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Food systems are increasingly challenged to meet growing demand for specialty crops due to the effects of climate change and increased competition for resources. Here, we apply an integrated methodology that includes climate, crop, economic and life cycle assessment models to US potato and tomato supply chains. 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 greenhouse gas emissions can be mitigated by waste reduction and process modification. Our integrated methodology can be applied to other crops, health-based consumer scenarios (fresh versus processed) and geographies, thereby informing decision-making throughout supply chains. Employing such methods will be essential as food systems are forced to adapt and transform to become carbon neutral due to the imperatives of climate change.

Food systems are now challenged as never before to meet nutritional needs in more sustainable ways[1]. Specialty crops, including vegetables, are the cornerstone of healthy diets, and consumers are strongly encouraged to eat more of these foods[2]. The supply chains for many important foods produced from these crops are experiencing remarkable 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 labour, efforts by supply chain actors to improve their sustainability profiles, and the rise of protected and peri-urban production[2]. Modest increases in US dietary intake have been reported[1], 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, especially labour and land[3,4]. Increasing temperature regimes in California are projected to significantly shift the production of major fruit and vegetable crops by 2040 (ref. [5]). 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 solution[6–9]. For example, processing plants are expensive and 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 labour 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.

To begin addressing this gap, we have developed an integrated modelling 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 the economic models, which consider both technology and demand trends to determine land-use change and future grower profitability. Finally, LCA modelling integrates this information to identify and evaluate cost-effective adaptation and mitigation opportunities in current and potential future supply chains. While there have been a number of other studies examining general

climate change impacts on fruit and vegetable production[12–14], our integrated approach explores climate adaptation and mitigation opportunities throughout these supply chains, with a high degree of geographic specificity and the ability to link the production and processing of food.

In our first application of this approach, we identify climate adaptation and mitigation opportunities for potatoes and tomatoes, the most widely produced vegetable crops in the United States, with annual production of 67.9 and 36.8 kg per capita, grown on 0.46 and 0.14 million ha, respectively[15]. The research reported here focuses on US supply chains for varieties of potatoes and tomatoes suitable for processing, which account for 61% of the total potato production and 92% of the total tomato production (Extended Data Fig. 1)[15]. 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 modelling approach to climate adaptation and mitigation has shown an unexpected resilience in processing potato and tomato supply chains projected through 2050, even though we used a scenario of comparatively high greenhouse gas (GHG) emissions, Representative Concentration Pathway (RCP) 8.5 (ref. [16]). 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 modelling did not consider extreme weather events or pest/disease pressures. Partial equilibrium economic modelling, 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. LCAs 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 (including improved irrigation) and expected yield increases.

Crop yield. Contrary to most results reported for major grain crops[17], 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 1 is a typical example for processing tomatoes grown in Crop Reporting District (CRD) CA51, which covers California's San Joaquin Valley—with the largest production area in California for potatoes, tomatoes and many important fruits and vegetables. The integrated modelling 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[18,19]. We believe that the primary reasons that yields for both of these crops will continue to climb faster than what has been projected for grain staple crops are that potatoes and tomatoes are normally fully irrigated (at least in western regions of the country, which provide most of the annual production volumes), with relatively high demand driving ongoing improvements in breeding and other technologies (for example, precision agriculture and automation).

Crop yields are expected to continue to increase in most current production areas, but there are major differences (Figs. 2a and 3a). 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 modelling results) to support local production of these crops. For potatoes, current yields are the highest in eastern Oregon (OR30) and eastern Washington (WA20, WA50 and WA90) and are projected to maintain this advantage through mid-century. Yields are significantly lower in the southern United States, 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 CO_2 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% ($\pm$9.4%). With the projected overall higher yields, crop demand for NPK fertilizer will increase by 4.8% by 2050, despite the reduced concentration of nutrients as a consequence of elevated atmospheric CO_2 (ref. [20]). In addition, shorter growing seasons and elevated CO_2 will reduce the stomatal conductance of crops and will therefore cause a reduction in water demand by 9.3%, with shorter growing seasons being the dominant effect. However, increased pest/disease/weed pressure, the possible impact of excess water, and other extreme climate events not considered here (for example, frost and strong wind) could significantly lower future yield[21].

