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Contributions of dairy products to environmental impacts and nutritional supplies from United States agriculture

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ABSTRACT

Questions regarding the balance between the contribution to human nutrition and the environmental impact of livestock food products rarely evaluate specific species or how to accomplish the recommended depopulation. The objective of this study was to assess current contributions of the US dairy industry to the supply of nutrients and environmental impact, characterize potential impacts of alternative land use for land previously used for crops for dairy cattle, and evaluate the impacts of these approaches on US dairy herd depopulation. We modeled 3 scenarios to reflect different sets of assumptions for how and why to remove dairy cattle from the US food production system coupled with 4 land-use strategies for the potential newly available land previously cropped for dairy feed. Scenarios also differed in assumptions of how to repurpose land previously used to grow grain for dairy cows. The current system provides sufficient fluid milk to meet the annual energy, protein, and calcium requirements of 71.2, 169, and 254 million people, respectively. Vitamins supplied by dairy products also make up a high proportion of total domestic supplies from foods, with dairy providing 39% of the vitamin A, 54% of the vitamin D, 47% of the riboflavin, 57% of the vitamin B_{12}, and 29% of the choline available for human consumption in the United States. Retiring (maintaining animals without milk harvesting) dairy cattle under their current management resulted in no change in absolute greenhouse gas emissions (GHGE) relative to the current production system. Both depopulation and retirement to pasture resulted in modest reductions (6.8–12.0%) in GHGE relative to the current agricultural system. Most dairy cow removal scenarios reduced availability of essential micronutrients such as α-linolenic acid, Ca, and vitamins A, D, B_{12}, and choline. Those removal scenarios that did not reduce micronutrient availability also did not improve GHGE relative to the current production system. These results suggest that removal of dairy cattle to reduce GHGE without reducing the supply of the most limiting nutrients to the population would be difficult.
Key words: dairy, calcium, protein, greenhouse gas

INTRODUCTION

The Food and Agriculture Organization of the United Nations recommends that food production approximately double the levels in 2009 by 2050 to ensure sufficient human nutrition worldwide (FAO, 2009). Increased food production is a major challenge because of existing limitations in land and water availability, food distribution and storage solutions to eliminate food waste, and yield efficiencies, among other factors (Gupta and Deshpande, 2004; Bruinsma, 2009; Sauer et al., 2010). A common recommendation when considering this impending food crisis is to eliminate or reduce animal production in favor of plant production (Aleksandrowicz et al., 2016). Many consider livestock and poultry production to be resource-intensive in terms of land use, greenhouse gas emissions (**GHGE**), and water use per kilocalorie of food produced, having significantly greater environmental impacts when compared with plant-source foods (Clark and Tilman, 2017). Despite the simplification of this issue, the public frequently views animal production as resource-intensive without considering variability or other factors such as food nutrient profile or viability of alternatives. There is also a portion of US society that strongly opposes the consumption of dairy products for reasons not related to GHGE, leading to the need to assess how humans could meet nutrient requirements without certain animal products. Accordingly, some research has called for reduced consumption of animal-derived foods (Pimentel and Pimentel, 2003; Weber and Matthews, 2008). Research from Shepon et al. (2018) and Searchinger et al. (2018) points out the potential for more efficient production of nutrients in plant-based systems.

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Shepon et al. (2018) claims that plant-based alternatives could replace nutrient contributions of each major livestock animal with 2 to 20 times the efficiency due to inefficient feed-to-food conversion in livestock. When considering the consumption of some animal products, Van Zanten et al. (2018) proposed the use of animals fed only "low-opportunity-cost feedstuffs," that is, feeds not consumable or not desired by humans. This method of using animals that do not consume any of the human-edible biomass would increase arable land availability for crops and still provide some of the nutrients associated with livestock production. Some suggest the near elimination of animal agriculture because of environmental, human health, and ethical issues (Willett et al., 2019). However, an assessment of US agriculture revealed increased micronutrient deficiencies in terms of human nutrient requirements per year (**HNRY**), despite greater food availability in a simulated system without farmed animals as food resources (White and Hall, 2017). A major difference between the White and Hall (2017) assessment and other studies is the assumption regarding land use in a system without animals. White and Hall (2017) assume similar land use to the current agricultural system, and other assessments assume land use will adapt to meet food demand (Emery, 2018). Neither of these strategies is ideal (Springmann et al., 2018) given that agricultural land use is dynamic and governed by physical, climatological, biological, economic, and social factors. As such, there is a need to consider the mechanics of how land use within the agricultural system might adapt under a scenario where society moves toward reduced consumption of animal products.

An additional important consideration in these assessments involves the assumptions about what happens to the supporting animal populations when we reduce consumption of animal-source foods. Although it may be easy to recommend a world without livestock, it is less comfortable to discuss how we might get to such a world. Assessing elimination of dairy cattle production is a logical starting place for this type of assessment for several reasons. First, dairy cattle predominantly consume TMR in confinement systems, making cows accessible, which allows for easier implementation of strategies aimed at reducing production (entire elimination and movement to pasture-based production, among others). It is important to consider these strategies for scaling back production because the environmental and human-food benefits from entire depopulation of cattle will undoubtedly differ from the benefits if cattle persist as a feral or semi-managed population. Dairy is also an interesting case because dairy products have unique nutrient composition (USDA, 2018b), and production of milk from dairy cattle has a lower environmental impact than does meat production (Nijdam et al., 2012; Luo et al., 2015) and some plant-source products, such as lettuce (Marvinney, 2016). Other research has considered the effects of rewilding, the effect of moving away from pastoralism toward more dense production using concentrates and grain. When nonlivestock animals, such as nondomesticated ruminants and termites, move into areas previously used by livestock, there is a significant effect on GHGE (Manzano and White, 2019). As such, understanding what role dairy products, specifically, play in the US agricultural system and the nutritional and environmental impacts associated with removing dairy production would be of use in assessing dairy production's utility in the US food production system.

The objectives of this study were (1) to ascertain the current contributions of dairy products to the nutrient supply in the United States, (2) to evaluate impacts of approaches to depopulation of the US dairy herd, and (3) to evaluate the potential impact of alternatives for land use for land previously used for crops fed to dairy cattle.

MATERIALS AND METHODS

Data on US dairy production were obtained from the analysis conducted by White and Hall (2017), which used data from the US Department of Agriculture (USDA, 2018a), Economic Research Service (USDA/ERS, 2018a,b), and Food Composition databases (USDA, 2018b), as well as the US Environmental Protection Agency (US Environmental Protection Agency, 2010), the United Nations Food and Agriculture Organization (FAO, 2013), and other peer-reviewed, published sources to estimate nutritional and greenhouse gas (**GHG**) contributions of livestock to US agriculture. In the current work, we disaggregated the reported animal metrics to specifically assess the contributions of the US dairy industry to nutrient supply and GHGE within the agricultural system. Unless otherwise specified, metrics are estimated as described in White and Hall (2017). The US population nutrient requirement estimations were created using 39 nutrients in the categories of energy, protein, carbohydrates, vitamins, minerals, AA, and fatty acids. The distribution of ages and sexes in the population was used to weight the nutrient requirements needed and produce the average nutrient requirement values for each nutrient per year, referred to as HNRY throughout. All GHGE estimations were derived from published life-cycle assessments or publicly available databases. All assessments terminated at fluid milk production and did not consider further processing; it did not include foods derived from dairy animal carcasses.

