Preserving global land and water resources through the replacement of livestock feed crops with agricultural by-products

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ABSTRACT

While animal source foods contribute to 16% of the global food supply and are an important protein source in human diets, their production uses a disproportionately large fraction of agricultural land and water resources. Therefore, a global comprehensive understanding of the extent to which livestock production competes directly or indirectly with food crops is needed. Here, we use an agro-hydrological model combined with crop-specific yields data to investigate to what extent the replacement of some substitutable feed crops with available agricultural by-products would spare agricultural land and water resources that could be reallocated to other uses, including food crop production. We show that replacing 11-16% of energy-rich feed crops (i.e., cereals and cassava) with agricultural by-products would allow for the saving of approximately 15.4-27.8 Mha of land, 3-19.6 km3 and 74.2-137.8 km3 of blue and green water, respectively for the growth of other food crops, thus providing a suitable strategy to reduce unsustainable use of natural resources both locally or through virtual land and water trade.

MAIN TEXT

INTRODUCTION

The global cereals market is projected to increase to 3 bln tons by 2030[1], though it is currently facing severe shortages resulting from the combination of the ongoing Russia-Ukraine war, the residual effects on food supply of the Covid-19 pandemic, and the ongoing drop in grain harvest caused by increasingly frequent extreme events such as floods, droughts, and heatwaves induced by climate change[2–4]. The expected increase is driven mainly by higher feed use, followed by food and other uses. Furthermore, it is supposed to take place mostly in developing countries due to the fast-expanding livestock sector[1]. One of the livestock production concerns is the competition for natural resources between the human food and the animal feed sectors [5]. Cereals stand out among all feed crops within this context. Currently, ruminants are still predominantly raised on permanent or temporary pastures, which account for one-fourth of Earth's landmass and 70% of the agricultural land[6]. Conversely, the production of monogastric livestock such as pigs and poultry underwent intensification through the use of feed from intensified agricultural production since the early phases of industrialization[7]. The ongoing *livestock revolution*, however, is intensifying production across the livestock sector, including ruminants[8], leading to industrial production systems where monogastric and some beef and dairy cattle require huge amounts of primary crops to be processed into concentrated feeds[7,9,10]. Thus feed production uses 40% of all arable land, including feed crops used as the energy source for livestock (cereals and tubers) and protein crops (oilseeds and pulses)[6,11]. About 40% of that land is cultivated with cereal grains and accounts for one-third of global cereal production and 60-70% of the total feed crop production. To these, an additional amount of land to produce cereal and legume silage and fodder beets is consumed[11], which are usually not accounted for in the cereal primary production databases that include crops harvested for dry grain only. Not only land but also water use associated with meat and dairy production is high[12–14]. Mekonnen and Hoekstra estimated that global animal production required about 2422 km^3 of water per year in the 2000s, equal to one-third of total agricultural use, and 98% of that refers to the water footprint of the feed[9]. These data combined with projections of increased demand for animal source foods (ASF) clearly show that meeting the ASF demand is one of the challenges of our century in a world where finite water, land, and other natural resources[15,16] are often used unsustainably, (e.g., the case of unsustainable irrigation)[17,18], thus exceeding the planetary boundaries[19].

Energy-rich food crops such as cereals account for almost half of the global daily calorie food intake, therefore, from the food security standpoint, prioritizing crops use for direct human consumption rather as livestock feed is desirable[20,21]. In fact, in the livestock sector energy-rich crops such as cereals and tubers represent 94% of the total human-edible feed intake (i.e., the food-competing feed)[11]. The healthy reference diet proposed by the EAT-Lancet Commission recommends the consumption of moderate quantities of poultry and eggs and very low amounts of red and processed meat [22]. Currently, in high and middle income countries ASF consumption is far from meeting healthy and sustainable diet requirements[23]. It is therefore necessary to find additional strategies to reduce both the environmental impact of human diets and the competition for cereals between the food and feed sectors through a more effective management of livestock production systems.

The reduction in the use of food-competing feed products and replaced by lower-impact feed seems to be a promising possible strategy that fits within the circular economy frame[24–27]. To date, a global comprehensive study on the current environmental impacts (here evaluated in terms of land and water use) of livestock production and the potential benefits of replacing food-competing feed with specific amounts of theoretically available alternative feed from agricultural by-products is still missing. While some specific global studies are available for the land use associated with cereal feed production up to 2010[11], there is a large gap in the literature on the related water consumption at similar scales and resolutions. A recent comprehensive study by Sandström *et al*[21] used an extensive literature review of feed experimental studies to explore feed replacement scenarios for cereal crops and cassava with agricultural by-products, which are the secondary products derived from the production process of primary crops such as cereal and sugar crops. They found that such replacements could free up about 307-440×10^{12} kcal of energy-rich food, globally. More specifically, up to 72-103 Mton of cereals and cassava could be reallocated from the livestock sector to human food use. Other studies proposed similar strategies promoting the replacement of feed types that compete with food needs with alternative lower-impact and low-cost products such as food waste[24,28–30], agricultural co- and by-products and residues[20,31–34], foodstuff discarded by food manufacturing companies (former food)[35,36], and slaughter by-products[31,37]. However, most of them simulate hypothetical replacement scenarios without ensuring compliance with the current food and feed laws or availability of the alternative feedstuffs. They also tend to focus on local or regional scales rather than the global scale.