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% ($\pm$6.9%), nutritional content will again be reduced due to higher CO_2, 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 generally 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, where potatoes and tomatoes are grown over a mild winter, increasing temperature mostly improves growing conditions without adding heat stress. In higher-production regions such as 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 modelling 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 trend[15] (Figs. 2b and 3b). Profitability, as measured by net revenue in real (inflation-adjusted) US dollars per hectare, will probably decline slightly in the future (Figs. 2c and 3c), which is again consistent with the historical trend[15]. 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 CRD CA51 and CRD CA50, where processing tomato returns have been most favourable. The crop model results (with adaptation) indicate continued yield increase in these CRDs that contributes to steady returns. The economic model also predicts that there may be opportunities for processing tomato production growth in Washington state, where increased yield is expected to lead to more favourable grower economics. A few of the CRDs exhibit increased real net returns, including ME10, MI80 and OR30, which have moderate levels of processing in place, allowing crop area to expand.
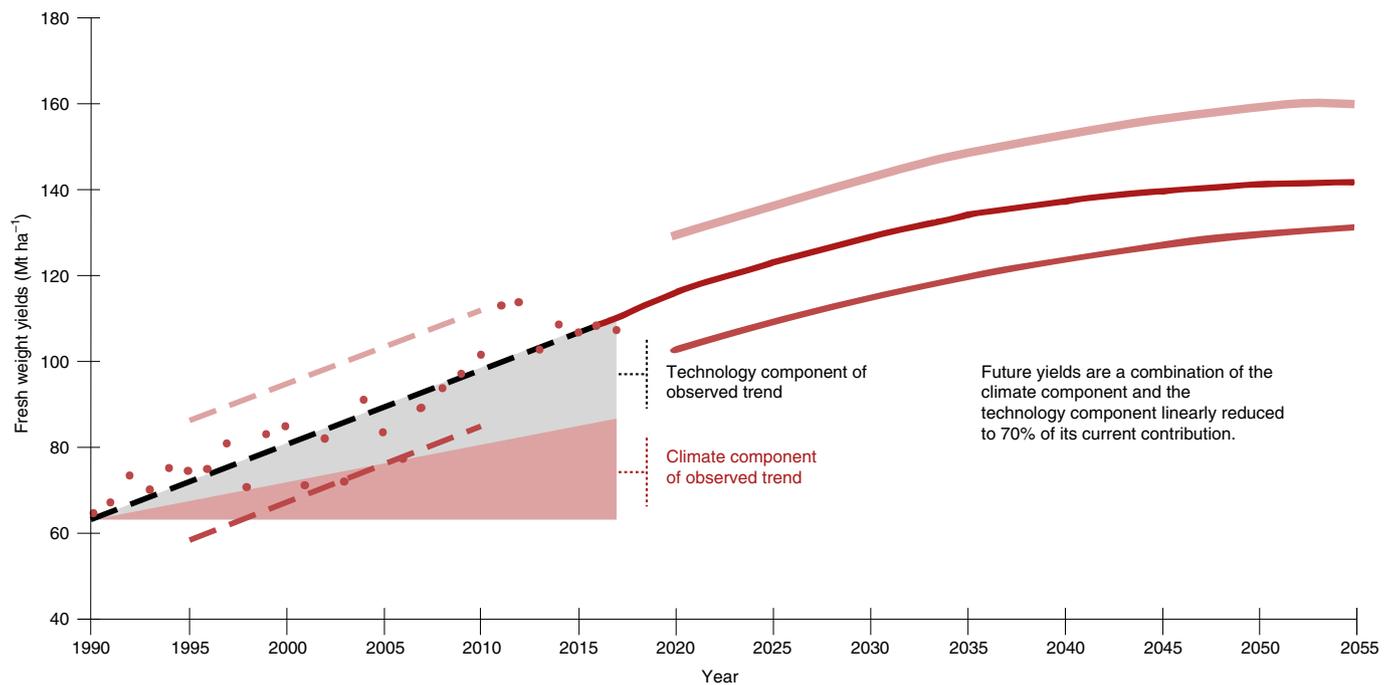
Fig. 1 | Crop yield projection methodology. Example of the yield projection methodology for processing tomatoes in CRD CA51, which covers the San Joaquin Valley, California's CRD with the largest production area for potatoes, tomatoes, and many important fruits and vegetables. The dots are reported yields and the dashed lines are the median, 25th and 75th percentile linear fits to the observed yield trends. The solid lines are the projected yield trends and median, 25th and 75th percentiles. The lightest shading is used for the 75th percentile.

Water use. Water use for potatoes and tomatoes through the farm gate is predominantly irrigation water. The dominant trend in our analyses suggests that irrigation water use per unit of production for both crops will decline, as noted above (Figs. 2d and 3d). 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 demand[22].

Overall environmental footprints. Cradle-to-grave LCA modelling of current and future US supply chains for French fries and pasta sauce are shown in Fig. 4. We fully acknowledge that neither of these processed foods has the health benefits normally associated with vegetables, but both represent large portions of the American diet and serve as excellent exemplars for the application of our integrated approach. 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, micronutrients and pesticides; ~10%), followed by energy consumed by farm operations (7% for potato and 22% for tomato). The processing stage contributed 34% and 39% to GHG emissions for French fries and pasta sauce, respectively. This is driven by the use and disposal of packaging materials and transportation. Retail contributed 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 for the losses and waste across the supply chain increase the environmental burdens by about 19% for French fries and 7% for pasta sauce. As shown in Fig. 4, the projected future GHG footprints are essentially unchanged, while the land and water footprints are lower in the future, given higher projected crop yield.

We thus expect that the mitigation options identified now will remain relevant through 2050.