Scenarios for Removing Dairy Products for US Use

We assessed 3 scenarios that differed in their assumptions about the removal of dairy cattle from the agricultural system. The method of animal removal was an attribute in the scenarios studied because it addressed societal concerns about the fates of animals and affected alterations in GHGE and land use. Assuming the US stopped consuming dairy products, the possible scenarios evaluated were: (1) depopulation (**DEP**), (2) current management; export dairy (**CME**), and (3) retirement (**RET**). In DEP, dairy animals would be depopulated in response to consumers ceasing consumption of dairy products. In CME, dairy cattle would be kept under current management, and milk produced would go to products other than human food or would be entirely exported for human consumption. In RET, dairy cattle would be retired to a pasture-based management system. In this third scenario, the number of lactating cows in the national herd was reduced to that which could be supported by the available pastureland. Land use was a focus in all animal removal scenarios because of the concerns raised in response to previous work (White and Hall, 2017; Emery, 2018; Springmann et al., 2018; Van Meerbeek and Svenning, 2018) and in the surprising findings of increased GHGE related to increased fruit and vegetable production that we have previously reported (White and Hall, 2018).

Depopulation. In simulating DEP, we only compared diets for the US human population and outputs before and after cattle depopulation. We considered the transition period to be instantaneous. That is, no food product resulted from the slaughter of the dairy cattle population, given the short duration and nonrenewable nature of the event. If dairy cattle are no longer present in US agriculture, we must consider downstream effects such as handling of pasture and grain land previously used for production of dairy feed, disposition of byproduct feeds, and fertilizer sourcing.

We modeled several cropland allocation options to reflect different sets of assumptions for repurposing land for crop production that previously grew feed for dairy cattle. White and Hall (2017) assumed that all cropland used to grow grain crops for animal feed would continue to be used for growing grain, though others contended that it may be more appropriate to reallocate this land along with the land used for silage production for the cultivation of nongrain crops (Emery, 2018; Springmann et al., 2018; Van Meerbeek and Svenning, 2018). Here, 2 options for dairy land reallocation to other crops were tested: (1) reallocate silage land only or (2) reallocate silage and grain land. All DEP scenarios did not repurpose pastureland because we assumed it could be repurposed for beef cattle production. To test how land-use change might influence scenario outcomes, we tested each of 4 land use (**LU**) options (LU-1 through LU-4) with reallocation of newly available land previously used to produce silage, or grain and silage, for dairy cattle. For LU-1, current proportions, all newly available land was replaced with crops according to the current proportions of crops grown in the United States; for LU-2, fruits and vegetables, all newly available land was planted to fruits and vegetables only, according to their current proportion of fruits and vegetables in the United States; for LU-3, nuts and legumes, all newly available land was planted to nuts and legumes only, according to their current proportion of nuts and legumes in the US; and for LU-4, non-grain, -oilseed, and -sugar, all newly available land was planted to any crop except those used to produce grains, oilseeds, and sugar, according to their current proportion of only those crops in the United States. Figure 1 shows land reallocation and land-use options within DEP. Table 1 shows land-use allocations for all scenarios.

We assumed land used for silage crops (3.1 million ha) to be dairy-specific and repurposed for production of other crops. To test the effect of reallocating the land for grain consumed by dairy cattle, it is essential to calculate the land area used for producing grain for dairy cattle. Eshel et al., (2014) estimated the proportions of grain consumed by the dairy industry (kilogram consumed by dairy cattle per kilogram produced). Yield data from USDA (2018a) was used to estimate land area for grain (proportion of grain consumed by dairy multiplied by land area for grain production). That liberated land area for grain (3.7 million ha) was then reallocated based on the previously described land-use options (Figure 1).

Other important assumptions in each dairy scenario included handling of byproduct feeds and fertilizer from dairy cattle. In DEP, other livestock used all dairy production byproducts, resulting in no net GHGE from the disposal of byproducts. Synthetic fertilizers replaced fertilizer produced using dairy manure nutrients, and these synthetic fertilizers accounted for additional agricultural GHG.

Current Management; Exports, No Human Products. Under CME, we assumed that dairy products would be exported with none entering the US food system, but the industry would continue to house and manage cows and bulls in a similar manner to the current practice. In this scenario, we assume no land liberation because cows would continue to eat silage, grain, and pasture as they do today. As such, none of the land-use options applied to CME. Similarly, dairy cows would continue to consume byproduct feeds and all manure would still be available for use as fertilizer.

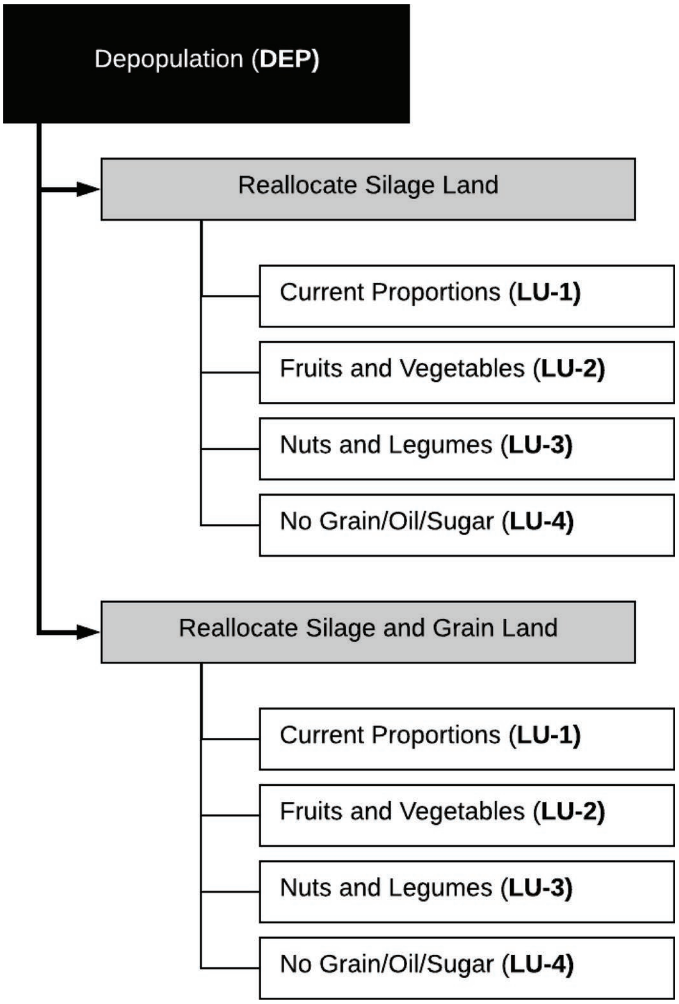

Figure 1. Description of the depopulation scenario describing how dairy cattle would be removed from US agriculture. Two different land reallocation options were used: reallocate only silage land previously used for dairy or additionally take grain land previously used for dairy out of production. The 4 uses for reallocated land are shown as LU-1 through LU-4: allocate new land based on current land use (LU-1), based on all land transferred to increasing production of fruits and vegetables (LU-2), to increasing production of nuts and legumes (LU-3), or to increasing production of all products except grains, oils and sugar (LU-4).

Essentially, CME retained all aspects of our current system, except for nutrient availability from dairy products and meat from culled animals to the US population. Although the DEP scenario would likely be met with concerns of how and if all dairy cows would be depopulated, the CME scenario maintains all cows and would likely be considered if humans were more opposed to the consumption of dairy products than the GHGE effects.