In this study, we assess the land and water (both green and blue) used for the production of energy-rich feed crops (i.e., cereals and cassava) in the 2016-18 period and the potential resource-saving that could be achieved by replacing these feed crops with by-products from the food system, including cereal bran, sugar beet pulp, molasses, distiller's grains and citrus pulp. We combined country data on feed use from the FAOSTAT database[6] with estimates of regional by-product availability and an analysis of suitable replacement criteria from Sandström *et al*[21]. We first reconstructed the global material feed flow associated with consumption and trade patterns. We then calculated the land and water resources used in the production of these feed types and their (virtual) transfer associated to these flows using crop- and country-specific yield data and a physically based and spatially distributed agro-hydrological model. We include a comprehensive and detailed trade analysis for the global cereal and cassava feed market, which enables a distinction between local and external cereal and cassava production and the quantification of the related virtual land and water trade. Lastly, we evaluated the land and water savings (and their geographic location) that would result from the replacement of feed based on cereals and cassava with by-products from the food system, introducing an allocation method to go beyond the mere assumption that such by-products have no additional environmental cost.

RESULTS

Current Scenario of Energy-Rich Crops Feed Use and Trade. On average, in the three-year period 2016-18 almost 980 million tons (802 Mtons of dry matter, DM) of cereals and cassava (hereafter referred to as 'energy-rich feed crops') were used annually as animal feed, which is about one-third of the global energy-rich crop production as reported by FAOSTAT[6]. In agreement with previous studies[6,21], maize is by far the most common energy-rich crop used as feed (64%), mainly in the Americas and in Asia, followed by wheat (13%), which is used as feed mainly in Europe and Oceania. Barley accounts for 9% of cereal consumption as feed, mainly in Europe and Western Asia, cassava for 9% (mainly in Africa), rice for 4% (mostly in Southern and South-East Asia), and finally Sorghum for 2% (mainly used in the Americas). These six crops cover 95% of the energy-rich crops used as feed. The major consumers of these crops can be found in Eastern Asia (27%), Europe (19%), and North America (16%). Because Southern Asia produces (and consumes) mainly dairy products from grazing ruminants and South America produces beef on extensive farms, the consumption of energy-rich feed is lower than in regions with growing monogastric or intensive ruminant livestock production (Fig. 1). Cereals and cassava are less traded than other crops such as oilseeds (soybean and oil palm); in fact, only 20% of these energy-rich crops used as feed do not come from local production. However, there are some exceptions such as the Caribbean, Northern Africa, and Western Asia, where the import share of energy-rich crops is higher than the domestic production (Fig. 1).

As a consequence of this complex trade system, the distribution of natural resource consumption by the livestock sector is uneven across regions, with large producer countries dominating the global scenario. Global feed trade is associated with lack of self-sufficiency (i.e., trade-dependence), virtual trade of natural resources such as land and water, and environmental impacts (e.g., pollution) (Fig. 2).

Current Scenario of Land and Water Resources Use for Energy-Rich Feed Crops. Cereal products and cassava fed to livestock required on average an annual use of 185.2 ± 7.0 Mha of agricultural land and 944.3 ± 39.8 km^3 of total water resources (Fig. 3, Table 1). While maize accounts for approximately 67% of energy-rich crop feed use, its production accounts for 54% of land used by energy-rich feed production and 45% of green water (GW) consumption by energy-rich feed crops. This is caused by the high use of agricultural inputs and efficient management practices associated with maize production, which achieves low yield gaps (10-15%) in the main producer countries such as the US, Brazil, and European countries[38] (Fig. 3, Figure S5, S6). Cereal and cassava production is relocated through trade and the associated virtual land flows. Eastern Europe, Northern America, and South America are net land exporters (Fig. 3, colored bars exceed dotted ones), while Eastern and Western Asia and Southern Europe are net importers (Fig. 3, dotted bars exceed colored ones). Western Europe, instead, stands out as both an importer and exporter region through virtual land trade (Fig. 2, Supplementary Figure S1).

Of the water volumes contributing to energy-rich feed crop production, just 81 km^3 (9%) come from irrigation water (or ‘blue water’, BW, withdrawn from surface water bodies and groundwater reservoirs), while the remaining 863.5 km^3 (91%) come from precipitation (‘green water’, GW, use). The geographic patterns of BW use for feed production are dictated by the distribution of irrigation infrastructures (Fig. 4, Supplementary Figure S2). In fact, Asia accounts for more than 70% of the total cereal irrigated area, across Eastern (72% of cereal fields are irrigated), Southern (58%), and South-Eastern (38%) Asia. Interestingly, BW tends to be less traded (8%) compared to land and GW (20%) (Fig. 2-3). In fact, rice, which accounts for 50% of cereal irrigated area, tends to be used as animal feed only in the areas where it is locally produced.

Potential Land and Water Savings with Energy-Rich Crop Replacement. The replacement of 88 Mton of energy-rich feed crop dry matter (or 111 Mton of fresh matter) as estimated by Sandrström *et al*[21] with available agricultural by-products suitable for livestock diets could save on average 21.6 ± 1.1 Mha of agricultural land, 106 ± 5.5 km^3 of GW and 11.3 ± 0.8 km^3 of BW, with no reduction livestock production (Table 1). However, because these by-products have an economic value and an environmental cost, we account for the fact that 2.8 – 5.1 Mha of land, 15.3 – 26.3 km^3 of GW, and 4 – 7.5 km^3 of BW are allocated to their production and processing from the primary crops they are derived from. In that case, slightly lower savings would be achieved (Table 1, Fig. 3-4).