Mitigation options. There are notable opportunities for mitigation of GHG emissions from these supply chains related to changes in method of transport (rail versus truck), cooking method (baked versus fried) and reduction of consumer food waste (Fig. 5). Food waste is a major contributor to climate change, and we simulated the potential mitigation that could be achieved through halving the consumer-stage losses[23,24]. Changes in consumer behaviour might be induced through the modification of 'use by' or 'best by' date labelling and consumer education regarding the meaning of these labels so that fewer products are discarded earlier than necessary[25–27]. We also evaluated the 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 labour, this integrated approach demonstrates that the 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 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, we focused our results on the upper range of GHG concentrations
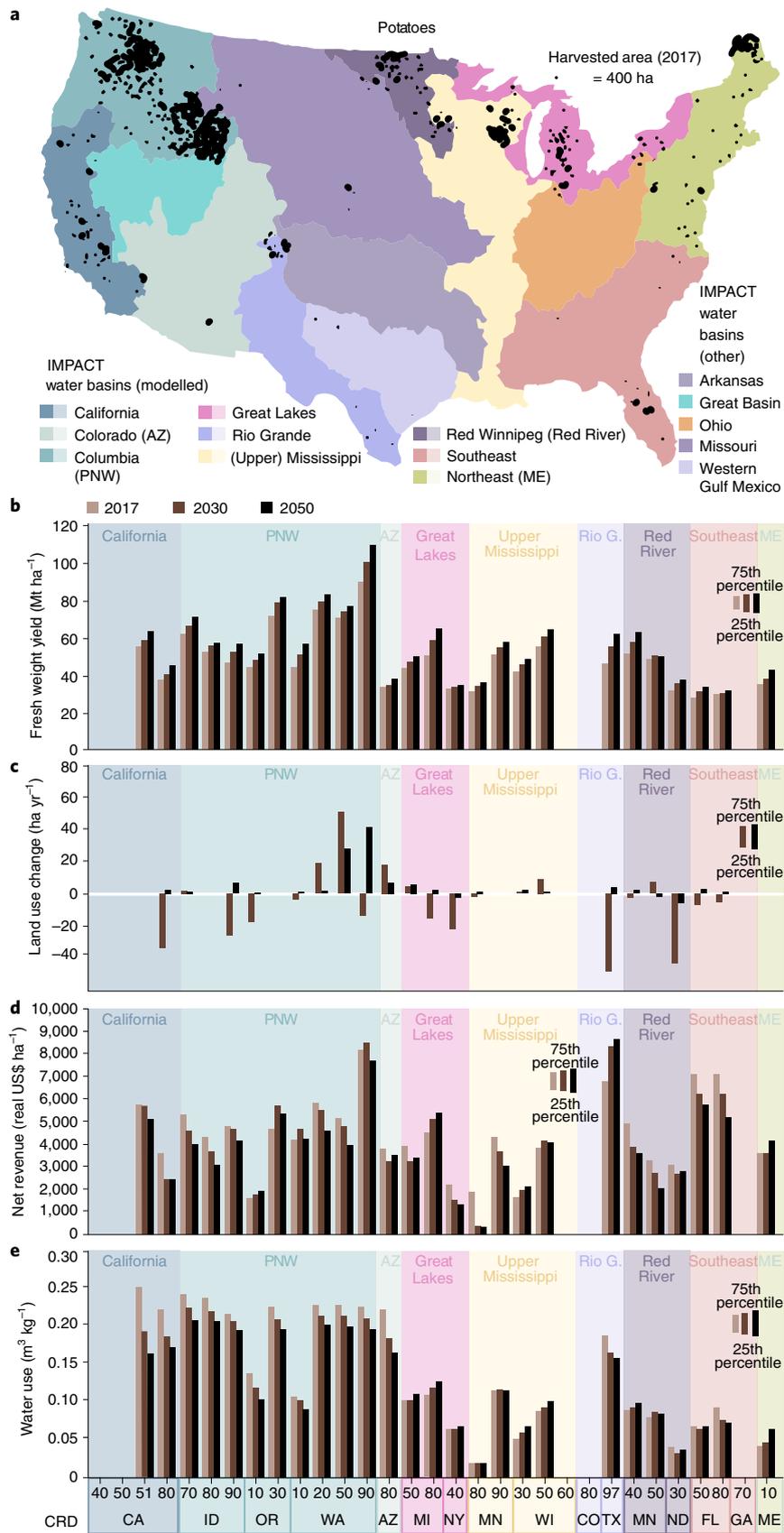
Fig. 2 | US potatoes. a, Current potato production regions, overlaid onto major water basins that cover the lower 48 states of the United States. IMPACT, International Model for Policy Analysis of Agricultural Commodities and