over time?
2. How have different final energy sources been used to power field work?
3. How did physical work contribute to land/labor productivity from 1800 to 2012?

By answering these questions, we describe the effect of mechanization on the amount, efficiency, and productivity of physical work and the impact of physical work on the land and labor productivity of farms.

How has the Efficiency of Converting Energy into Physical Work Evolved Over Time?

Figure 8 shows the growth in individual and aggregate final-to-useful conversion efficiencies since 1800.

Before the widespread deployment of machines in Europe and North America, the efficiency of conversion of final energy to physical work remained remarkably stable for 150 years, from 1800 to 1950. The weighted average efficiency did not increase, as human workers and draft animals' efficiencies were both relatively stagnant or even declining (Fig. 8). When they were introduced in the 1910s and 1920s, tractor and electric motor efficiencies were already much higher than human and animal efficiencies. The weighted average energy efficiency increased from 5 to 20% as a result of growing use of tractors and electric machines from 1950 to 1990 (Fig. 10).

Growth in aggregate efficiency has started to decline since the late 1990s. Liquid fuel and electricity-powered equipment were made steadily more efficient between 1910 and 1990. However, efficiency improvements for tractors have plateaued since 2000 and improvements may soon plateau for electric motors too (Fig. 8). Tractor efficiency steadily increased, rising from 16% in 1910 to 31% by 2010. Electric motors for pumps and processing equipment increased steadily too. Electric motors for pumps from the 1960s had efficiencies of 70%. By 2000, manufacturers were making standard electric motors for pumps with efficiencies

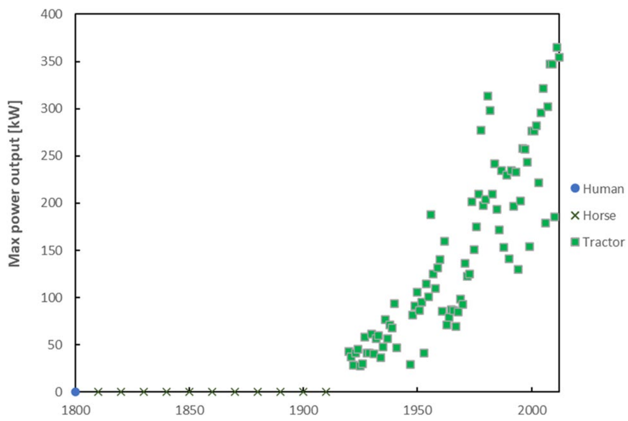

Fig. 9 Historical evolution in max-rated power output available from an agent in a given year, 1800–2012. Human and horse power, at 0.1 and 0.6 kW, respectively, did not increase above 1 kW over 215 years. The first tractors for which power data were available had power ratings between 2 and 43 kW, much higher than horses or humans. Tractor power ratings, unlike animal and human power, have grown tremendously since 1910, evolving from a max of 43 kW in 1920 to a max of 350+kW in 2012. (Tractor data Source: Nebraska Tractor Test Laboratory (2021)

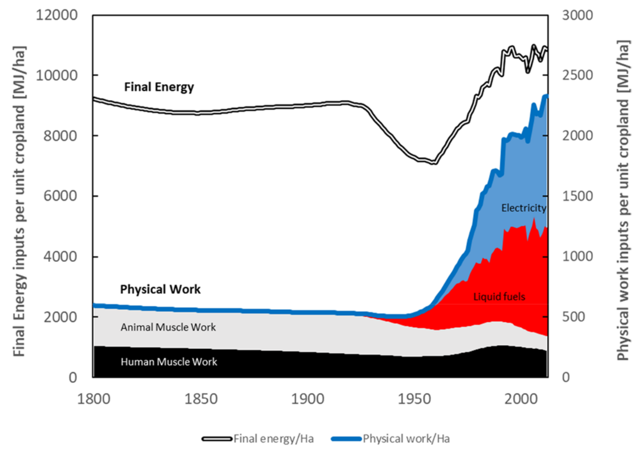

Fig. 11 Final energy inputs per unit of cropland (left axis) and physical work inputs per unit of cropland (right axis) 1800–2012

