Intermediate Agricultural Machines Energy Efficiency: The Example of Harvesting and Threshing

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traction in the sowing, haymaking and harvesting operations. For example, in 1826 one of the first successful reapers was created by Patrick Bell, characterized by being pushed by a pair of horses. In the 1930s, Cyrus McCormick developed a two-horse drawn reaper, followed by the introduction of automatic rakes and the development of a reaper-binder [4]. In the 1980s, animal traction was pushed to its upper limit, as in the case of the Houser combine harvesters, which make use of a number of horses between sixteen and forty [5]. The introduction of internal combustion engines has marked an epochal turning point in agriculture, with a significant reduction in manual labour, a reduction in working times and a consequent huge increase in productivity. One of the factors that characterized this process was the increase in the power density of the prime mover: from 1 W/kg of animated engines (human power, HP, and animal power, AP) to 1 kW/kg typical of internal combustion engines (ICE) of the early 1900s [1], with an increase of three orders of magnitude.

The increase of labour productivity, made possible by the exploitation of fossil energy sources, is well evidenced by the fact that while a single peasant farmer at the beginning of the 19th century dedicated 30 hours of work to produce a ton of wheat, at the beginning of the 20th century he devoted less than 7 hours, up to the few minutes of our days. While it is evident and widely documented that with the evolution of agricultural machinery, associated with the increase in available power, there is a significant increase in the productivity of each individual worker, it is difficult to have data in terms of energy efficiency.

The aim of the work is to evaluate the effect of the increase in power available for each individual operator, due to the technological evolution of the prime movers and machines used in agriculture, both in terms of productivity and energy efficiency. The paper considers, by way of example, only the case of wheat harvesting and threshing, even if a similar analysis was conducted by the authors for the main agricultural operations.

In the paper, a brief history of the evolution of the machines used for the harvesting and threshing the wheat is presented, with particular focus on the evolution from an entirely manual processing to one that involves the use of animal traction, up to the introduction of the internal combustion engines. Subsequently, the methodology adopted to evaluate the effect of increasing the power available for each individual operator on the productivity and on the corresponding energy efficiency is described. Finally, the data obtained are presented and discussed

2 Harvesting and threshing the grain

For this study we choose technologies starting from XIX century, because of the slow and moderate development of the agricultural machinery and methods in a precedent period. The method (Table 1) is characterized by the processing of harvesting and threshing in a separated or combined way with different technologies, period and prime mover. For each technology we collect the data for power exerted and productivity from literature, as described in section 3 and 4.

Table 1. Harvesting and threshing technologies

	METHOD	TECHNOLOGY		AGE	PRIME MOVER
#	**Denomination**	**Harvesting**	**Threshing**	**Year**	
1	Ancient Traditional	Sickle	Trampling + Sieve	1800	HP+AP
2	Preindustrial Traditional	Cradle Scythe	Flail + Sieve	1800	HP
3	Preindustrial 1870	New Yorker - Reaper	Pitt's Thresher	1870	HP AP
4	CH Preindustrial - Houser	Combine Harvester		1900	HP AP
5	Small Size Appropriate Technology	Manual Reaper	POP Thresher + POP Cleaner	2013	HP
6	Medium Size Appopriate Technology	Appleby Twine Binder	POP Thresher + POP Cleaner	2013	HP + AP
7	Industrial Medium Enterprise	Towed Reaper	Fixed Thresher	1950	ICE
8	Industrial Small Enterprise	Self Propelled Reaper	Fixed Thresher	1950	ICE
9	Modern Small Enterprise	Self Propelled Reaper	Mobile Crop Tresher	2000	ICE
10	Modern Medium Enterprise	Towed Reaper	Mobile Crop Tresher	2000	ICE
11	CH Industrial Romanello	Combine Harvester		1950	ICE
12	CH Industrial Caterpillar	Combine Harvester		1950	ICE
13	CH Modern New Holland	Combine Harvester		2013	ICE
14	CH Modern Medium Size CLAAS	Combine Harvester		1993	ICE
15	CH Modern Big Size CLAAS	Combine Harvester		2014	ICE

AP animal power; CH Combine Harvester; HP Human Power; ICE Internal Combustion Engine; POP Pedal Operated

Starting from the *Ancient Traditional* one, we selected the sickle as technology for harvesting the grain [6]; for threshing, the trampling method by horses and a sieve for cleaning [1, 7]. The *Preindustrial Traditional* adopt a cradle scythe [7] that avoid the collection from the ground and the flail as manual instrument for threshing [1], typical for the XIX century. The *New Yorker* is the first mechanical technology selected for the *Preindustrial 1870* method, a reaper-binder which gain success in the American crops, pulled by horses; the *Pitt's Thresher* was a horse powered technology which included also the sieving operation [7]. The *Houser* was the most famous preindustrial combined harvester, pulled by 37 - 40 horses [1].