Trade. **b**–**e**, Bar charts showing baseline and future CRD-scale crop yields (**b**), production area changes (**c**), net grower revenues (**d**) and water use (**e**) for growing processing potatoes. The insets show the average spread between the 25th and 75th percentile levels of each parameter.
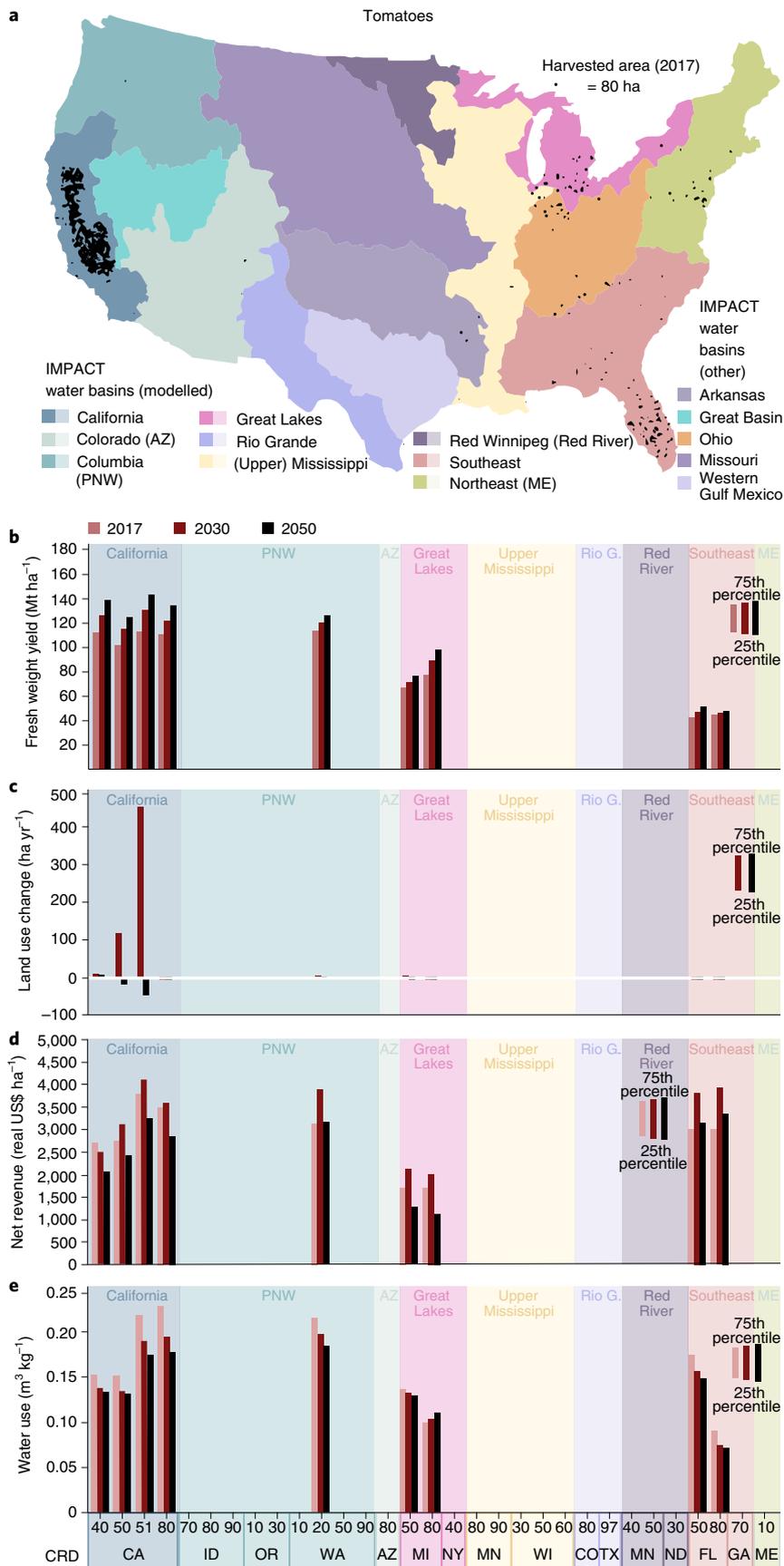
Fig. 3 | US tomatoes. a, Current tomato production regions, overlaid onto major water basins that cover the lower 48 states of the United States. **b–e**, Bar charts showing baseline and future CRD-scale crop yields (**b**), production area changes (**c**), net grower revenues (**d**) and water use (**e**) for growing processing tomatoes. The insets show the average spread between the 25th and 75th percentile levels of each parameter.
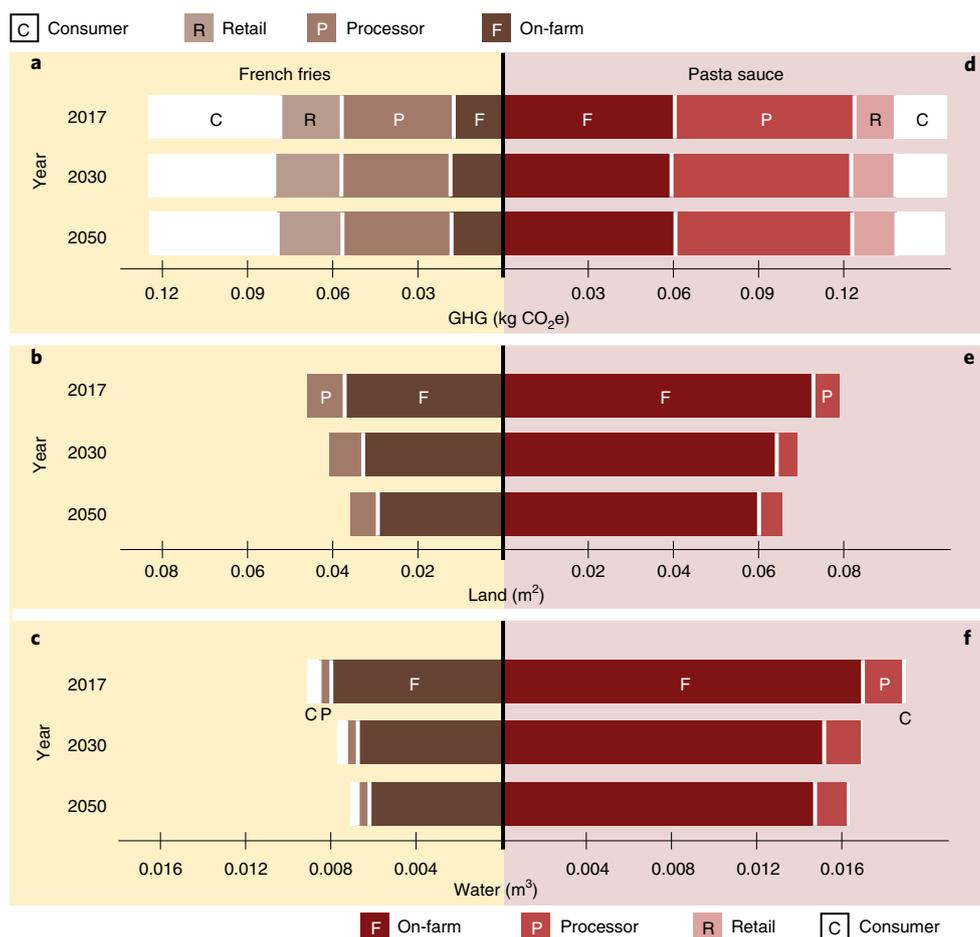
Fig. 4 | Environmental footprints. a–f, Baseline and future cradle-to-grave environmental footprints for 0.1 kg servings of French fries (GHG emissions (**a**), land use (**b**) and water use (**c**)) and pasta sauce (GHG emissions (**d**), land use (**e**) and water use (**f**)), in US supply chains, showing the relative contributions of the various elements of the supply chain: on-farm, processor, retail and consumer.

