

Integrated Approach to Climate Adaptation and Mitigation: Processed Potato and Tomato

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Abstract

Food systems are increasingly challenged to meet growing demand for specialty crops due to the effects of climate change and increased competition for resources. We apply a novel integrated methodology that includes climate, crop, economic, and life cycle assessment (LCA) models to US potato and tomato supply chains. We assess the effectiveness of changing management strategies to address climate change and the opportunity to relocate away from regions with increased water scarcity. We find that supply chains for two popular processed products in the United States, French fries and pasta sauce, will be remarkably resilient, through planting adaptation strategies that avoid higher temperatures. Land and water footprints will decline over time due to higher yields, and GHG emissions can be mitigated by waste reduction and process modification. Our integrated methodology can be applied to other crops and geographies, and the results could inform decision-making at multiple steps along supply chains.

Introduction

Food systems are now challenged as never before to meet nutrition needs in more sustainable ways¹. Specialty crops, including vegetables, are the cornerstone of healthy diets, and consumers are strongly encouraged to eat more of those². The supply chains for the many important foods produced from these crops are experiencing significant innovation and transformation as a result of multiple drivers, including demand for fresh produce grown locally; climate change and increased competition for natural resources; cost and availability of labor; efforts by supply chain actors to improve their sustainability profiles; and the rise of protected and peri-urban production². Modest increases in US dietary intake have been reported¹, but medium- and long-term prospects for greater production and consequently consumption of specialty crops are threatened by the combination of climate change and variability, extreme weather, loss of freshwater availability for irrigation, and increasing competition for other resources, including especially labor and land^{3,4}. Increasing temperature regimes in California are projected to significantly shift production of major fruit and vegetable crops by 2040⁵. Climate impacts extend beyond production, downstream through specialty crop supply chains, which have requirements that raise special concerns for decision-makers who might contemplate geographic relocation of production as a potential adaptive solution⁶⁻⁹. For example, processing plants are expensive, highly specialized and are usually located near the production areas, which presents a major financial barrier to relocation as an adaptation tactic. Such facilities also require ready access to water, energy, skilled labor and transportation. While many climate change challenges have been studied in detail for commodity cropping systems^{10,11}, there remains a large gap in our understanding of specific adaptation and mitigation options for specialty crops.

In order to begin addressing this gap, we have developed a novel integrated modeling methodology that includes climate, crop, economic, and life cycle assessment (LCA) models. The crop models are driven by current climate and future climate projections from global climate models and determine the impact of

climate change on yield and crop water demand in current production areas as well as for future production regimes. The crop simulations are used as input for economic models, which consider both technology and demand trends in order to determine land-use change and future grower profitability. Finally, LCA modeling integrates this information to identify and evaluate cost-effective adaptation and mitigation opportunities in current and potential future supply chains.

In our first application of this new approach, we identify climate adaptation and mitigation opportunities for potatoes and tomatoes, the most widely produced vegetable crops in the US with annual production of 67.9 and 36.8 kg per capita, grown on 0.46 and 0.14 million ha, respectively¹². The research reported here focuses on US supply chains for varieties of potatoes and tomatoes suitable for processing, which account for 61% of total potato and 92% of the total tomato production (see **Figure 1**)¹². Although we have chosen to report results here for just two products made from potatoes and tomatoes, the methodology is applicable to other food products.

Results

Our integrated modeling approach to climate adaptation and mitigation has shown an unexpected resilience in processing potato and tomato supply chains projected through 2050, even though we utilized a scenario of comparatively high greenhouse gas emissions, RCP 8.5¹³. Subject to water availability (not expected to be limiting for these high-value crops), an ensemble of crop models suggests relatively small impacts on yield in current production areas. When interpreting these results, however, it is important to note that the crop modeling did not consider extreme weather events or pest/disease pressures. Partial equilibrium economic modeling, accounting for domestic demand as well as international trade, indicates only minor changes in total production area and relatively flat net farm income through the forecast period. Lifecycle assessment of current and expected future impacts indicate that supply chain GHG emission intensity will remain stable at approximately current levels and water and land use will decline, driven by technology and expected yield increases.

Crop yield

Contrary to most results reported for major grain crops¹⁴, we find that the combined effects of technology gains and climate change impact on yield of both potatoes and tomatoes will be positive in most US regions through 2050. **Figure 2** is a typical example for processing tomatoes grown in the Crop Reporting District (CRD CA51) that covers California's San Joaquin Valley - with the largest production area in California for potatoes, tomatoes, and many important fruits and vegetables. The integrated modeling approach allowed us to separate the technology trend and climate change components in the overall rate

of gain in crop yield. The relative contributions to yield increase are about equal in this case and slow over time, as the technology trend is attenuated to 70% of its current contribution^{15,16}.

Crop yields are expected to continue to increase in most current production areas, but there are major differences (**Figure 3a and 4a**). Within each region, the clusters of bars show baseline and projected crop yield for each CRD that has current or future potential (based on our modeling results) to support local production of these crops. For potatoes, current yields are highest in eastern Oregon (OR30) and eastern Washington (WA20, WA50, WA90), and are projected to maintain this advantage through mid-century. Yields are significantly lower in the southern US, primarily due to the timing of planting (typically mid-winter, rather than the typical spring planting further north) to maintain seasonal uniformity in supply for processors and to avoid high summer temperatures in these regions.

Simulation results show a negative temperature effect on potato yield due to a shorter crop cycle and increased exposure to heat stress, but this will be more than compensated by the growth stimulus from elevated atmospheric CO₂ and a simple adaptation measure by shifting the growing cycle towards the earlier, cooler part of the year, leading to overall national increases of 9.7% (+/- 9.4%). With the projected overall higher yields, crop demand for NPK fertilizer will increase 4.8% by 2050, despite the reduced concentration of nutrients as a consequence of elevated atmospheric CO₂¹⁷. In addition, shorter growing seasons and elevated CO₂ through reduction of stomatal conductance of crops will cause a reduction in water demand by 9.3%, with the former being the dominant effect. However, increased pest/disease/weed pressure, the possible impact of excess water, and/or other extreme climate events (e.g. frost, strong wind) not considered here, could significantly lower future yield¹⁸.

With these same caveats, the projected climate impacts on processing tomatoes through the year 2050 are similar: national level, area-weighted yield will increase by 15.2% (+/- 6.9%), nutritional content will again be reduced due to higher CO₂, water use will decline by 15.2%, and NPK fertilizer demand will increase by 11.9%, assuming earlier planting dates as an adaptation measure.

Adaptation by earlier planting

Earlier planting as a simple adaptation measure, if the field cropping schedule allows for it, will improve yield in most US cropping regions. Earlier planting shifts the crop cycle into an earlier, cooler period, enabled by a general warmer climate. It also avoids or reduces exposure to increasing heat stress during

the growth of the harvestable product in eastern and northern regions during summer. In the American Southeast (SE) where potatoes and tomatoes are grown over a mild winter, increasing temperature mostly improves growing conditions without adding heat stress. In higher productive regions like the Pacific Northwest (PNW) where vegetables are grown in spring and summer, the increase in temperature and in particular heat stress in summer will have larger negative impacts on crop yield, albeit, on a higher yield level. In other northern regions currently less suitable for large scale vegetable production, a longer season could enable the production of these crops in the future.

Economic modeling results

Future total US production increases for potatoes and tomatoes will be sustained by higher yields, with minor area and geographical shifts, generally toward the higher-yielding and most profitable regions, continuing the historical trend¹² (**Figure 3a and 4b**). Profitability, as measured by net revenue of real (inflation-adjusted) US dollars per hectare, will likely decline slightly in the future (**Figure 3c and 4c**), which is again consistent with the historical trend¹². There will be some modest increases seen in production regions where yields are forecast to continue to increase, with the prices for both crops (expressed in real US dollars per kg received by the grower) continuing the historical decline of falling food prices. Processing tomato production is currently focused in California's CRD51 and CRD50 where processing tomato returns have been most favorable. The crop model results (with adaptation) indicate continued yield increase in these CRD's that contributes to steady returns. The economic model also predicts there may be opportunities for processing tomato production growth in Washington state where increased yield is expected to lead to more favorable grower economics. A few of the CRD's exhibit increased real net returns, including ME10, MI80, OR30, which have moderate levels of processing in place allowing crop area to expand.

Water use

Water use for potatoes and tomatoes through the farm gate is predominantly irrigation water. The dominant trend in our analyses suggests irrigation water use per unit of production for both crops will decline, as noted above. (**Figure 3d and 4d**). The regions with projected increases in water use are those with higher available irrigation potential (Great Lakes, Upper Mississippi, and Maine). These results are consistent with previous assessments of climate impact on regional irrigation demand¹⁹.

Overall environmental footprints

Cradle to grave LCA modeling of current and future US supply chains for French fries and pasta sauce are shown in **Figure 5**. The results reveal surprisingly high GHG impacts for the processing and consumption steps – in some cases considerably higher than on-farm activities. The farming system contributed 19% and 40% of GHG emissions for French fries and pasta sauce, respectively. This is primarily related to the production and use of agro-chemicals (NPK, micro nutrients and pesticides; ~10%), followed by energy consumed for farm operations (7%: potato and 22%: tomato). The processing stage contributed 34% and 39% to GHG emissions for French fries and pasta sauce, respectively. This is driven by use and disposal of packaging materials and transportation. Retail contributed from 11-25% for the processed products. The consumption stage was among the highest contributors, mainly for fries (40% of GHG emissions); driven by the use of vegetable oil for deep frying. Interestingly, the induced on-farm emissions required to compensate the losses/waste across the supply chain increase the environmental burdens by about 19% and 7% for French fries and pasta sauce. As shown in **Figure 5**, the projected future GHG footprints are essentially unchanged, while land and water footprints are lower in the future, given higher projected crop yield. Thus we expect mitigation options identified now will remain relevant through 2050.