For the *Small* and *Medium Size Appropriate Technologies* we choose a manual reaper [8] and the Appleby Twine Binder, the most famous automated reaper-binder moved by two horses [7], the best technology available in the late XIX century; we do not use a more recent solution for the lack of reliable data in literature. For threshing we selected a Modern Pedal Operated (POP)Thresher and a Pedal Operated Cleaner [9].

For the *Industrial and Modern Medium and Small Enterprise* methods the harvesting remains separated by the threshing but we see the appearance of the internal combustion engine as prime mover, used to feed the machine or the tractor (which will power the machine via the PTO); this is the difference between respectively self propelled and towed reaper (data collected from technical datasheets of BCS, Alvan Blanche, Cicoria).

The last sequence of method is represented by *Combined Harvesters* (CH) from different periods, power and brands driven by internal combustion engines [10-13].

3 Materials and methods

The article examines, also with a historical glance, the agricultural processes that allow to obtain the grain starting from the wheat in the field, i.e. *reaping* and *threshing*, distinguishing:
- *the prime mover*, or the source of the power: Human (HP), Animal (AP), or Internal Combustion (ICE);
- *the technology*, i.e. the exosomatic tool or the machine used to carry out the processing: sickle, scythe, reaper, reaper-binder, thresher, combine harvester, etc.

In order to compare the fifteen different processing methods reported in Table 1, three variables were taken into account: *individual power*, *individual productivity*, and *specific productivity*.

The *individual power* (kW man^{-1}) expresses the power absorbed by the prime mover (human, animal or internal combustion) referred to the individual operator and necessary for the operation of a specific technology in a specific agricultural process. For manual work, three levels of power can be expressed by a 70 kg worker continuously for 8-10 hours, that is one working day: low (40 W), moderate (75 W), medium-high (100 W) and high (130 W). As regards animal traction, the average power exerted by a horse, that is 750 W, was instead considered. As regards agricultural works carried out by human and/or animal powered, first is calculated the total power necessary for the execution of the different operations by a team (overall power) and then referred to the individual (individual power).

Individual Productivity (ha h^{-1} man^{-1}) represents the amount of surface treated in a given process per unit of time by a single operator using a specific technology. In the case of the harvest, it simply expresses the field surface cut in the unit of time, including binding and collecting of the sheaves. As regards threshing, productivity in the literature is generally provided in terms of mass of grain obtained per unit of time (kg h^{-1}). In order to be able to carry out the comparison with the harvesting, the threshed mass was brought back to the corresponding field surface through the crop yield expressed in kg of grain obtained per unit area.

Specific Productivity (ha kW^{-1} h^{-1}) describes the effectiveness with which the processing is performed. It is obtained by dividing the individual productivity by the individual power. In addition to indicating the amount of field worked per unit of energy, it provides a measure of how much area per unit of time can be worked with a given power.

It was necessary to refer to the single operator to compare pre-industrial agricultural methods with modern methods: in fact, while to a man who uses a combine to harvest and thresh it is simple to associate the individual power corresponding to that exerted by the combustion engine of the combine harvester itself, when it is considered the preindustrial methods, the agricultural operations must first divided into harvesting and threshing, and it must be considered that are often performed in work teams.

For example, referring to the method #3 *Preindustrial 1870* (Table 1), eight operators were needed to use the New Yorker reaper: one operator to guide the horses (low-intensity effort of 40 W); two operators to collect and prepare the sheaves and five to tie the same (both efforts to medium-high intensity equal to 100 W); two horses (750 W). The total power was then 2240 W and the total productivity 0.6 ha h^{-1}. Pitt's Thresher instead provided for the use of two operators (medium intensity effort of 75 W) and two horses, for a total power of 1650 W and a productivity of 270 kg h^{-1}. Considering a soil yield of 1350 kg ha^{-1}, typical of the 19th century wheat fields in the USA, the total productivity was equal to 0.2 ha h^{-1}.