under a 'no climate policy' scenario[28] and probably the upper envelope of projected climate impacts. Less extreme changes are plausible (for example, through the use of RCP 4.5 or other scenarios), which could result in different yield responses as shown in this study's projections. Our multi-model ensemble approach increased the projected accuracy and enabled the quantification of projected uncertainties.

Regional variation in the production of processing potatoes. The PNW is the most important production region for potatoes, with the highest yields in the country (Fig. 2). This yield advantage is projected to continue and even expand, with some gains in production area in eastern Washington. Other regions with important 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 that 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 the production of processing tomatoes. The geographic pattern of processing tomato production is very different from that of potatoes (Fig. 3). The majority (>95%) of all processing

tomatoes are now produced in California, and most of those come from the two CRDs 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 a result of the Sustainable Groundwater Management Act[29], other published work suggests that high-value crops such as these will continue to have full access to future water supplies in these regions[30]. Accordingly, our modelling analysis did not include the potential for constraining irrigation water supply. We thus 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 subsequent two decades. Projected tomato yields and net grower revenues are competitive with California in both the PNW and the Southeast, 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 centred on a small number of plants in Indiana. Nevertheless, the modelling shows that processing plants could be supported elsewhere in the country, should water constraints force processors out of the San Joaquin Valley[21]. Extensive fruit and vegetable processing capacity is already present in the PNW, which should dramatically lower the expense associated with such a move.
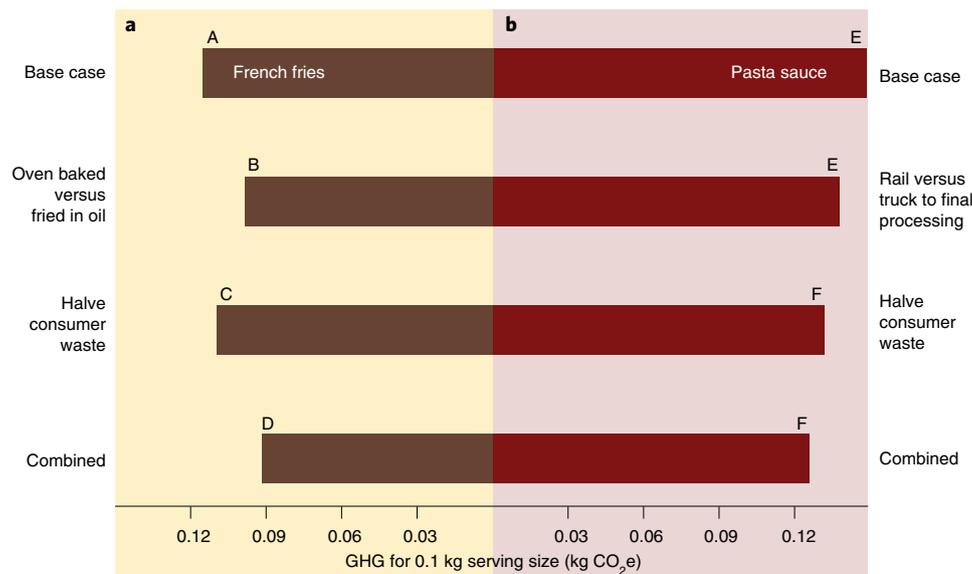
Fig. 5 | Mitigation options. a,b, Impact of various options for mitigating the cradle-to-grave GHG emissions for 0.1 kg servings of French fries (**a**) and pasta sauce (**b**), in US supply chains. Bars labelled with the same capitalized letter (A–F) are not statistically different from each other ($P = 0.01$).