Retirement. Retirement reflects the idealistic perspective of ending milk production while allowing remaining dairy cattle to continue in a pasture-based setting. This scenario reflects what might happen if we allowed a reduced population of cattle to roam and breed freely on unmanaged grassland areas. The RET scenario also addresses the magnitude of possible animal numbers given the carrying capacity of the land and impacts of the retained herd. We assumed equal pasture and silage land areas for cattle roaming compared with current day dairy production. We did not assess costs of fencing, infrastructure, or other peripherals. The conversion of silage land and use of pastureland means that none of this land would be available for additional crop production; as a result, this scenario did not consider any of the land-use options described in DEP. The carrying capacity of cows on this land was calculated based on maintenance intake (National Research Council, 2001) of pasture (12.8 kg of DM/d) and an estimated annual yield of 6,200 kg of DM/ha of pasture. The carrying capacity was estimated at 4.176 million individual animals, which is approximately 44% of the current dairy cattle population (USDA, 2018a). To achieve this population size, animals would either have to be released onto the fenced lands, leading to issues of survival and oscillations in population size with changes in pasture availability, or humans would have to intervene to cull the animals in excess of the carrying capacity of the available pastureland.

Handling of byproduct feeds and fertilizer in RET was assumed to be a hybrid of the DEP and CME. Byproduct feeds previously consumed by dairy cattle were assumed to be repurposed for consumption by other livestock industries, meaning that no environmental penalty was considered for byproduct feed disposal. Although it is possible for animals to be maintained on pasture in a low-input management system that produces some meat and milk, this possibility was not included in calculations. Furthermore, even though some meat and milk products could be taken from retired dairy cows, the purpose of RET is to provide an alternative to simply removing all cows from production, as in DEP. Nutrients in dairy manure were assumed to be deposited directly onto the pasture and not recovered for use as fertilizer. As such, we assumed that additional synthetic fertilizer would be produced to replace the manure fertilizer that would previously have been produced by the dairy industry and used on cropland.

In previous work by White and Hall (2017), the production of food products estimated the carbon footprint of the agricultural system. The kilograms of milk produced by all dairy cows estimated the GHGE associated with the dairy industry, approximately 1.23 kg of carbon dioxide equivalents (CO_2-e) per kilogram of fat- and protein-corrected milk (Thoma et al., 2013); however, the carbon footprint estimate for milk is only valid for the current US dairy industry and would not be an appropriate reflection of the emissions from the dairy cattle RET system. As such, we only used enteric and manure methane and nitrous oxide emissions to estimate emissions from RET. Enteric methane emissions were estimated based on the equations listed in (Ellis et al., 2007) and pasture composition data from the DairyOne feed library (dairyone.com). Manure methane and nitrous oxide emissions were calculated using Intergovernmental Panel on Climate Change tier II methodology (Eggleston et al., 2006). Methane and nitrous oxide were converted to CO_2-e assuming 25 kg of CO_2-e/kg of CH_4 and 289 kg of CO_2-e/kg of N_2O. These CO_2-e were used for consistency with other GHGE estimates, though it should be noted that other research has called into question the validity of CO_2-e estimates on enteric methane estimates (Allen et al., 2018).

Comparisons Among Scenarios

The proposed dairy cow removal scenarios, land reallocation, and land-use options described above were intended for specific comparisons. The way in which cattle are removed from the food production system was examined by comparing DEP LU-1 (current proportions) with silage and grain land reallocation, CME, and RET. This comparison is important because the way in which we eliminate or export production has potential relevance on the environmental impacts and nutritional profile (in terms of HNRY) of the food produced by the agricultural system. A second set of comparisons relies on evaluating the different land-use options within the DEP scenario. If we were to remove dairy cattle entirely from US agriculture, it is important to consider what agricultural products might take their place.

RESULTS AND DISCUSSION

Current Contributions of the Dairy Industry to Nutrient Supplies and GHG Emissions

Dairy products contribute substantially to the supply of human-edible nutrients in the current US agricultural system. The current system provides sufficient fluid milk to meet the annual energy, protein, and calcium requirements of 71, 169, and 254 million people, respectively. Calcium content and availability in dairy products makes it feasible to meet calcium nutrient requirements from foods, whereas achieving that on a strictly plant-based diet is largely impractical without fortification or supplements (Weaver et al., 1999). Dairy products are a significant component of the protein supply in the US, providing 20% of the protein and 20 to 30% of many essential AA. According to previous assessments, the digestible indispensable AA score (**DIAAS**; a reflection of the nutritional value of proteins to humans) of whole-milk protein is greater than that of legume protein sources by 15.5% (Ertl et al., 2016) to 30% (Rutherfurd et al., 2015). The new DIAAS system measures the true ileal digestibility of proteins. The DIAAS system gives greater credit to the AA quality of animal protein sources for meeting human needs than the previous protein digestibility–corrected AA score system, which truncated the sum of values of animal proteins at 100% and generally overestimated nitrogen digestibility of plant-based proteins (Rutherfurd et al., 2015). A report by the FAO (2013) recommended the adoption of DIAAS as a replacement for the protein digestibility–corrected AA score system as a more accurate descriptor of protein nutritional value.

Vitamins supplied by dairy products also make up a high proportion of total domestic supplies, with dairy

Table 1. Comparisons of all scenarios and land-use allocation options used in study

		Change from baseline land use[1] (%)							
Category	Baseline (ha)	Current, no reallocation	Current, reallocation	Fruits and vegetables, no reallocation	Fruits and vegetables, reallocation	Nuts and pulses, no reallocation	Nuts and pulses, reallocation	Nongrain, no reallocation	Nongrain land use, reallocation
Fruit	1,181,058	2.8	6.3	119.7	261.0	0.0	0.0	8.6	18.7
Grain	69,749,095	2.8	0.7	0.0	−5.3	0.0	−5.3	0.0	−5.3
Legume	32,416,697	2.8	6.3	0.0	0.0	9.2	20.1	8.6	18.7
Nut	1,205,757	2.8	6.3	0.0	0.0	9.2	20.1	8.6	18.7
Oil	4,849,841	2.8	6.3	0.0	0.0	0.0	0.0	0.0	0.0
Sugar	832,723	2.8	6.3	0.0	0.0	0.0	0.0	0.0	0.0
Vegetable	1,410,691	2.8	6.3	119.7	261.0	0.0	0.0	8.6	18.7
Hay	19,578,913	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Silage	3,101,221	−100.0	−100.0	−100.0	−100.0	−100.0	−100.0	−100.0	−100.0
Croppable pasture	57,278	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[1]Change is the percentage increase or decrease of hectares used in the alternative land-use allocation compared with the baseline.

providing 39% of the vitamin A, 54% of the vitamin D, 47% of the riboflavin, 57% of the vitamin B_{12}, and 29% of the choline available for human consumption in the United States. These vitamins are often in low supply in the US food production system (White and Hall, 2017), but are essential for eye (vitamin A), bone (vitamin D), brain (vitamin B_{12}), organ health (choline), and energy metabolism (riboflavin). A study of the contribution of dairy products to essential micronutrient intakes in France identified vitamins (B_{12}, choline, D, and A) as important contributors of dairy to human diets (Coudray, 2011).