In order to combine harvesting and threshing, has been recalculated the number of operators and the corresponding overall power needed to ensure that threshing operation had the same productivity as the harvesting operation (i.e. the triple, 0.6 ha h^{-1}): six operators for a total power of 4950 W.

Finally, calculated the total power needed to reap and thresh with the same total productivity of 0.6 ha h^{-1}, equal to 7190 W, the individual power was calculated by dividing it by the total fourteen operators involved in both the operations. The total productivity of 0.6 ha h^{-1} was also divided by the number of operators to calculate the individual productivity.

4 Results and discussion

With the methodology described in chapter 3, for each of the fifteen grain processing methods described in section 2 and summarized in Table 1, individual power, individual productivity and specific productivity were calculated. The results are summarized in Table 2.

Technologies involving the use of a human or animal prime mover reach a maximum individual power of 1.74 kW man^{-1}. With the introduction of the internal combustion engine there is a significant increase of individual power: almost an order of magnitude more with the 15 kW man^{-1} of the solution called *Modern Small Enterprise*. But going from the entirely manual *Preindustrial Traditional* solution to *CH Modern New Holland* there is an increase in individual power of about four thousand times.

Figure 2 shows, on a double logarithmic graph, the trend of individual productivity as a function of individual power. It is evident that, with increasing individual power, there is an increase in individual productivity. But while this increase at low powers is very marked, with increasing power it is less favourable. In the zone of pre-industrial technologies driven by animate motors, for example, it can be observed that with the passage from the method called *Preindustrial Traditional* to that called *CH Preindustrial-Houser*, there is an increase in productivity of 10 times compared to an increase in power of 14 times . In the combine harvesters area, on the other hand, in the transition between the *CH Preindustrial-Houser* solution and the *CH Modern New Holland* solution, there is a 120-fold increase in productivity compared to a 275-fold increase in power.

Table 2. Productivity and specific productivity of harvesting and threshing technologies

#	METHOD Denomination	INDIVIDUAL POWER kW man^{-1}	INDIVIDUAL PRODUCTIVITY ha h^{-1} man^{-1}	SPECIFIC PRODUCTIVITY ha h^{-1} kW^{-1}
1	Ancient Traditional	0.62	0.007	0.012
2	Preindustrial Traditional	0.12	0.008	0.065
3	Preindustrial 1870	0.51	0.043	0.084
4	CH Preindustrial - Houser	1.74	0.083	0.048
5	Small Size Appropriate Technology	0.11	0.012	0.109
6	Medium Size Appopriate Technology	0.14	0.015	0.106
7	Industrial Medium Enterprise	21.79	0.525	0.024
8	Industrial Small Enterprise	16.42	0.473	0.029
9	Modern Small Enterprise	15.94	0.405	0.025
10	Modern Medium Enterprise	58.58	0.800	0.014
11	CH Industrial Romanello	16.17	0.175	0.011
12	CH Industrial Caterpillar	34.90	1.460	0.042
13	CH Modern New Holland	479.96	10.021	0.021
14	CH Modern Medium Size CLAAS	172.73	1.500	0.009
15	CH Modern Big Size CLAAS	367.50	4.200	0.011