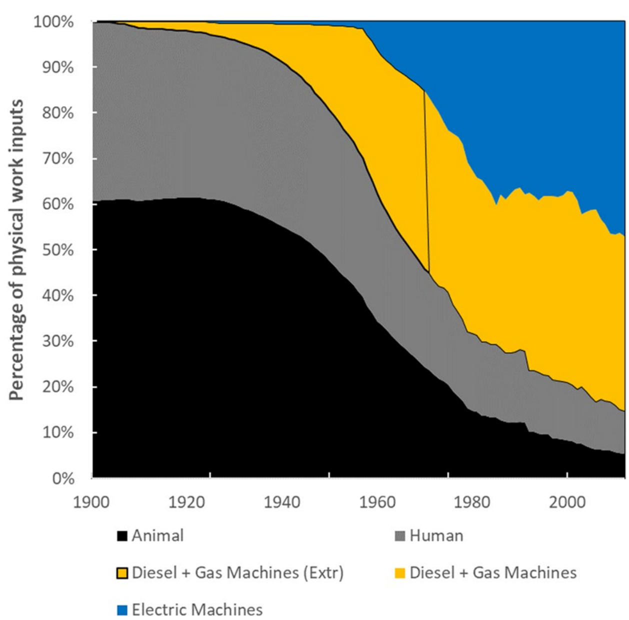

Fig. 10 Time series of physical work contributions by muscles (humans and animals) and machines (diesel+gas and electric) 1920–2010. Data for Diesel+Gas machines were extrapolated ("Extr") before 1971 (Color figure online)

of 95% (Smil 2000, p. 133). Now that electric motors are reaching near ideal efficiencies of 100%, there is little more room for efficiency improvements. The trend of efficiency improvements may soon plateau for electric motors, and thus, for pumps as well.

Aggregate animal efficiency has been relatively consistent since 1800 (Fig. 8), despite systemic changes in the types of draft animals being used. European and North American agriculture was once powered primarily by horses, which convert final-to-useful energy at about 7% efficiency. European and North American farmers have largely adopted machines that take the place of horses with much higher associated final-to-useful efficiencies. Asian and Latin American farmers still use large amounts of draft animals, especially oxen (final-to-useful efficiency of 5%). As machinery has displaced horses in Europe and North America, Asian and African oxen along with other animals have grown to represent a higher proportion of the world's draft animals. The changing composition of draft animals has not caused aggregate animal efficiency to change more than ± 1% overall.

Human worker efficiency has declined to about 5% from its peak of 11%, largely as a result of decreasing working hours and increasing food wastage. When one works less hours, physical work output declines while metabolic needs change little ($\downarrow \eta_{F-U,x} = \frac{\downarrow E_{u,x}}{\rightarrow E_{f,x}}$). Workers of today both eat more unnecessarily and waste more food, and thus, they increase their final energy food supply. Food supply increases but work output does not change, so efficiency declines as a result ($\downarrow \eta_{F-U,x} = \frac{\rightarrow E_{u,x}}{\uparrow E_{f,x}}$).