Mitigation options

There are significant opportunities for mitigation of GHG emissions from these supply chains related to changes in method of transport (rail vs. truck), cooking method (baked vs. fried), and reduction of consumer food waste (**Figure 6**). Food waste is a significant contributor to climate change and we simulated the potential mitigation that could be achieved through halving the consumer stage losses^{20,21}. Changes in consumer behavior might be induced through modification of “use by” or “best by” date labeling and consumer education regarding the meaning of these labels so fewer products are disposed earlier than necessary²²⁻²⁴. We also evaluated adoption of alternate cooking (oven instead of deep frying) for French fries; the benefit is derived from removing the vegetable oil from the supply chain. Finally, we evaluated an alternate transportation scenario for inter-plant transportation of intermediate tomato products (rail replacing road).

Discussion

Despite the general perception that US agriculture is severely threatened by the combination of climate change, dwindling natural resources, and competition for labor, this novel integrated approach demonstrates that supply chains for two highly popular plant-based foods, French fries and pasta sauce, are remarkably resilient.

Uncertainty considerations

Key sources of uncertainty in this study include those associated with projected future atmospheric GHG concentrations and the resultant climate response, downscaling processes, model inputs, model parametrization and model structure, and certain factors outside the scope of this work such as impacts of stressors related to both excess and too-limited moisture, pests, diseases and weeds on crop production. By choosing RCP 8.5, our results focus on the upper range of GHG concentrations under a “no climate policy” scenario²⁵, and likely the upper envelope of projected climate impacts. Less extreme changes are plausible, which could result in different yield responses as shown in this study’s projections. Our multi-model ensemble approach increase the projected accuracy and enabled the quantification of projected uncertainties.

Regional variation in production of processing potatoes

The PNW is the most important production region for potatoes (**Figure 1**), with highest yields in the country (**Figure 3**). This yield advantage is projected to continue and even expand, with some gains in production area in Eastern Washington. Other regions with significant potato production include the Upper Midwest and northern Maine. Although yields are generally projected to remain lower than in the PNW, reduction in production area will be minor, with net grower revenue remaining steady or slightly higher. Lesser amounts of potatoes are produced in several southerly portions of the country but are less concentrated. In these areas, potatoes are grown primarily in the winter months and therefore help smooth the seasonal variation in supply. We find this overall production pattern will persist through mid-century, with continued steady yield gains, little loss of production area, and only minor losses of net grower revenue.

Regional variation in production of processing tomatoes

The geographic pattern of processing tomato production is very different from potatoes (**Figure 4**). The majority (>95%) of all processing tomatoes are now produced in California, and most of those come from the two CRD’s in the Central Valley: CA50 (the Sacramento river basin) and CA51 (the San Joaquin). While there is a potential for disruption in irrigation water availability in California as result of the Sustainable Groundwater Management Act²⁶, this modeling analysis did not include the potential for constraining irrigation water supply. Accordingly, we find no significant reduction in production area, and even a modest increase in CA51 through the year 2030, followed by only a slight decline in the following two decades. Projected tomato yields and net grower revenues are competitive with California in both the PNW and the SE, but neither of those areas currently supports a processing tomato industry. Unlike

potatoes, which can be stored and transported considerable distances for processing, tomatoes must be processed within a few hours of harvest, forcing concentration of production near a processing plant. For economic reasons, a production area of approximately 5,000 ha is needed to supply tomatoes for one processing plant. The only commercial-scale processing tomato industry outside of California is centered around a small number of plants in Indiana. Nevertheless, the modeling shows that processing plants could be supported elsewhere in the country, should water constraints force processors out of the San Joaquin Valley²¹.

Water scarcity issues

Since most irrigation water in the US is not allocated at market prices, water resource allocation for irrigation is not predictable based upon marginal value or scarcity. However, trans-sector competing demands (industrial, municipal and instream flows for fish/ecological needs) for water during scarcity events often results in loss of availability for the agricultural sector. The high concentration of specialty crops in California, a relatively arid state, means that much higher total amounts of irrigation water are used in the vegetable production areas of California than in any other vegetable production areas of the US. This region has the highest risk for allocation-induced scarcity for production of the regions analyzed in this study. Due to the relatively higher profitability of potatoes and tomatoes, irrigation water availability is unlikely to constrain future production in most regions (possible exception, California's San Joaquin Valley). Due to future restrictions on water use in California²¹, irrigation may be diverted away from less-profitable crops (e.g. pasture for animal feed) in order to sustain continued potato and tomato production.

Demand considerations

Domestic consumer demand for processed potatoes is projected to grow at a compound annual growth rate of 0.9 percent over the 2019 to 2050 period. The growth rate varies by end use with canning use growing the fastest at 1.7% per year but also starting from a very low level of use. Chipping, dehydrated, and frozen potato uses grow at slightly less than 1 percent per year but start from significantly higher levels. Frozen potatoes (primarily French fries) demand is expected to grow 2.4 million metric tons over the 2019 to 2050 period. Domestic consumer demand for processed tomatoes has been relatively steady over the past decade following some decline in the previous decade. The modeling includes a slight positive trend in consumer demand for processed tomatoes which combined with US population growth results in a compound annual growth rate of 1.1 percent over the 2019 to 2050 period.

Opportunity assessment

One of the key uses of this new integrated approach is for identifying hotspots in the supply chain and provide opportunities for improving environmental performance in potato and tomato supply chains. Our approach can also be used to identify new regions where production of such crops can be profitable and be accompanied by reduced environmental footprints, particularly the potential for less consumption of water than in current production regions where water supplies are threatened by climate change or regulatory activity²⁶.

There are also opportunities elsewhere in the supply chain. Mitigating emissions beyond the farm gate – in processing, retail, preparation, and consumption – might be more effective than altering field production for climate change impacts. For instance, our findings show that the choice of cooking method is more important than supply chain packaging considerations with respect to the carbon footprint of consumed French fries. Decisions on the method of potato and tomato food processing and preparation can have larger impacts on carbon footprints than farmers' decisions. Water conservation is increasingly important in many production regions, and in potato production, current irrigation technologies are less water efficient than drip irrigation²⁷. A production scenario for potato production using drip irrigation shows 6% reduction in water use and corollary 2% reduction in climate change impact because of improved water application efficiency and improved nutrient use efficiency (lowering the nitrous oxide emissions due to relatively higher crop N-uptake efficiency)

Recommendations for future research

The impact of extreme weather events and other kinds of tipping points (or thresholds) that could be reached are not considered in our current modeling but could be critical³⁰. Our results could also be enhanced by detailed analysis of irrigation water availability by region, and better economic input data to support economic modeling at the fine geographic scale (CRD-scale). Other opportunities to improve the crop modeling include consideration of the stress caused by excessive moisture, a common issue in the Upper Midwest³¹.

Next steps with this new integrated approach

The methodology presented in this paper builds on the successes of the Agricultural Intercomparison and Improvement Project (AgMIP)^{9,27}, which coupled climate projections from GCMs with crop models and simulated yield and water use from crop models with economic models that consider other variables (e.g.

production, consumption, prices, trade, etc.). The new integrated approach adds a fourth component for LCA analysis with coupling points to both the crop and economic models. While AgMIP until now mainly has focused on important cereal and legume crops, the paper concentrated on two of the most important vegetable crops, i.e. potatoes and tomatoes. Although it was discussed earlier that there were many uncertainties associated with the impact and risks assessment that was conducted, it also creates opportunities to add a new dimension for yield quality with respect to nutrient composition. Future climate change studies will need to address both food and nutrition security, with vegetables and fruits playing a major role for nutrition security. Although we have chosen to report results here for just two products made from potatoes and tomatoes, the novel integrated methodology described here can, pending data availability, be applied to examine all crops needed for a balanced diet for any region in the world. That would help producers, processors, traders, and policy makers efficiently adapt to the challenges of accelerating global climate change, increasing competition for water and other natural resources. It would also help ensure long-term economic and environmental sustainability at farm, regional, national and global scales.

Methods

We employed an integrated assessment methodology based on crop, economic, and LCA modeling to investigate climate change adaptation and mitigation scenarios for processing potato and processing tomato supply chains, starting with current conditions through the year 2050.

Selection of representative counties for modeling

Crop Reporting Districts (CRDs) were selected by first sorting them in a descending manner by total crop area for eight fruit and vegetable crops (including potatoes and tomatoes) that are targeted in the broader project comprising this study. For more detail see the Supplementary Information (SI). We then included the CRDs necessary to capture 80% of the total production area for the crops, resulting in a list of 31 CRDs. The counties having the highest target crop production area within each of these CRDs were then selected for the crop modeling, with one additional county (St Johns, Florida), added in order to better represent potatoes in that state).

Selection of processing varieties for modeling

The crop modeling was based only on processing varieties and excluded fresh market varieties. Crop varieties for processing have more homogeneous growth patterns and harvest periods while varieties for fresh markets are extremely variable in terms of growing season, shape, color, and yield to adapt to specific markets, which makes them more difficult to parameterize for modeling purposes.