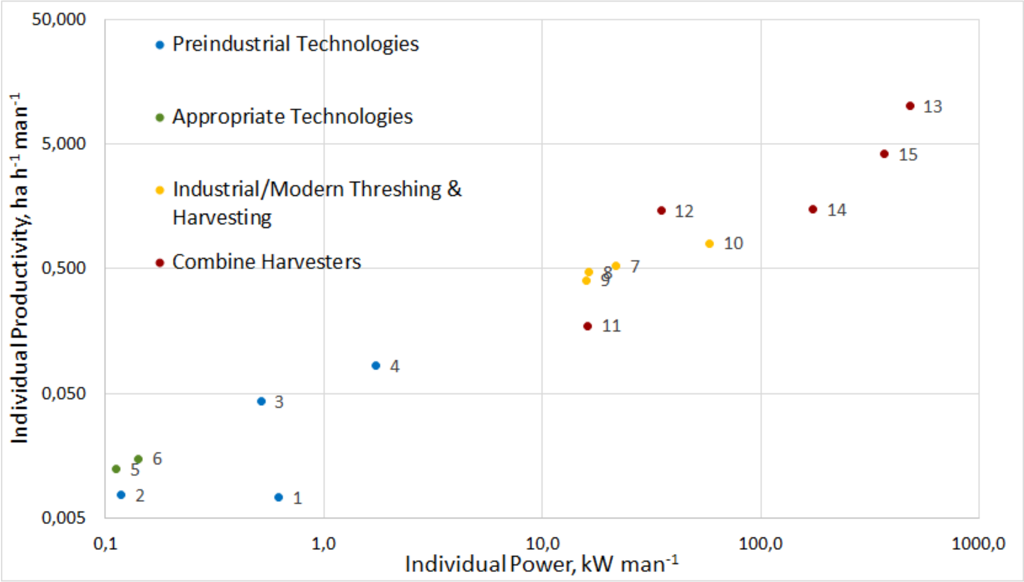

Fig. 1. The individual productivity versus the individual power of the harvesting and threshing technologies

The graph of the specific productivity versus the individual power (Fig. 2) highlights that the higher energy efficiency is achieved by low power solutions. If with the method called *Small Size Appropriate Technology* with one kWh of energy it is possible to process 0.11 ha of field, with a *Combine Harvester* with high power internal combustion engine you cannot process more than 0.02 ha, but often you stop at 0.01 ha with ten times less energy efficacy.

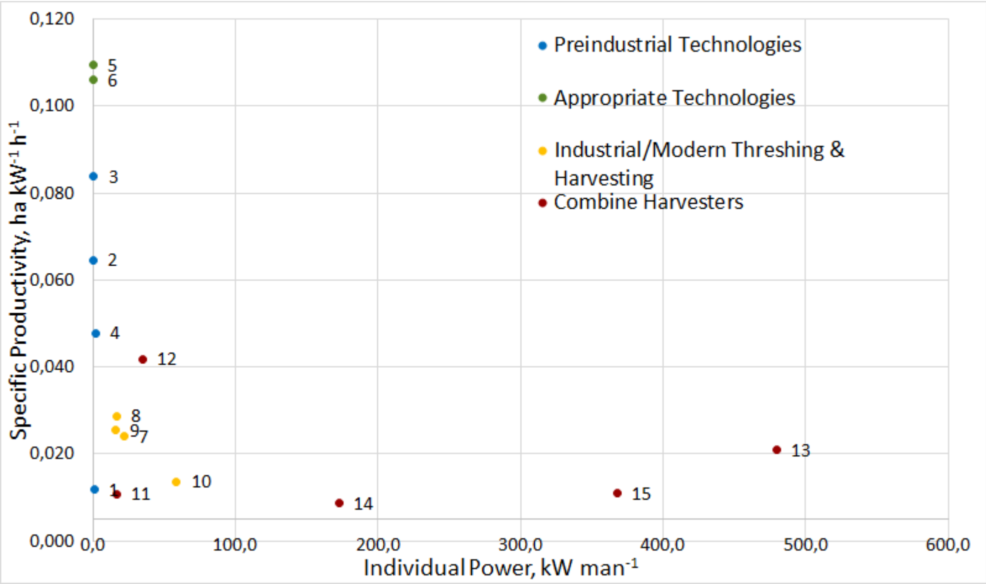

Fig. 2. The specific productivity versus the individual power of the harvesting and threshing technologies

5 Conclusions

In the paper, fifteen different methods of harvesting and threshing wheat were compared, from traditional entirely manual ones to modern combine harvesters. For each method, individual productivity, in terms of hectares of field worked per hour by an operator, and specific productivity, in terms of hectares worked per unit of energy have been calculated. The data were then correlated with the individual power, available to each operator involved in the operation.

As individual power increases, productivity increases. But while for low individual power the increase in power leads to substantial increases in productivity, this effect is less evident at high individual power.

On the other hand, in general, specific productivity is higher in the case of low individual power solutions, while it remains low, up to ten times less, in the case of high individual power solutions.

The historical evolution of agricultural machinery seems to have been oriented mainly towards increasing individual productivity, effectively obtained with the increase in individual power available, going from manual solutions, to animal-powered machines, to internal combustion engines. However, the evolution led to solutions with low specific productivity.

In order to adopt more sustainable practices, in the spirit of the UN Sustainable Development Goals, we are called to limit energy consumption. On the basis of this analysis it seems that a way forward, also in agriculture, consists in the development of intermediate solutions, capable of combining productivity and energy efficiency [14]. Schumacher's appeal to small-scale economies [15] and Illich's invitation to limit individual energy availability with a view to a fairer society [16] seem to be confirmed in our analysis.

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