Global Sustainability

cambridge.org/sus

Research Article

Cite this article: Braun J, Stenzel F, Bodirsky BL, Jalava M, Gerten D (2022). Dietary changes could compensate for potential yield reductions upon global river flow protection. *Global Sustainability* **5**, e14, 1–13. https://doi.org/10.1017/sus.2022.12

Received: 6 November 2020
Revised: 18 October 2021
Accepted: 29 June 2022

Key words:
agriculture; earth systems (land; water and atmospheric); land use; modeling and simulation

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Dietary changes could compensate for potential yield reductions upon global river flow protection

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Non-technical summary. Globally, freshwater systems are degrading due to excessive water withdrawals. We estimate that if rivers' environmental flow requirements were protected, the associated decrease in irrigation water availability would reduce global yields by ~5%. As one option to increase food supply within limited water resources, we show that dietary changes toward less livestock products could compensate for this effect. If all currently grown edible feed was directly consumed by humans, we estimate that global food supply would even increase by 19%. We thus provide evidence that dietary changes are an important strategy to harmonize river flow protection with sustained food supply.
Technical summary. To protect global freshwater ecosystems and restore their integrity, freshwater withdrawals could be restricted to maintain rivers' environmental flow requirements (EFRs). However, without further measures, reduced irrigation water availability would decrease crop yields and put additional pressure on global food provision. By comparing the quantitative effects of both global EFR protection and dietary changes on regional and global food supply in a spatially explicit modeling framework, we show that dietary changes toward less livestock products could effectively contribute to solving this trade-off. Results indicate that protection of EFRs would almost halve current global irrigation water withdrawals and reduce global crop yields by 5%. Limiting animal protein share to 25, 12.5 and 0% of total protein supply and shifting released crop feed to direct human consumption could however increase global food supply by 4, 11 and 19%, respectively. The effects are geographically decoupled: water-scarce regions such as the Middle East, or South and Central Asia would be most affected by EFR protection, whereas dietary changes are most effective in North America and Europe. This underpins the disproportionally high responsibilities of countries with resource-intensive diets and the need for regionally adapted and diverse strategies to transform the global food system toward sustainability.
Social media summary. Combining dietary changes and global river flow protection could contribute to a more sustainable food system.

1. Introduction

The global food system is a dominant driver of environmental change, thereby substantially contributing to transgressions of planetary boundaries (Campbell et al., 2017; Gerten et al., 2020; Gerten & Kummu, 2021; Rockström, Edenhofer, Gaertner, & Declerck, 2020; Willett et al., 2019). Expansion of agricultural land through conversion of natural ecosystems and agricultural intensification through fertilizers, pesticides and irrigation have cumulatively led to biodiversity loss, global warming, soil degradation, eutrophication and pollution at the global scale (Foley et al., 2011). Freshwater ecosystems, such as rivers, lakes and wetlands, are among the most severely threatened habitats worldwide and particularly impacted by agricultural activities. Apart from water pollution and eutrophication through fertilizers and pesticides, an estimated 2158–3185 km^3 of water are withdrawn for irrigation every year, corresponding to around 70% of total human water withdrawals (Droppers, Franssen, van Vliet, Nijssen, & Ludwig, 2020 and references therein; FAO, 2020). While ~30–40% of irrigation water requirements are abstracted from groundwater, ~80% of net irrigation abstractions (after accounting for return flows) originate from surface waters (Döll et al., 2012, 2014). With a further growing population and an increasingly bio-based economy, irrigation water demands are likely to increase and further intensify the pressure on riverine ecosystems (Stenzel, Gerten, Werner, & Jagermeyr, 2019; Wada & Bierkens, 2014).

To prevent future detrimental effects on freshwater ecosystems and restore already degraded ecosystems, it has been advocated to restrict human water withdrawals

(Arthington et al., 2018; Hogeboom, Bruin, Schyns, Krol, & Hoekstra, 2020; Richter, Davis, Apse, & Konrad, 2012). By setting a water withdrawal cap at the river basin scale, human water appropriation could be kept within ecological boundaries. Aiming at defining ecological water needs, the concept of environmental flow requirements (EFRs) was suggested, that is, the 'quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being' (Arthington et al., 2018). While rainfed agriculture has little effects on river flow and can even lead to increases in runoff (Rost et al., 2008), current transgressions of EFRs can largely be attributed to water withdrawals for irrigation (Jägermeyr, Pastor, Biemans, & Gerten, 2017). In an attempt to define dangerous levels of human interference with the water cycle, the planetary boundary for freshwater use is currently defined, among other elements, by these EFRs (Gleeson et al., 2020; Steffen et al., 2015). While international implementations of EFR protection policies could thus help to get back into a safe operating space regarding water withdrawals, they would – all else being equal – unavoidably reduce the amount of available irrigation water and thereby the yields on irrigated cropland. Thus, restricting water use could not only result in economic disadvantages for farmers at the local level (Pang, Li, Sun, Yang, & Yang, 2018), but irrigation water constraints at the global level might even threaten food security (Liu et al., 2017). In order to respect social boundaries (Raworth, 2012), among them sufficient food for everyone, global environmental flow protection measures would thus have to be accompanied by a sustainable increase of food supply within limited water resources. Only then, Sustainable Development Goals addressing both freshwater ecosystems and hunger can be jointly achieved (Jägermeyr et al., 2017; UN, 2015).

Different measures have been proposed to reduce the food system's water footprint or to sustainably increase food supply without increasing water use, among them better farm water management and a reduction of food losses and waste (e.g. Davis, Rulli, Seveso, & D'Odorico, 2017; Jägermeyr et al., 2015; Kummu et al., 2012). More recently, dietary changes toward less animal-based products are receiving increasing attention (Berners-Lee, Kennelly, Watson, & Hewitt, 2018; Jalava, Kummu, Porkka, Siebert, & Varis, 2014; Poore & Nemecek, 2018). Since animal-based products are generally associated with higher water footprints than plant-based products (Hoekstra, 2012), dietary changes toward higher shares of plant-based products might significantly reduce the water consumption of global agriculture or, respectively, increase food supply without additional water use. These potentials can be explained by the unfavorable resource conversion efficiency from plant matter to animal products: to produce 1 calorie of animal product, several calories of feed are needed (Berners-Lee et al., 2018). By reallocating human-edible feed to direct human consumption or by freeing up land for growth of plant-based alternatives to animal products (Foley et al., 2011; Godfray et al., 2010), dietary changes toward less animal-based products are thus recognized as one important cornerstone for achieving future food security vis-à-vis limited resources, among them water.