Eastern Asia and North America would greatly reduce their energy-rich feed crops consumption (Fig. 3). In the case of Eastern Asia this big reduction is explained by the fact that this region (particularly China) is a major producer of animal source foods and therefore exhibits high rates of total feed demand. While Eastern Asian savings would take place both domestically and on imports, North America would mostly achieve high levels of saving in domestic cereal production since the United States and Canada are major cereal producers with limited dependence on imports. However, this pattern changes when it comes to the saved land and water resources. In fact, as far as land and GW savings are concerned, the regions that would most benefit from the use of agricultural by-products would be Southern, Eastern and South-Eastern Asia, and Eastern Europe. These regions still have relatively low agricultural yields compared to Northern America and Western Europe, where the yield gap is smaller, especially for cereals[38] (Fig. 4, Figure S5-S6). BW savings are expected to occur in Asia, where cereal production is traditionally irrigated (Fig. 4, Supplementary Figure S2-S3).

DISCUSSION

Livestock consumed annually about 980 Mton of fresh energy-rich crops on average in the three-year period 2016-18. The production of the energy-rich feed needed to meet this demand required 185.2 Mha of agricultural land. This area represents one-fourth of the global area harvested with energy feed crops and 13% of all arable land[6]. At the same time, 80.9 km^3 and 863.5 km^3 of BW and GW, respectively, were needed to grow these feed crops. These volumes represent 8% of total BW use in agriculture and 15% of total GW use for crop production worldwide, as estimated with the WATNEEDS model for 2016[39] (see Methods). The results of this effort can be compared with the few existing studies on this subject (Table 2). Looking at land use, both FAO and Steinfeld[7] and Mottet *et al*[11] estimated that 211 Mha of land is devoted to cereal feed production, which is slight higher than our estimate (185 Mha). The difference can be a result of the fact that we included just the five main cereals used as feed and cassava (95% of total energy feed crop production) which are also the ones with the lowest yield gaps, the different time period analyzed, and thus, the use of up-to-date agricultural yields. In fact, the GAEZ v4 database shows a crop yield achievement in several regions compared to the first decade of the century[38]. To compare our estimates of water use for energy-rich feed production to published data, we applied shares of feed use from FAOSTAT[6] to total water use estimates from other studies[9,14,39,40] for the six crop included in our study (Table 2). Our results are in line with these other studies, with a slight increase in water use for all crops, except sorghum. This increase is consistent with the estimated increase in the shares of production used as feed and in agricultural harvested area in the last few years.

Agricultural by-products are typically low-value commodities from local production or intra-regional trade, while concentrate feeds used both as whole grain and as meal often undergo inter-regional trade. Even though cereals are much less traded than other crops such as oilseed and sugar crops[6] their trade contributes to a global displacement of the environmental impacts of livestock production. Because global trade data are only available at the country scale aggregating food and feed uses, this study assumed that cereals used for food and feed purposes are traded in the same proportions and following the same trade paths. However, the European Feed Manufactures' Federation (FEFAC) reported that cereals grown specifically for animal feed purposes are usually of lower quality compared to that grown for human consumption[41], suggesting that cereal feed are most likely less traded compared to cereals directly consumed as food.

Cereals are the feed crops that compete the most with the human food sector. While cereals do not account for a large fraction of the diet of ruminants, they are used as feed supplement and as the main energy source for feedlot or dairy production diets. Conversely, cereals represent at least 60% (up to 90%) of the diet for monogastric livestock[42,43].

In a world with limited land and water resources for agriculture, food availability is strongly affected by the competition of the livestock sector that uses a substantial amount of cereals as feed[11]. Interestingly, even if some leftovers from the agricultural sector can also be used for bioenergy and other purposes, their use as livestock feed appears to be the most valuable and sustainable option[44]. However, biogas production can potentially compete with the livestock sector for by-products such as beet pulp and molasses included in this analysis, particularly as a result of financial incentive to mitigate the recent energy crisis[45]. On the other hand, biofuel industry is even able to produce a large amount of distiller's grains, which are products usable as animal feed. Furthermore, resource savings and avoidance of competition between food and other uses are also strictly dependent on geographic distribution of production, availability, and demand for agricultural by-products. In regions where both the demand for livestock feed and bioenergy use is high, these other uses of energy-rich feed crops and by-products can typically rely on a relatively wider range of available substitute products, as in Northern America and Eastern Asia. At the same time, while by-product availability is generally high in regions with relatively high demand for livestock and energy-rich feeds (Northern America and Eastern Asia), there are other regions such as South America, Southern Asia and South-Eastern Asia where by-product availability is high, but livestock are still predominantly raised in extensive grazing systems. In such regions, to date, the demand for energy-rich feeds is relatively lower compared to other regions, making more by-products available for other uses such as bioenergy.

By-product availability, in fact, can be seen as an encouraging factor in regions where they are abundant. However, they also represent a limiting factor in other regions, depending both on their local production and their current use in the livestock sector. As reported by Sandrström *et al*[21], molasses and cereal bran turn out to be the most available products because cereals and sugar crops (i.e., sugar cane or sugar beet) are produced everywhere. On the other hand, beet and citrus pulps are restricted to the main sugar beet and citrus producer regions, while distiller's grains are restricted to the main biofuel producer regions, thus potentially limiting the potential replacement of animal feed with agricultural by-products in several regions.

This study investigated the effects of the substitution of cereal- and cassava-based feed with agricultural by-products from the food system. We found that such substitutions can offer a winning strategy to reconcile the competing needs of the staple food and livestock sectors. Indeed, because these energy-rich feed crops account for 60-70% of feed consumption, substitution strategies focusing on these feed types may lead to larger land and water savings than scenarios concentrating on other less-common feed crops such as tubers, oilseeds or pulses that account for lower shares of animal diets, regardless of the fact that these less used feed crops typically allow for higher savings per unit mass of product replaced (because of their higher land and GW requirements and higher yields gap). As far as blue water consumption is concerned, on the other hand, the decrease in cereal feed use among the crops used as feed would have the strongest reduction in irrigation water use in the agricultural sector because it is the most frequently irrigated crops (mainly rice and wheat) with respect to tubers (potato and sweet potato) and many oilseeds used as livestock feed (e.g., soybeans) which are often rainfed (South America).