Estimation of yield impacts from climate change

We utilized a multi-model approach based on AgMIP protocols³² to estimate changes in yield, irrigation water requirements, and crop nutrient requirements (N, P, K) in all cropping areas of interest through 2050. Climate change impacts by 2050 on potatoes in 32 main potato growing districts in the US were estimated with an ensemble of five process-based models (SIMPLE³³, CropSyst^{34,35}, LINTUL-POTATO-DSS³⁶, EPIC^{37,38}, and DSSAT-Substor-Potato^{39,40,41}), and one statistical model⁴². Three crop models (SIMPLE, CropSyst, and DSSAT CSM-CROPGRO-tomato⁴³) and a statistical model were used to estimate the impact of climate change on tomatoes in eight main tomato districts for processing tomatoes across the US. National or regional level impacts were derived from district averages by weighting the corresponding crop areas. The crop models were calibrated to field-experimental-based-corrected district yields⁴⁴ for potatoes⁴⁵. Due to the lack of tomato data, the tomato models used previous cultivar calibrations⁴⁶. The statistical model was trained on data from the USDA NASS dataset⁴⁷. Crop and statistical model estimates used gridded downscaled⁴⁸ daily weather data (4 km x 4 km) for a baseline (1981-2010)⁴⁹ and two future time slices (2021-2050 and 2041-2070) from five general circulation models, GCMs^{48,49} for a Representative Concentration Pathway 8.5¹³. No water or nitrogen limitations were assumed in the potatoes and tomato cropping systems. As a possible adaptation to a warmer climate, an earlier planting date was considered. Nitrogen, phosphorus and potassium fertilizer demand was calculated after the crop simulations based on simulated yield and nutrient concentrations^{50,51} and their changes with elevated atmospheric CO₂ concentrations¹⁷. The simulated baseline yields were bias-corrected to the regression yield for 2017 based on CRD yields for each CRD (see crop modeling protocol⁴⁵ for more details).

Future climate scenarios

Higher future atmospheric CO₂ concentrations will stimulate growth if other nutrients are not limiting⁵². The yearly changing atmospheric CO₂ concentrations for the baseline (1981-2010) and future periods (2030s and 2050s) under the RCP 8.5 scenario were applied²⁵. Five GCM's were used (GFDL-ESM2M, HadGEM2-ES365, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M), consistent with ISIMIP – the Inter-Sectoral Impact Model Intercomparison Project⁵³.

Yield projection method

The projected future yields included climate change impacts (temperature and CO₂ change), the effect of earlier planting as an adaptation and a projected technology trend on yield improvement. The technology trend is a combination of improved seeds, more effective use of fertilizer, water, and various inputs, as well as better equipment and other improvements. A step-wise process was utilized. First, a regression line was fitted to the observed yield trends for each CRD (based on USDA NASS), with the slope of this line assumed to have two linear components: technology and climate. The technology component was determined as the difference in slopes between the overall observed trend and the simulated baseline trend due to climate change during that same time period. The technology component observed in the past was then attenuated to 90% by 2030 and 70% by the year 2050, causing the partial flattening of the yield curves over time¹⁵. The climate component was determined based on the percentage linear increase in simulated crop yield from the baseline period through the 2030s and then removed from the observed historical yield trend (to create a climate-corrected technology trend). The overall future yield trend was constructed from the simulated climate change effects with the attenuated technology trend added. In order to characterize overall modeling uncertainty, the same yield projection methodology was applied to the 25th- and 75th-percentile ensemble results, in addition to the ensemble median, which was treated as the best single estimate of future yield.

Economic modeling overview

Structural partial equilibrium models for the US fresh and processed potato and tomato were developed to simulate the impact of climate variation and mitigation practices on crop net returns and land use change. In order to capture the geographically detailed output from the crop yield simulation models, area, yield, and production equations were developed for the 31 US CRD's with one additional region to capture the remainder of the US. Each area equation is driven by the ratio of gross market returns with the cost of production for the crop they are producing and the previous year's planted area (otherwise known as the "lagged planted area"). Based on input from agricultural extension personnel and growers regarding production practices, processors and growers select specific varieties of potatoes and tomatoes depending on the end use of the product. Therefore, substitution between the processed and fresh sectors is very limited or nonexistent. The implication for economic models is that crops produced for the fresh sector are generally considered a different commodity than the same crop produced for the processing sector. The area of specialty crops like potato and tomato is often linked closely to the number of contracts offered by a processor rather than being driven by competing crop returns. The inclusion of lagged planted area in the economic model reflects a short-term constraint against significantly changing processing capacity with processors preferring to operate their facilities at optimal capacity⁵⁴.

Demand equations were developed at the national level based on the fresh and processed demand as detailed in USDA's Economic Research Service datasets. Whether processed or fresh, future consumer demand for potatoes and tomatoes was driven by inflation-adjusted income, population, overall consumption trends (reflecting tastes and preferences), and inflation-adjusted price.

International partial equilibrium economic potato and tomato models focused on the primary US trading partner countries were also developed and used as part of the modeling system employed in this study (see SI for details). Because climate impacts on crops and yield vary by region, it was important to determine if trade would be affected by the climate impacts on other trading partners⁵⁵. The international models and US models were combined to form a set of global models. The global partial equilibrium models solve simultaneously for the set of crop prices that balance the global supply and demand of each commodity.

Land use change

Although they are the two vegetable crops with the largest total cropped area in the US, the area devoted to potatoes and tomatoes is still very small in comparison with major row crops (e.g., maize, soybeans, etc.). Typically, returns per hectare for vegetables are significantly higher than row crop returns, and combined with their relatively small area footprint and rotational requirements they do not significantly compete with row crops for area. However, in some cases they do compete for irrigation water. Although the specialty crop returns usually exceed row crop returns substantially, row crop producers with water rights may choose to continue their operations rather than leasing those rights to specialty crop producers. Therefore, the modeling system also incorporated WAEES existing models of global row crops (see SI). While the economic models constrain total irrigated area to the existing CRD irrigated area, the constraint was not found to be significantly binding in this analysis.

One important consideration with respect to land use for both potatoes and tomatoes is the presence of shared soil borne diseases (nematodes) for these *Solanaceae* crops. Neither crop can typically be cultivated on the same land within a period of 4 years. The need for such a lengthy crop rotation may put a burden on land cultivated by vegetable growers when demand increases, where, just as with the irrigation, farmers growing row crops may not be that forthcoming to share land with vegetable farmers.

Data limitations

The crop modeling teams noted that there was significant variation in climate impacts on yield within individual states necessitating the use of sub-state production regions. Both county and CRD's were evaluated as possible geographies, but ultimately CRD's were chosen due to more complete data sets. Data on the production of US fruits and vegetables by CRD primarily relies on the five-year agricultural censuses with many missing data points because of USDA disclosure rules. To the extent that NASS reported historical annual CRD data, this was used in the analysis. When needed, interpolation between the census years was done by aligning the sum of the CRD data with the annual NASS data reported at the state level. In order to estimate the supply elasticities, historical time series of area, yield, and production for each CRD over the 2000 to 2017 period were assembled.

Interdisciplinary data exchange among the modeling teams

The economic modeling drew on information from across the interdisciplinary teams. The crop model teams provided yield impacts with and without adaptation for US potatoes and tomatoes for the 31 CRD's under the RCP 8.5 GHG emissions scenario. The extension teams provided insight into crop production practices, input use and costs of production. The yield impacts under the RCP 8.5 scenario on regions outside the US and/or for crops other than potatoes and tomatoes were provided by the IFPRI IMPACT model^{56,57}. Finally, technical parameters such as fruit and vegetable water content were provided by the LCA team. Outputs on the current and projected levels of input use, realized yield, processing use, technology trend and land use change were reported to the other modeling teams, as needed.

Life Cycle Assessment (LCA)

The life cycle assessment methodology included the development of life cycle inventories (LCIs) of the supply chains for two processed products made from potatoes and tomatoes: frozen French fries and pasta sauce. This work was governed by a protocol that fully describes the "cradle to grave" approach (see SI for details). An integrated supply chain model was constructed to account for all major raw materials needed at each stage of the supply chain. Data on yield, fertilizer inputs and irrigation were derived using the results provided by the crop and economic modeling teams. The on-farm LCI represents the average farm management and production of each crop reporting district (CRDs). Post-harvest stages include processing plants with some LCI data based on engineering estimates. The protocol also specifies assumptions used for evaluating future crop production scenarios. Mitigation analyses were performed for a full cradle-to-grave system, including farm-to-processor transport, processing and packaging, distribution through retail, consumption and final disposal. The LCA assessment methodology is compliant with ISO standards.⁵⁸

Life-cycle Inventory modeling

The life-cycle inventory model couples the output from process models of potato and tomato production using a semi-automated workflow to map data into the LCA software. The data were supplemented with and verified against available information from USDA statistical websites, including National Agricultural Statistical Service (NASS), Agricultural Resource Management Survey (ARMS), and Economic Research Service (ERS). Some data were difficult to obtain, and for the processing stages, data were partly based on the processing plant (e.g. for tomato) and on engineering estimates and available literature.

LCA modeling

The model is constructed of three elements: (i) Production; (ii) Postharvest; and (iii) Biowaste-handling (see SI for detail). In brief, the first element characterizes crop production in each CRD⁴⁵, and the subsequent stages of the supply chain include processing (with warehouse storage of potatoes), retail/supermarket and consumer activities which are modeled to account for material and energy consumption and related emissions. The third element models three alternate methods for biowaste (scraps and food waste) handling.