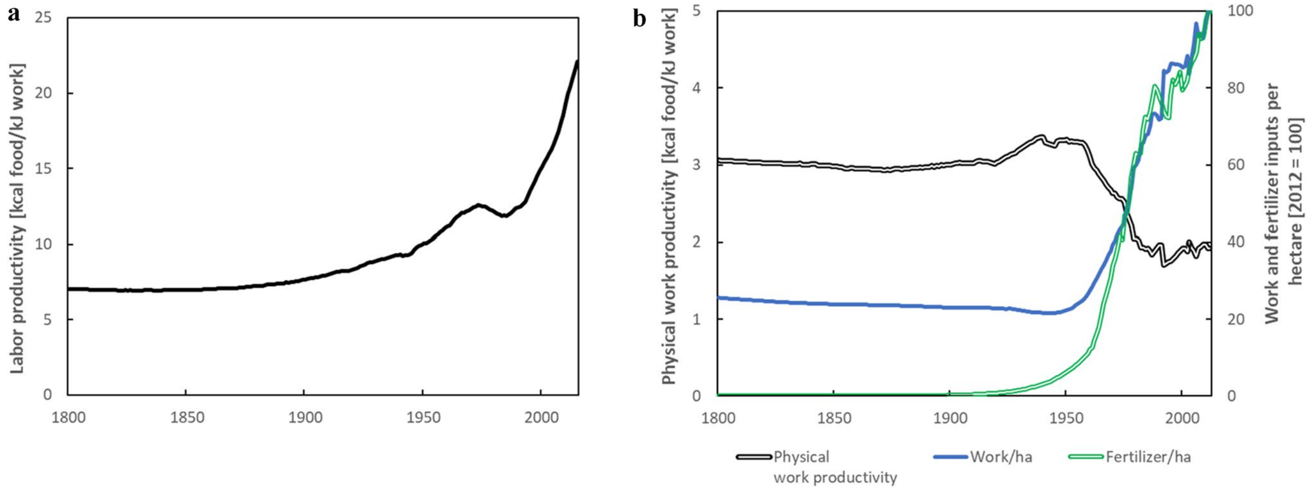

Fig. 12 Left: Human labor productivity 1800–2012. Right: Physical work productivity and physical work (from muscles and machines) and fertilizer inputs. Although work and fertilizer inputs per hectare have grown since 1950, physical work productivity has unexpectedly declined

How Have Different Energy Sources Been Used to Power Field Work?

Power Outputs

The machines farmers operate with liquid fuels and electricity can be far more powerful than a human or animal. For humans, maximum power output has varied little, and a sustainable working day's power output is only around 0.07–0.1 kW. As Smil (2017) shows, each transition was characterized by an order of magnitude increase in power. Moving from human hand power (0.1 kW) to a two-horse team working at 1.2 kW represents a 12-fold increase in power. In 1920, a farmer and tractor could exert roughly 15–20 kW, more than ten times that of a horse team. Today, the farmer–tractor team can easily exert 100 + kW, more than 100 times the power of a single farmer (Fig. 9).

Irrigation, once a passive task, is increasingly being accomplished by high-powered machines. Today's irrigation pumps could be anywhere between 2 and 52 kW (or 2.5–70 Brake HP) (Scherer 2017), or at least twenty times the manual power of the farm worker.

Fueling Field Work

The source of physical work inputs since 1920 is shown in Fig. 10. Farmers have gradually adopted liquid fuel and electricity-powered machines to do more of the total share of field work (Fig. 10). In 1920, 97% of work was being fueled by the food or feed that humans or animals ate. By 2012, food/feed inputs were less than 20%, with over 80% of work inputs being powered by liquid fuels and electricity. Liquid fuels and electricity can drive increasingly powerful machines that produce more work than a single human or animal alone (Fig. 9).

Between 1920 and 1950, machines that were up to three times more efficient than muscles at producing were introduced (Fig. 8). Rather than doing more work, machines simply did the same work once done by humans and animals. Because machines in this period did the same amount of work just more efficiently, final energy use fell (Fig. 11).

However, after 1950, total work inputs per hectare have increased more than fourfold, as shown in Fig. 11. Liquid fuels and electricity-powered work have been responsible for the entirety of the increase in work/ha.