The replacement of other feed types that compete with food used for direct human consumption such as oilseed co-products (i.e., soybean and palm kernel cakes) would be a winning strategy to reduce human pressure on the environment because oilseed production is a major driver of land use change, large scale deforestation, biodiversity losses and GHG emissions. Specifically, soybean is the most widely used protein source for livestock globally, mainly in the monogastric sector[42,43]. Approximately 85% of soybeans are processed annually to obtain two co-products: oil and cake. Soybean oil has different uses, in the food, industrial and energy sector, while soybean cake is consumed almost entirely in the livestock sector because it is not edible by humans. Nevertheless, soybean cake is often considered among feed types that compete with the food system because it is the main driver of soybean production, which contributes to deforestation in the Amazon, and in other regions competes for fertile land with food crops[42,43]. However, soybean replacement is not included in the analysis since, as it is now, the most suitable replacements are other oilseed meals (from rape and canola, sunflower, cotton) that already almost entirely used as feed[21]. Animal by-products seem to be another viable alternative, but their use often undergoes strict regulations due to the associated risk of pathogen transmissions. Thus, soybean cake is not easily replaceable with other agricultural by-products with similarly high protein content and efficiency as protein source for livestock, particularly monogastric species.

Agricultural by-products are just an example of a wide range of "alternative feed" that can be introduced into animal diets both to reduce the feed-food competition and natural resource consumption. Former food products defined by the EU law as safe and nutritious products coming from the food industry since are not marketable anymore for several reasons[28,35,46], food waste[24,29], plant by-products[28], but also insects could be used as feed substitutes. In fact, insect meal seems to be an attractive alternative to soybeans, as protein source both as food and feed[47–49], and should future studies confirm its environmental and socio-economic benefits.

However, while the use of low-impact feed ingredients can reduce the rate of natural resource consumption and cross-sectoral competition, a decrease in ASF consumption – as suggested by the EAT-Lancet recommendations – remains the most effective strategy in this regard. Furthermore, the strategies applied to the livestock sector have to be accompanied by measures and solutions aiming to reduce the unsustainable water consumption associated with irrigation in the whole agricultural sector. Figure S3, in fact, shows that BW savings, despite being of small-scale, concentrate in regions (mainly Southern and Eastern Asia, followed by Northern America) where water consumption for irrigation is unsustainable because it exceeds water availability and therefore entails losses of groundwater stocks and environmental flows. Furthermore, Rosa *et al*[18] reported that our six selected crops accounted for 55% of the global unsustainable water use for irrigation in 2015, with rice (38%) and wheat (34%) appearing as major cereals contributors to this unsustainable use. Being the usage of maize more widespread (67%) as energy source in animal feed compared to wheat (14%) and rice (4%), the potential reduction in unsustainable water use is limited (Figure S3). Hence, the coupling of strategies as the one suggested in the analysis with measures that improve water use efficiency are crucial to ensure both water and food security.

Our results shed light on the role of Eastern Europe as a breadbasket not only of Europe, but the world. Europe's agro-food sector plays an important role in the global geopolitics of food security[50]. Eastern Europe accounts for 24% of cereals traded for livestock feed purposes. Indeed, Southern and Western Europe, Western Asia and Northern Africa are heavily dependent on Eastern Europe's production, as they meet more than 35% of their cereal feed demand with imports from this region. Ukraine contributes to 8% of global cereal exports, specifically, 12% of maize's exports, 10% of barley's and 8% of wheat's[6]. At the same time, Russia accounts for another 8% of cereal exports (9% of barley and 15% of wheat exports)[6]. The Russia-Ukraine war is already undermining the world's cereal supplies and stocks, both for the food and the livestock feed sectors. This crisis threatens global food security, especially in vulnerable trade-dependent countries. Thus, the implementation of new strategies to reduce cereal demand in the livestock sector and dependence on international trade would enhance the resilience of the global food system also in sight of future pandemics such as Covid19 or other disruptions that could limit the food and feed supply chain, as it has already happened in recent years.

CONCLUSIONS

Livestock consumes about 980 Mton of energy-rich crops as feed per year, which come back to humans as meat and dairy products contributing to 16% of global food supply (8×10^{12} kcal) and 33% of global protein supply (73×10^{12} g of protein). The production of these feed crops requires the use of valuable natural resources such as freshwater (81 km^3) and fertile land (185 Mha) suitable for human food production. We demonstrated that not only can more efficient use of food system's by-products in livestock diet reduce the feed-food competition and increase the global food supply[21], but also decrease the pressure on land and water resources which are increasingly scarce. In fact, the substitution of these crops with estimated available by-products could potentially make room for 17.6-25.4 Mha of fertile land and provide about 8.5-13.6 km^3 of freshwater. An additional volume of 87-124 km^3 of green water would be available for the growth of other food crops. The EAT-Lancet Commission recommends reducing the consumption of all kinds of ASF, to improve human health while lowering the environmental impact of human diets. Indeed, the reduction of ASF consumption remains the most efficient way to make our food system more sustainable. However, as the demand for livestock products is expected to grow over the next half-century, any strategy aimed at curbing the demand for primary commodities has the benefit of reducing environmental impacts on both locally and in distant areas of the world while reducing the trade-dependency of importer countries, in a time where global food security is threatened by several factors.