System boundaries and Functional Unit

A full “cradle-to-grave” perspective (farm to consumer, including waste management) was adopted to define the system boundary. It is common in agricultural LCA, to define the functional unit (FU) as product mass (fresh or dry) or as land occupied (hectare). Although mass is widely used as FU, its appropriateness is debated⁵⁹, particularly considering the large variation among foods’ characteristics: water and nutritional content, for example. Alternate functional units have been suggested; however, these have not been adopted for this study⁶⁰⁻⁶². Reference flows are the quantitative outputs from processes contained in a product system that are required to deliver the functional unit. (see SI). The defined FU’s for potato and tomato are 1 kg French fries consumed or 1 kg pasta sauce consumed, respectively. Because the FU includes consumption at the consumer stage, the reference flows of the raw crops fully account for the loss fractions at each stage of the supply chain. As an example, to consume 1 kg of frozen fries, 1.22 kg must be purchased based on consumer stage waste of 18%. Ultimately, to deliver the 1 kg of frozen fries, 2.16 kg of raw potato must be produced (see SI for waste fractions along the supply chain).

LCA impact categories and impact assessment methods

ISO 14044:2006 recommends that the choice of impact categories and impact assessment methods be based on the specific requirements of the LCA practitioner to meet the objective of a study⁶³. This study protocol considered three impact categories: global warming potential (GWP₁₀₀) (in kg CO₂ eq), water consumption (m³ eq), and land use (m²-a). These were considered most relevant in the context of resiliency of specialty crop supply chains under climate change scenarios.

Handling of products and co-products

Most production systems generate multiple products with various functions and services. The handling of multifunctionality in LCA requires a choice among different approaches, such as subdividing the multifunctional processes, system expansion or allocation⁶⁴. This often occurs in the food processing industry, where processing plants are built with multiple processing lines, which generate arrays of products (e.g. raw potato processed to frozen fries, chips, dehydrated products; and tomato to paste, diced, sauces etc.). In such cases, as suggested by others⁶⁵, physical causal relationships can be applied to distribute the burdens among the multiple products. In this study, it is assumed that the production lines are independent, that is the quantity of frozen fries produced does not affect the quantity produced for potato-chips, when both are manufactured in a single facility. Hence, from the total annual raw materials consumed in an ideal processing plant, the sub-division of raw material inputs to each processing line was estimated based on typical product yields from the facility. For calculating the energy inputs at retail/supermarkets, we relied on data available for shelf space occupied by product category⁶⁶.

Biowaste treatment scenarios

Estimates of the quantity of waste generated across the supply chain were based on Buzby⁶⁷, and other sources⁶⁸⁻⁷⁰. Biowaste includes peels and scraps as well as damaged products removed at sorting. In the basic scenario we have considered biowaste management as: composting (on-farm waste), livestock feed (processor and retail waste) and for consumer waste following composting, incineration and land-fill⁷¹. The features and assumptions for the alternative biowaste management scenarios are fully described in the SI. Transportation of biowaste to conversion facilities is excluded, considering the high uncertainty of the distances in different CRDs.

Uncertainty Assessment

The mitigation scenarios were compared using a Monte Carlo bootstrap statistics approach^{72,73}. Briefly, 1000 simulations were conducted with a fixed seed for random number generation to provide paired samples for each of the mitigation and baseline models. Subsequently 300 replications of 100 samples with replacement were performed and a distribution of Student-t and associated p-values produced for each pair. If the upper 95th confidence interval p-values was less than 0.01, the null hypothesis that the mean values of the two distributions are equal is rejected.

Declarations

Data availability

All data utilized in this paper are freely available upon request to the corresponding author (dgustafson@foodsystems.org).

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Additional information

Supplementary information contains additional details concerning modeling methodology, as noted in the text.

Competing interests:

The authors declare no competing financial interest.

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Figures

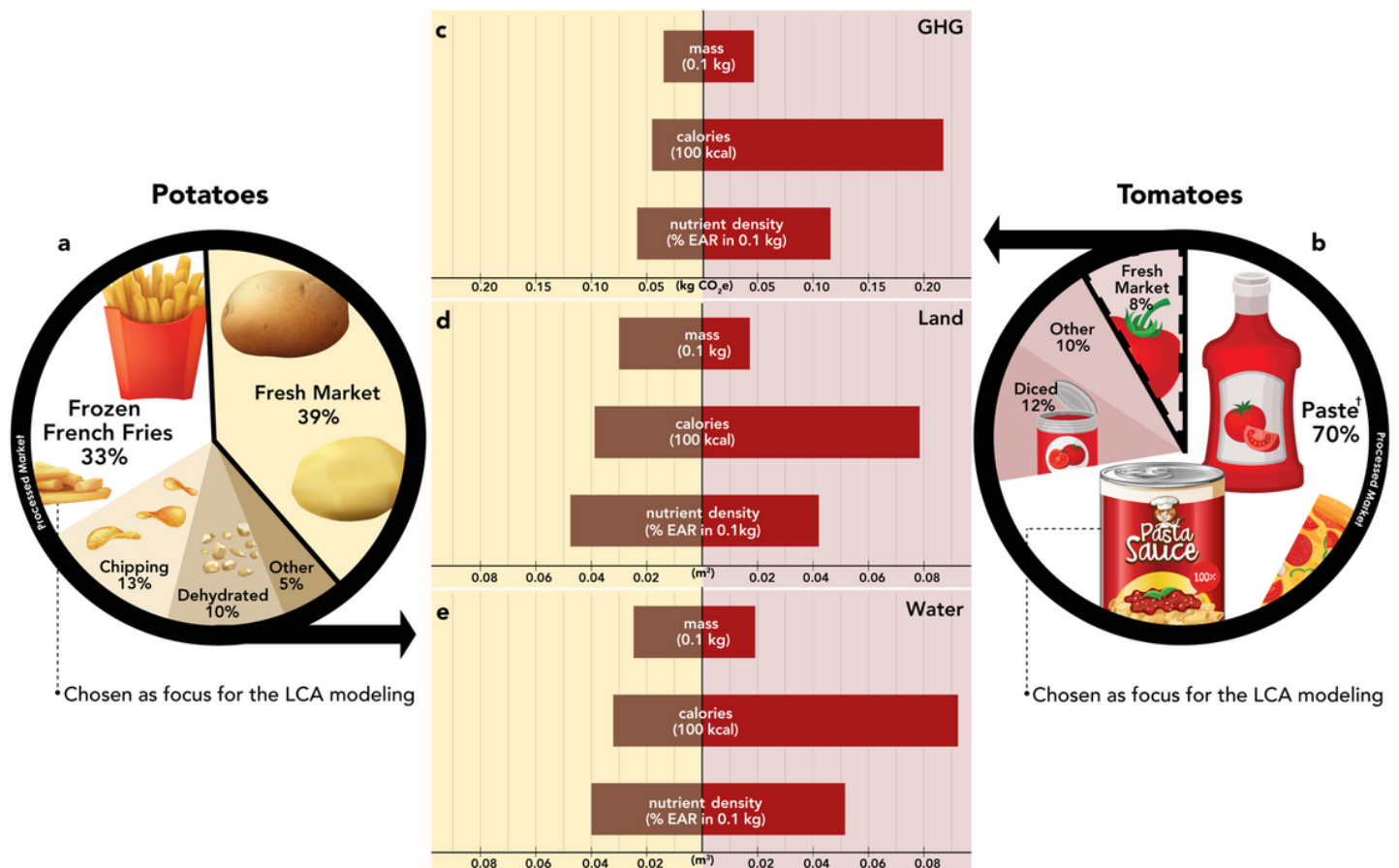


Figure 1

The pie charts (a potatoes, b tomatoes) show the relative amounts of different foods sourced from potatoes and tomatoes in the United States. The bar charts show the relative environmental footprints (c

greenhouse gas emissions, d land use, e water use) of potatoes and tomatoes at harvest, using three alternative life cycle assessment (LCA) functional units: mass, caloric content, and nutrient density.