In agreement with the present study, numerous other reports have identified the nutritional importance of dairy products in developed (Hess et al., 2015) and developing countries (Hoddinott et al., 2013; Murphy et al., 2016). In particular, studies find that dairy products are an important source of Ca (Murphy et al., 2016), a macromineral essential for bone and tooth health, muscle and enzyme function, and blood clotting, among other functions. Dairy products provide a greater amount of absorbable Ca per serving than the majority of vegetable sources (Weaver et al., 1999). Although this study only followed fluid milk production, it is also important to note that microorganisms in fermented dairy products can also contribute to human health (Fernández et al., 2015) both directly (probiotics) and indirectly through the production of metabolically active compounds such as vitamins, linoleic acid, and others. As with other foods, dairy products are not free from speculation about negative effects on human health. Melamine-tainted milk can be toxic, especially to infants, and is added to milk to boost apparent protein content; additionally, male milk-drinkers may be more likely to get prostate cancer (Thorning et al., 2016; Zhu and Kannan, 2018). However, the role of dairy products in providing a substantial supply of essential, bioavailable nutrients for human consumption is clear.

The US dairy industry accounts for 16% of GHGE from all of US agriculture (White and Hall, 2017). Based on the 2020 inventory of US GHGE and sinks from the Environmental Protection Agency, 9.9% of total US GHGE were the result of agricultural activities (US Environmental Protection Agency, 2020). This estimation accounts for direct GHGE inputs only. Using the assumption that dairy production accounts for 16% of agricultural GHGE, and agricultural emissions makeup 9.9% of total US GHGE, our numbers suggest that the US dairy industry is responsible for approximately 1.58% of total US GHGE. All subsequent results regarding GHG values and reductions reported herein will be in terms of their proportion of current agricultural GHGE.

Impacts of Cattle Removal Strategy

If the United States were to discontinue dairy production, the question of what should happen to the current dairy herd carries animal welfare and public perception concerns. Figure 2 shows the estimated total agricultural GHGE with each of the 3 dairy cow removal scenarios (DEP, CME, and RET) compared with current production. Figure 3 includes the nutrient supplies estimated from these scenarios. By design, CME showed no difference (±0.0%) from current production in terms of GHGE (Figure 2), as dairy production continued, and products were not used as human food in the United States. Additionally, using dairy cows for nonconsumable products (i.e., leather, animal feed, or manure) and exports yielded a decrease in many domestic, human-edible nutrient supplies in terms of HNRY when compared with current diets and when compared with the DEP scenario (Figure 3). A RET scenario showed an 11.97% decline in total agricultural GHG (Figure 2) compared with current emissions. This GHG decline with RET is likely because of the reduced population of cows sustainable on available pastureland. Despite this improvement in agricultural GHGE with RET, domestically available supplies of all nutrients decreased. The CME and RET scenarios used the same amount of land and therefore both averaged an 18% reduction in HNRY supply compared with current production across all nutrients measured (Figure 3). All 39 nutrients either declined or remained the same in CME and RET. Total energy HNRY harvested from the agricultural system in RET decreased by 11% compared with current production. Although CME and RET could be considered more publicly-favored because they retain dairy cows in the United States, the DEP scenario allows more freedom in terms of land reallocation. Under DEP assumptions, GHGE declined 7.2% compared with current levels (Figure 2). Nutrient supplies under DEP rose 42% on average, with 30 of the 39 nutrients measured increasing compared with levels in our current system. However, several essential nutrients declined. Comparing potential dairy removal scenarios demonstrated the likely trade-offs inherent in effecting change in agricultural systems; namely, it is difficult to find scenarios that simultaneously increase supplies of critically limiting nutrients and decrease GHGE. Table 2 compares GHGE changes on the basis of total agricultural GHGE, dairy GHGE only, and total US GHGE.

Although RET has limited economic justification, it was important to assess it from the social dimension. The approximately 44% of the national dairy herd retired to pastureland would produce 11.6% less of national agricultural GHGE, declining from the current

16% because of 2 major factors: reduced numbers of cows and change in the management of those animals. Because existing pastureland would need to sustain all retired cows, RET would sustain only an estimated 44% of the current dairy cattle population. Additionally, whereas current dairy production relies heavily on high intakes (25–30 kg of DM/cow per day) of TMR comprising silage, grains, and byproduct feeds to support milk production, the RET scenario assumed low intake (12.8 kg of DM/cow per day) of pasture only. These differences are important because methane emissions on forage-based diets are proportionally higher than diets with greater inclusion of cereal grains and byproduct feeds, and because total feed (energy) intake is the major driver of emissions (Johnson and Johnson, 1995). One important caveat is that cattle on pasture with adaptive multipaddock grazing schemes have shown potential to offset carbon emissions through additional carbon sequestration in the soil (Stanley et al., 2018). Carbon sequestration is not considered explicitly in the Intergovernmental Panel on Climate Change tier II methodology, making findings such as those in Stanley et al. (2018) important to consider. Land use in these more efficient grazing schemes is typically greater than less intensive methods, but findings related to carbon sequestration provide an avenue for a shift to pastoral systems without greater GHGE costs. A lesser factor contributing to the decline in GHG under RET is the accounting of emissions associated with fertilizer synthesis. In RET, we assumed synthetic fertilizer production would increase because of the challenges associated with harvesting fertilizer from pasture systems. This synthesis of fertilizer, through processes such as the Haber Bosch process (Haber and van Oordt, 1905), accounted for a 1.0% increase in agricultural GHGE in RET, or about 9% of the GHG that would have been lost by removing excess dairy cows.

Although GHGE considerations are important, dairy cows must ultimately produce foods for human consumption. In addition to achieving minimal or no reductions in GHGE, estimated production decreased in many nutrients in scenarios which retained dairy cows

