A Multi-Scale Analysis of Food Waste Reduction: Sustainable Gains and Equity Challenges

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Abstract: Reducing food waste (FW) is a key strategy for achieving multiple Sustainable Development Goals (SDGs), including food security (SDG 2), responsible consumption and production (SDG 12), climate action (SDG 13), and economic growth (SDG 8). While enhancing sustainability, FW reduction also introduces economic trade-offs, particularly in labor-intensive agricultural sectors. This study employs a multiscale modeling framework to assess both global sustainability gains and localized economic challenges. At the global scale, a Stochastic Frontier Analysis (SFA) estimates FW as household technical inefficiency, and these estimates are integrated into the Simplified International Model of agricultural Prices, Land Use, and the Environment (SIMPLE). A 50% reduction in FW by 2050, aligned with SDG 12.3, reduces cropland use by 3% and lowers annual greenhouse gas emissions by approximately 1.5 gigatons, easing pressure on natural resources. These changes also lead to lower global crop prices (6.8%–8%), improving food affordability and reducing undernourishment, particularly in Sub-Saharan Africa (7.6 million fewer undernourished individuals) and South Asia (4 million fewer).At the local scale, the Simplified International Model of agricultural Prices, Land Use, and the Environment – Gridded version (SIMPLE-G-US) evaluates the effects of FW reduction on U.S. agricultural water use and labor markets. Irrigation water use declines by an average of 5.6%, with reductions up to 11.6% in water-scarce regions, contributing to water conservation efforts. However, FW reduction also results in a 4.25%–11.8% decline in agricultural employment, with wage losses of up to $3 per hour, particularly in labor-intensive regions like the Fruitful Rim. These findings highlight the need for coordinated policies that maximize sustainability benefits while addressing economic equity concerns, ensuring that FW reduction strategies support both environmental and social well-being.

Key words: Food waste mitigation, Sustainable Development Goals, Multiscale modeling, Land use and emissions, Agricultural labor markets

Introduction

Food loss and waste (FLW) is a pressing global challenge, with approximately 30% of all food produced—1.3 billion tons valued at $1 trillion annually—going to waste (FAO, 2013). This inefficiency exacerbates food insecurity, environmental degradation, and economic losses, making it a critical issue for policymakers, businesses, and researchers (Lopez Barrera & Hertel, 2023). FLW reduction is widely recognized as a key strategy for achieving multiple Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). However, while FW mitigation improves food security and resource efficiency, it also reduces food demand, potentially affecting labor-intensive agricultural sectors, raising concerns about SDG 8 (Decent Work and Economic Growth).

Despite growing interest in FW mitigation, quantitative assessments of its systemic impacts remain limited. A primary challenge in studying food waste is the lack of standardized definitions and measurement methodologies, leading to inconsistencies in estimation and valuation (Bellemare et al., 2017). Traditional data collection methods, such as food diaries, household surveys, and curbside collection, are costly, labor-intensive, and difficult to scale (Cicatiello & Giordano, 2018; van Herpen et al., 2019; Qi et al., 2020). Moreover, FLW patterns vary across geographic and income levels: food waste is more prevalent in higher-income countries, while food loss dominates in lower-income regions due to post-harvest inefficiencies (Thyberg & Tonjes, 2016; Poore & Nemecek, 2018).

While prior studies have examined the environmental and food security benefits of FW reduction (Lopez Barrera & Hertel, 2022), few have explored its potential equity implications. Specifically, reducing food demand through FW mitigation may lead to lower agricultural employment and wage reductions, particularly in regions reliant on labor-intensive production. The U.S. agricultural sector employs approximately 2.4 million hired farmworkers, with significant labor concentration in fruit and vegetable production (USDA ERS, 2021). The Fruitful Rim, one of the most affected regions, depends heavily on seasonal and migrant labor, with an estimated 50-70% of farmworkers being of Hispanic origin, many of whom are undocumented or employed under temporary work visas (Martin, 2022; NAWS, 2020). Given that farm labor wages are already lower than the national average, with median hourly earnings of $14.62 in 2021 compared to $22.00 across all private industries (BLS, 2022), the economic effects of FW reduction could disproportionately impact marginalized agricultural workers and rural economies.