By now, the potential negative effect of global EFR protection on yields (Bonsch et al., 2015; Jägermeyr et al., 2017; Rosa et al., 2018, 2019) and the potentials to increase calorie supply through dietary changes (Berners-Lee et al., 2018; Cassidy, West, Gerber, & Foley, 2013; Foley et al., 2011; West et al., 2014) have been mostly investigated separately. By combining agro-hydrologic simulations from the dynamic global vegetation and water balance model LPJmL (Schaphoff et al., 2018b) with a calorie accounting scheme based on FAO Food Balance Sheet data (FAOSTAT, 2017), this scenario study quantifies whether and to what extent regional and global dietary changes (assuming different levels of reduction in livestock production) could compensate for yield declines on irrigated cropland that would occur under rigid EFR protection. In other words, instead of analyzing direct effects of dietary changes on agricultural water use, we estimate possible increases in food supply through a reallocation of crop feed to direct human consumption, both from rainfed and irrigated cropland. This approach is based on (here updated and expanded) calculations in Gerten et al. (2020), who estimated potentials from different measures, among them dietary changes, to sustainably increase food supply within planetary boundaries including the freshwater boundary defined by EFR constraints.

2. Methods

To compare the effects of EFR protection and dietary changes on global calorie supply, this study integrates (1) simulations with a global model capable of representing a hypothetical EFR protection scenario and the resulting effects on crop yields with (2) a calorie calculation scheme which converts the crop yields to plant and livestock calorie supply depending on livestock production levels. In the following, we first introduce the LPJmL model used and the two irrigation scenarios considered (current irrigation and reduced irrigation due to EFR protection). Then we describe the calculation scheme used to convert yields to calorie supply based on current dietary habits and three scenarios with incrementally decreased livestock production including a scenario without livestock production at all. Ultimately, this allows us to compare both separate and combined effects of irrigation and diet scenarios on potential global and regional calorie supply.

2.1 The dynamic global vegetation and water balance model LPJmL

LPJmL (here, version 3.5) dynamically simulates the growth and productivity of both natural and (irrigated or rainfed) agricultural vegetation in an internally consistent framework by interconnecting underlying water, carbon and energy fluxes (for a detailed model description and evaluation see Schaphoff et al., 2018a, 2018b). Simulations are performed at daily time steps with a spatial resolution of 0.5°. To represent agricultural production, managed grasslands and 12 crop functional types (CFTs) are specified. Food crops which are not covered by the 12 CFTs are pooled and parametrized as managed grasslands as well (CFT13, 'others'). Assimilated carbon is distributed to four plant organs (roots, leaves, the harvestable storage organ and a pool representing stems and mobile reserves), depending on phenological stage and water availability. While agricultural land-use patterns and the extent of irrigated areas are defined by the land-use input, the required irrigation volume on irrigated cropland is calculated internally based on grid cell- and CFT-specific water requirements and the prevailing irrigation system. For this, daily net irrigation requirements are calculated for each CFT and cell, based on the soil water deficit of the top 50 cm soil layer. Additionally, system-specific inefficiencies are determined for drip, sprinkler and surface irrigation, which take into account the system-specific inefficiencies (geographic distribution and parametrization according to Jägermeyr et al., 2015). The

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resulting gross irrigation requirements are requested for withdrawal if soil moisture falls below a CFT-specific threshold, thus determining the daily scheduling of irrigation events. Water withdrawals for household, industry and livestock (drinking and cleansing water) are prescribed according to Flörke et al. (2013) and prioritized over irrigation. In the baseline scenario (no EFR protection), total water withdrawals per grid cell are constrained only by total local availability of renewable freshwater resources (river discharge including groundwater baseflow, lakes and reservoirs). Non-renewable abstractions from groundwater are not considered, but are estimated to constitute <20% of global irrigation water withdrawals (Wada, van Beek, & Bierkens, 2012). River discharge is computed based on accumulated surface and subsurface runoff along the river network (Rost et al., 2008; Schaphoff et al., 2018b); its seasonality is reproduced reasonably well in many regions (Schaphoff et al., 2018a). To account for the impact of reservoirs and dams on discharge as well as irrigation water availability, LPJmL includes a reservoir module (Biemans et al., 2011) with a generic reservoir operation model that differentiates reservoir functions (irrigation *vs.* other purposes), covering ∼7000 dams and reservoirs of the GRanD database (Lehner et al., 2011). The minimum water release from reservoirs to the river is set to 10% of the mean monthly inflow, while the remainder can be diverted to irrigated land if needed to meet a cell's irrigation demand in addition to local discharge.

2.2 Simulation protocol and irrigation scenarios

For this study, grid-cell-specific model outputs from two irrigation scenarios were comparatively analyzed regarding crop yields and irrigation: (1) in a *baseline scenario* water withdrawals were constrained by total local freshwater availability and (2) in an *EFR scenario* water withdrawals were additionally constrained by local EFRs (to represent their protection). For both scenarios, land use with geographically explicit distribution of rainfed and irrigated CFTs was held constant at year 2005 level over the simulation period. The respective land-use input is based on the MIRCA 2000 dataset (Portmann, Siebert, & Döll, 2010) with an adapted extent of irrigated areas for 2005 (Siebert et al., 2015) and geographically explicit distribution of irrigation systems (Jägermeyr et al., 2015). To represent regional differences in land-use intensities, averaged national FAO yield statistics for 2000–2009 (FAOSTAT, 2020) were used to calibrate simulated yields for management (for a description of the procedure and land-use dataset, see Fader, Rost, Müller, Bondeau, and Gerten, 2010 and Jägermeyr et al., 2015). In general, simulations forced with transient climate from 1901 to 2009 (CRU TS3.10 monthly temperature and cloudiness, Harris, Jones, Osborn, & Lister, 2014; GPCC monthly precipitation, Schneider et al., 2014) were preceded by a 900-year spin-up without anthropogenic land use followed by a 120-year spin-up based on the fixed land-use pattern and recycling climate for 1901–1920. All simulation outputs were averaged over 1980–2009 to take out climate variability. For more details on the simulation protocol, see the Supplementary information in Gerten et al. (2020).

2.3 EFR calculation

As described in Gerten et al. (2020), EFRs were estimated based on the average monthly grid-cell discharge during the last 30 years of the model spin-up with potential natural (pristine) vegetation and climate input for 1951–1980, that is, without human land use and reservoirs and in the absence of water withdrawals. The reference river state thus constitutes a potential natural flow under current climatic conditions, albeit neglecting that some rivers have been anthropogenically modified for centuries. The variable monthly flow (VMF) method (Pastor, Ludwig, Biemans, Hoff, & Kabat, 2014) was used to determine monthly EFRs for each grid cell, which aim at sustaining river ecosystems at least in a 'fair' status and were calculated based on flow regime-dependent percentages of mean monthly flow (MMF) *vs.* mean annual flow (MAF) of the pristine discharge. We precautionarily took into account the considerable uncertainties in determining ecological water needs by increasing the published values of the VMF method by 15%, as proposed in Steffen et al. (2015): in low-flow months ($MMF < 0.4 \times MAF$), EFRs are estimated to be 75% of MMF; in intermediate-flow months ($MMF > 0.4 \times MAF$ and $MMF \leqslant 0.8 \times MAF$) 60% of MMF and in high-flow months ($MMF > 0.8 \times MAF$) 45% of MMF. The resulting EFR thresholds are used to constrain total water withdrawals in each month in the EFR scenario. Upon irrigation reduction, all crop stands receive proportionally less water. LPJmL simulated EFR estimates based on the VMF method have been successfully validated against local case study estimates in Jägermeyr et al. (2017).

