How much meat should we eat? Improved estimates accounting for food system dynamics influencing water use

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Abstract

Eating less livestock products can reduce agricultural resource use, but it has also been argued that a portion of livestock products does sustainably contribute to food security. Given that diet change impacts arise through modification of food production systems, evaluating such changes requires explicit modelling of system dynamics. This paper uses a novel global integrated optimisation model, "Aalto OptoFood", to investigate changes in water use when replacing livestock protein with plant-based protein sources in human diets and reallocating associated cropland and pasture. Our findings reveal that the first cuts are the deepest – moderate reductions in livestock protein decrease water consumption more than suggested by comparing global average crop and livestock water productivities. Further reductions show diminishing returns, with no clear optimum. In terms of water use, it is beneficial to eat less livestock products, even if there is no clear case for or against universal adoption of a vegan diet.

Introduction

The growth of the human population and efforts towards adequate, healthy diets are placing increasing demands on food production and distribution systems[1]. Land and water are critical agricultural resources, and in many cases, further increasing their use would have detrimental effects on ecosystems and competing human needs[2], e.g. non-food agriculture and water for domestic, industrial and cultural uses.

Many measures exist to mitigate the pressure imposed by food production[3], operating on both production and demand side. Yield gap closure[4,5] and cropland reallocation[6,7] aim to improve food production efficiency, reducing resource use per unit output. Demand-side measures reduce the amount of food production needed to satisfy human nutritional needs, by cutting food losses and waste[8,9] and overconsumption, or shifting demand towards equivalent products that require less resources[10–12].

A commonly discussed demand-side approach involves shifting towards diets with less livestock products, while maintaining (or improving) caloric and protein intake, as well as other nutrition guidelines[10,13,14]. The need to feed animals means that livestock products are generally more resource intensive than alternatives. From this perspective, the livestock sector is inefficient and replacing livestock products with vegetal products could free up resources for the environment or other human uses[3,15–17]. From another perspective, animals are an integral part of the food system that can enhance food security through more effective use of resources: livestock is able to convert non-food crops, food co-products and substandard quality food crops into human edible food. For example, Davis and D'Odorico[18] estimated that 56% of animal calories in human diet do not compete with crop use. Similarly, Mottet et al.[19] state that 86% of the livestock feed intake is not currently edible by humans.

Water use is a key resource for food production. The impact of diet change on water use is commonly evaluated using water footprint methodologies[20]. These methodologies have the advantage of providing water consumption estimates for final products (e.g. vegetal or livestock food products) by aggregating water usage throughout production, processing and distribution chains. This allows comparison of the footprints of livestock products and their alternatives.

However, aggregating water usage necessarily means that this type of product water footprint is tied to the actual production areas and practices at the time of assessment. When dealing with (large) production changes, it is likely that product water footprints would change too. Demand-side measures such as diet change only affect resources and the environment indirectly, through the food supply chain and agricultural production systems. Change in consumption needs to be accompanied by reduced production of livestock products, reduced production of feed crops, and increased production of high protein crops used to replace them (e.g. soybeans, pulses)[21]. In addition, freshwater is a local resource and conditions vary largely by river basin. In some conditions, a certain level of water use is ecologically disastrous, while in some other location it is considered negligible. It is therefore important to explicitly model the spatial changes in crop production and water use.

However, although understanding of the global food system has evolved greatly over the past years on various fronts[22,23], it remains difficult to predict how production would change spatially in response to large shifts in food demand. Market dynamics and government response are likely to result in substantial changes to cost structures, technologies, and trade relationships. While we cannot predict the future, we can develop plausible scenarios that capture different views of present trends or answer "what if" questions. Dynamic land use models such as MAgPIE build on present trends by making assumptions about gradual decreases in livestock consumption and gradual change in technologies and costs[24]. One possible "what if" question is to ask: "what if crop and livestock production were reallocated optimally in response to diet changes?" This provides idealised scenarios providing a reference for what is possible when optimising key indicators, such as minimising water use or its impacts, and, perhaps more importantly, providing a situation where key features of system behaviour can be more easily analysed and understood.

In this paper, we analyse for the first time the potential impact of diet change on water use while explicitly modelling optimum spatial reallocation of crop and livestock production in response to changes in livestock consumption. Specifically, we focus on replacing protein obtained from livestock products by vegetal protein in pulses and soy, at multiple levels of diet change, varying the amount of protein replaced. Other uses of agricultural production, as well as aquaculture and seafood consumption are kept constant. The newly developed Aalto OptoFood model then determines land use and livestock production patterns using ideal optimisation objectives that minimise water use or its impacts in average conditions (agriculture in the year 2000, climate 1975-2005) while meeting human diet requirements and livestock feed demand. This allows us to explicitly capture food system dynamics in response to diet change and thus to provide a more thorough answer than currently available to the question: how much meat should we eat?

Results and interpretation

Effect of diet change on water use

Based on existing literature identifying parts of livestock feed inputs not competing with human food[18,25], we expected that as livestock products were replaced by pulses and soy, water use would first decrease, but as livestock based food approaches zero percent, an increase or "uptick" in water consumption would occur. Marginal benefits would diminish to zero, yielding to a marginal cost of reducing consumption of livestock products. This is because food from animals grown on low-water inputs must be replaced by thirsty protein-rich crops.