Water scarcity issues. Since most irrigation water in the United States is not allocated at market prices, water resource allocation for irrigation is not predictable based on 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 a 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 United States. This region has the highest risk of allocation-induced scarcity for production of the regions analysed 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 (a possible exception is California's San Joaquin Valley). Due to future restrictions on water use in California[21], irrigation may be diverted away from less-profitable crops (for example, pasture for animal feed) to sustain continued potato and tomato production[30]. It is acknowledged, however, that short-term drought in other parts of the United States (for example, potato yields in the Northeast[31]) can limit production, particularly when irrigation infrastructure is not present or is inadequate.

Demand considerations. Domestic consumer demand for processed potatoes is projected to grow at a compound annual growth rate of 0.9% from 2019 to 2050. 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% per year but start from significantly higher levels. The demand for frozen potatoes (primarily French fries) is expected to grow by 2.4 million metric tons from 2019 to 2050. Domestic consumer demand for processed tomatoes has been relatively steady over the past decade after some decline in the previous decade. The modelling includes a slight positive trend in consumer demand for processed tomatoes, which, when combined with US population growth, results in a compound annual growth rate of 1.1% from 2019 to 2050.

Opportunity assessment. One of the key uses of this integrated approach is to identify hot spots 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 the production of such crops can be profitable and can 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 activity[29].

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 irrigation[32]. A production scenario for potato production using drip irrigation (not included in our assumed technology trend) shows a 6% reduction in water use and a 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)[33,34].

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 modelling but could be critical[35]. Our results could also be enhanced by detailed analysis of irrigation water availability by region and better economic input data to support economic modelling at the fine geographic scale (the CRD scale). Other opportunities to improve the crop modelling include consideration of the stress caused by excessive moisture, a common issue in the upper Midwest[36]. Another opportunity for enhancing the integrated approach would be to include social and health aspects, which are often considered intrinsic to sustainability.

Next steps with this 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 general circulation models with crop models and simulated yield and water use from crop models with economic models that consider other variables (for example, production, consumption, prices and trade). Our integrated approach adds a fourth component for LCA analysis with coupling points to both the crop and economic models. While AgMIP until now has focused mainly on important cereal and legume crops, we concentrated on two of the most important vegetable crops: potatoes and tomatoes. Although there were many uncertainties associated with our impact and risks assessment, it also creates opportunities to add a new dimension to 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 in nutrition security. Although we have chosen to report results here for just two products made from potatoes and tomatoes, the integrated methodology described here can be applied to examine all crops needed for a balanced diet for any region in the world (pending data availability). One sustainability and health-based consumer scenario would be to examine shifts from processed to fresh foods. We acknowledge that data availability in the United States made it possible to apply the approach with higher geographic and food-type specificity than might be possible elsewhere, but the methodology is still fully applicable to other countries. Such an approach would help explore scenarios for sustainable and healthy diets that also help ensure a transition to food systems for future generations that are resilient to climate change. All such assessments would help producers, processors, traders and policymakers efficiently adapt to the challenges of accelerating global climate change and 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 modelling to investigate climate change adaptation and mitigation scenarios for processing potato and processing tomato supply chains, starting with current conditions through the year 2050. The suggested method is more clearly presented in the Supplementary Information; here just the used models are named and briefly explained. A schematic of the overall integrated approach is provided in Supplementary Fig. 1.

Selection of representative counties for modelling. 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. 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 modelling, with one additional county (St Johns, Florida) added to better represent potatoes in that state.

Selection of processing varieties for modelling. The crop modelling 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, colour and yield to adapt to specific markets, which makes them more difficult to parameterize for modelling purposes.