2.4 Calorie calculation scheme

To implement dietary change scenarios, simulated yields from all CFTs were converted to crop and livestock calorie supply depending on livestock production and associated crop feed demand. As livestock production is not modeled in LPJmL, comprehensive post-processing calculations were performed based on data from the FAOSTAT database (FAOSTAT, 2017, 2018), among others on feed productivities and composition as well as dietary energy and protein content of different aliments. The applied calculation scheme summarized in the following and visualized in Figure 1, adapts and refines the scheme described in the Supplementary information of Gerten et al. (2020). For more details on single calculation steps and processing of external data, see Supplementary text and Figure S1.

2.4.1 Calculation of baseline livestock production

We derived the reference regional livestock production under current dietary habits (see reference diet in Figure 1) based on livestock production data from FAO Food Balance Sheets (FBS) for 2005 (FAOSTAT, 2017) and simulated pasture and roughage production from LPJmL. By dividing pasture and roughage production as simulated in the baseline scenario by total livestock production from FBS, roughage requirements per unit of average livestock product for 12 world regions were determined. To obtain current regional livestock production levels for each irrigation scenario, we divided the irrigation scenario's pasture and roughage production by these regional roughage requirements per livestock product. For countries not included in the FBS, we assigned the average roughage requirement of the world region the country belongs to.

2.4.2 Calculation of crop production for human consumption

To derive the regional crop production intended for direct human consumption (Crop Food), we removed CFT- and region-specific shares for 'other uses' (O) such as bioenergy and seed production as well as feed (F) from simulated edible plant production (P),

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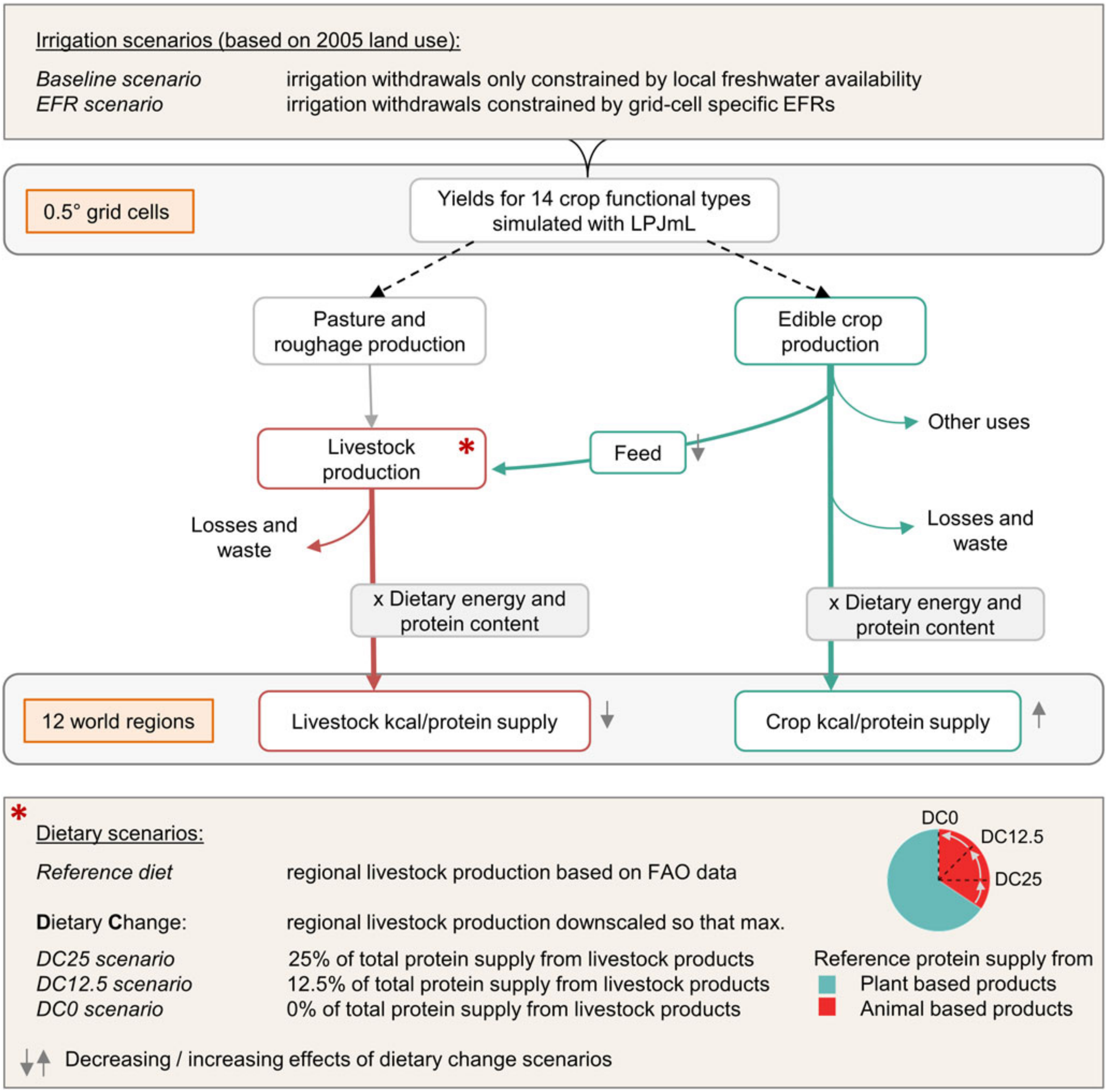

Fig. 1. Overview of scenarios and calorie calculation scheme used to convert simulated crop yields to regional calorie supply depending on the dietary scenario. Feed requirements per livestock product, other uses such as bioenergy and seed production as well as dietary energy and protein content for each CFT and 12 world regions were derived from FAO Food and Commodity Balance Sheets for 2005. Losses and waste amounts were taken from Gerten et al. (2020). Gray arrows visualize the effects of downscaling livestock production.

which was aggregated for the 13 CFTs and 12 world regions:

$$Crop\ Food_{reg,cft} = P_{reg,cft} \times (1 - O_{reg,cft}) - F$$

O is a product and country-dependent share of crop production allocated to these purposes according to the FBS utilization accounts, averaged for regions and CFTs by allocating FBS food items to CFTs, and assumed to be constant between different scenarios. F is calculated as the product of region-specific crop feed requirements per livestock product ($FReq_{reg,cft}$ = weight of each CFT needed to produce 1 kg of an average livestock product) and the regional livestock production (LP):

$$F = FReq_{reg,cft} \times LP_{reg}$$

$FReq_{reg,cft}$ was derived from FBS data for 2005 and adjusted to LPJmL production amounts (for details see Supplementary text). We also included food manufacture by-products used as feed (brans, molasses, oilseed cakes, allocated to the respective CFTs) obtained from the FAO Commodity Balances for 2005 (FAOSTAT, 2018). While trade flows within each of the 12 world regions are implicitly accounted for through regional aggregation, our analysis of regional calorie supply potentials does not model trade flows between regions. Our estimates therefore reflect the domestic feed production potential.