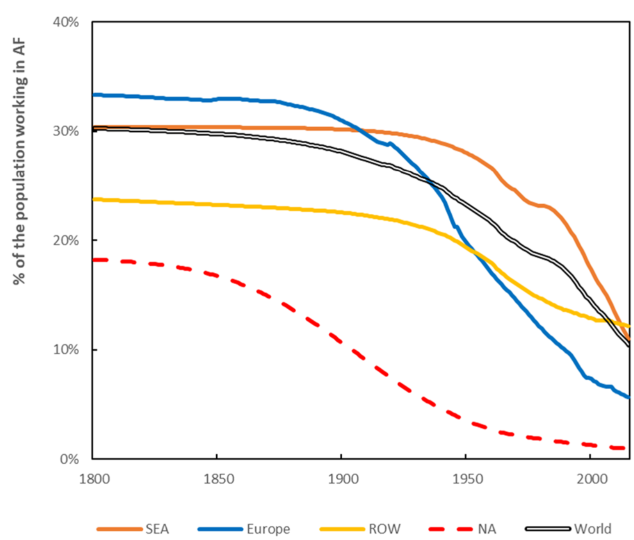

Fig. 13 Population working in agriculture or forestry (AF) as a percentage of the world population total

The work done by liquid fuel and electricity-powered machines since 1950 has been an addition to the work already being done by humans and animals (Fig. 11). The combined amount of animal and human work per hectare has declined only 33% since the advent of fossil fuels and electricity. Human work in particular has remained relatively stable even through periods of large changes in population (e.g., World Wars, the Great Leap Forward, recent population explosions in South and East Asia, etc.). Even though world population continues to grow, Human Muscle Work inputs remain relatively steady because less of the world's population is now working in Agriculture and Forestry (Fig. 13).

After 1950, machines, particularly those run by electricity, started doing more work than had been done before. Some of the additional work done on farms has been used to irrigate farms that were previously not irrigated or relied on gravity irrigation. Before pumps were introduced, the work of irrigation was largely being done passively by gravity. After the 1950s, however, pumping for irrigation became more common. Pumping for irrigation and sprinkling makes up a large part of overall demand for electricity work. Work done by irrigation pumps made up more than 45% of overall electric work for most countries in the years with data available (Fig. 5). The increase in work done for electric irrigation helps explain why more electric work has been needed.

Work inputs per hectare were relatively constant from 1800–1949 and then increase fourfold from 500 to 2400 MJ/ha during the post-1950 fossil fuel powered era (Fig. 11). Work inputs declined 14% on a per hectare basis between 1800 and 1949 because the amount of cropland under cultivation was growing at very fast rate (Fig. 7). The growth in cropland may have been due in part to Westward expansion in North America. The rate of cropland expansion declined around 1960 shortly after the explosion of work inputs on farms in 1950. The fourfold increase in work/ha from 1950–2012 coincides with increasing average energy conversion efficiencies for liquid fuel and electricity-driven machines (Fig. 8). Increasing efficiencies moderated the growth in final energy consumption after 1950, even as the work done on farms grew significantly from 1950 to 1980.

Considering work contributions from humans, animals, and machines, we identified 3 different historical periods in world agriculture, based on which agent was doing most of the physical work. Our definition of a period is that time span in which more than 50% of the total physical work contributions come from one energy source (Fig. 10). First was the animal period, when animals were doing a majority of field work (1800–1949). After the animal period, there was a 15-year transition period, where neither humans, animals, or machines contributed more than 50% of world work inputs. After the transition period, society entered the liquid fuels and electricity period (1966–2012). These periods, and their unique characteristics, are reviewed in Discussion section below (3.3).

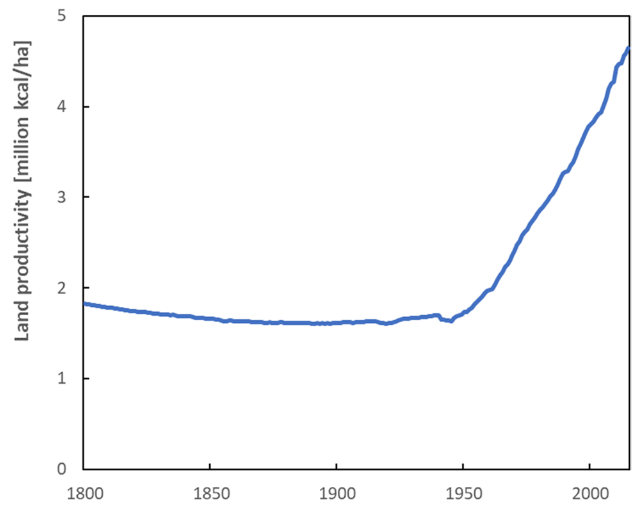

Fig. 14 Land productivity (million kcal/ha)

How did Physical Work Contribute to Labor and Land Productivity from 1800 to 2012?