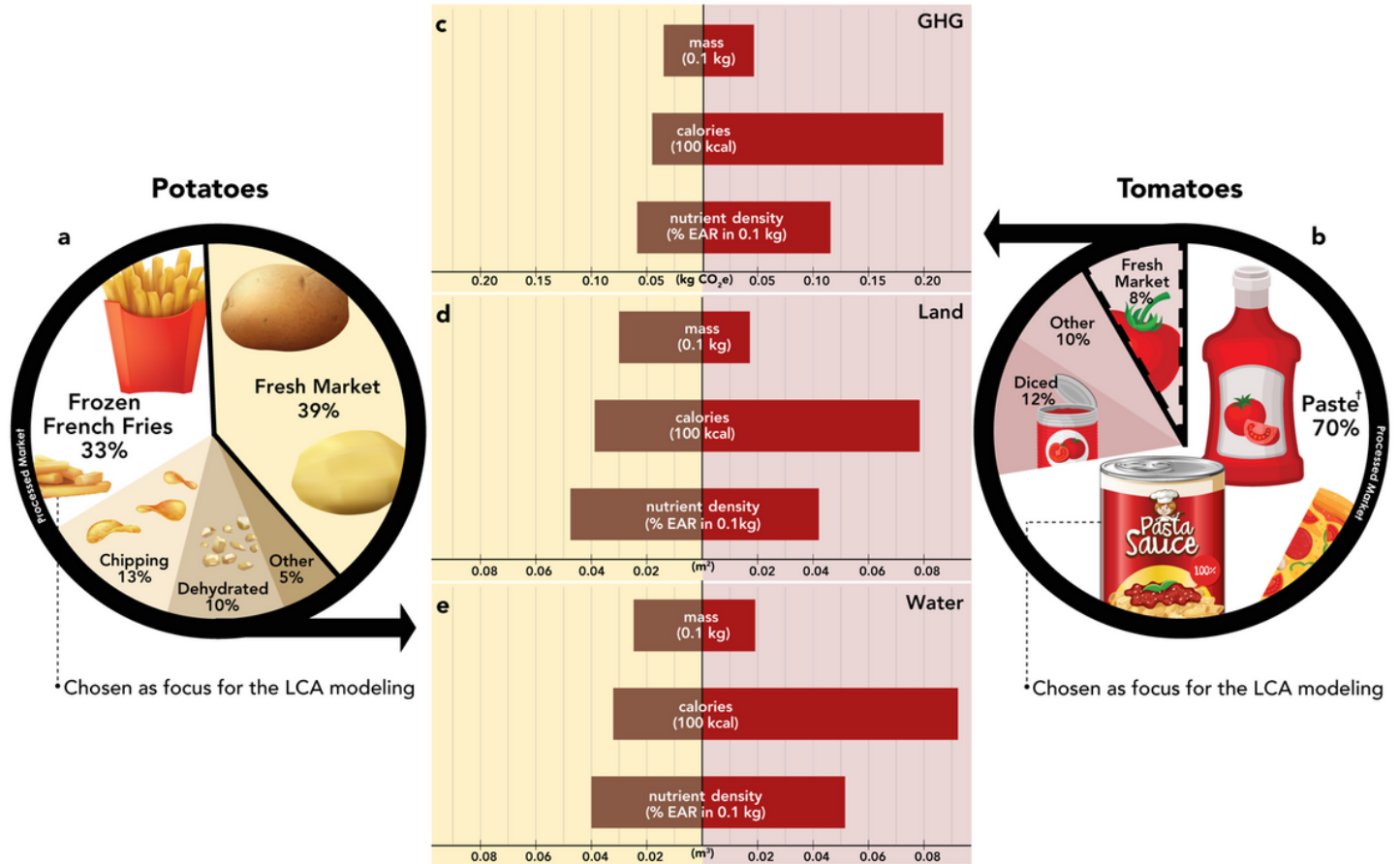


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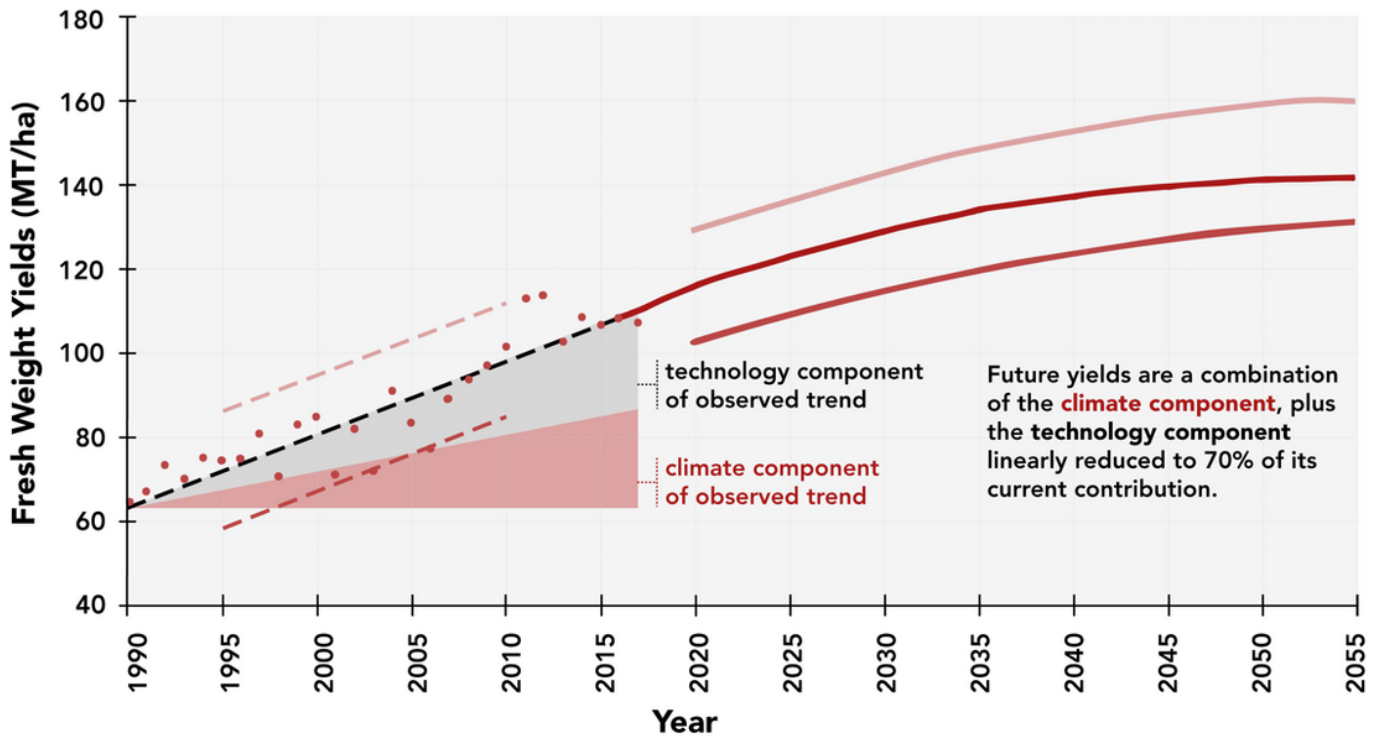


Figure 2

Example of the yield projection methodology for the Crop Reporting District (CRD CA51) that covers the San Joaquin Valley, California’s CRD with the largest production area for potatoes, tomatoes, and many important fruits and vegetables. A regression line was fitted to observed yields and the slope was assumed to have two components, one due to technology advances and the other due to the effects of more favorable climate as found using crop modeling, which included the positive effect of higher CO₂. The technology component was assumed to be attenuated from its current 100% contribution to 90% of that value by 2030 and 70% by the year 2050, causing a flattening of the yield curves over time. The central of the three curves is based on the median of the entire climate/crop modeling ensemble. In order to help characterize overall modeling uncertainty, the same methodology was applied to the 25th- and 75th-percentile results of the modeling ensemble, which generated the upper and lower curves.