To test this expectation, we used the Aalto OptoFood model to assess the changes in crop production areas resulting from diet change. New production areas were obtained by minimising evapotranspiration for food crop production (see Supplementary Information, "*MinET*"). Here, we visualise the results by plotting the evapotranspiration from cropland and arable grassland against percentage of protein in the diet obtained from livestock sources (Figure 1). Consistent with previous work [18,25] (see Discussion), a portion of non-arable rangelands is considered "free" – meaning that not all non-irrigated grass is counted in water use. Figure 1 shows three scenarios: 0%, 50% and 75% of non-irrigated grass considered to be "free".

Figure 1 shows that there is indeed a rapid reduction in total water consumption as the percentage of livestock based protein decreases in all of the scenarios. Taking 75% free grass scenario as an example (solid blue curve in Figure 1), reducing the livestock protein content in the diet by one fifth (from 34% to 27%) decreases water use by 24% – over 79% of the maximum reduction potential. As the diet change then progresses towards even less livestock-based foods, the modelled water use does level off, but the actual size of the uptick, if any, varies depending on the assumptions regarding water allocation to different non-food feedstuffs. The percentage of grassland assumed non-arable has the greatest effect on this. The higher the proportion of the free grass, the lower total water use, but the shape of the curve also differs.

The dashed lines in Figure 1 show the change in water use expected by simply comparing global average crop and livestock water productivities, i.e. subtracting the average water volume currently needed for livestock production, and adding the average water needed for pulses and soy. This reflects the argument for diet change used in consumer education that the (global) water footprint of livestock is higher than its plant alternative. Our results show a notably steeper initial reduction in all scenarios; more water is saved than estimated with this average water footprint method – widely used in existing literature.

As shown by the slight uptick in some of the scenarios (e.g. Figure 1 "75% free grass"), it is possible for livestock to provide a positive contribution to food supply – such that consumption of some livestock products is better than none. It appears that system dynamics mean that this contribution may be quite small or, depending on the assumptions, even non-existent. Depending on the scenario, 0-20% of protein could originate from livestock sources with relatively small change to water use compared to the exclusively vegetarian diet. This is still much less than the current ~34% of protein from livestock sources, but it does leave some scope for debate on sustainable limits for livestock product consumption. We further explore the assumptions affecting this conclusion in the following sections.

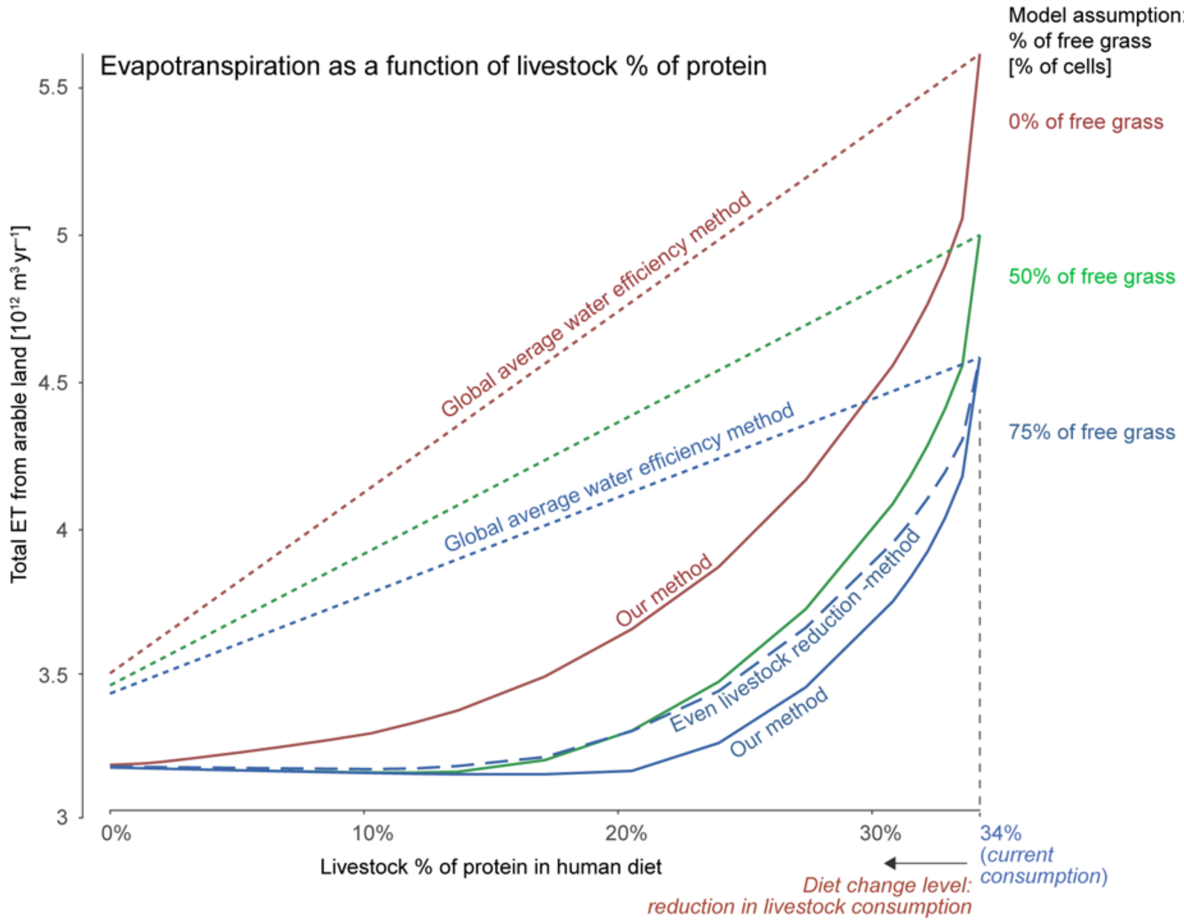

Figure 1: Evapotranspiration from arable land in several scenarios. % of free grass denotes the percentage of cells with ET closest to natural that are considered to be non-arable and not contributing to the total ET. The solid curves ("Our method") denote water use with optimised cropland and livestock with different amounts of pasture considered rangeland (not contributing to total ET). Dotted lines ("Global average water efficiency method") denote the effects of the same diet change, using the baseline global average water efficiency for livestock-based and replacement plant-based protein. The dashed line ("Even livestock reduction method") denotes optimisation of cropland while reducing livestock production evenly from each production system and region, rather than allowing it to be optimised.