Labor Productivity

Figure 12 shows the human and physical work productivities. One of the main benefits of increasing the power of fossil fuel powered machinery is increasing human labor productivity (Fig. 12). We see the effects of increased labor productivity in the gradual flow of the population out of agricultural occupations (Fig. 13).

Our estimates show that human labor productivity for the world as a whole has grown significantly since the 1860s, with only a slight decline in the 1980s and 1990s. The growth of human labor productivity after 1860 was at first driven by draft animals that provide higher muscle work power. These draft animals provided a steady supply of work even as human work inputs decreased between 1860 and 1950 (Fig. 10). The discontinuity in labor productivity growth in the 1980s was due to a temporary growth agricultural workforce that outpaced growth in cropland use. Between 1970 and 1990, there was a temporary stabilizing in the percentage of the South and East Asian population working in agriculture (Fig. 13). At the same time, overall population growth in South Asia was peaking, reaching 2.2% in 1980 (World Bank 2021). For several years, this stability of occupations, coupled with growth in the overall population, meant that the agricultural workforce in South and East Asia grew. Workforce growth outpaced cropland growth which led to a temporary increase in Human Muscle

Work inputs per hectare, and a decrease in human labor productivity between 1970 and 1990.

Physical work productivity has declined since the 1950s despite the increase in physical work/ha and fertilizer/ha (Fig. 12). In short, increasing work inputs since 1950 have shown diminishing returns in terms of producing more food supply for humans (Fig. 12). If work productivity was defined in terms of total crop outputs (which may have increased at a faster rate), productivity may not have shown diminishing returns. Diminishing returns to work inputs have meant that farmers have had to use more and more work per hectare to continue improving their land and labor productivity (Fig. 11). Farmers have used more and more fertilizer per hectare, too (Fig. 12). Thus, despite more work and fertilizer inputs, farms have had to use more joules of work to produce each kilocalorie of food to sustain the increase in land productivity (Fig. 12).

Land Productivity

Figure 14 shows how land productivity has changed since 1800. In Fig. 14, we see that land productivity has been increasing since 1950. The roughly 2.75-fold increase from 1950 to 2012 is similar to Pellegrini and Fernandez's finding that there was a threefold increase in crop production 1961–2014 (2018). Land productivity has increased since 1950 because farmers have used higher yield crop types in combination with more (1) Industrial fertilizers, (2) Irrigation water, and (3) Physical work.

We will focus next on the contribution of physical work to productivity as this contribution has typically only been studied for labor productivity. We now study work's contribution to productivity using the physical work dataset that we have created.

Physical Work Inputs: A Historical Perspective

Prior to 1950, land and human labor productivity were relatively constant at a global scale (Figs. 12 and 14), in part because it was not economical to increase levels of farm work or fertilization (Wrigley 2016). Prior to 1950, farmers could only do more work by having more farmhands or more animals. Farmhands either have to be paid wages or, in the case of family members, are an extra mouth to feed. Draft animals too have to be fed, which meant more land dedicated to raising feed. Fertilizer imports were low, as much of the fertilizer had to be shipped in from distant places, as with Saltpeter from Chile and guano from Peru. Synthetic fertilizers, which are often labor saving, were little used in the early twentieth century as production was energy intensive and, therefore, costly (Smil 2001). The prohibitive expense of land on which to grow extra food or feed, as well as the limited supply of all fertilizers and manure hindered land productivity from growing between 1800 and 1949.