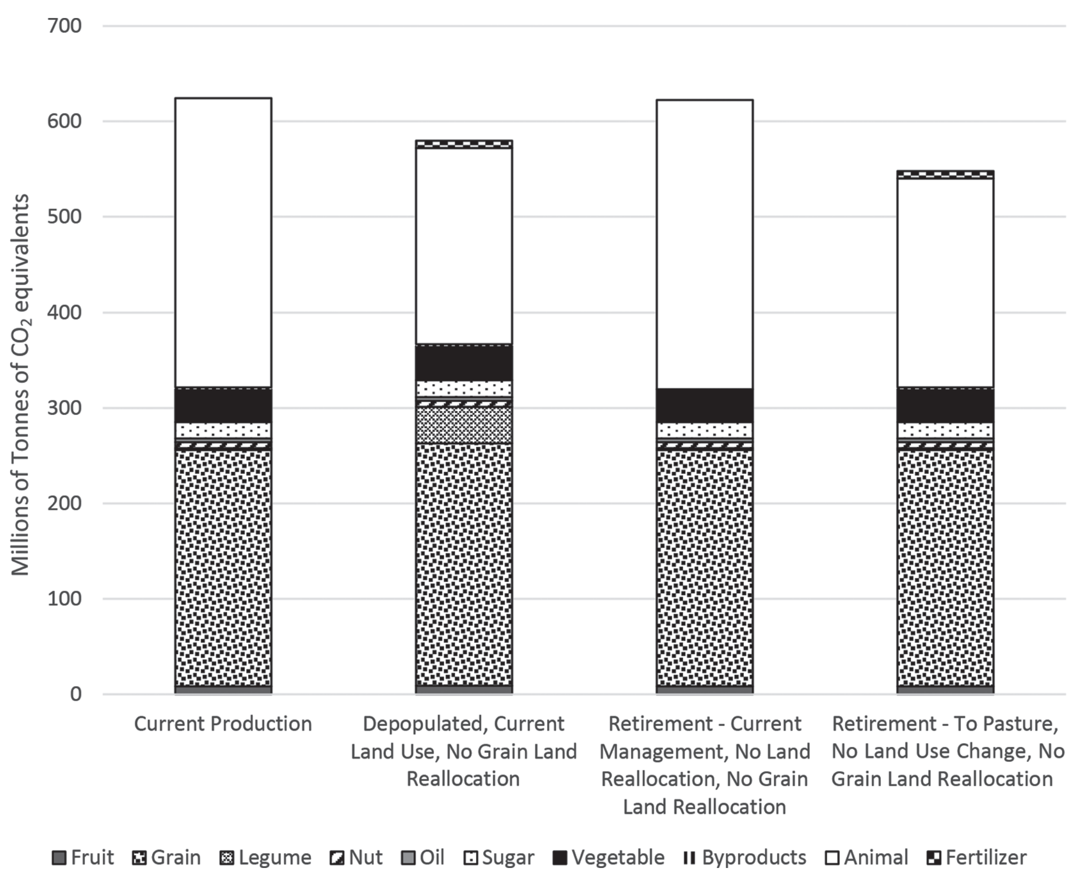

Figure 2. Comparison of greenhouse gas emissions from agriculture in kilograms of CO_2 equivalents between the current production system and 3 alternative scenarios: depopulation = all dairy animals are removed; current management with exports = a scenario where animals are kept under current management and dairy products are not consumed in the United States; retirement = dairy animals are retired to a pasture-based system.

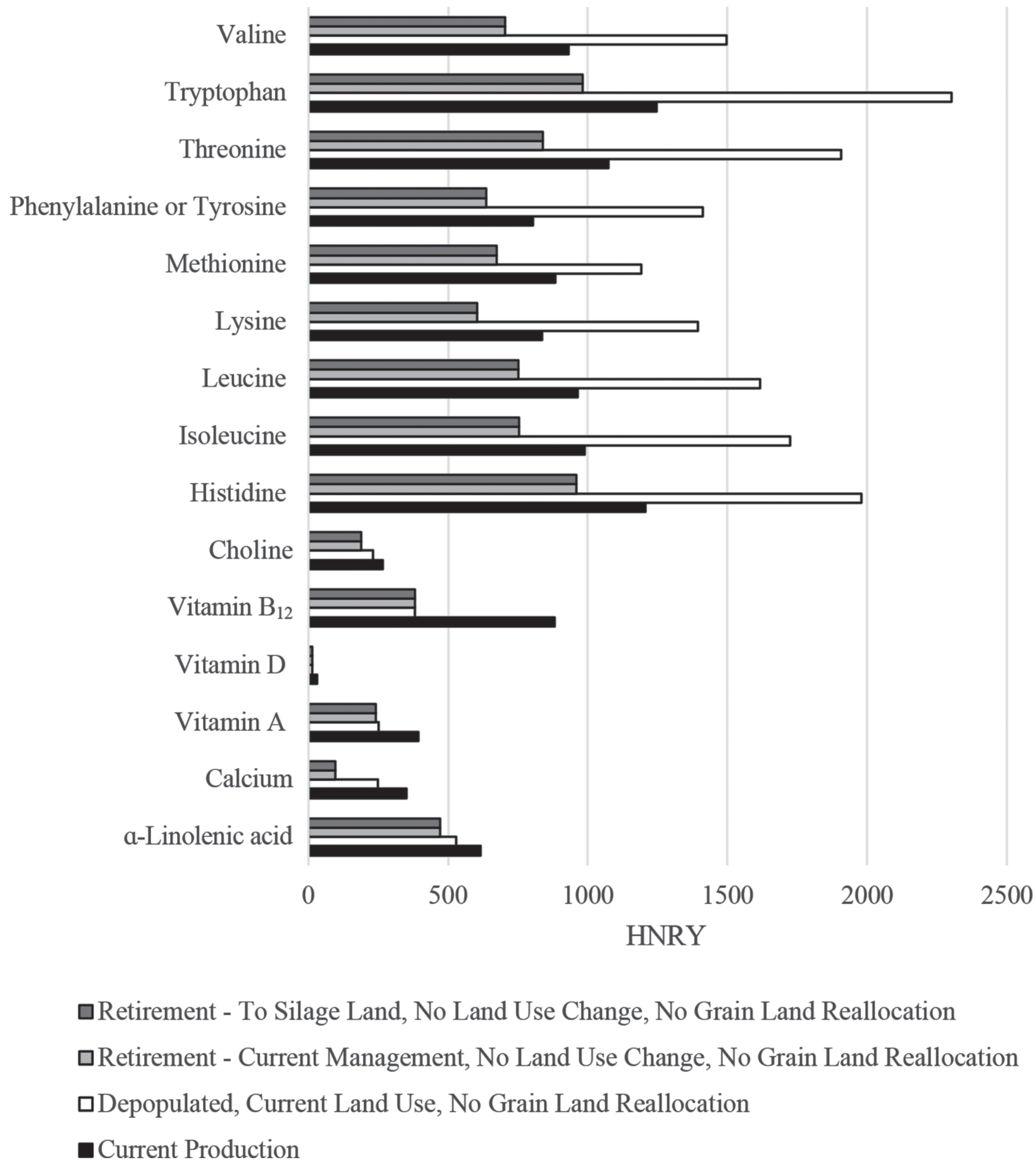

Figure 3. Nutrient supply of current production compared with that of 3 dairy cow removal strategies in terms of human nutrient requirement years (HNRY) met, in millions.

Table 2. Percentage change in greenhouse gas (GHG) emissions of 4 select scenarios on the basis of US dairy GHG, total US agricultural GHG, and total US GHG

Item	Depopulated, current land use, no grain land reallocation	Depopulated, current land use, grain land reallocation	Retirement—current management, no land reallocation, no grain land reallocation	Retirement—to pasture, no land-use change, no grain land reallocation
US dairy GHG (%)	−42.98%	−31.93%	0.00%	−74.84%
US agricultural GHG (%)	−6.88%	−5.11%	0.00%	−11.97%
US total GHG (%)	−0.58%	−0.43%	0.00%	−1.01%

(CME or RET) when compared with the current HNRY supply. Calcium, α-linolenic acid, vitamin A, vitamin D, vitamin B_{12}, choline, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine all decreased 20% or more in HNRY in CME and RET scenarios compared with current production system (Figure 3). Total protein is not in the figure because its decline relative to the baseline was only 19%. Relative to the current contributions of dairy to the US agricultural system, domestically produced supplies of Ca (−72.6%), vitamin B_{12} (−56.7%), and vitamin D (−53.9%) were the nutrients most markedly affected by retiring dairy cattle. These reductions translate to 254 million less people meeting their Ca requirements for the year, 500 million less for B_{12}, and 16 million less for vitamin D. The nutritional importance of Ca to humans was discussed above. Vitamin B_{12} is essential for normal function of the central nervous system, formation of red blood cells, and cellular metabolism (Wokes et al., 1955), and is particularly important for the correct development of the brain (Müller-Wielsch et al., 2010). Vitamin D is essential for skeletal homeostasis and prevention of bone disorders. Additionally, suboptimal vitamin D status is implicated in chronic autoimmune and cardiovascular disease, hypertension, and common cancers (Hewison, 2012). Although not considered specifically in this work, vitamin K_2 has recently been shown to have numerous health benefits not found in vitamin K_1, including anticancer effects (Tokita et al., 2006). Vitamin K_2 is commonly found in dairy products (Dasari et al., 2018). When considering the impact of removing any animal production system, we should consider the nutrients produced and the proportion of the population whose nutrient requirements will be met.