Role of spatial variability in production

The spatial variability in production conditions and efficiency is the primary driver of the steep initial water savings and diminishing returns from diet change. Crop yields and evapotranspiration have considerable spatial variation due to differences in factors such as soil, climate and terrain – leading to changes in evaporative water consumption efficiency when reallocating crop production.

If we look at big changes in production (like the diet change levels considered here), we do not know where the new production of protein rich plant products would occur. Therefore, there is substantial uncertainty in the total water requirements of the new diet. This is illustrated in Figure 2, which shows total evapotranspiration as a function of production, for pulses. If all cropland could be freely allocated to any crop, the range of water use is shown with dotted lines. With no production, consumptive water use is zero, and when all suitable cropland is used (outside the limits of the graph), the total evapotranspiration is also known. In between, the vertical distance between the curves represents the uncertainty in the water use at each level of total production.

It makes sense, however, to restrict how cropland can be allocated. At the current level of production, the current land use pattern corresponds to a single modelled or estimated total evapotranspiration. We then assumed that the existing land use is maintained when increasing production, and decreases in production occur by reducing existing cropland ("land use stickiness constraints", see Method). This yields a characteristic "butterfly diagram", where increases in production always yield increases in evapotranspiration (dashed lines), and similarly for decreases (solid lines). As production reduces, the minimum ET occurs when the least efficient land in terms of water productivity is displaced first, and vice versa for the maximum (see Figure 2). Similarly, as production increases, the minimum ET occurs when the most efficient land from the available pool is used first.

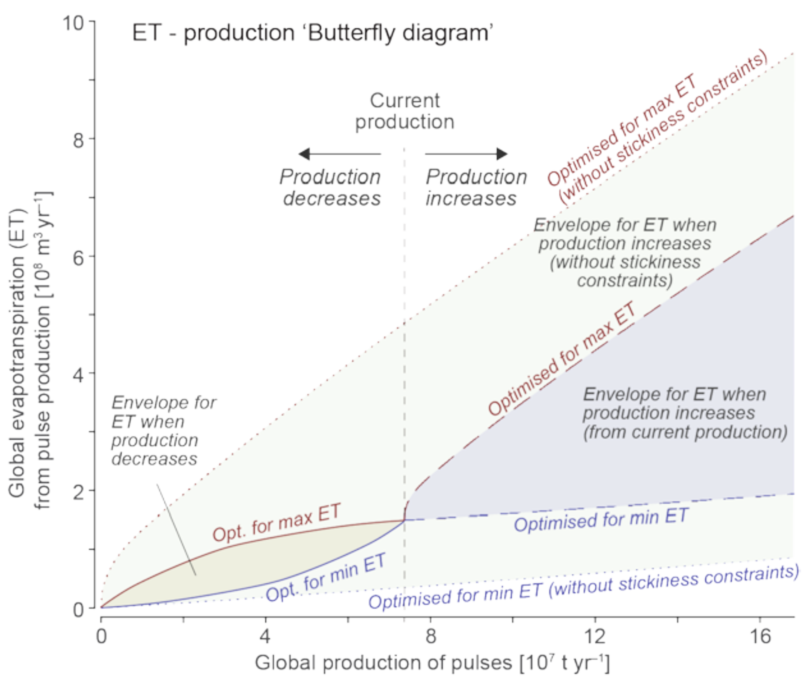

Figure 2: Evapotranspiration changes due to shifts in total production. The vertical distance between the land offering the lowest and highest ET per amount produced represents the uncertainty in water use due to evapotranspiration.

Within these bounds, Aalto OptoFood selects the crop areas that optimise water use (in this case, minimising total ET from pasture and cropland). It is important to note that this is not the same as following the lower curve in a butterfly diagram (Figure 2). The same land may be optimal for several crops, such that the optimisation needs to manage the trade-off between them. The land freed by crops with decreasing production and used by crops with increasing production depends on the properties of all the crops and changes to their demand.

A similar principle applies to livestock products. While the water requirements to produce a kilogram of a certain *crop* are roughly determined by the production location, however, many paths can lead to similar *livestock* products having very different water footprints. Livestock production can to some extent adjust to available feed supplies[26,27]. We also apply "stickiness" constraints to livestock production systems, such that no livestock product or production system can increase production as a result of the diet change, i.e. no production can be moved from one area or system to another. The dashed line in Figure 1 ("Even livestock reduction method") shows the change in water use if instead of optimising livestock production, all production systems and regions are reduced in the same proportion. This shows that variability in livestock does contribute substantially to the shape of the curve.

The initially steep water savings (Figure 1) occur because the optimisation is able to stop using the least efficient livestock production systems and pasture and cropland used for livestock feed. Further, the most efficient cropland is used when growing pulses and soy to replace the lost livestock protein. Diminishing returns then occur because the livestock production systems and pasture and livestock feed land being abandoned next are more efficient, and the cropland being used for pulses and soy is less efficient; the difference between them thus decreases.