2.4.3 Calculation of calorie and protein supply

To calculate livestock and crop fresh matter supply for human consumption from net production amounts, post-harvest/-production losses, processing losses and food waste were subtracted using regionally averaged percentages (Gustavsson, Cederberg, Sonesson, van Otterdijk, & Meybeck, 2011; Jalava et al., 2016; Kummu et al., 2017). As FAO data exclude production losses and LPJmL crop yields were calibrated with these data, harvest losses are implicitly considered. The calorie and protein supply from livestock and crops was obtained by multiplying fresh matter supply with regional dietary energy and protein content derived from FBS food supply quantities in terms of energy, protein and mass units. While energy and protein contents of crops were specifically calculated for each CFT, the regional factors for livestock production represent an average over the sum of all livestock products with a composition depending on the respective regional production ratios. By averaging the livestock sector, we avoid complexity regarding co-products such as beef and milk, and the attribution of feed to individual livestock species.

2.5 Dietary changes

In order to investigate potential calorie supply changes resulting from dietary changes toward less livestock products, one reference diet with regional livestock production derived from FBS data (see above) and three dietary change scenarios were implemented. Building upon dietary change implementations published in Jalava et al. (2014), regional livestock production was incrementally downscaled so that protein share from livestock products is limited to 25% (DC25), 12.5% (DC12.5) and 0% (DC0) of total protein supply, respectively (Figure 1). In regions where livestock protein share is below 25%, livestock production is not altered in the DC25 scenario. While these dietary change scenarios refer to protein supply since livestock products primarily contribute to protein provision, results on total food supply changes refer to calories as this is the most relevant indicator for food provision. It is also important to note that the approach is production-based, thereby only indirectly reflecting changes in dietary habits. In contrast to the approach described in Gerten et al. (2020), the dietary change scenarios do not impact underlying land-use patterns. Calorie supply changes thus solely result from a changed calorie calculation scheme with (1) a decreased livestock production and supply and (2) reallocation of freed crop feed to direct human consumption (see gray arrows in Figure 1). Our analysis of regional calorie supply potentials allows us to locate these increases in crop calorie supply within the same region where feed demand is caused. Since food processing by-products are included in the CFT feed requirements, simple reallocation of livestock crop feed to direct human consumption would imply that these, in principle mostly human-edible products, are consumed by humans instead of livestock, which would require changes in consumption behavior. In this context, we assume that food processing by-products which are already currently partly being used for human food production can contribute to calorie supply (all molasses and brans; soybean-, groundnut-, coconut- and sesame seed-cakes) whereas the remaining oil seed cakes cannot (sunflower-, rape-, mustard-, cotton seed- and other oilseed-cakes, palm kernels). For a sensitivity analysis regarding the effect of the edibility of food processing by-products on the results see Supplementary Table S1.

While the dietary changes would also reduce pasture feed requirements, potential indirect effects through abandonment of pasture areas and potential conversion to arable land or increases in uniquely grass-fed ruminants are not considered here. Since the livestock sector was averaged for each of the 12 regions, regional production ratios of different livestock products are preserved upon dietary change, which implies that all livestock products are reduced equally. Implementing more specific dietary scenarios such as a vegetarian diet was not possible due to the used input data: FAO does not provide feed composition per livestock product but only total feed quantity per crop type. Also, as the study focuses on reallocation of current crop production in terms of calories and proteins from feed to food, shifts to healthy and nutritious diets to increase food security especially in low-income countries, which would imply changes in cropping patterns, are not analyzed here.

2.6 Comparing the effects of EFR protection and dietary changes

To finally assess the combined effect of EFR protection and dietary changes on calorie supply for each world region and globally in an integrated framework, the dietary change scenarios were employed on the simulated reduced yield levels of the EFR scenario. Obtained calorie supply was then compared to calorie supply based on yield levels from the baseline scenario and current livestock production. Calorie supply thereby serves as an integrated ‘response variable’ for both EFR and diet change scenarios. We thus did not analyze water-saving potentials from dietary changes and its effect on EFR transgressions but – conversely – analyzed whether reallocating crop feed, both from rainfed and irrigated cropland, to direct human consumption could counteract calorie supply reductions upon EFR protection.

3. Results

3.1 Potential yield reductions upon EFR protection

According to the land-use dataset used, roughly 300 Mha of agricultural land were irrigated in 2005, corresponding to 18% of total arable land. If EFRs were to be protected globally following requirements derived from the VMF estimation method (EFR scenario), water withdrawals for irrigation on these areas would decrease from 2500 km^3 $year^{-1}$ (baseline scenario, see Supplementary Table S2 for a comparison to other model-based estimates) to 1330 km^3 $year^{-1}$ (averaged for 1980–2009 climate). This suggests that 47% of global irrigation water withdrawals are currently at the expense of EFR provision. These excess water uses occur primarily in irrigation hotspots of the northern hemisphere, for example, in South Asia, the Middle East and the Mediterranean (see Supplementary Figure S2). A reduction of available irrigation water would in turn impact agricultural yields: total global crop yields from irrigated areas would be reduced by 23.2% if EFRs were preserved globally. In other words, almost half of irrigation water withdrawals and almost a quarter of irrigated crop production rely on the transgressions of EFRs, at the expense of river ecosystem integrity and biodiversity. Given that 18% of cropland is irrigated, this translates into a total yield reduction (rainfed and irrigated together) of 5.2% upon EFR protection.