METHODS

Regional-scale energy-rich feed crop production and material flow of animal feed use were mapped to investigate the existing international feed trade framework and the associated use of natural resources (i.e., land, green water, blue water), both locally and globally. Current conditions were used as a baseline to evaluate potential changes in material flows resulting from a hypothetical scenario in which energy feeds are replaced by available agricultural by-products from the global food system. Changes in feed demand and flows would lead to savings in the natural resources used by the livestock sector.

The analysis was performed for a three-year average of 2016-2018 and for the 19 FAO world's regions[6] (Table S1) to be consistent with data on the regional availability of by-products in the livestock sector from Sandström *et al*[21].

Current Feed Use and Feed Trade Matrix. We collected *feed use* data from the Food Balance Sheets (FBS) from the Food and Agriculture Organization of the United Nations (FAOSTAT)[6] for the energy crops that are most consumed as feed in the livestock sector worldwide (i.e., barley, cassava, maize, rice, sorghum, and wheat, which account for 95% of energy feed demand). Cassava was included in the cereal feed analysis despite being a *tuber* because it is also substitutable with by-products from the food system, consistent with data from Sandström *et al*[21].

For each crop *c*, and region *r*, we quantified (1) the percentage of the consumption of crop c that in that region is used as feed (including all uses) (see Eq 1), (2) the percentage of crop feed use that is contributed by that specific crop *c* (see Eq 2).

$$q_{c,r}\ [\%] = \frac{Feed\ use_{c,r}}{Domestic\ consumption_{c,r}} \times 100 \tag{1}$$

$$p_{c,r}\ [\%] = \frac{Feed\ use_{c,r}}{\sum_{c \in C} Feed\ use_{c,r}} \times 100 \tag{2}$$

where C=barley, cassava, maize, rice, sorghum, wheat}, *Feed use* and *Domestic consumption* are from FAOSTAT[6] of the crop *c*, in region *r*.

Feed demand is rarely completely met by domestic production in a country or region. Therefore, feed imports are usually required. Due to gaps in existing datasets or global estimates on cereal-specific trends on feed trade among regions, the same trade and production shares of cereal food commodities were assumed as already done in other studies[51–53]. Import and domestic shares of crop feed consumption are, thus, calculated as follows:

$$i_{c,r}\ [\%] = \frac{Import_{c,r}}{Domestic\ consumption_{c,r}} \times 100 \tag{3}$$

$$d_{c,r}\,[\%] = 100\,\% - i_{c,r} \tag{4}$$

where *Import* data are from FAOSTAT[6] of the crop *c,* in region *r*.

Regional crop feed use was then subdivided into domestic and import feed as a combination of Eq (1), (3), and (4).

$$imp_{c,r}\,[ton] = Feed\,use_{c,r} \times i_{c,r} \times DM_c \tag{5}$$

$$dom_{c,r}\,[ton] = Feed\,use_{c,r} \times DM_c - imp_{c,r} \tag{6}$$

DM_c indicates the global mean value (as percentage) of dry matter content of crop c from Feedtables[54].

To trace the origin of cereals and cassava consumed in a specific region, data from the Detailed Trade Matrix (DTM) for 208 countries were taken from FAO[6] and then aggregated for the 19 world regions, according to FAO[6] and consistent with regional data from Sandström *et al*[21] (Table S1). DTM data were downloaded for cereals and cassava traded both as raw material and as a by-product available to be used as feed. Specific conversion factors from FAO[55] and DM content from INRAE, CIRAD & AFZ[54] were used to obtain material flows on a dry matter basis. Furthermore, the data treatment approach by Kastner *et al*[56] was applied to DTM data to identify crop producer and final consumer countries, avoiding double-accounting of re-import and re-export.

By-Product Substitution in Animal Feed and New Feed Flows. Data on the potential replacements of cereal feed and cassava with by-products from the food system and their availability were taken from Sandström *et al*[21] and used to evaluate the potential reduction in energy-rich crop feed demand. Sandström *et al*[21] suggested two cases for cereal and cassava replacement, one considering the replacement just with available agricultural by-products (cereal bran, sugar beet pulp, molasses, distiller's grains and citrus pulp) that did not have an impact on livestock productivity, and a second case where they added the replacement of crop residues to agricultural by-products. This second case was not included in our analysis because it would lead to a 40-80% decrease in ruminant productivity and compete with bioenergy uses of crop residues[21]. Data on the replacement potential, given nutritional replacement constraints and regional availability of by-products were taken from Sandström *et al*[21]. The values were reported as the median, 5th percentile, and 95th percentile of the uncertainty range the authors obtained with Monte Carlo simulations for the input data. Because Sandström *et al*[21] reported no crop-specific values for cereals feed replacement for the 19 world regions, shares calculated with Eq (2) were applied to obtain crop-specific cereal and cassava substitutions.

$$crop\_subs_{cr}\,[ton] = Pot\_replacement_r \times p_{c,r} \tag{7}$$

where $Pot\_replacement_r$ indicates data of potential energy-rich feed replacement from Sandström *et al*[21].

These data were then subtracted from the current baseline conditions of cereal and cassava feed use. It was assumed that the domestic and the import shares of each crop would be reduced proportionally. New feed material flows were then obtained.