Estimation of yield impacts from climate change. We used a multi-model approach based on AgMIP protocols[37] to estimate changes in yield, irrigation water requirements and crop nutrient requirements (N, P and K) in all cropping areas of interest through 2050. Climate change impacts by 2050 on potatoes in 32 main potato-growing districts in the United States were estimated with an ensemble of five process-based models (SIMPLE[38], CropSyst[39,40], LINTUL-POTATO-DSS[41], EPIC[42,43] and DSSAT-Substor-Potato[44–46]) and one statistical model[47]. Three crop models (SIMPLE, CropSyst and DSSAT CSM-CROPGRO-tomato[48]) and a statistical model[47] were used to estimate the impact of climate change on tomatoes in eight main tomato districts for processing tomatoes across the United States. The lower number of models for tomatoes was based solely on model availability but is still consistent with the multi-model AgMIP approach[37]. National and regional impacts were derived from district averages by weighting the corresponding crop

areas. The crop models were calibrated to field-experimental-based-corrected district yields[49] for potatoes[50]. Due to the lack of tomato data, the tomato models used previous cultivar calibrations[38]. The statistical model was trained on data from the US Department of Agriculture (USDA) National Agricultural Statistical Service (NASS) dataset[51]. Crop and statistical model estimates used gridded downscaled[52] daily weather data (4 km × 4 km) for a baseline (1981–2010)[53] and two future time slices (2021–2050 and 2041–2070) from five general circulation models[52,53] for RCP 8.5 (ref. [16]). No water or nitrogen limitations were assumed in the potato and tomato cropping systems. As a possible adaptation to a warmer climate, an earlier planting date was considered. Another plausible adaptation strategy could involve a change in cultivars, but this was outside the scope of this study. Nitrogen, phosphorus and potassium fertilizer demand was calculated after the crop simulations on the basis of simulated yield and nutrient concentrations[54,55] and their changes with elevated atmospheric CO_2 concentrations[20]. The simulated baseline yields were bias-corrected to the regression yield for 2017 on the basis of CRD yields for each CRD (see the crop modelling protocol[50] for more details).

Future climate scenarios. Higher future atmospheric CO_2 concentrations will stimulate growth if other nutrients are not limiting[56]. The yearly changing atmospheric CO_2 concentrations for the baseline (1981–2010) and future periods (2030s and 2050s) under the RCP 8.5 scenario were applied[28]. Five general circulation models were used (GFDL-ESM2M, HadGEM2-ES365, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M), consistent with the Inter-Sectoral Impact Model Intercomparison Project[57].

Yield projection method. The projected future yields included climate change impacts (temperature and CO_2 change), the effect of earlier planting as an adaptation and the effect of 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; better equipment; and other improvements. A stepwise process was used. 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 (Fig. 1). 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 period. The technology component observed in the past was then attenuated to 90% by 2030 and 70% by 2050, causing the partial flattening of the yield curves over time[18]. The climate component was determined on the basis of 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. To characterize overall modelling 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 modelling overview. Structural partial equilibrium models for US fresh and processed potatoes and tomatoes were developed to simulate the impact of climate variation and mitigation practices on crop net returns and land use change. To capture the geographically detailed output from the crop yield simulation models, area, yield and production equations were developed for the 31 US CRDs, with one additional region to capture the remainder of the United States. 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'). On the basis of 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. Substitution between the processed and fresh sectors is therefore very limited or non-existent. 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 appreciably changing processing capacity, with processors preferring to operate their facilities at optimal capacity[58].

Demand equations were developed at the national level on the basis of the fresh and processed demand as detailed in the 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 that focused on the primary US trading partner countries were also developed and used as part of the modelling system employed in this study (see the Supplementary Information for the details). Because climate impacts on crops and yield vary by region, it was important to determine whether trade would be affected by the climate impacts on other trading partners[59]. 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 United States, the area devoted to potatoes and tomatoes is still very small in comparison with major row crops (for example, maize and soybeans). 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 materially 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, row crop producers with water rights may choose to continue their operations rather than leasing those rights to specialty crop producers. Therefore, the modelling system also incorporated WAEES existing models of global row crops (Supplementary Information). While the economic models constrain total irrigated area to the existing CRD irrigated area, the constraint was not found to be crucially 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 four years. The need for such a lengthy crop rotation may put a burden on land cultivated by vegetable growers when demand increases; just as with irrigation, farmers growing row crops may not be willing to share land with vegetable farmers.

Data limitations. The crop modelling teams noted that there was significant variation in climate impacts on yield within individual states, necessitating the use of sub-state production regions. Both counties and CRDs were evaluated as possible geographies, but ultimately CRDs were chosen due to more complete datasets. 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, these data were 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. To estimate the supply elasticities, historical time series of area, yield and production for each CRD from 2000 to 2017 were assembled.

Interdisciplinary data exchange among the modelling teams. The economic modelling 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 CRDs 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 United States and for crops other than potatoes and tomatoes were provided by the IFPRI IMPACT model[60,61]. 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 modelling teams, as needed.

LCA. The LCA 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 published LCA protocol[62] that fully describes the cradle-to-grave approach (see the Supplementary Information and a recent publication[63] for the 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 modelling teams. The on-farm LCI represents the average farm management and production of each CRD. 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-processer transport, processing and packaging, distribution through retail, consumption, and final disposal. The LCA methodology is compliant with ISO standards[64].