Impacts of Land Allocation Strategies

Of the approximately 134 million ha of land considered in this analysis, the 3.1 million ha of arable land previously allocated to silage was available for reallocation in DEP. Under LU-1 with silage and grain land reallocation, the grain supply decreased by 2%, and under LU-2, LU-3, and LU-4, grain production decreased by 5% compared with current production. Grains provide an energy- and nutrient-dense food source (Macdiarmid et al., 2012). Optimization of diets for either cost, environmental impact, or both tend to have high amounts of grains because grains can be produced efficiently and can also be fortified with missing, but required, nutrients (Clydesdale, 1994; Cook et al., 1997; Macdiarmid et al., 2012). The relatively small change in grain land when accounting for land previously used to feed dairy cattle suggest that dairy cattle consume very minimal quantities of human-edible grains grown specifically for them, and thus may be minimally competitive for human food.

Assessing the different land-use options makes it clear that shifts in use of relatively small land areas (e.g., the 3.1 million ha of land in the United States allocated to silage currently compared with the approximately 134 million ha of US cropland in the baseline scenario) can have substantial effects on the production of nutrients from the agricultural system. Figure 4 compares current or baseline GHGE to DEP with silage and grain reallocation and land use for fruit and vegetable production (LU-2). Figure 5 illustrates food production (in kg) and CO_2-e under LU-2, broken down by food product. Under LU-2 with silage and grain land reallocation, GHGE increased by 9.9% when compared with current emissions. However, LU-2 without grain land reallocation resulted in a net neutral effect (+0.04%) on GHGE. Following the assumptions of DEP with no grain land reallocation, using LU-1, LU-3, and LU-4 resulted in decreased GHGE of 6.88%, 8.18%, and 7.59% of agricultural GHGE, respectively, when compared with current production. Fruits and vegetables tend to be more carbon-intensive GHG-emitting crops compared with grains, making them less likely to appear in optimized diets (Macdiarmid et al., 2012; Wilson et al., 2013; Gephart et al., 2016). Although fruits and vegetables can provide some of the same nutrients as dairy products, such as vitamins A and C, the increased GHG cost makes this option less desirable. As described above, the non-fruit and -vegetable scenarios also resulted in reduced availability of critical micronutrients supplied in high concentrations in dairy products. Figure 6 compares the GHGE of all land reallocation scenarios and land-use options. As a result, our analysis suggests that although some land reallocation options result in a decrease in GHGE, they concomitantly decrease the supply of specific essential nutrients available to meet the requirements of the population.

The removal of dairy cows from the US agricultural system under DEP, with each land-use option, increased land available and crop yields (approximately 17%) in terms of total energy of nutrients supplied. However, under any dairy removal scenarios, the land allocation options further reduce the supply of vitamin D, choline, calcium, vitamin A, and α-linolenic acid, which are all within the 11 least abundant nutrients in our analysis. In the current food production system, calcium is in sufficient supply to meet the requirements of approximately 350 million humans. Under DEP with grain land reallocation and LU-1, LU-2, LU-3, and

LU-4, calcium supply would change by −89.1, −57.6, −87.4, −85.3 million HNRY, respectively. Figure 7 shows the changes in calcium and other least abundant nutrients within the DEP scenario under all land-use options with grain land reallocation. The data suggest reduced availability of these micronutrients, regardless of land use and grain land reallocation. The declines in supply of the most limiting nutrients of the US food production system illustrates the nutritional impact of removing dairy cows from agriculture: dairy cows provide a relatively efficient, nutrient-dense source of valuable micronutrients that cannot currently be mirrored in common plant-source foods.

Practical Feasibility of Land-Use Options

Another important consideration for the different land-use options is the actual suitability of land for various agricultural practices. There is diverse literature evaluating indices to characterize the suitability of agricultural land (Littleboy et al., 1996; Reshmidevi et al., 2009; Singha and Swain, 2016; Senagi et al., 2017). Although some horticultural crops, tree nuts, and fruits can be competitive with grain crops in terms of land use (Wolz and DeLucia, 2019), many are particularly sensitive to climate, and there is concern over how climate change will influence the productivity of these

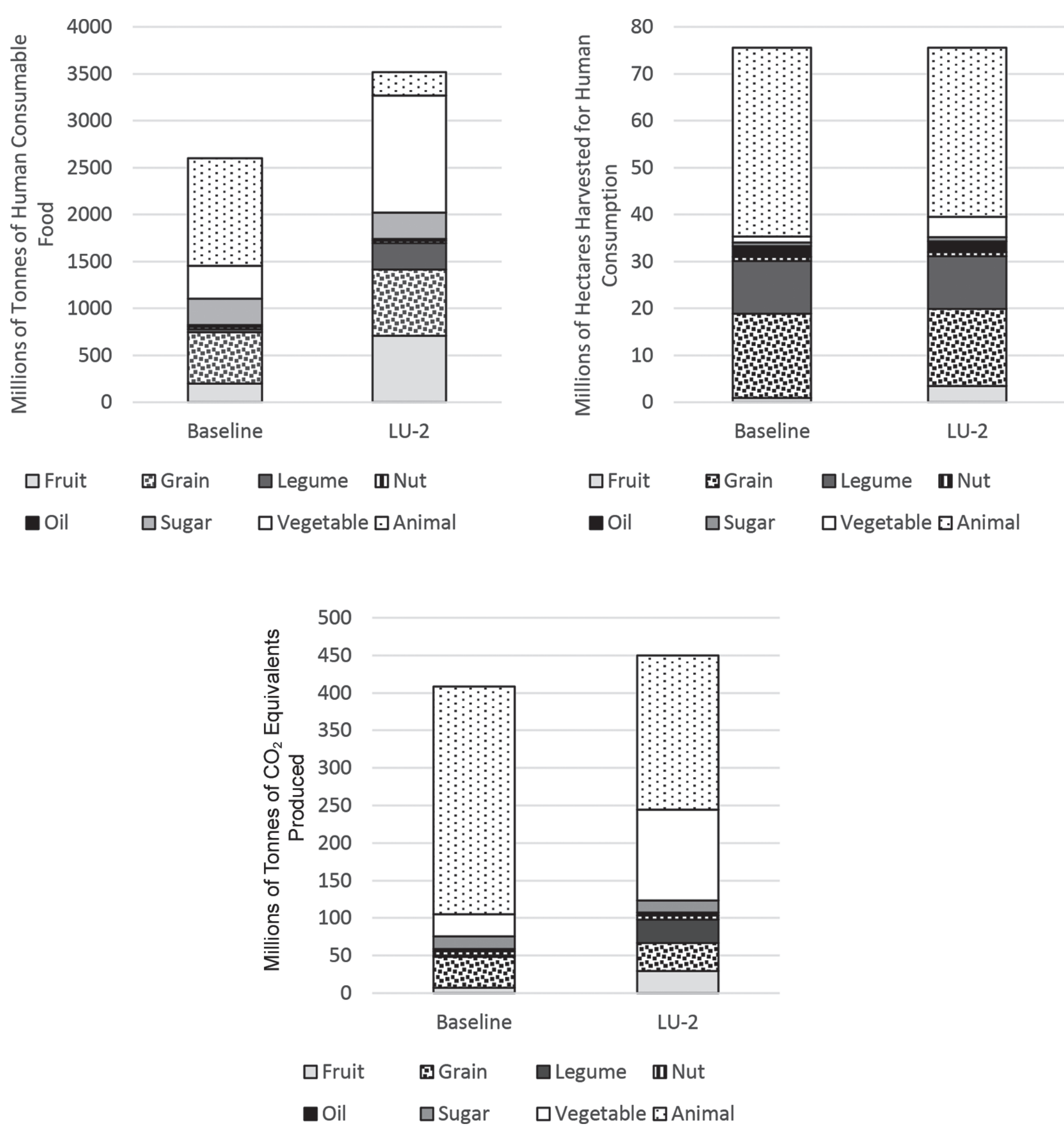

Figure 4. Comparison of land-use classifications under current conditions (baseline) and a scenario where grain land previously used for dairy cattle feed is repurposed for fruit and vegetable production (LU-2). Although land-use shifts involve only 6.8 million ha of land, the shifts in consumable food produced and in carbon emissions are substantial because of the high yields of fruit and vegetable products per unit of land area.