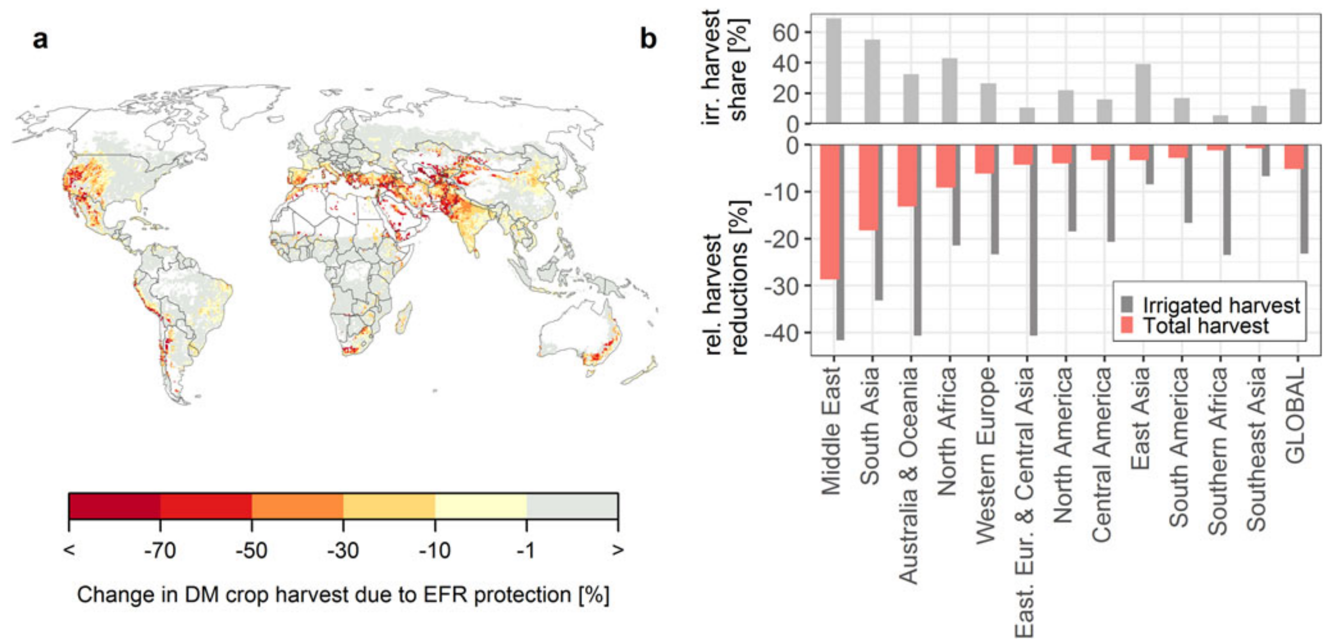

Fig. 2. Simulated impact of EFR protection on global and regional yields. (a) Percent decrease in dry matter (DM) crop yields (rainfed and irrigated) if EFRs were to be preserved globally. (b) Relative irrigated and total (irrigated and rainfed) yield reductions upon EFR protection aggregated for 12 world regions, ordered by magnitude. Top panel displays the share of yields from irrigated areas in the baseline scenario. All results are based on 2005 land use and 1980–2009 climate.

Strongest relative yield reductions are simulated in the Middle East and Central Asia. In some countries in these regions (e.g. Israel, Oman, Saudi Arabia, Uzbekistan and Turkmenistan), >50% of yields (dry matter, rainfed and irrigated together) rely on EFR transgressions (see Figure 2a). In terms of absolute yields, countries with strong EFR transgressions, like India, Pakistan, the United States and China, would be most severely affected by a protection of EFRs: 20.4% of total global yield reductions in the EFR scenario would occur in India alone, attaining 38.1% together with Pakistan (12%) and China (5.8%), and 11.5% of absolute reductions would be located in the United States. Against the backdrop that approximately one-third of globally undernourished people live in India and Pakistan alone (FAO et al., 2021), this result emphasizes the potential severe trade-off between food security and EFR protection in some regions.

Aggregating the results for the world regions emphasizes differences in the dependence of crop production on EFR transgressions. Relative reductions in yields due to EFR protection are highest in the Middle East with 28.7%, followed by South Asia (18.3%) and Australia and Oceania (13.2%) (Figure 2b). These regions are characterized by high shares of irrigated crop production (Figure 2b, top panel), due to low amounts of naturally available freshwater and/or irrigation-intensive crop growth such as rice, for example, in large parts of South Asia. Furthermore, irrigated drylands like in the western United States and southern Europe rely more on EFR transgressions than regions with less intensive agriculture, such as sub-Saharan Africa. In East Asia, yield reductions are low despite high irrigation shares, as EFRs are simulated to be maintained in many parts due to the rain-laden subtropical monsoon climate which cover large parts of south-east China.

3.2 Potential calorie supply increases through dietary changes

To assess whether the (hypothetical) negative effects of EFR provision on regional and global calorie supply could potentially be buffered or compensated for by dietary changes, the simulated crop yields from the baseline scenario were converted to calorie supply depending on livestock production levels. By consecutively down-scaling the protein supply from livestock products from the current levels to a maximum of 25% (DC25), 12.5% (DC12.5) and 0% (DC0) of total protein supply in each world region, the associated shifts in crop use from feed to food could increase global calorie supply as the nutritionally inefficient conversion from feed to livestock product is circumvented (Figure 3a, 'GLOBAL'). Even without considering the possible additional use of freed pasture areas for crop growth, global calorie supply in the DC25 scenario is calculated to increase by 4.2%. The additional calorie supply from crop feed shifted to human consumption thus overcompensates the mean global reductions of livestock calories (−24.6%). A mean reduction of livestock calories by 59.6% in the DC12.5 scenario leads to an overall calorie supply increase of 10.7% and in the scenario without livestock production (DC0), calorie supply increases by 19.0% at the global level (for a sensitivity analysis regarding the edibility of feed for humans, see Supplementary Table S1).

While the DC25 scenario entails a 23% increase of calorie supply in Western Europe, the DC0 scenario even indicates a calorie supply gain of about 48% both in Western Europe and North America (see Figure 3a; for regional percentages of calorie supply change for all three scenarios see Supplementary Table S1). In terms of absolute calorie supply, 50% of the increases in the DC0 scenario occur in Western Europe and North America alone, attaining 75% together with Eastern Europe and Central Asia and East Asia. The high effectivity of dietary changes calculated for these regions can be attributed to (1) high initial livestock calorie share and (2) high crop feed shares, that is, crop feed divided by total feed amount as calculated with the applied calorie calculation scheme (see Figure 4). In other words, for Western Europe, North America and Eastern Europe and Central Asia, assumed crop feed shares are relatively high and