LCI modelling. The LCI 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 NASS, the Agricultural Resource Management Survey and the Economic Research Service. Some data were difficult to obtain, and for the processing stages, the data were partly based on the processing plant (for example, for tomato) and on engineering estimates and available literature.

LCA modelling. The model is constructed of three elements: production, post-harvest and biowaste-handling[62,63]. In brief, the first element characterizes crop production in each CRD[50], and the subsequent stages of the supply chain include processing (with warehouse storage of potatoes), retail/supermarket and consumer activities, which are modelled 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. The cradle-to-grave approach for this study accounted for all the activities and raw materials associated with (1) the background system (that is, upstream production processes, where the production and supply of agro-chemicals, energy/fuel and farm implements and other associated raw materials occur) and (2) the foreground system (that is, downstream processes). The foreground system is the central component where the principal activities for the production, processing and consumption of the selected commodities occur; the full upstream supply chain is included in the system boundary via input flows to the three primary supply chain stages that are explicitly in the foreground. During the simulations of the life cycle impacts, the related emissions occurring in the upstream processes were accounted for using the Ecoinvent life cycle database, v.3.6 consequential[65]. The system boundary also included the treatment of packaging waste and biowaste (food waste) occurring across the supply chain. We have fully followed our previously published LCA protocol for this study[62].

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 the FU, its appropriateness is debated[66], particularly considering the large variation among foods' characteristics (water and nutritional content, for example). Alternate FUs have been suggested; however, these have not been adopted for this study[67–69]. Reference flows are the quantitative outputs from processes contained in a product system that are required to deliver the FU (Supplementary Information). The defined FUs for potato and tomato are 1 kg of French fries consumed and 1 kg of pasta sauce consumed. 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 assuming consumer-stage waste of 18%. Ultimately, to deliver the 1 kg of frozen fries, 2.16 kg of raw potato must be produced[63].

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 study[70]. This study protocol considered three impact categories: global warming potential (in kg CO_2e), water consumption (in m³ equivalent) and land use (in 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 allocation[71]. This often occurs in the food processing industry, where processing plants are built with multiple processing lines, which generate arrays of products (for example, raw potato processed to frozen fries, chips and dehydrated products; and tomato to paste, diced and sauces). In such cases, as suggested by others[72], 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 of potato chips produced when both are manufactured in a single facility. Hence, from the total annual raw materials consumed in an ideal processing plant, the subdivision of raw material inputs to each processing line was estimated on the basis of 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 category[73].

Biowaste treatment scenarios. Estimates of the quantity of waste generated across the supply chain were based on Buzby et al.[74] and other sources[75–77]. 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 composting, incineration and land-fill (consumer waste)[78]. The features and assumptions for the alternative biowaste management scenarios are fully described in the LCA protocol[62]. The 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[79,80]. Briefly, 1,000 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's t and associated P values was produced for each pair. If the upper 95% confidence interval P value was less than 0.01, the null hypothesis that the mean values of the two distributions are equal was rejected.

Data availability

Source data are provided with this paper. All other data used in this paper are freely available upon request from the corresponding author.

Code availability

All code utilized in this paper are freely available upon request from the corresponding author.

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Author contributions

D.G. served as the convening lead author and co-led the overall project with S.A., who led the crop modelling team (C.S., K.R., C.G., T.K., Y.L., K.G., E.M., R.L.N., A.P., R.R., A.A.R., F.v.E., G.W., L.X. and C.Z.) and served as a lead author on the text. J.K. led the economic modelling team (P.I. and M.R.) and served as a lead author on the text. G.T. led the LCA modelling team (R.P. and D.G.) and served as a lead author on the text. C.F. served as a project co-lead after the departure of S.A. and co-led the extension component of the project with C.K. G.H., M. Matlock, M. McLean, T.B.S. and K.W. served as internal project advisors and as co-editors of the text. D.S. served on the project advisory committee and provided critical data to the LCA modelling for processed tomato supply chains. L.T. led communications for the project and created the figures.

Competing interests

The authors declare no competing interests.

Additional information

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c GHG

mass (0.1 kg)

calories (100 kcal)

nutrient density (% EAR in 0.1 kg)

0.20 0.15 0.10 0.05 (kg CO₂e) 0.05 0.10 0.15 0.20

d Land

mass (0.1 kg)

calories (100 kcal)

nutrient density (% EAR in 0.1kg)

0.08 0.06 0.04 0.02 (m²) 0.02 0.04 0.06 0.08

e Water

mass (0.1 kg)

calories (100 kcal)

nutrient density (% EAR in 0.1 kg)

0.08 0.06 0.04 0.02 (m³) 0.02 0.04 0.06 0.08

a Potatoes — Processed Market

Frozen French Fries 33%

Fresh Market 39%

Chipping 13%

Dehydrated 10%

Other 5%

Chosen as focus for the LCA modeling

b Tomatoes — Processed Market

Fresh Market 8%

Other 10%

Diced 12%

Paste 70%

Chosen as focus for the LCA modeling

Extended Data Fig. 1 | US Potato and Tomato Supply Chains. 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.