Current Land and Water Use for Feed. Livestock production draws heavily on natural resources, especially when it comes to intensive animal farming systems requiring high amounts of concentrate feeds, including any feed containing relatively low fiber (< 20%) and high total digestible nutrients (> 60%), rich in energy and/or protein, as cereals and oil meals. Land and water resources are essential for the production of primary commodities such as cereals. We hereby evaluated the land and water resources involved in the production of cereals and cassava for feed purposes.

The cropland area needed to produce these feeds was calculated using crop-specific and region-specific agricultural yields (fresh matter yields) from FAO[6]. Land use linked to the consumption of a specific crop in a certain region was split into two components: land consumed domestically (local yield) (LL) and land virtually transferred from other regions through feed trade (yield of the exporter region) (VL).

$$LL_{c,r}\,[ha] = \frac{dom_{c,r}}{yield_{c,r}} \tag{8}$$

$$VL_{c,r}\,[ha] = \sum_{r \in E} \frac{imp_{c,r}}{yield_{c,r}} \tag{9}$$

where *yield* data are from FAOSTAT[6] of the crop *c*, in region $r \in$ E {exporting regions}.

Subsequently, agricultural water consumption associated with crop feed production was computed with the WATNEEDS model[39]. The model solves the vertical soil water balance at a 5 arc-min resolution to return a spatially distributed crop-specific monthly analysis of green (GW) and blue water (BW) requirement. The model runs on irrigated and rainfed global distributions of crop-specific cultivated areas from the MIRCA2000 dataset[57]. The monthly outputs- of crop GW and BW requirement obtained with climate and soil gridded data were averaged to obtain mean regional values, then multiplied by the amount of land cultivated with that specific crop, in that specific region. As for the land use, both GW and BW use components were split into local water (LGW, LBW) and virtual water trade (VGW, VBW).

$$LGW_{c,r}\,[km^3] = (GW_{c,r} \times 10 \times LL_{c,r} \times Rainf_{c,r} + GW_{c,r} \times 10 \times LL_{c,r} \times Irrig_{c,r}) \times 10^{-9} \tag{10}$$

$$LBW_{c,r}\,[km^3] = (GW_{c,r} \times 10 \times LL_{c,r} \times Irrig_{c,r}) \times 10^{-9} \tag{11}$$

$$VGW_{c,r}\,[km^3] = \sum_{r \in E}(GW_{c,r} \times 10 \times LL_{c,r} \times Rainf_{c,r} + GW_{c,r} \times 10 \times LL_{c,r} \times Irrig_{c,r}) \times 10^{-9} \tag{12}$$

$$VBW_{c,r}\,[km^3] = \sum_{r \in E}\left(GW_{c,r} \times 10 \times LL_{c,r} \times Irrig_{c,r}\right) \times 10^{-9} \tag{13}$$

where *GW* and *BW* represent the water [mm] needed to grow the crop *c,* in region *r*, as output of the model, while *Rainf* and *Irrig* are the percentages of each crop that is cultivated as rainfed or irrigated in each region[57].

The results are shown in Figure 3, in two different ways: firstly, the resources consumed and obtained as the sum of the resources domestically consumed in the region and the resources virtually imported from other regions (importer/consumer use), secondly the resources consumed both for domestic use in the region but also virtually exported to other regions (exporter/producer use).

Potential Land and Water Savings with Replacement. Land and water savings that are potentially achievable by replacing part of the cereal feed use with by-products of the food system are calculated as the difference between the land and water use in the current baseline condition and the substitution scenario.

However, the environmental impact of by-products included in the replacement scenario cannot be neglected and assumed equal to zero, thus an allocation method adapted from Gerber *et al*[53,58], and already used in similar studies[11,42], was used. This method allowed to assign the share of land ($L_{bp,r}$ see Eq. 15) and water use ($GW_{bp,r}$ and $BW_{bp,r}$, see Eq. 16, 17) attributable to each by-product by referring to the agricultural yield and the water demand of its primary crop. The allocation was based on the relative mass, economic and feed use fractions. Because Sandström *et al*[21] reported no by-product-specific values for energy-rich feed replacement for the 19 world regions, shares were calculated by applying their method for the estimate of the replacement potential. This was done starting from the reported data on current feed use of each by-product, their potential production and the replacement constraints[21]. In this way the regional amount of each by-product replaced was obtained ($byprod\_subs_{bp,r}$, see Eq. 14$_)$ and subject to the allocation method. By-products are presumed not to be traded among regions, but only intra-regional trade was assumed, as data from FAO Supply Utilization Accounts reported that less than 4% of cereal bran produced globally was traded in 2016-18, and less than 10% for molasses[6]. Thus, no distinction between local and virtual natural resource use is reported for by-products.

$$byprod\_subs_{bp,r}\ [ton] = Pot\_replacement_r \times\ byprod\_replacement_{bp,r} \tag{14}$$

where $byprod\_replacement_{bp,r}$ indicates the share [%] of each by-product *bp* that replaces the energy-rich feed crops in region *r*.

Concerning by-products composition, several assumptions were made on the primary crop they refer to. First, cereal bran composition include bran from barley, maize, millet, oats, rice, rye, sorghum and wheat, according to regional production data from FAO Supply Utilization Accounts[6]; second, molasses from sugar processing is subdivided between sugar beet and sugar cane as primary crop according to regional processing data from FAO Supply Utilization Accounts[6]; third, sugar beet pulp originates entirely from sugar beet processed into sugar; fourth, citrus pulp composition include pulp production from lemon and limes, oranges, and tangerines, mandarins, and clementines according to regional processing data from FAO Supply Utilization Accounts[6]; as last, distiller's grains include brewer's grain from beer brewing (barley as primary crop) and spent grains from corn ethanol production (maize as primary crop), according to regional data from FAO Supply Utilization Accounts[6] and data from Iram *et al*[59] for the main corn ethanol producer countries, according to Sandström *et al*[21].