How can livestock make a positive contribution to food supply?

Livestock can be considered to contribute positively to human food supply when they provide an efficient use of resources, in particular, when the feed required for the animals does not have some better use (human or other), i.e. the benefits of livestock are higher than their opportunity cost. This study focuses on whether it would be possible to redirect feed production into other food products. We do not consider the potential to redirect feed production into, for example, biofuels, which also has co-production dynamics with livestock[28], or improvement of biodiversity, which is only represented in our results by reduction in human water and land use.

In this context, whether an "uptick" occurs – i.e. whether water use is lower with some livestock protein rather than none – depends on how much of current pasture can be used for crops, and how crops are used, as summarised in Table 1. Figure 3 shows the production from crops and pasture as livestock protein decreases. Pastures that can be used for crop production are converted first, leaving behind non-arable rangelands. Feed from food-grade crops is then eliminated, and the uptick begins – further reductions in feed do not reduce total water use. The feed from human food crops is either 1) a by-product of food production for oilseeds (in Figure 3, Sunflower, Groundnuts, Rapeseed, Soybean, and oilseeds in "Others"), 2) not food-grade, for the rest of the crops, or 3) not edible, i.e. "crop residues". It should also be noted that, because resource use is optimized at every level of livestock protein, increasing these feed sources has a limited effect on the uptick – resource use is reduced at every point in the curve.

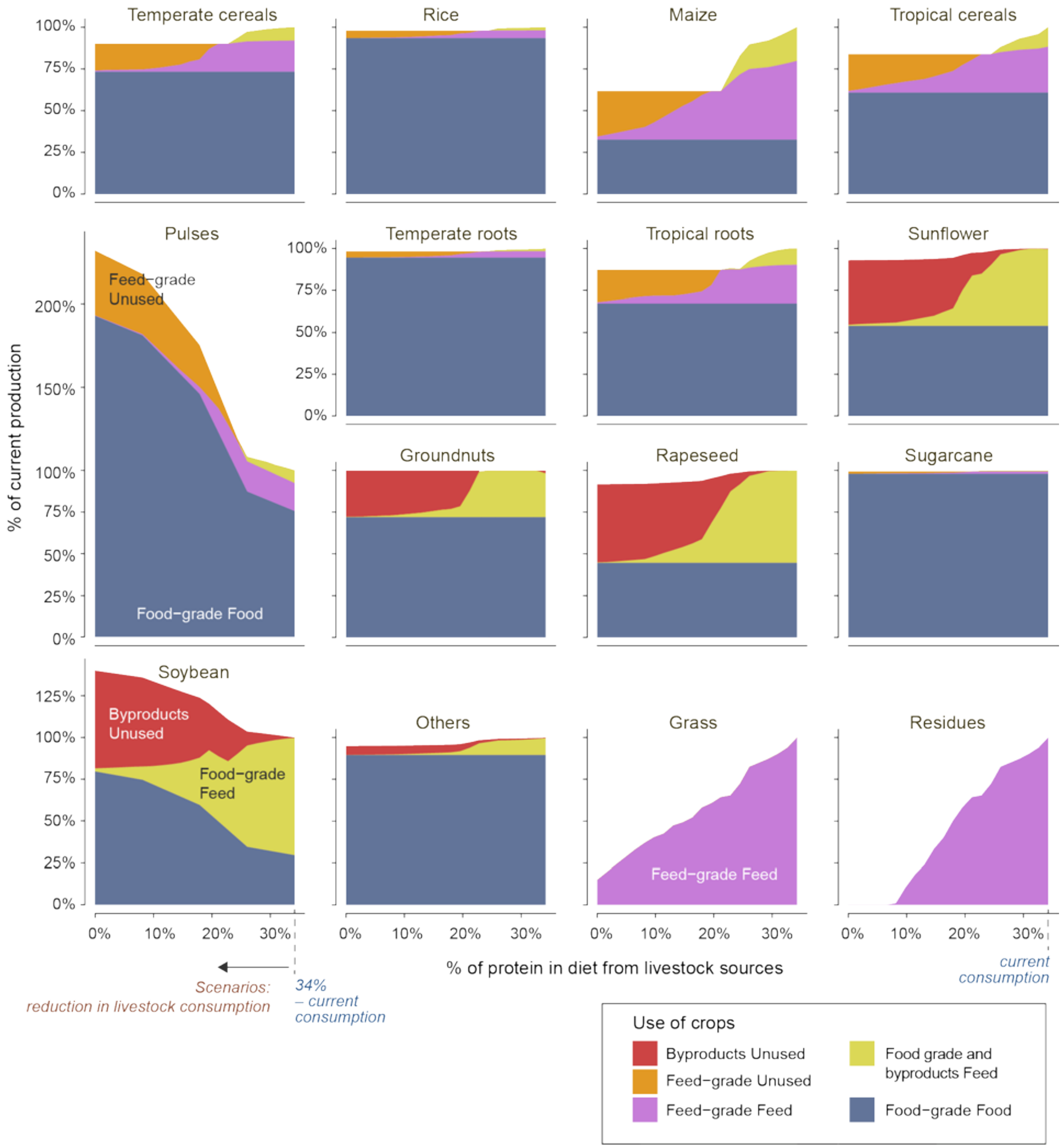

Figure 3: Total global crop and pasture production, when optimizing land use and livestock production systems for different levels of protein from livestock sources, with 75% of "free" grass from rangelands.