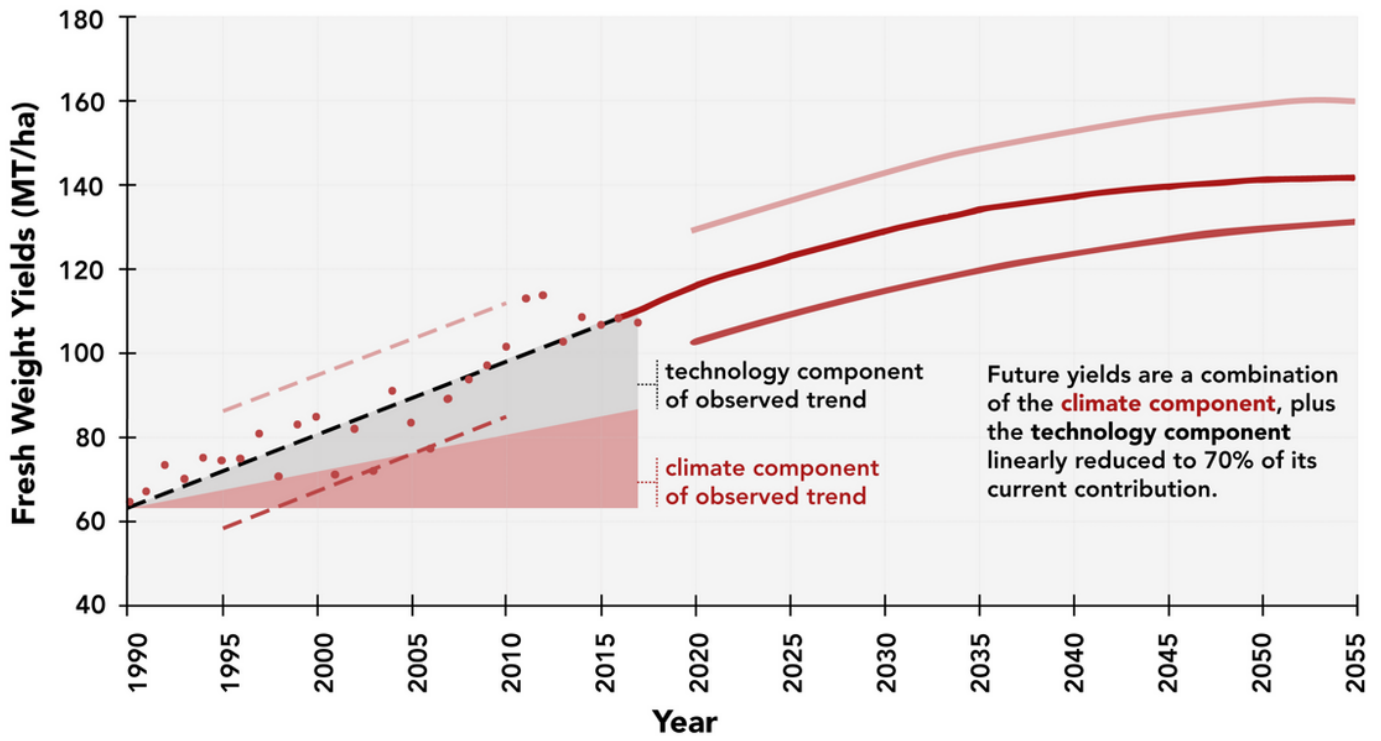


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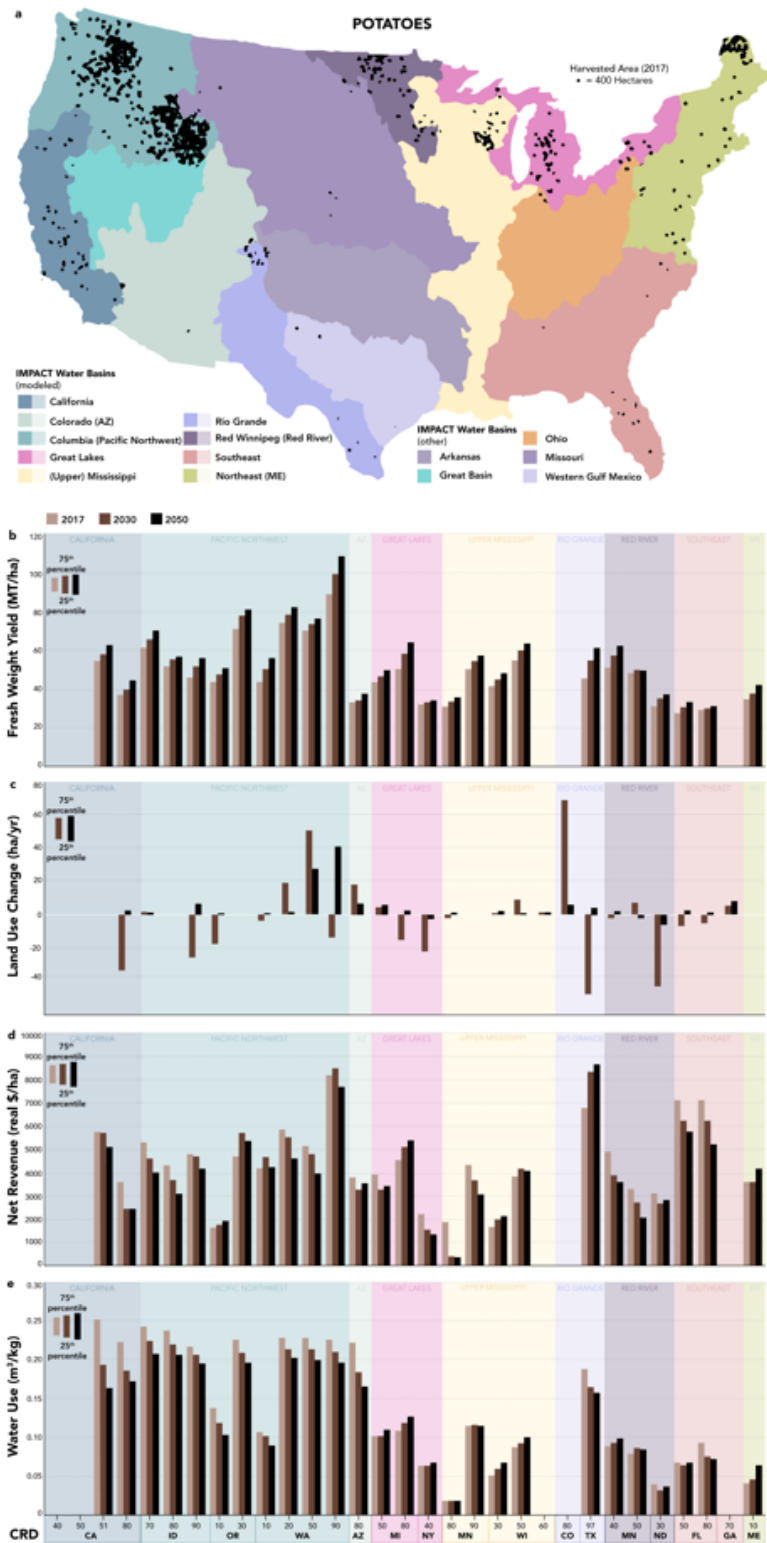


Figure 3

The map at top (a) shows current potato production regions, overlaid onto major water basins that cover the lower 48 states of the US. The bar charts show baseline and future CRD-scale crop yields (b), production area changes (c), net grower revenues (d), and water use (e) for growing processing potatoes. Insets show the average spread between the 25th and 75th percentile levels of each parameter.