Land, GW, and BW associated with the energy-rich crops substituted with by-products ($LL_{subs,c,r}$, $VL_{subs,c,r}$, $LGW_{subs,c,r}$, $VGW_{subs,c,r}$, $LBW_{subs,c,r}$, $VBW_{subs,c,r}$) were computed with the same methods as for the current conditions, with equations from (8) to (13).

The land and water use allocated to agricultural by-products are calculated as follows:

$$L_{bp,r}\ [ha] = \frac{byprod\_subs_{bp,r}}{yield_{pc\_bp,r} \times FUF_{bp}} \times \frac{EFA_{bp}}{MFA_{bp}} \tag{15}$$

$$GW_{bp,r}\ [km^3] = (GW_{pc\_bp,r} \times 10 \times L_{bp,r} \times Rainf_{pc\_bp,r} +\ GW_{pc\_bp,r} \times 10 \times L_{bp,r} \times Irrig_{pc\_bp,r}) \times 10^{-9} \tag{16}$$

$$BW_{bp,r}\ [km^3] = (GW_{pc\_bp,r} \times 10 \times L_{c,r} \times Irrig_{pc\_bp,r}) \times 10^{-9} \tag{17}$$

where the subscript *pc_bp* refer to the yield, GW, BW, rainfed and irrigation shares of the primary crop *pc* processed into the specific by-product *bp* in region *r*, while FUF, EFA, and MFA indicates the feed use, economic and mass fraction of each by-product.

Potential resource savings are obtained from the sum of the local and virtual resource use to produce the amount of energy-rich feed crops replaced with by-products, then removing the resource use allocated to these by-products, as follows:

$$Land\_saving_r\ [ha] = \sum_{c \in C} LL_{subs,c,r} + \sum_{c \in C} VL_{subs,c,r} - \sum_{bp \in \mathrm{B}} L_{bp,r} \tag{18}$$

$$GW\_saving_r\ [km^3] = \sum_{c \in C} LGW_{subs,c,r} + \sum_{c \in C} VGW_{subs,c,r} - \sum_{bp \in \mathrm{B}} GW_{bp,r} \tag{19}$$

$$BW\_saving_r\ [km^3] = \sum_{c \in C} LBW_{subs,c,r} + \sum_{c \in C} VBW_{subs,c,r} - \sum_{bp \in \mathrm{B}} BW_{bp,r} \tag{20}$$

where B= {cereal bran, sugar beet pulp, molasses, distiller's grains, citrus pulp}.

Uncertainty Analysis. Sandström *et al*[21] reported their potential replacement scenarios with the median, 5th percentile and 95th percentile values of the uncertainty range. However, the assessment of the natural resources associated with energy-rich feed use and the potential replacement is subjected to additional uncertainties. Hence, uncertainty propagates at each step of the analysis when new uncertain variables are involved. The uncertainty is here estimated in terms of the standard deviation, σ, from the mean value, $\overline{x}\ (\sigma \pm \overline{x})$.

Concerning land, we performed Monte Carlo simulations for the agricultural yields. To do so, we collected crop-specific agricultural yields from FAOSTAT[6] for 187 countries from 2014 to 2020. These data were aggregated to the 19 world regions to obtain the regional weighted mean and the relative standard deviation for each crop. We then used the mean and standard deviation to generate 500 random values of potential yields assuming a truncated normal distribution ranges from 0 and the maximum yield value achieved by the crop in each region (Supplementary Material, Figure S3, S4, and S5).

Concerning water, a sensitivity analysis was conducted on the WATNEEDS model on the initial conditions and the kc values as described in Chiarelli *et al*[39]. A technical validation showed a discrepancy lower than 3% comparing the cumulative results from WATNEEDS with the ones from Siebert and Döll[40], while a crop-by-crop pixel-by-pixel comparison showed a difference lower than 20% for 90% of the harvested area between the two dataset[39].

After estimating the independency of the variables that come into play with the Kendall's τ coefficient (two-sided test, p-value=0.2669, τ=0.1930), we evaluated with standard methods the propagation of the uncertainty[60] as

$$\sigma_{L\_replac_{c,r}} \approx \left[\sqrt{\left(\frac{\sigma_{R_{c,r}}}{|crop\_subs_{c,r}|}\right)^2 + \left(\frac{\sigma_{Y_{c,r}}}{|yield_{c,r}|}\right)^2}\right] \times \left|\frac{crop\_subs_{c,r}}{yield_{c,r}}\right| \tag{21}$$

$$\sigma_{L\_replac} \approx \sqrt{\sum_{r\in R}\sum_{c\in C}\left({\sigma_{L_{c,r}}}^2\right)} \tag{22}$$

where σ represents the standard deviation of the replacement ($\sigma_{R_{c,r}}$), the yield ($\sigma_{Y_{c,r}}$), and the land saved with the replacement ($\sigma_{L\_replac_{c,r}}$), for each crop $c \in C$, and region $r \in R$ ={Caribbean, Central America, Central Asia, Eastern Africa, Eastern Asia, Eastern Europe, Middle Africa, Northern Africa, Northern America, Northern Europe, Oceania, South-Eastern Asia, South America, Southern Africa, Southern Asia, Southern Europe, Western Africa, Western Asia, Western Europe}.

The same equations were used to evaluate the propagation of the uncertainty for the current cereal and cassava feed use, the related current land use, and the water calculations for the current conditions and the replacement scenario. Eq. 21 was used for product or fraction relations between variables, while Eq. 22 for sum or difference.