After 1950, the amount of work done per hectare began to increase rapidly to fuel industrial agriculture, which has high land and labor productivity. That said, farmers and their animals were not the ones doing the extra work. Rather, the extra work was accomplished by high-powered, comparatively energy efficient liquid fuel, and electricity-powered machines (Fig. 8). The fuel for these machines came from beyond the farm, meaning that farmers could do more work without having to grow more fuel on their land. As animals were replaced by machines, farms lost their plentiful supply of one of the other beneficial outputs of animals, organic fertilizer. However, fertilizer use, especially from synthetics, increased to more than make up for the decline in organic fertilizer production (Fig. 12). In industrialized agriculture, the ceiling on farmers' work output, land productivity, and labor productivity have been lifted. Farmers no longer needed animal manure for fertilizer, and their land and labor productivity rose as a result.

Discussion

The growth in world population has raised concerns that people will use up all available farmland. Had land productivity not changed from its 1800 levels, the present population of the world would have faced a land shortage without land productivity gains. If productivity had not changed since 1800, the world would need a total of 5.1 trillion ha of cropland to feed the human population; between 0.5 and 2 trillion ha above current estimates of the total amount of cultivable land (Fischer and Heilig 1997; PSAC 1967; Revelle 1976). Instead, land productivity has increased by 275% since 1950 to keep feeding a growing population (Fig. 14), and the *rate* of cropland expansion has declined from its pre-1950 levels (Fig. 7). This 275% growth in land productivity is evidence for Boserup's theory that food supply increases in response to population pressures (1965).

Land productivity growth was enabled by the availability of new yield-raising crops (Pingali 2012), chemical fertilizers (van Zanden 1991), and more powerful and efficient mechanical technologies powered by liquid fuels or electricity. Mechanical technologies have improved land productivity in part by doing more physical work (e.g., plowing, tilling etc.). As Binswanger points out, more physical work (e.g., better tillage) can be done by either animals, humans, or machines such that any agent can raise land productivity (1986). However, machines are more efficient and their energy cost per unit of work is lower such that it is less costly to do more work with machines than with humans/animals.

Mechanical technologies have also increased land productivity by increasing the application of agrochemicals and irrigation, thereby increasing yield by raising inputs per hectare. According to FAO, the total irrigated land area in the world in 2000 increased to 18.3% of the World's total arable land, compared to just 10.3% forty years earlier (Federico 2005, p. 45). With the new task of irrigating this land came the new demand for additional technology and work inputs, above and beyond what was needed for traditional farm tasks. Mechanical technologies have improved labor productivity by increasing the amount of physical work a farmer can do with fewer laborers. Tractors and other liquid-fueled machines have increased farmers' labor productivity by substituting for the work once done by many humans and animals (Binswanger 1986). An exception to Binswanger's observation that machines tend to substitute for human/animal labor is found in irrigation. The movement of irrigation water from far away reservoirs was a task once rarely done by humans but which is now regularly done by machines. Machines have contributed additional value by doing work that only they could do and raising productivities as a result.

By adding additional work inputs per hectare, farmers have increased both their land and labor productivity. Farmers in 2012 applied 4.5 × more work inputs to each hectare of cropland than they did in 1800 and have achieved a roughly 2.75-fold increase in land productivity and threefold increase in labor productivity as a result. As Wrigley (2016) points out, the growth in work inputs per hectare and land productivity would not have been possible in an organic economy. In an organic economy, the land would have been used to grow crops to feed humans and animals. In contrast, the fossil fuels that powered the increase in work after 1800 came from non-arable land. Thus, the increasing use of these fuels did not inhibit the growth in land productivity. Use of fossil fuels is a "land-sparing" activity (Harchaoui and Chatzimpiros 2018). When cropland is spared from being used to grow fuels for animals, more of a farmer's physical work inputs can be used to grow food for others and thereby increase land productivity. van Zanden points out that the adoption of chemical fertilizers and purchased feedstuffs for livestock in Europe after 1870 not only raised land productivity but also "were typically land saving" (1991, p. 216). However, when more land is used to grow feed for livestock used for their milk/meat, this land-sparing effect is not fully exploited and land productivity does not increase as much as it could. The land-sparing effect has likely not been fully exploited since 1950 due to a steady demand for milk/meat by a growing population (Fig. 6).