This study contributes to the literature by advancing the methodology for assessing FW reduction's economic and environmental effects by integrating household technical inefficiency estimates into a global economic model. It is the first to quantify both the global benefits, such as food security improvements and resource efficiency gains, and the localized trade-offs, particularly labor market impacts and wage reductions, providing a more comprehensive view of FW mitigation's systemic effects. To achieve this, we develop a multiscale modeling framework that evaluates both the global sustainability benefits and localized economic trade-offs of FW reduction. At the global scale, we use Stochastic Frontier Analysis (SFA) to estimate food waste as household technical inefficiency, integrating these estimates into the Simplified International Model of agricultural Prices, Land Use, and the Environment (SIMPLE). This allows us to project long-term price, land use, and food security impacts under a 50% FW reduction scenario, aligned with SDG

12.3. At the local scale, we use SIMPLE-G-US to assess the distributional effects on U.S. agricultural labor markets and water use, capturing both resource efficiency gains and employment trade-offs.

Our findings underscore a fundamental policy challenge: while FW reduction enhances food affordability, resource efficiency, and greenhouse gas mitigation, it reduces labor demand and wages in key agricultural regions. These results emphasize the need for coordinated policies that balance sustainability goals with economic equity, ensuring that FW mitigation strategies do not disproportionately impact agricultural communities and workers.

Materials and methods

This study employs a multiscale modeling framework to assess the sustainability gains and economic trade-offs associated with reducing food waste. At the global level, food waste is estimated as a form of household technical inefficiency using Stochastic Frontier Analysis (SFA) and integrated into a partial equilibrium agricultural model, the Simplified International Model of agricultural Prices, Land Use, and the Environment (SIMPLE). At the local level, the gridded version of SIMPLE (SIMPLE-G-US) is used to analyze the implications of food waste reduction on U.S. agricultural labor markets, water use, and regional employment dynamics.

At the global scale, SFA is used to estimate household food waste inefficiency following the approach of Yu and Jaenicke (2020). This methodology allows food waste levels to be inferred without requiring direct measurement, overcoming limitations in traditional data collection methods such as self-reported surveys or waste audits. Food waste is defined as the gap between food availability and the minimum calories required for observed body mass index (BMI) levels, effectively capturing excess food intake that does not contribute to nutritional outcomes. These SFA-derived food waste estimates are integrated into SIMPLE, a widely used global partial equilibrium model of agricultural markets (Hertel & Baldos, 2016). SIMPLE represents agricultural supply and demand across multiple global regions, using a constant elasticity of substitution (CES) production function to model crop and livestock production. The model accounts for land-use dynamics, trade interactions, and food price adjustments, enabling an examination of how food waste reduction affects global food security, land use, and greenhouse gas emissions. A 50% reduction in food waste by 2050—consistent with Sustainable Development Goal (SDG) 12.3—is introduced as a counterfactual shock to per capita food demand, differentiating impacts by commodity type and region. The model projects adjustments in global crop prices, agricultural production, and resource use under these mitigation efforts.

To evaluate the distributional effects of food waste mitigation at a finer spatial scale, SIMPLE-G-US is employed. This extension of SIMPLE incorporates high-resolution data on agricultural production, labor markets, and water use across the United States, linking global-scale food system changes to localized economic and environmental outcomes and capturing regional disparities in employment losses and water savings. The model integrates USDA Farm Resource Regions and Commuter Zones (Tolbert & Sizer, 1996) to refine labor market impacts, allowing for a more accurate representation of farm labor mobility and employment dependencies in agricultural hubs such as the Fruitful Rim. The study also assesses water use reductions by linking crop-specific irrigation requirements with the projected declines in agricultural production following food waste reduction. The model accounts for regional variations in groundwater and surface water use, emphasizing water-scarce regions where food waste mitigation could alleviate resource pressures.

The counterfactual scenario assumes exogenous reductions in food waste-induced demand, leading to a reallocation of food availability and lower agricultural output. By comparing the baseline (SSP2 projections for 2050) and counterfactual scenarios, the analysis examines sustainability gains such as reduced land use, lower greenhouse gas emissions, and improved food security, alongside economic trade-offs in the form of declining agricultural employment and wages, particularly in labor-intensive farming regions. This approach integrates insights from prior Computable General Equilibrium (CGE) studies on food waste mitigation (Friman & Hyytiä, 2022; Philippidis et al., 2019), extending the literature by incorporating spatially explicit labor market effects and regional water use dynamics. The findings inform policy discussions on how to balance sustainability goals with the economic realities of farming communities.