Table 1: Effect of key assumptions on water use, and therefore positive contribution of livestock to food supply, as livestock protein decreases

System characteristics	Effect when decreasing livestock protein
Should evapotranspiration of pastures count? Use of part of the pasture as cropland is not practical or efficient due to terrain, soil and climate conditions. Sustainable grazing may even enhance biodiversity and increase water availability.	If some portion of grass is "free", then water use actually increases when replacing livestock products – some level of livestock product consumption increases food supply/decreases water use
Crop utilisation	
Food-feed co-production – by-products Economic feasibility of certain crops depends on also utilising parts of crops not used for human food[29] e.g. oilseeds produce oil and cake, typically fed to livestock	By-products of food production cannot be avoided, even if they are no longer needed for feed. Resource use does not decrease.
Use of non-food-grade crops Crops are of variable quality, and those not meeting quality requirements are often used as feed	Production of non-food-grade crops cannot be avoided, but they cannot be used for food when feed use is abandoned.
Crop residues Usable as roughage feed, decreasing the use of grass	Residues replace a part of roughage feed. This is a "free" resource rendered unused when feed use decreases.

Effect of optimisation objective

Minimising absolute water use (i.e. here evapotranspiration, see Figure 1) is not the only possible objective. While saving water anywhere in the world improves water productivity and potentially food security[30], it is also easy to consider that a drop saved is worth more where water is scarce than where it is abundant, or that we should be trying to minimise change from natural conditions to avoid detrimental effects on the hydrological cycle. Figure 4 shows the change in three objectives, and their spatial distribution: evapotranspiration, water stress, and change in evapotranspiration from natural conditions. Figure 4A-C shows the spatial distribution of evapotranspiration in the current land use pattern as well as the optimised cropland use when 20% of livestock protein is replaced by pulses and soy.

In Figure 4D-F we illustrate how the results change when weighting water use by availability, i.e. as a measure of water stress[31] (see "*MinStress"* in Supplementary Information). The combination of initial rapid decline and diminishing returns, here in average water stress, is even more prominent than when minimising water use directly. Global average stress, across all basins, decreases rapidly by removing production from high stress areas, with many basins rapidly dropping below the commonly used threshold of 20% use-to-availability to be classified as not stressed[31]. Mapping water stress confirms that with 27% of protein from livestock, water stress due to agriculture is eliminated in most basins by a combination of diet change and associated redistribution of production. Out of 425 originally stressed basins, stress remains in 46. The agricultural land affected by stress is reduced by 85%.