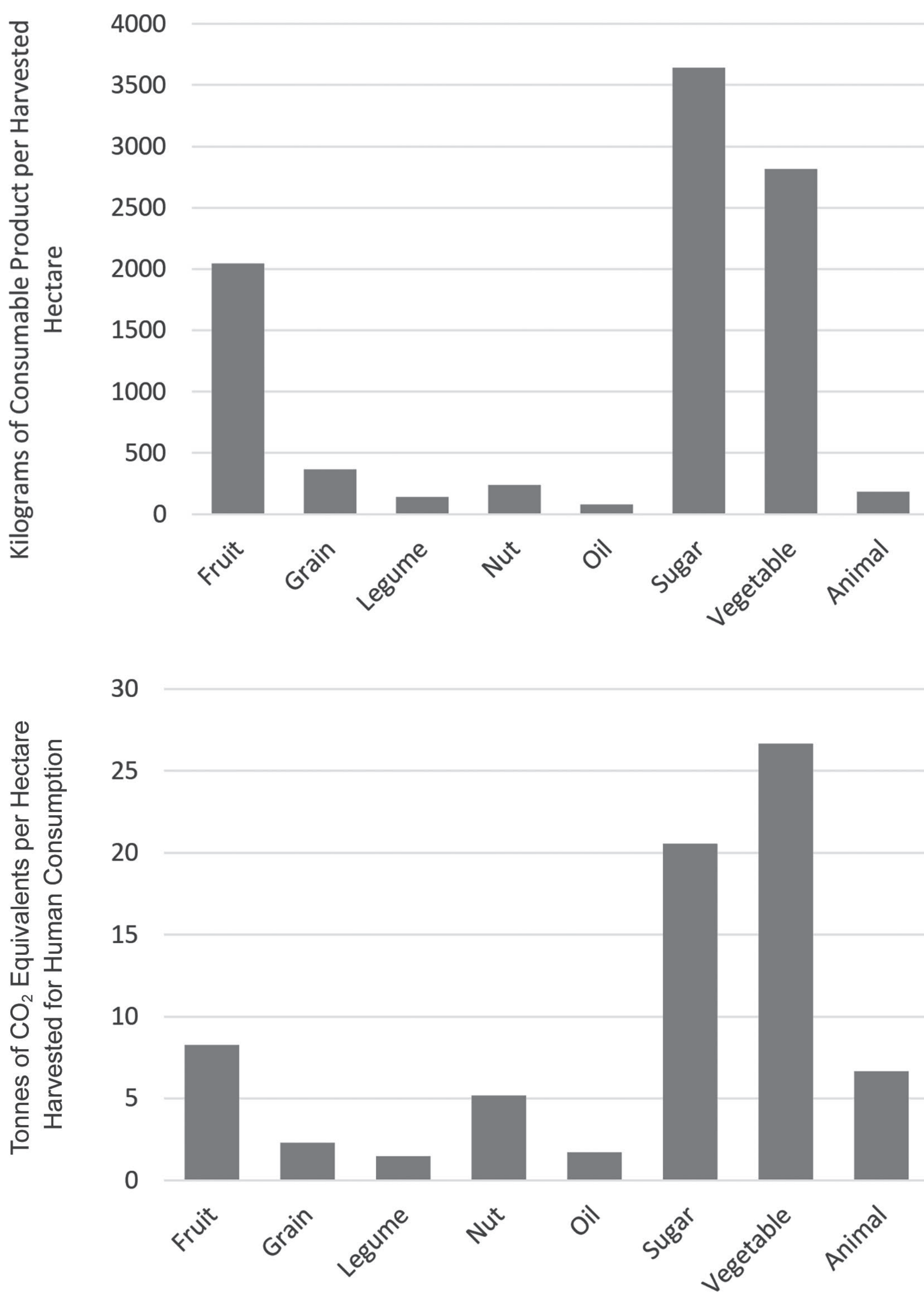

Figure 5. Consumable product and tons of CO_2 equivalents, broken down by food category, of a land reallocation strategy where grain land previously used for dairy cattle feed is repurposed for fruit and vegetable production. Fruits and vegetables account for an increased amount of consumable product, but also disproportionately increase total greenhouse gas costs.

crops (Luedeling et al., 2009; Parker and Abatzoglou, 2017). Indeed, a geospatial analysis of the United States based on suitability of land for growing selected fruits and vegetables suggests only 144,000 ha of agricultural land area is suitable for repurposing for fruit and vegetable production (Conrad et al., 2017). For reference,