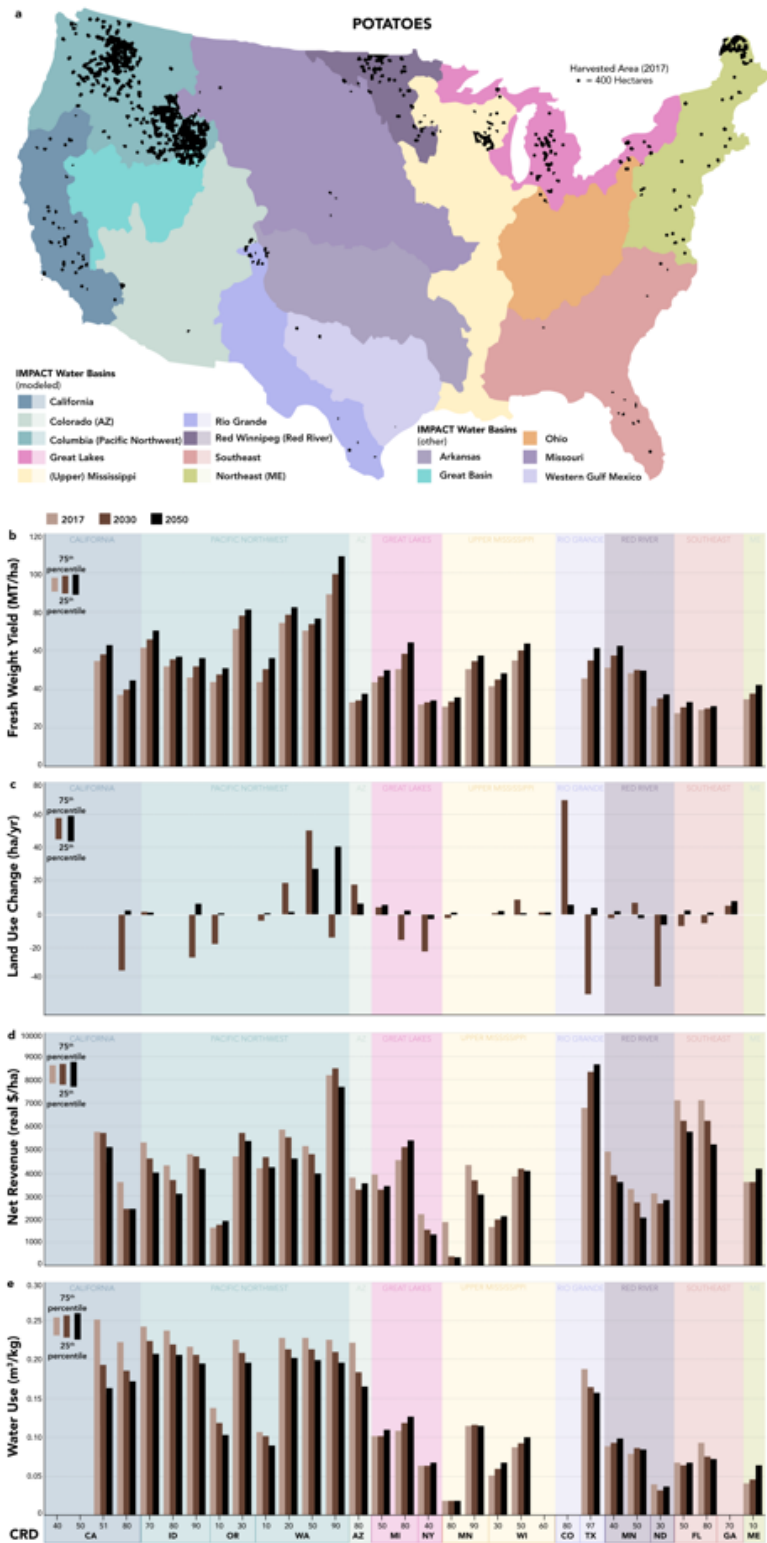


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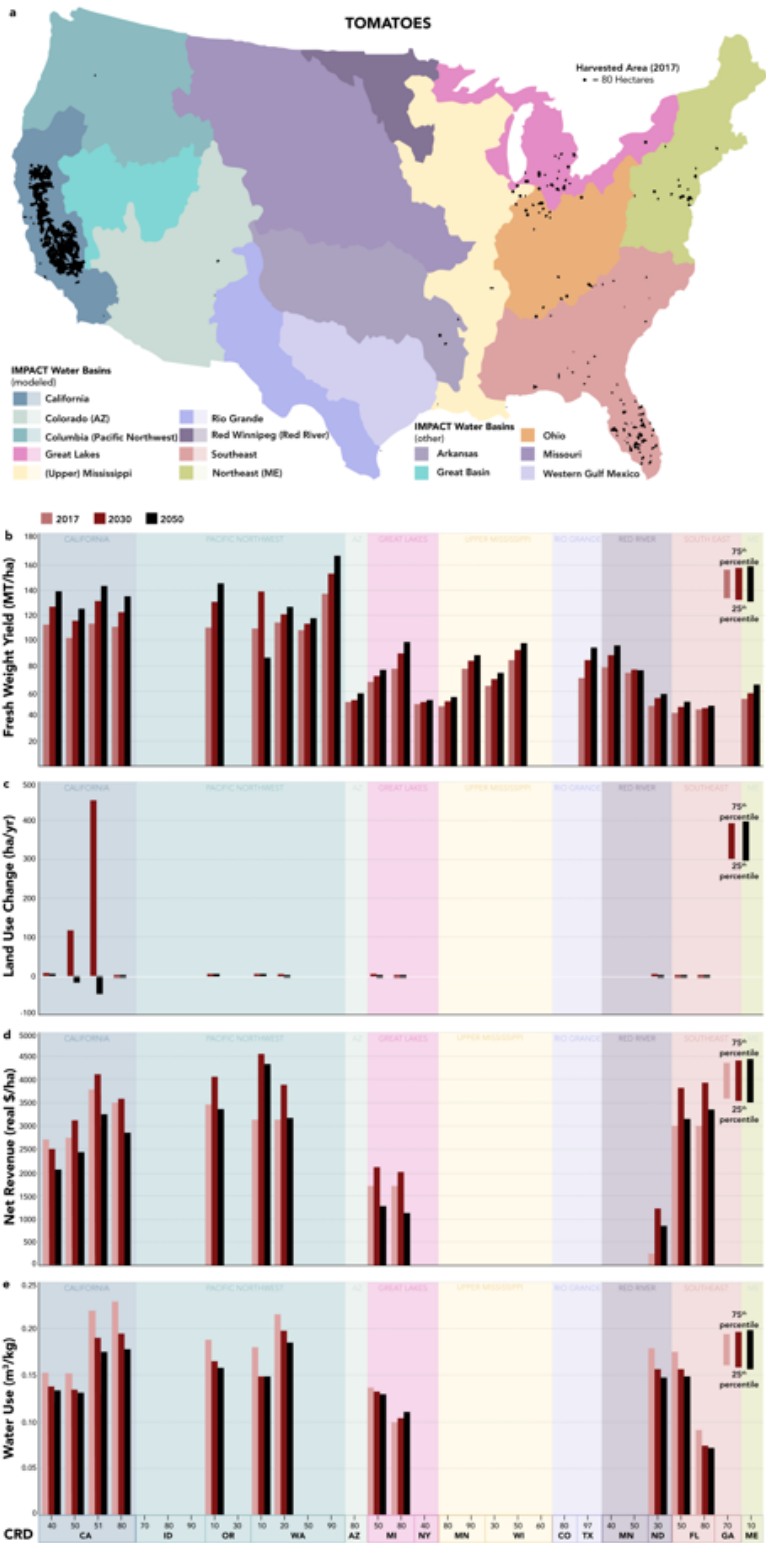


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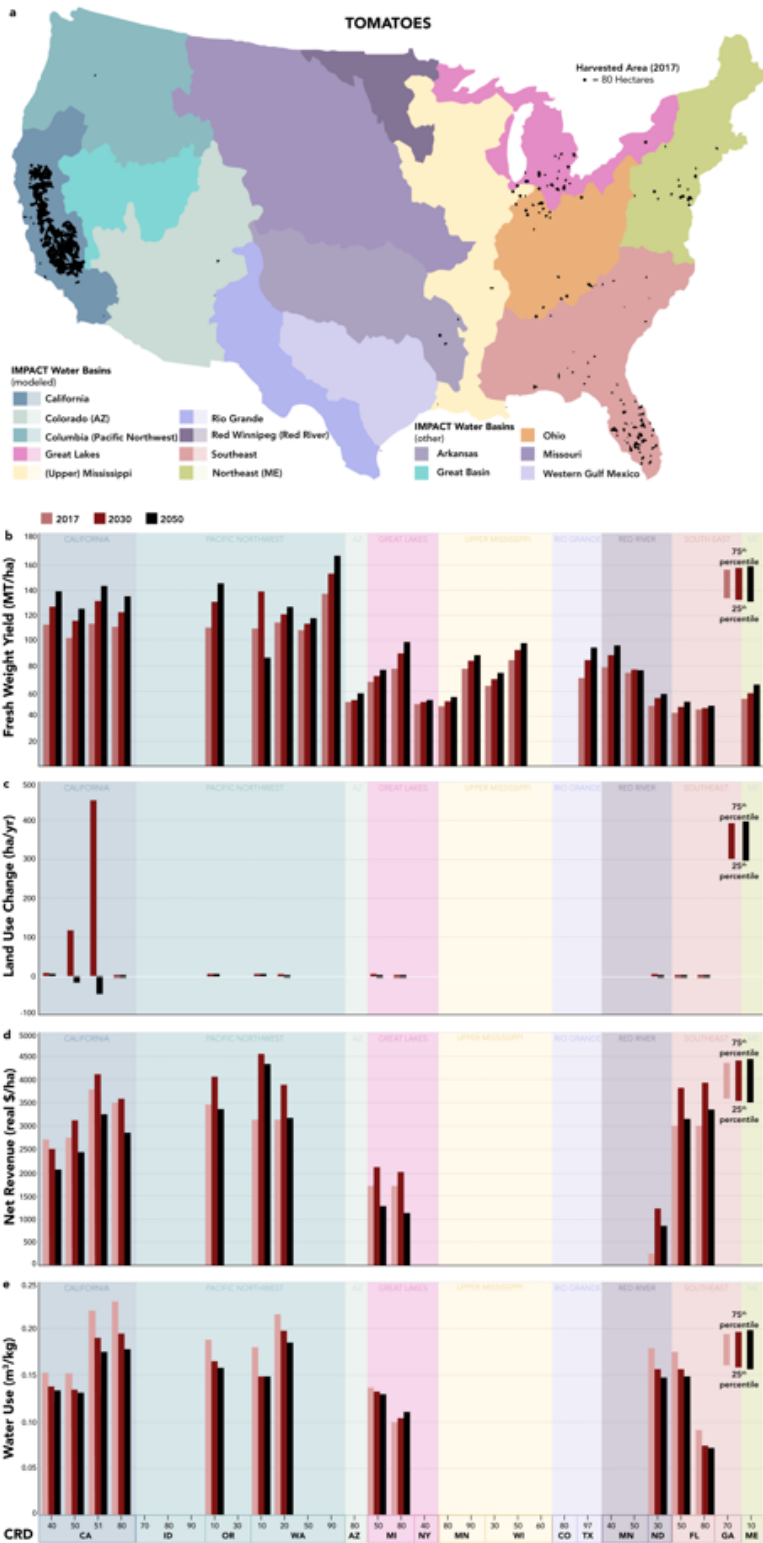


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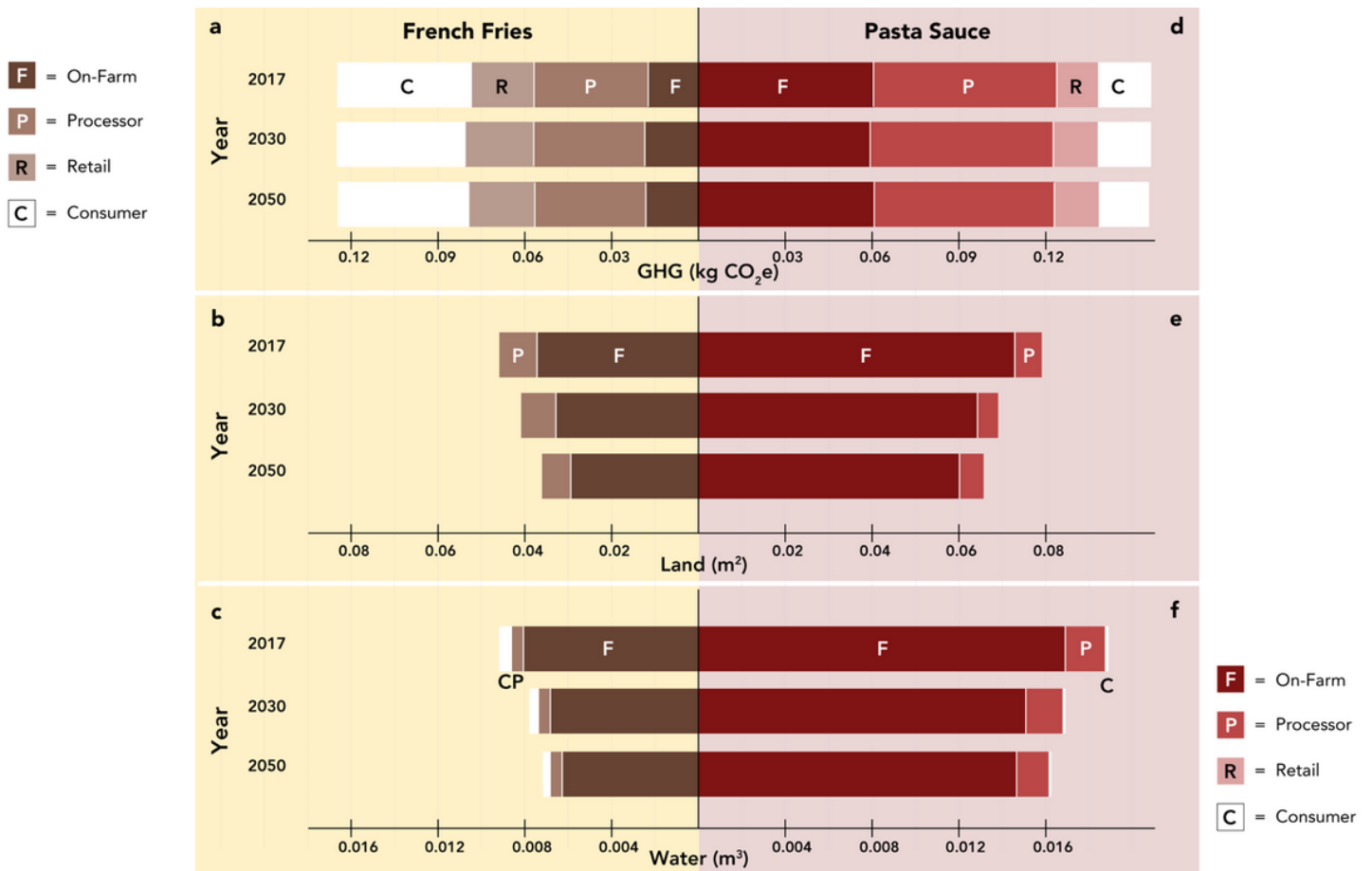


Figure 5

Baseline and future “cradle to grave” environmental footprints for 0.1 kg servings of French fries (a greenhouse gas emissions, b land use, c water use) and pasta sauce (d greenhouse gas emissions, e land use, f water use), in US supply chains, showing the relative contributions of the various elements of the supply chain: on-farm, processor, retail, and consumer.