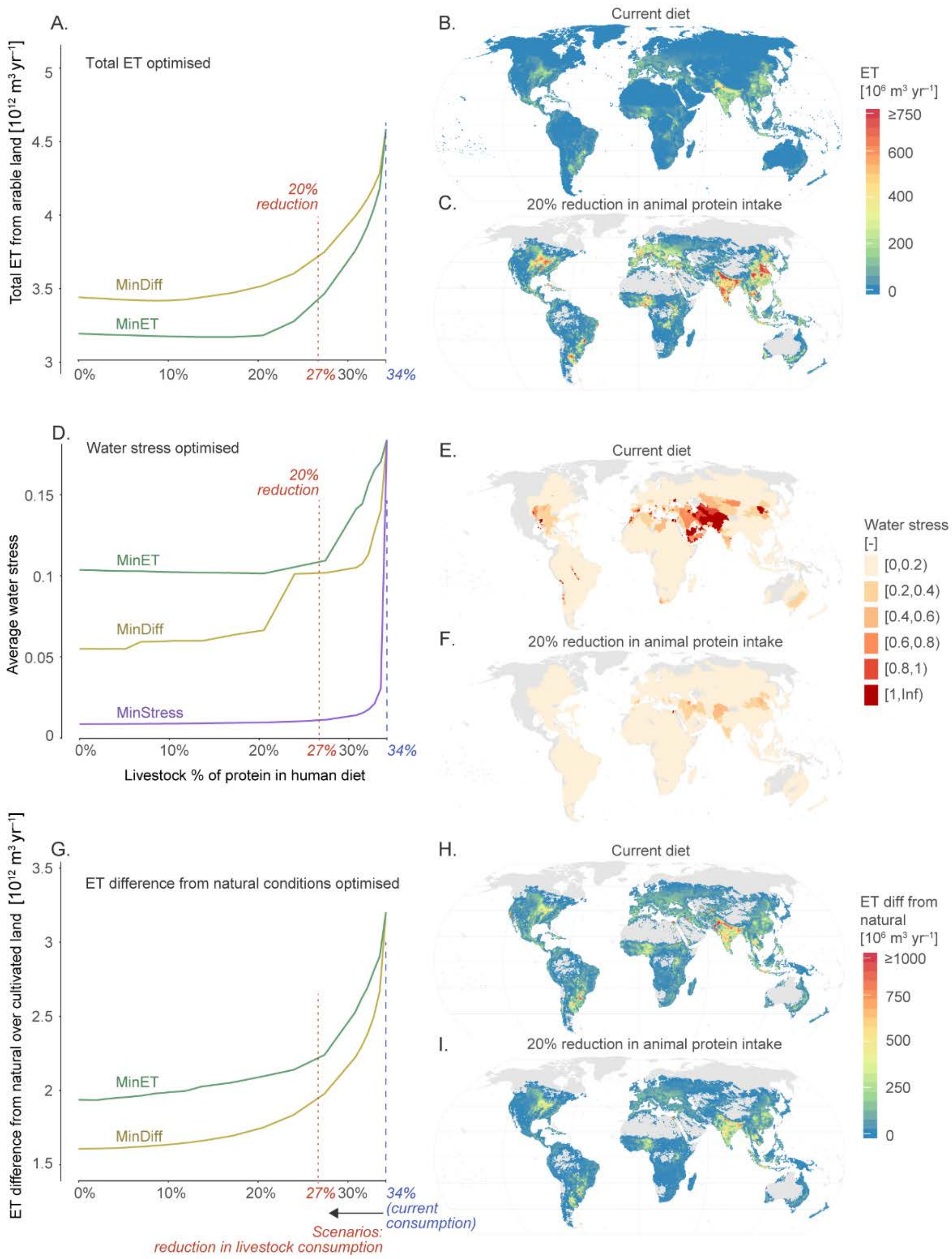

Figure 4: Optimisation objective globally and spatially with alternative objective functions: (A-C) minimizing evapotranspiration, MinET, (D-F) minimising average water stress, MinStress, and (G-I) deviation from natural evapotranspiration, MinDiff. Average water stress corresponds to the percentage of evaporative water consumption for irrigated agriculture relative to availability, averaged across all basins. Water stress is not sensitive to changes in rainfed agriculture, and ET and deviation from natural ET are therefore not shown for that objective.

Figure 4G shows the result of our third objective function, minimisation of absolute difference from natural evapotranspiration (see *MinDiff in S*upplementary Information). This objective reflects the idea that minimising evapotranspiration is not always beneficial, e.g. bare ground often has lower evapotranspiration than natural vegetation. While the shape of the curve is again similar, the spatial change in the objective (Figure 4H-I) and the agricultural land allocation are markedly different from that when minimising evapotranspiration (see Supplementary Information Figure S1), this time following the regional differences between agricultural and natural ET (Figure 4G, and for comparison, Bosmans et al.[32]).

Discussion and conclusions

While other studies have tackled the issue of sustainable limits on livestock product consumption, for the first time we dynamically modelled the resource use efficiency across the whole system consisting of both crop and livestock sectors and the different uses of the products. We show that reducing livestock protein consumption would use less water, but it still remains inconclusive, whether some livestock protein is better than none.

Various studies highlight the fact that many of the inputs to livestock production are not palatable to humans[18,25,33]. Our results partly support estimates of the amount of livestock production that competes with human food by Davis and D'Odorico[18] and Mottet et al.[19], even though we reallocate resource use rather than only evaluating edibility of feed products. Their results would suggest retaining 56% or 86% of current livestock-based calories, respectively. Our results range from 0% (no livestock) to ~60%. With 0% free grass (Figure 1), lowest water use and impacts would be achieved by eliminating livestock-based products. With 75% free grass, water consumption is lowest at ~20% of protein from livestock-based sources or 60% of current levels, which translates to 61% of current calories from livestock.

Our results support existing recommendations to reduce livestock product consumption, but do not provide a clear picture of what the livestock sector should look like in future. So what is needed to achieve a more definite answer?

The first question is: should water consumption by grazing count? Our analysis clearly illustrates that attributing whether pasture comes from arable land or rangelands is a major factor influencing whether livestock can provide a positive contribution to food supply from a resource use point of view (Figure 1). We are specifically interested in the subset of rangelands where grazing at a sustainable intensity is beneficial for biodiversity and ecosystem functioning[34–36] and where cropping is not only non-economical, but also represents a substantial departure from a natural environment[37]. Water availability for other uses is actually potentially larger with grazing than without, as shorter grass has a lower leaf area index[38], which decreases evapotranspiration[39] – though the opposite has been observed in some dry areas[40]. It is then a question of differences in values whether simply by appropriating the biomass production through livestock into human use[41], water consumption by grazing should be counted in evaluating the resource use of food production, or whether it can be considered "free".

Secondly, how much meat we should eat is clearly also constrained by factors other than water use. Livestock is a major source of greenhouse gas emissions[42]. Weighing resource consumption and climate effects fairly against each other is difficult[43], but will be needed, notably because low-intensity grazing may, in fact, be higher in greenhouse gas emissions than other livestock production systems[44]. Livestock also has other benefits. The use of animal draft power is still important in large parts of the world, but declining fast[45,46]. Meat, eggs and dairy products represent culturally important components of human food, and are also important in terms of nutritional value. Although evidence that large amounts of livestock products and especially red meat in the diets are detrimental to human health is accumulating[47,48], they represent an important part of food security for large parts of the world[49]. Livestock may also be a part of emergency food supply strategies, smoothing variability in crop yields between years[50], and providing an economically valuable use in years with surplus or poor quality crop production.

Thirdly, these results are only a first estimate using this type of production reallocation model. The precise numbers are likely to change as methods are improved. Estimates of resource use and productivity could be improved with data allowing increased detail in how management practices are represented, including water management, multi-cropping, and spatially explicit modelling of livestock. Given we are dealing with large system-wide changes, it is difficult to anticipate future structure of the economy, but it would still be useful to further include possible future scenarios relating to improved agricultural management and its incentives, trade, and climate change. Examining resource use and scarcity across seasons and years would also help understand the role of animals as a risk management strategy, and interactions with aquaculture, seafood and other agricultural uses should also be integrated[3].