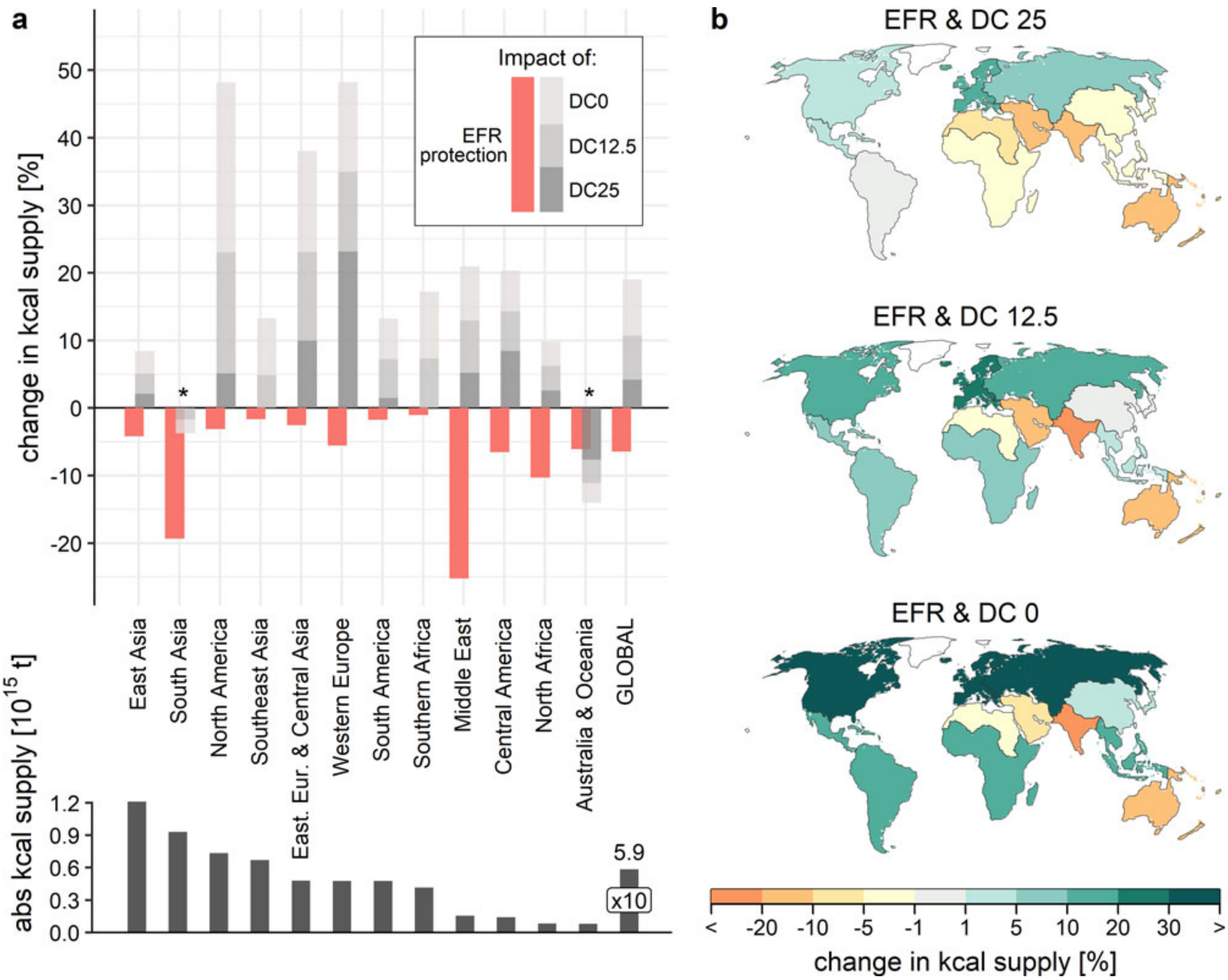

Fig. 3. Impacts of dietary changes on calorie supply in the context of EFR protection, aggregated to world regions. (a) Relative change of calorie supply in comparison with the baseline scenario (current irrigation practices, livestock production as derived from FAO data for 2005), resulting from EFR protection (red bars) and dietary change scenarios with gradually reduced livestock production (light gray bars) to a maximum of 25% (DC25), 12.5% (DC12.5) and 0% (DC0) of total protein supply. Regions are ordered by their absolute calorie supply (dark gray bars in the bottom). Asterisks (*) mark regions with negative effects of dietary changes. (b) Calorie supply changes resulting from combined effects of EFR protection and the three dietary change scenarios.

dietary change therefore frees up more cropland for food use. Conversely, the crop feed shares in South Asia and Australia and Oceania are very low, which leads to a negative effect of dietary change on total calorie supply: if livestock production is reduced, only small amounts of crop feed are reallocated to direct human consumption. Here, calculated calorie supply increases from plant-based products are smaller than animal calorie supply reductions. This is in line with observational data on the high share of grass-fed and/or by-product-fed livestock in these regions (Herrero et al., 2013). Also, the DC25 scenario does not change calorie supply at all in South Asia, Southeast Asia and Southern Africa given that livestock protein share in these regions is already below 25% (see Figure 4).

3.3 Potential compensation of EFR protection effects through dietary changes

Our further analysis suggests that comparatively modest dietary changes (DC25 scenario) could partly compensate for calorie supply reductions resulting from EFR protection (see Figure 3a). Stronger livestock reductions as in the DC12.5 and DC0 scenarios could even largely overcompensate the effects of EFR provision on the global level. Globally, EFR and DC effects would cancel each other out if animal protein share was capped at 19.4%, corresponding to a mean calorie share from animal products of 10.4% and a global mean reduction of the livestock calorie share by 42%. While this implies drastic large-scale dietary changes, such limited intake of livestock products could also benefit health and individual well-being (Godfray et al., 2018; Tilman & Clark, 2014; Willett et al., 2019).

Analyzing regional potentials of dietary changes to compensate for EFR protection effects results in a heterogeneous picture, suggesting that regions with strong reliance on EFR transgressions do not necessarily show high dietary change potentials and vice versa (Figure 3b). Limiting the animal protein share to 25% (DC25) suffices to at least compensate calorie reductions from EFR provision in Central America, Eastern Europe and Central Asia, North America and Western Europe (Figure 3b, top map).

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	Kcal change (DC0)	Livestock kcal share	Livestock protein share	Crop kcal used for feed	Crop feed share
East Asia	8.4	21.8	34.8	27.7	41.3
South Asia	-3.7	11.5	22.5	10.1	4.5
North America	48.2	19.7	29.3	40.7	41.4
Southeast Asia	13.3	5.3	21.3	15.8	14.7
East. Eur. & Central Asia	38.0	20.9	35.6	39.1	37.4
Western Europe	48.3	36.3	53.5	54.8	43.5
South America	13.2	19.2	28.3	25.6	12.8
Southern Africa	17.2	8.3	22.6	21.2	11.6
Middle East	20.9	18.1	36.0	31.8	21.9
Central America	20.3	17.7	44.6	36.8	22.9
North Africa	9.8	21.6	42.8	28.4	10.8
Australia & Oceania	-14.0	37.1	47.4	27.0	4.4
GLOBAL	19.0	18.0	32.6	29.6	23.0

Fig. 4. Domestic production-based estimates of regional characteristics (in %), which underlie the regional dietary change potential, that is, the change in total calorie supply if edible crop feed was used for human consumption (DC0 scenario, gray bars). Displayed are livestock production contributing to total calorie supply and total protein supply as well as the share of crop calorie production allocated to feed and the share of crop feed in total feed amount (roughage and grass included) for a regionally specific average livestock product. All factors are based on FAO-derived input data for 2005 and the calorie calculation scheme as described in the Methods.