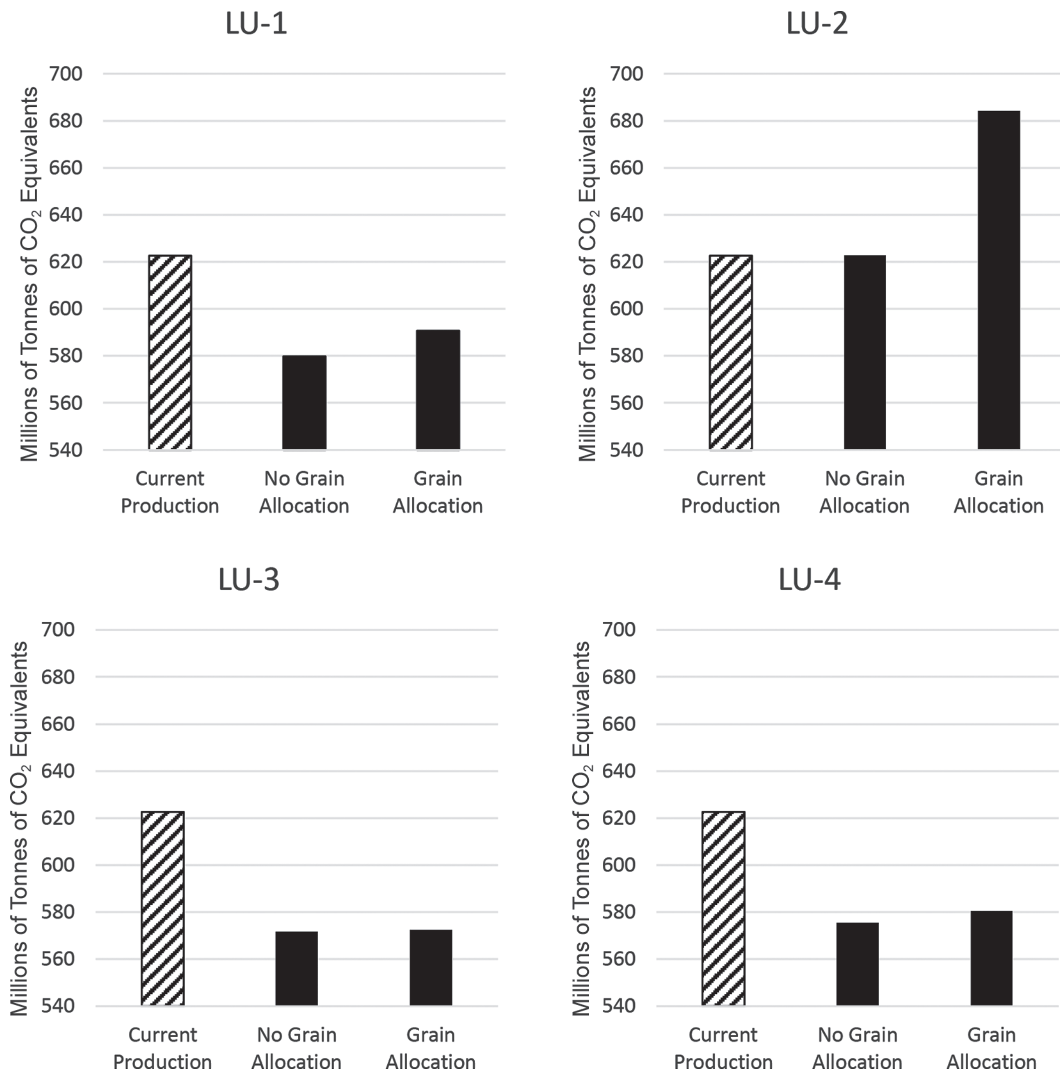

Figure 6. Comparison to current production system (baseline) of total greenhouse gas emissions under land reallocation scenarios using various crop replacement methods. LU-1 = replant vacated land with crops in proportion to their current production in the United States, LU-2 = replant land with only fruits and vegetables; LU-3 = replant land with only nuts and pulses; LU-4 = replant land in proportion to current US crop production without planting any additional grain. No Grain Allocation = only reallocate land directly freed from removal of dairy animals or used for silage. Grain Allocation = reallocate land directly freed from removal of dairy animals, used for silage, and used for dairy feed grain.

the current assessment reflects a 3.1 to 6.8 million ha change in land use (21–47 times the expected suitable land area). To effect such a change in land use, there would need to be substantial technological improvements to support growing fruits and vegetables on land currently unsuited to the purpose. Overall, analyses of the soil characteristics, climatological parameters, and other factors for agricultural areas across the United States suggest limited opportunity to expand fruit and vegetable production in particular, and we must take these practical challenges into account when planning alternative land uses in agricultural systems.

CONCLUSIONS

Our investigations into the impacts and alternatives when removing dairy cows from US production agriculture suggest that GHGE changes would be minor, equivalent to 0.7% of total US GHGE. Emissions increase under scenarios that reallocate arable land for production of more carbon-intensive crops, such as fruits and vegetables in LU-2, to improve the nutrient supply to the US population. At the same time, supplies of some limiting essential nutrients for the human population would decline under all dairy removal sce-

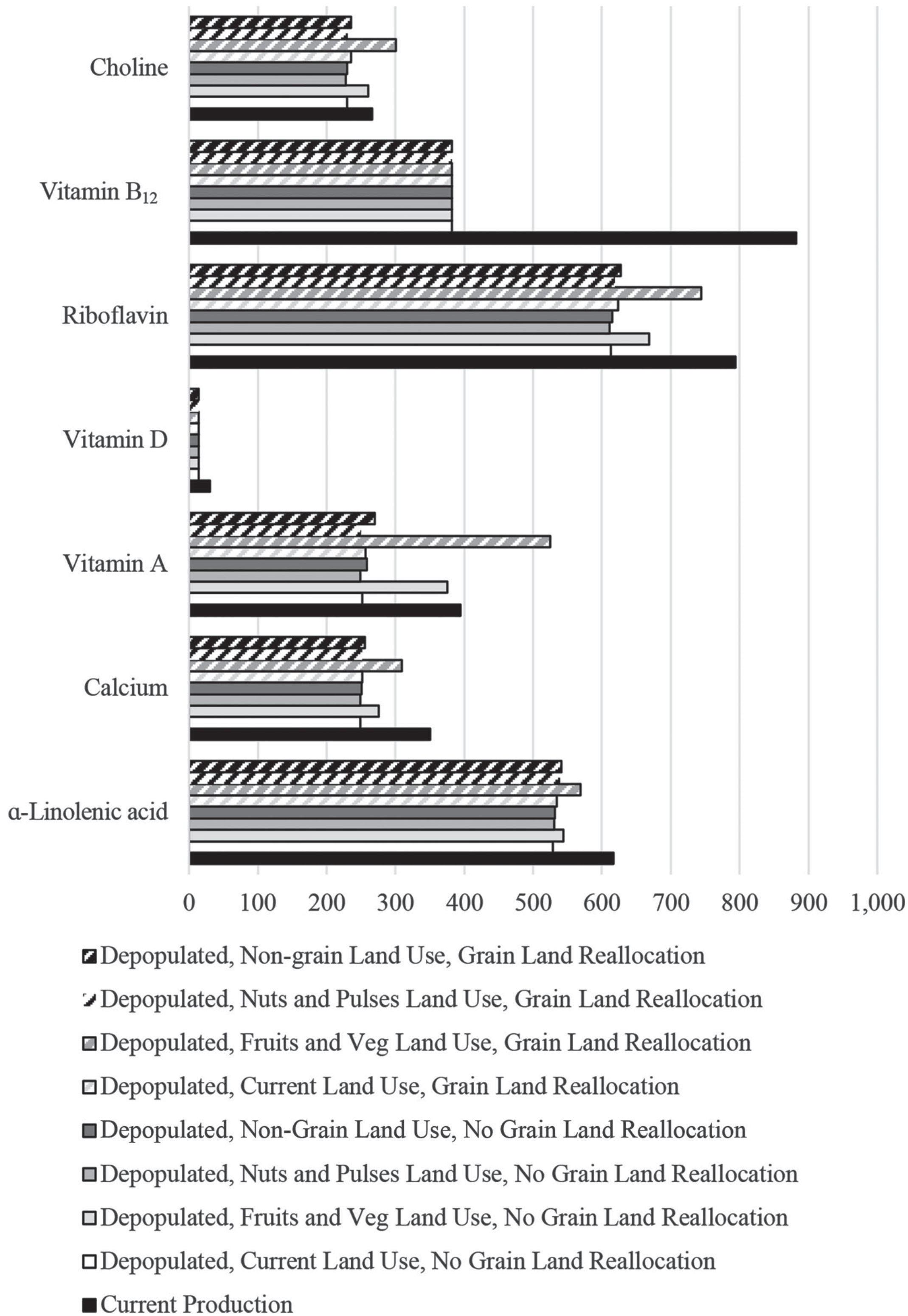

Figure 7. Comparison of nutrient supplies among land-use options in a scenario where dairy cattle are depopulated from the agricultural system. Nutrients shown are those that had reduced supply in one or more land-use option compared with the baseline scenario.

narios. Essential nutrient production decreased under all reallocation scenarios that decreased GHGE, making the dairy removal scenarios suboptimal for feeding the US population. Lastly, any reductions in GHGE or increases in available cropland for growing other crops come at the cost of culling more or all dairy cattle. Scenarios involving such culling incurs ethical costs not assessed in the current work.

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