We do, however, expect that, in most cases, the curve in Figure 1 would still show diminishing returns – and hence recommend some reduction in livestock product consumption. Increasing returns would mean that marginal water savings are initially small, and become larger with large diet changes. For this to occur, efficient land for feed production would need to be retired first, and replaced with inefficient land for pulses and soy. It is only later, as diet change progresses, that inefficient land for feed production would be retired, and efficient land for pulses and soy would be brought into production. It is likely that markets, governments and civil societies would actively avoid this scenario.

Our key message remains that a moderate change from current diets towards consuming less livestock-based foodstuffs can be even more efficient in saving water than suggested by previous estimates using current water efficiency in replacing foodstuffs. Moving further towards diets without products from livestock shows less additional benefits from water saving perspective, but realistic scenarios show at most a small increase in water consumption even when farmed animal foodstuffs are completely abandoned. Our results indicate that preserving many of the benefits offered by livestock is possible while at the same time substantially reducing existing overuse of water resources. Even a moderate reduction in livestock production goes a long way towards saving resources, if done wisely, which may help in initiating change; it is not an all or nothing proposition.

Methods and data

Here we present an outline of the data used and the functionality of the Aalto OptoFood model. See Supplementary Information for a more detailed description with equations.

Scenario design

In order to capture the important dynamics in the human food systems, the Aalto OptoFood model combines food supply, water availability, and agricultural crop and livestock data with a linear programming optimisation model that finds the optimal land use patterns for crops (at 0.5 degree grid resolution) and optimal spatial distribution of livestock production (in 10 world regions and 3 production systems) to fulfil a given food demand. In order to analyse the effects of different levels of diet change, the optimisation model is run for a range of animal protein shares (from current to none). These diet changes are modelled by adjusting current food demand, gradually replacing livestock-based foods with an amount of pulses and soy with equal protein content, similar to Vanham et al[14]. Separate model runs are conducted with different levels of non-arable pasture (see Results: "Effect of diet change on water use") and different optimisation objectives (see Results: "Effect of optimisation objective"), which are key factors influencing the results.

The model is calibrated to current conditions (including diet and agricultural practices) in a multi stage process, accounting for discrepancies between data sources (for full description, see "Model calibration" in Supplementary Information). Estimates of crop yields, evapotranspiration and current harvested areas are obtained from the LPJmL model[51] (see "Crop data" below), which is calibrated to FAOSTAT yields[52] (see Supplementary Figure S2). Food demand is taken from FAO Food Balance Sheets, adjusted to match LPJmL production. Feed use parameters and current livestock production systems are adopted from existing sources, and the composition of concentrate feed is calibrated to match LPJmL production and FAO demand.

Restrictions are placed on the optimisation model to obtain more realistic land use patterns, notably regarding permitted land use, water availability, and feed (see Supplementary Table S2). Nevertheless, some model assumptions are subject to high uncertainty, but have a reasonably large effect on the system. As such, the scenarios should be considered representative of different possible behaviours of the system rather than absolute predictions of water use.

Model structure: Optimisation problem definition

A summary of the optimisation problem and data in the OptoFood model is provided in Supplementary Table S4.

Three different criteria can be optimised in the model (for full definition, see "Objective functions" in Supplementary Information). First, crop water consumption can be minimised to find the lower bound of evaporative water use in food production. This objective is referred to as *MinET*. Second, average water stress across basins can be minimised by objective *MinStress*, weighting blue water evapotranspiration by water availability. Third, as an indicator of deviation from the natural state due to the land conversion, it is possible to minimise the difference between the evapotranspiration (ET) of natural vegetation and that of the optimised agricultural land use. We refer to this objective as *MinDiff*.

The decision variables in the linear programming model are i) harvested areas within 0.5 degree grid cells for each combination of crop functional types (CFTs) and available irrigation types[53] (none, flood, sprinkler, drip), as represented by the LPJmL model, and ii) production amounts of each of six livestock products (see Supplementary Figure S3 A-F). Harvested areas are used to calculate production (area multiplied by crop yields [t/ha]) to meet crop demand, evaporative water use (area multiplied by modelled evapotranspiration [mm] during the growing period) and irrigation water use (area multiplied by modelled net water withdrawals [mm]). The livestock production is used to calculate crop feed demand.

Crop data

We use LPJmL version 3[51] as a data source for yields, crop residue (unutilised crop biomass usually left on the field), evapotranspiration and irrigation requirements during the reference year (2000), driven by historical climate data CRU TS3.10[54] and averaged during the period 1975-2005. LPJmL assigns all agricultural crops used into 12 explicit crop functional types (CFTs, listed in Supplementary Table S1). A 13th CFT contains “other” crops not explicitly represented elsewhere, simulated as grasslands, and a 14th CFT is defined for pasture. Pasture (CFT 14) is treated differently from other crops. First, the share of CFT 13 (other crops), that is not covered by the FBS, is moved to CFT 14 and considered roughage feed. Second, because LPJmL’s CFT 14 is not calibrated, the yield and evapotranspiration of CFT 14 are regionally reduced to match the share of roughage consumed by livestock according to the feed conversion ratios. This is based on the assumption that the livestock biomass utilisation ratio is preserved when livestock production is reduced. Third, depending on the scenario, a percentage of non-irrigated grass production is considered to occur on non-arable rangeland; grass production from these cells does not contribute to the total evaporative water consumption of food production (see “Discussion and conclusions” for rationale). This rangeland is chosen by a fixed percentage of cells where grass evapotranspiration is closest to natural vegetation ET (see Figure 1).