A further reduction of the animal protein share to 12.5% in each region (DC12.5) additionally leads to a compensation of EFR protection induced calorie supply reductions in East Asia, Southeast Asia, South America and Southern Africa (Figure 3b, middle map). Dietary changes are not sufficient to compensate for calorie supply reductions in the Middle East and North Africa, and in Australia and Oceania and South Asia, dietary changes might even be counterproductive to sustain regional food supply due to low crop feed shares (Figure 3b, bottom map). As such, the results suggest that in some regions with high reliance of food production on EFR transgressions, which are partly also severely impacted by food insecurity (i.e. South Asia), dietary changes do not seem appropriate to solve the trade-off between EFR protection and food supply. At the same time, it is important to note that in these regions (1) disproportional land use through pasture-fed animals and resulting possibilities to convert pastures to arable land or to maintain pasture-fed livestock production were not considered in this study, and (2) international trade among regions could compensate for such deficits by balancing limited calorie production in these regions.

4. Discussion

We show that, at the global level, dietary changes up to a scenario with no livestock production could clearly overcompensate calorie supply reductions that would occur if irrigation was limited to maintain EFRs worldwide. Thus, current calorie production inefficiencies due to feeding animals with human edible crops (Shepon, Eshel, Noor, & Milo, 2018) seem to be far more pronounced than current crop production amounts relying on transgressions of environmental flows. In other words, diet changes could compensate for potential calorie supply losses, not directly due to lowered water demands, but due to calorie and protein losses inherent in livestock production. In the following we compare results on effects of EFR protection and dietary changes to literature, discuss limitations and embed our findings in a broader context of food supply within the planetary boundary for freshwater use.

The simulated 47% reduction of irrigation water withdrawals upon global EFR protection is in good agreement with earlier estimates: 41% in Jägermeyr et al. (2017) (the same model but average based on four hydrological EFR methods), 40% in Rosa et al. (2018) (different model but the same EFR calculation method), 52% in Rosa, Chiarelli, Tu, Rulli, and D'Odorico (2019) (different model, more conservative EFR estimate based on annual flow, depletion of groundwater stocks included) and 39% in Droppers et al. (2020) (different model, the same EFR method but without precautionary + 15%, additional EFRs for groundwater baseflow). Besides uncertainties in modeled discharge, reservoir management and irrigation water withdrawals resulting, for example, from different land use (Puy, Borgonovo, Lo Piano, Levin, & Saltelli, 2021) and climate data (Biemans et al., 2009), these differences can also be explained by more or less conservative EFR estimates: hydrological EFR methods such as the one applied here represent rough estimates and need local refinements using more holistic methods (Pastor et al., 2014). Additionally, their definition also comprises a normative component regarding the 'best compromise' between human and environmental water needs. Furthermore, not considering non-renewable groundwater abstractions and groundwater depletion, might lead to an overestimation of water withdrawals from surface waters and, thus, EFR transgressions in regions with high irrigation volumes from groundwater such as Northern India, Western United States and Pakistan (see Gerten et al., 2020). Fossil groundwater abstractions can however be regarded as unsustainable which justifies not to take them into account in the 'sustainable' EFR scenario which should neither invoke EFR transgression nor depletion of fossil aquifers. Also, groundwater abstractions translate into decreased river streamflow even before substantial groundwater depletion occurs (de Graaf et al., 2019) and thus significantly contribute to EFR transgressions (Droppers et al., 2020). This might also explain why our estimate of irrigation water withdrawals relying on EFR transgressions is in good agreement with other estimates which explicitly consider groundwater depletion (see above).

Due to the more precautionary estimate of EFRs used in this study in line with the current definition of the planetary boundary for freshwater use (Steffen et al., 2015), the total yield reduction (5.2%) resulting from EFR protection is slightly higher than the 4.6% found by Jägermeyr et al. (2017).

Regarding the potential calorie supply increases through direct use of crops grown for animal feed, our estimate (19% in the DC0 scenario) is lower than previous estimates (Cassidy et al., 2013; Foley et al., 2011). These estimates include more by-products used as feed, for example, from bioenergy production and/or assume that more by-products could be directly consumed as human food. In accordance with this, the share of calorie production used for feed calculated in this study is lower than in other global estimates (see Supplementary Table S2 for an evaluation of global estimates of simulated key variables against independent datasets). Also, global crop production in LPJmL is generally slightly underestimated (Jägermeyr et al., 2017). Due to the adjustment of feed requirements to LPJmL production amounts, this results in lower feed requirements per livestock product. Therefore, the here presented estimates of the potentials of dietary changes to increase calorie supply can be seen as conservative.

Our results also show that potential calorie supply increases through dietary changes are geographically concentrated in regions with high percentages of concentrate feed and calorie supply from animal products: 75% of absolute calorie supply potentials in the DC0 scenario are located in North America, Western Europe, Eastern Europe and Central Asia and East Asia. This is in good agreement with West et al. (2014) who found that shifting crop feed to direct human consumption in the United States, Western Europe and China could account for 54% of the global 'diet gap'. Dietary changes in these regions can thus be regarded as a major leverage point to sustainably increase food supply within limited resources, among them water (West et al., 2014).

The uneven distribution of effects does not only underpin (1) the disproportionally high responsibilities of countries with resource-intensive diets and (2) the importance of trade as a vehicle to provide water-scarce regions with food from regions with high calorie supply increases upon dietary changes. It also points to (3) the need for regionally adapted solutions and a broad spectrum of measures addressing both production and demand. Such measures comprise among others a sustainable intensification of agriculture, for example, through better water management, increased livestock water productivity or sustainable expansion of irrigation particularly in low-income countries (Heinke et al., 2020; Jägermeyr et al., 2017; Rosa et al., 2018), as well as reductions of food losses and waste (Gerten et al., 2020; Kummu et al., 2012; Springmann et al., 2018). Given the strong alteration of streamflow through dams and reservoirs in many basins (Grill et al., 2015), removal of dams or optimized operation rules for reservoir outflow could also help to sustain EFRs by minimizing flow regime alteration (Yin, Yang, & Petts, 2011). Such technical improvements might provide near- or mid-term solutions in addition to rather long-lasting societal transformations as required for example for large-scale dietary changes. While we looked at one option to ease trade-offs between ecosystem water needs and food security, the combined effects of several measures could be simulated integratively in further research.