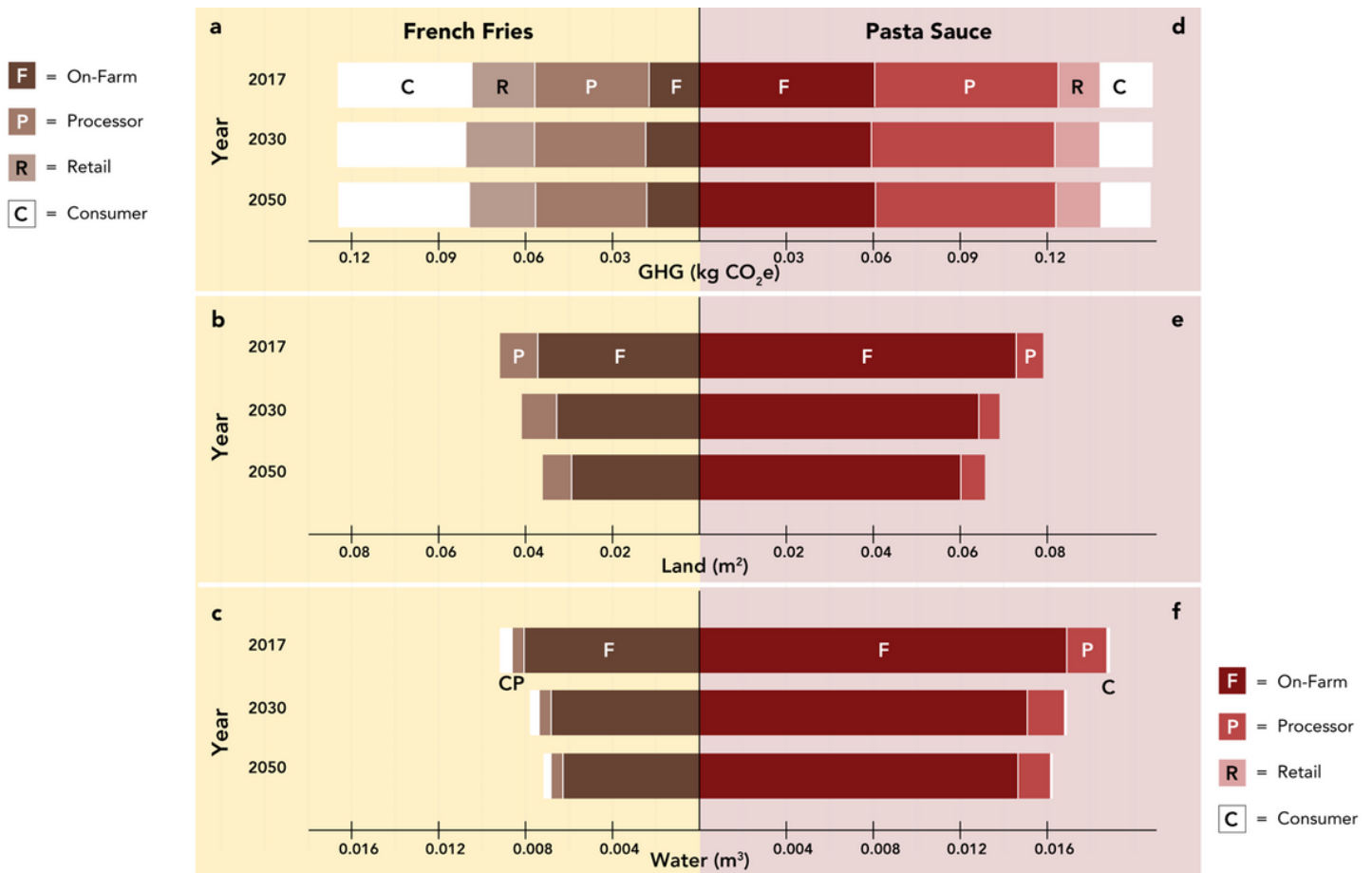


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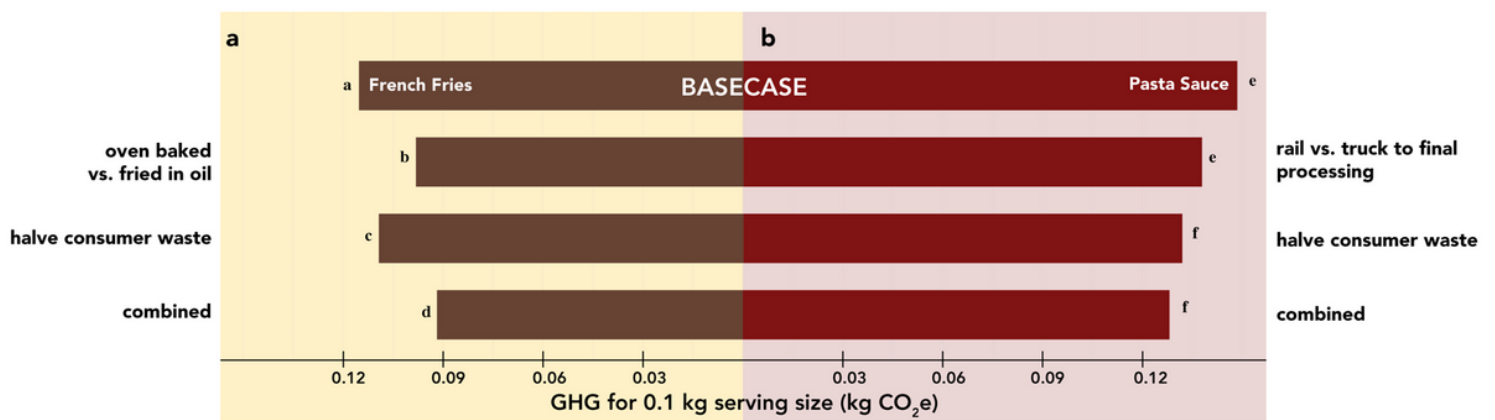


Figure 6

Impact of various options for mitigating the “cradle to grave” greenhouse gas (GHG) emissions for 0.1 kg servings of French fries (a) and pasta sauce (b), in US supply chains. Bars labeled with the same letter (a-f) are not statistically different from each other ($p = 0.01$).

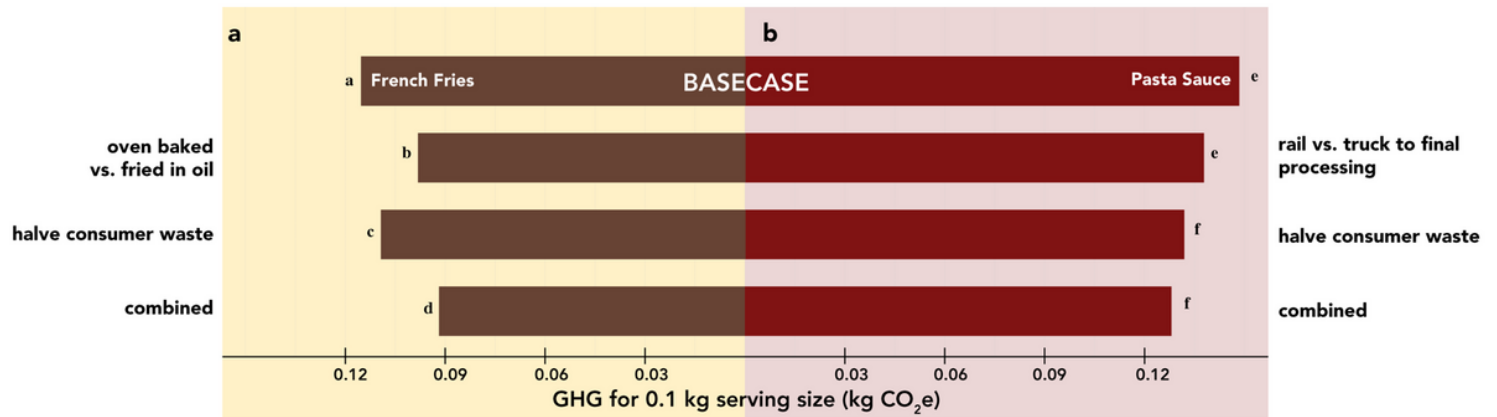


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