After 1950, farmers were able to apply more work inputs on their farms because machines and the fuels they ran on were growing more efficient and affordable. Humans and animals could not have provided so much extra work because they were constrained by a limited land supply (Wrigley 2016). Improvements in the tools used by humans and animals before 1950 could not change the efficiency of the underlying food-to-muscle energy conversions that enabled farm work (Fig. 8). On the other hand, liquid fuel and electricity-powered equipment could provide the extra work inputs at a reasonable price, because they were much more efficient than humans or animals. The earliest liquid fuel equipment had more than double the efficiency of humans or animals. By 2012, tractor efficiencies were more than three times higher than human or animal efficiencies, and electric motor efficiencies were nine times higher. In times of high cost of wages, the obvious solution for farmers is to mechanize and so avoid paying wages (van Zanden 1991). Many farmers have mechanized which caused liquid fuel and electric equipment usage to increase significantly between 1920 and 2012, and, as a result, aggregate energy efficiency nearly tripled. The growth in aggregate energy efficiency allowed farmers to do more work with the same energy inputs.

Mechanical technologies spare land and use energy resources more efficiently but they are often used to work the land more intensively, thus, contributing to the depletion of soil fertility in the long run. In the period between 1800 and 2012, soil fertility remained sufficient to continue improving land productivity via increasing inputs. To continue raising land productivity in the future, soil fertility must be considered.

Conclusion

From 1800 to 1949, land productivity was stagnant at 1.7 [M kcal/ha], in part because the types of fuels available limited the work farmers could do. In this period, it was difficult to raise land productivity. Farmers had to either hire more laborers, raise more draft animals, or (before emancipation) enslave more people to do more work. These extra laborers and animals needed food to eat. The food for these laborers and animals came from the land they worked, which meant that, to get more fuel, they would have to cultivate more land. The dependence on the land for fuel limited land productivity during this period. From 1950 to the mid-1960s, land productivity began to grow steadily, increasing linearly by 0.05 M kcal/ha per year. The move to industrialize and scale up farms in industrialized countries was being increasingly powered by liquid fuels and electricity, which could fuel on-farm work more efficiently and subsequently at lower cost to farmers. By 1966, the majority of global on-farm work was being powered by liquid fuels and electricity. From 1966 to 2012, land productivity continued to grow nearly linearly at 0.05 M kcal/ha per year, reaching 4.7 M kcal/ha in 2012. Demand for both liquid fuels and electricity grew such that large, industrialized farms now use five times more fossil fuels per hectare than do traditional small-scale farms

(Rosa et al. 2021). Demand for power irrigation drove up electricity-powered work, such that it matched and then exceeded work powered by liquid fuels by the early 2000s. By the end of the period, the majority of on-farm work was being powered by electricity.

For all of the growth in work inputs, there have been diminishing returns to land productivity. Although work/ha increased by 4.5 times between 1950 and 2012, land productivity increased by only 2.75-fold. To achieve greater land productivity to feed a growing population, increasingly more work has historically been needed per hectare. In the future, several factors might have an impact on this relationship such as biophysical constraints on soil productivity, change in precipitation patterns or the collection and processing of data associated with precision agriculture. However, if more farm work is needed in the future, it is likely that more final energy will be needed too, since machine efficiencies are starting to plateau. If trends continue as in the period 1950–2012, more final energy will be needed to increase future land productivity. Simultaneously, responding to the climate crisis has led to goals for reduced energy consumption. Future increasing final energy consumption in farming will work against climate goals, leading to uncertainty about how both land productivity goals and final energy use targets can be met.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s41247-022-00096-z.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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