Data Availability

All data inputs to the analysis in this study were retrieved from publicly available sources that are cited in the manuscript (e.g., FAOSTAT, Sandstrom et al 2022, Chiarelli et al 2020) and that are described in the main text and/or methods section. Results that are additional to those provided in the text and in the supplementary materials are available from the authors upon reasonable request.

Code Availability

The algorithm used for this study is available in the Methods and the Supplementary Material. The Arcgis Pro and Matlab codes, as well as Excel files, however, are available from the authors upon reasonable request.

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Author Contribution Statement

C.G., M.C.R., and L.P. designed the research, C.G. performed the analysis, C.G. and P.D. drafted the article, M.C.R., P.D. and L.P. conducted review and editing.

Competing Interests Statement

The authors declare no competing interests.

Table 1 | Current scenario and potential savings with energy-rich feed crop replacement

Feed use	Raw material *DM Mton*	Land use *Mha*	GW use *km^3*	BW use *km^3*
Current use	802.5	185.2 ± 7.0	863.5 ± 36.9	80.8 ± 2.9
Replacement – potential saving	88 ± 3.4	21.6 ± 1.1*	106.0 ± 5.5*	11.3 ± 0.8*
By-products	72-103	2.8-5.1	15.3-26.3	4-7.5

The results are presented with their associated uncertainty (standard deviation, see Methods).

*Potential savings estimated without accounting for the resource use allocated to by-products production. The actual savings would be lower if we subtract the allocated by-products' resource use reported in the table.

By-products resource use refers to the land and water used for these by-products, accounting for their mass fraction used as feed, and associated economic value with respect to the whole crop they are derived from (see Methods).

Table 2 | Comparison with other studies

Reference study and authors		Our study, 2023	Mottet *et al,* 2017	FAO and Steinfeld, 2006	Mekonnen & Hoekstra, 2012	Siebert & Döll, 2010	Chiarelli *et al,* 2020	Heinke *et al,* 2020
Reference year		2016-18	2010	2002	1996-05	1998-02	2016*	1998-02
Energy-rich crop, feed use *(Mton DM)*		803	858	680				
Land use for energy-rich feed *(Mha)*		185	211	211				
GW use for energy-rich feed *(km^3)*	Barley	125				92	95	
	Cassava	85				44	40	
	Maize	389			336	329	352	
	Rice	67			33	31	31	
	Sorghum	34				62	59	
	Wheat	165			131	112	120	
BW use for energy-rich feed *(km^3)*	Barley	5				7	6	
	Cassava	0				0	0	
	Maize	43			29	41	43	
	Rice	17			10	15	13	
	Sorghum	2				4	4	
	Wheat	14			35	36	34	
Total water use for energy-rich feed *(km^3)*	Barley	130			123	99	101	96
	Cassava	85				44	40	
	Maize	432			365	370	395	458
	Rice	84			43	46	44	
	Sorghum	36				66	63	
	Wheat	179			166	148	154	117

*climate data refers to the year 2016, but harvested area to the MIRCA2000 dataset[57].

Fig. 1 | Global map of livestock production and energy-rich crop replacement, including their origin. Global distribution of protein production, including meat and dairy products, adapted from FAO[6] combined with data on region-specific energy-rich feed crop replacement from Sandström *et al*[21] and shares of cereal and cassava feed use coming from domestic production or imports (see Methods). World regions are taken from FAO[6], adapted from country borders retrieved from GADM[61] (https://gadm.org/) (Table S1). Credits: Basemap sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community[62].

Fig. 2 | Net trade of energy-rich crops for feed purposes and the associated virtual land and water trade. Flows of raw material (DM, dry matter) for feed use **(a)** (sum of the six crops considered in the analysis) traded between the 19 world regions and the related diagrams of virtual land **(b)**, green water **(c)** and blue water **(d)** trade. The double color of the lines indicates the flow direction, from the exporting (orange) to the importing regions (blue). Here reported the estimated mean values.
Feed use include maize, wheat, barley, rice, sorghum, cassava. Region abbreviations reported in Table S1.

Fig. 3 | Global use of natural resources to produce energy-rich feed crops and the associated potential savings achievable with their replacement. The barplot shows the current land, green and blue water use for the major energy-rich crops in the 19 world regions. The resource use is shown both from the point of view of the exporter (colored column) and importer (dotted column) region. The land, green water and blue water currently used for energy-rich feed crop production and the ones potentially savable are presented, including the added resource use allocated to the by-products. The error bars represent the uncertainty range (standard deviation, see Methods).
"Added by-products" resource use refers to the land and water used for the production of by-products replacing cereals and cassava, accounting for their mass fraction used as feed, and associated economic value with respect to the whole crop they are derived from (see Methods).
Importer/consumer point of view: the regions where cereals and cassava are actually used to feed livestock, independently of whether they come from local production or feed imports; this means that demand from these regions drives the production of these crops, the importer region is therefore responsible for the associated land and water consumption.
Exporter/producer point of view: the regions where cereals and cassava are actually produced, either for domestic use or for exports; this means that land and water resources are actually consumed in those regions to produce cereals and cassava even if a portion of these crops is exported to feed livestock in other regions as "virtual land and water trade".

Fig. 4 | Geographic distribution of natural resource savings and their interplay with the drivers. The regional land, green and blue water savings are mainly influenced by feed replacement, feed export, agricultural yield (for land and GW) and irrigated area (for BW). The values of all variables were normalized (range 0-1) according to the maximum and minimum median regional values shown in Table S2. Region abbreviations are reported in Table S1.

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