Regarding livestock production, the heterogeneity in regional calorie supply improvements due to dietary changes also suggests that reduced consumption of livestock products does not necessarily increase calorie supply within limited freshwater resources. While allocation of human-edible crop feed to livestock production usually represents a net loss of human available calories and causes a competition between feed and food for valuable natural resources such as land and water (Foley et al., 2011), livestock uniquely fed by food processing by-products, crop residues, food waste and grass could avoid this competition (Nonhebel, 2004; Schader et al., 2015). This is in line with the simulated low potentials of dietary changes to increase food supply in regions with low crop feed shares, such as South Asia and Australia and Oceania. Additionally, livestock production can contribute valuable proteins, vitamins and micronutrients especially in low-income countries and may generate income at the household level in rural regions and thereby support livelihoods (Garnett, 2013; Mottet et al., 2017). Globally limiting livestock production to marginal pastures and leftovers could thus serve both food security and freshwater ecosystem protection by decoupling livestock production from arable land and its irrigation (Van Zanten et al., 2018). We here assumed that all livestock production systems and products are reduced equally in the DC scenarios, concentrating on effects from reallocation of crop-feed. Further studies could however represent dietary change scenarios, which specifically decrease crop-fed livestock systems while maintaining or increasing 'crop-feed-free' systems. This would necessitate an extended calorie calculation scheme representing feed flows for distinct livestock production systems and products. A first rough estimate based on calculations from Van Zanten, Meerburg, Bikker, Herrero, and de Boer (2016) indicates that extensive grazing on all global pasture areas (2961 Mha according to our land-use input) could provide 2.5×10^{14} kcal and 2.1×10^{10} kg proteins from ruminant meat and milk per year (see additional text and calculations in Supplementary Table S8). This could increase the calorie supply in the DC0 scenario (=0% crop feed for livestock) by an additional 4%, from 19 to 23% in comparison with the baseline scenario with current livestock production. Studies, which explicitly examined potential livestock production without relying on crop feed (Röös et al., 2017; Schader et al., 2015; Van Zanten et al., 2016, 2018), estimate an even higher potential global production if not only grass but also crop residues, food waste and/or by-products were extensively exploited as feed in future (see Supplementary Table S9 and explanatory Supplementary text). In light of a growing world population, such a 'sustainable boundary for livestock production' would imply a reduction of per capita livestock production and consumption at the global level with strong reductions in most high-income regions, but still allow for a restricted growth in parts of Africa and Asia (Van Zanten et al., 2018). From both a food security and EFR protection perspective, such a 'crop-feed-free' livestock production could be preferable over the stylized diet without livestock products as implemented in the DC0 scenario. On the other hand, abandonment of some pasture areas currently used for animal grazing as implicitly assumed in our DC scenarios could also significantly contribute to attaining other sustainability targets such as biodiversity protection and climate change mitigation, for example, through reforestation of pasture areas, which replaced natural forest ecosystems in the past, or by rewilding overgrazed areas (Hayek, Harwatt, Ripple, & Mueller, 2021; Kemppinen et al., 2020).

Both the EFR scenario and the DC scenarios do not include secondary effects such as changes in land use and trade. The scenarios are thus not representing pathways but explicitly isolate and compare the effect of EFR provision and dietary changes on calorie supply. Thereby, they offer an opportunity to study their individual effects based on spatially detailed, process-based calculations of yields and water fluxes. To elucidate the complex interactions, tradeoffs and synergies of dietary choices as well as water regulation policies with land-use patterns and trade flows, simulations with integrated assessment models could provide additional insights (Bonsch et al., 2015; Kim et al., 2016; Pastor et al., 2019; Weindl et al., 2017). Also, including trade in further studies would likely shift some of the calories supply increases upon DC from countries with high livestock production, such as Western Europe, to feed producing countries, for example, the Americas for soy (Wang et al., 2018). Furthermore, it is likely and from a nutritional perspective desirable that reductions in animal product consumption are accompanied by increases in fruit, vegetable, nut, oil and legume consumption (Tilman & Clark, 2014; Willett et al., 2019). Regarding protein supply, the energy share contributed by proteins would only be slightly reduced through the implemented dietary change scenarios and would still remain within healthy limits at a global level (see Supplementary Table S3). Nevertheless, increases in protein-rich plants are important to sustain or increase protein intake upon dietary changes in low-income countries. While these plant-based commodities are in general substantially less resource-intensive than animal products, they may consume more natural resources than human edible animal feed such as feed grains and oil seeds (Poore & Nemecek, 2018). Transitioning to healthy, primarily plant-based diets for all may thus pose more challenges with regard to EFR compatible food supply than simulated here, in particular for the cultivation of vegetables and fruits, which are often irrigated. It is also important to note that dietary changes, unaccompanied by EFR protection policies, might not directly lead to reductions in EFR transgressions.

This study is designed to analyze combined effects of ambitious measures targeting different levels of the food system, thus contributing to the broader discussion on food supply within planetary boundaries (Gerten et al., 2020). It confirms that dietary change from animal to plant-based products is a powerful measure to increase calorie supply within environmental constraints such as EFR protection. However, current trends in water withdrawals and diets (Bodirsky et al., 2020) point to the opposite direction. With a growing population and projected increases in livestock product consumption especially in developing nations, water and land requirements for agriculture are expected to further grow in the future (Tilman, Balzer, Hill, & Befort, 2011). Additionally, climate change and biomass-based climate change mitigation strategies will put both agriculture and natural resources under increasing pressures (Bonsch et al., 2016; Gosling & Arnell, 2016; Schewe et al., 2014). Despite large implementation obstacles (Arthington et al., 2018; Eker, Reese, & Obersteiner, 2019), both EFR protection and dietary changes seem indispensable in a broader context of the twin challenge of reaching food security within environmental limits (Jägermeyr, 2020) and need more political and social attention if ecological and social sustainability targets are to be met jointly.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/sus.2022.12

Acknowledgments. We thank Vera Heck for providing analysis scripts.

Author contributions. JB, FS and DG designed the study. JB analyzed the data and wrote the manuscript draft, with support from FS and DG. BLB contributed to specific parts of the study design and MJ to specific parts of the data analysis. All co-authors commented on and revised the manuscript.

Financial support. This work was supported by the European Union's Horizon 2020 research and innovation program (JB, grant agreement No. 869192), the German Federal Ministry for Environment, Nature Conservation, Building and Nuclear Safety (JB and FS, IKI project No. 16_II_148_Global_A_IMPACT) and the MVTT (MJ). FS additionally acknowledges funding by the CE-Land+ project of the German Research Foundation's priority program SPP 1689 'Climate Engineering – Risks, Challenges and Opportunities?'.

Conflict of interest. The authors declare they have no conflict of interest.

Data and code availability. Data supporting the results of this study are provided in the supplementary material. Model code and analysis scripts are available from the corresponding author on request.

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