Optimisation constraints

Demand constraints

The total crop demand consists of three components: extrinsic human food supply varying between diet change levels, static supply for other uses, and intrinsic livestock feed demand. Livestock demand is externally specified through diet change, and also includes small amounts of static supply for other uses. Crop production is required to be at least as large as the sum of direct human crop demand including losses and feed consumption, with livestock production at least as large as direct human livestock demand (for equations, see “Demand constraints” in Supplementary Information). Production of each of the CFTs is determined for each cell as the product of the harvested area and modelled crop yield. The demand is global – we assume free trade for both the crops for human consumption and crop feed for livestock. Current trade arrangements cannot easily be assumed to stay constant in the presence of large demand changes.

The extrinsic crop demand is the sum of human food and all other crop uses. We consider the other uses constant, but the food demand varies according to the diet change level. The current average human diet for each country is derived from FAOSTAT Food Balance Sheets[55]. Population data is based on HYDE database version 3.2[56].

For each diet change level, a given percentage of livestock products is replaced with pulses and soy (see Supplementary Table S3), keeping the protein content constant, which then means there is some variation in energy content (4% decrease from 2157 kcal/cap/d to 2065 kcal/cap/d in the included food items, including food waste). The ratios between livestock products are kept constant globally to avoid introducing additional dynamics. The ratio between pulses and soy is also preserved.

For oilseed crops, we differentiate between the portion of the crop resulting in oil vs cake during the processing stage. The ratio of production of oil and cake is treated as constant with values derived from FAOSTAT Commodity Balances[55] (see Supplementary Table S1). In the baseline situation all of the current oil production is for human consumption and most of the cake goes to feed use (see “Model calibration” in Supplementary Information for details). The cake is, however, protein-rich. As part of the diet change, the whole soybean crop is therefore used as food – with no distinction between oil and cake.

The fraction of crop demand for human food must be satisfied by crops fulfilling safety and quality requirements set for food. These regulations vary by country, and quality statistics availability is limited. Crops not fulfilling food grade requirements can often be used as feed. A fixed percentage of crop production is assumed to be feed-only quality globally. In absence of reliable global crop quality data, 70% of the amount of each CFT currently used as feed is assumed feed-only quality. How well the average modelled feed composition fits with the human food demand structure determines how much of the substandard quality crop production can enter the food supply chain through the livestock sector.

The relationships between livestock production and feed requirements are derived from the appendix tables of UNESCO Value of Water series Report 48[57]. The crop composition of concentrate feed is derived from FAOSTAT Commodity balances[55] (part of the Food Balance database). In optimisation, production systems are permitted to use either regional or global feed composition for concentrate feed, consistent with our free trade assumptions.

The livestock crop feed requirements are handled by the demand constraints, but a large percentage of feed consists of grass and other roughage. The roughage comes from the yield of CFT 14, and additionally it can consist of a limited amount of crop residues of CFTs 1-12. The crop residues are limited to a maximum of 40% of the total roughage to avoid large changes in feed composition. As roughage is relatively inexpensive, we assume that it cannot be effectively traded across region boundaries. In practice, it is largely utilised directly as pasture or harvested and stored as silage, but still consumed relatively close to the site of production.

Harvestable area

The potentially harvestable area is derived from the current land use pattern as the sum of the harvested areas of all crops. It is further divided into four categories depending on irrigation equipment – rainfed, flood irrigated, sprinkler irrigated or drip irrigated land[53]. Rainfed cropland is excluded if it is unsuitable according to FAO GAEZ Suitability Indices[58]. Within a raster cell, the harvested area of all crops must fit within the harvestable area and the irrigated growing areas must not exceed the area equipped for the corresponding irrigation type, i.e. neither agricultural land area nor irrigated area is allowed to expand. This is possible within our analysis because the emphasis is on utilising existing agricultural land as efficiently as possible in terms of water (objectives *MinET* and *MinStress*) or in a way that is hydrologically as close to natural as possible (objective *MinDiff*). Diet change reducing animal content in diets tends to decrease rather than increase land and water use, and as long as population or diet requirements per person are not increasing, new agricultural land is not needed. Expansion scenarios could easily be introduced using alternative land use patterns.

Constraints on spatial re-allocation of production: “stickiness”

We assume that completely reallocating crop production according to the per-crop productivity would be infeasible due to extensive changes in agricultural practices and machinery. Thus, relocation of preserved production is prevented by “*stickiness” constraints*. This means that the harvested area for a crop with increasing demand (later referred to as an “increasing crop”) can only increase or stay constant in any cell, and the harvested area for a crop with decreasing demand (“decreasing crop”) can only decrease or remain unchanged in any cell, making the current and unchanging production amount “stick” to its location. The increasing production for example for oilseeds can thus only occupy areas freed from decreasing production of crops and grass used for livestock feed. Reallocation can occur wherever suitable cropland becomes available, allowing trade patterns to change.

Production of meat, milk and eggs are each split into grazing, mixed, and industrial production systems. These are defined according to Mekonnen and Hoekstra[57] to be compatible with their feed conversion efficiency data. Similarly to the stickiness constraints used with cropland reallocation, each livestock product within each region and each production system can only decrease as a result of the diet change, i.e. no production can be moved from one area or system to another.

Water availability

Irrigation in each grid cell is limited by the current net withdrawals (irrigation water withdrawals – irrigation return flows), as modelled by the LPJmL ILIM model configuration[59]. The total net withdrawals per basin (after return flows) are not allowed to increase. Decreases in irrigation may be transferred to downstream cells within a basin. The drainage directions for raster cells are determined by the STN-30p simulated topological network [60], as used by LPJmL in the ILIM simulation.

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