Results

A 50% reduction in food waste (FW) by 2050, aligned with Sustainable Development Goal (SDG) 12.3, leads to substantial global sustainability gains but also introduces localized economic trade-offs, particularly affecting agricultural labor markets. At the global scale, FW reduction improves food security, lowers cropland expansion, and reduces greenhouse gas (GHG) emissions, while at the local scale, it alters agricultural labor markets and water use patterns across U.S. farming regions.

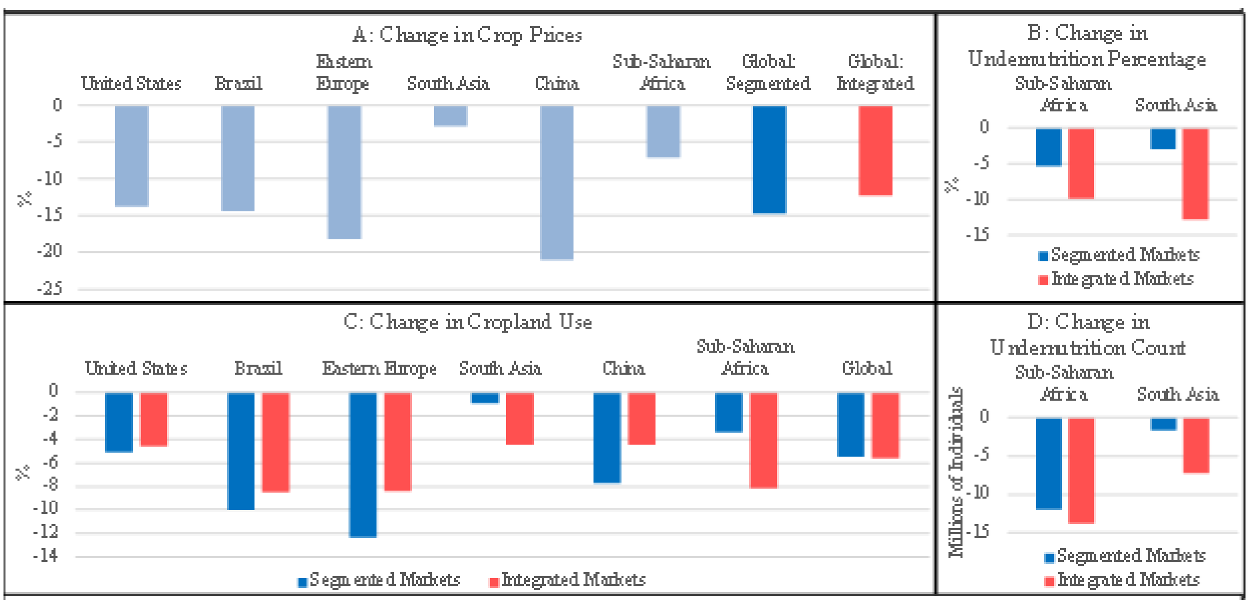

Figure 1: Global cropland and undernutrition reduction due to food waste mitigation. This figure presents the percentage changes in key agricultural and food security indicators under a 50% food waste reduction scenario compared to the 2050 baseline projection. The bars represent the percentage changes relative to the baseline scenario, calculated by subtracting the baseline values from the alternative scenario values and dividing the result by the baseline values. Panel A shows the change in crop prices across different regions. Panel B displays the change in undernutrition rates for Sub-Saharan Africa and South Asia. Panel C illustrates the change in cropland use across selected regions. Panel D presents the absolute change in the number of undernourished individuals, measured in millions, for Sub-Saharan Africa and

South Asia. The blue bars represent results from a segmented global market scenario, while the red bars correspond to the integrated global market scenario.

At the global level, FW mitigation leads to a 3% reduction in cropland use, relieving pressure on natural ecosystems by reducing the need for further agricultural expansion (**Figure 1, panel C**). This reduction in agricultural production lowers GHG emissions by approximately 1.5 gigatons of CO_2-equivalent annually. Additionally, reduced demand for agricultural commodities contributes to a 6.8%–8% decline in global crop prices, improving food affordability and enhancing food security outcomes in regions most affected by food insecurity **(Figure 1, panel A and B)**. The model projects that undernourishment declines by 7.6 million individuals in Sub-Saharan Africa and by 4 million in South Asia, primarily due to lower food prices making staple crops more accessible **(Figure 1, panel D)**. However, these benefits are not uniform across regions, as food-exporting countries experience larger price declines, potentially impacting farm revenues.

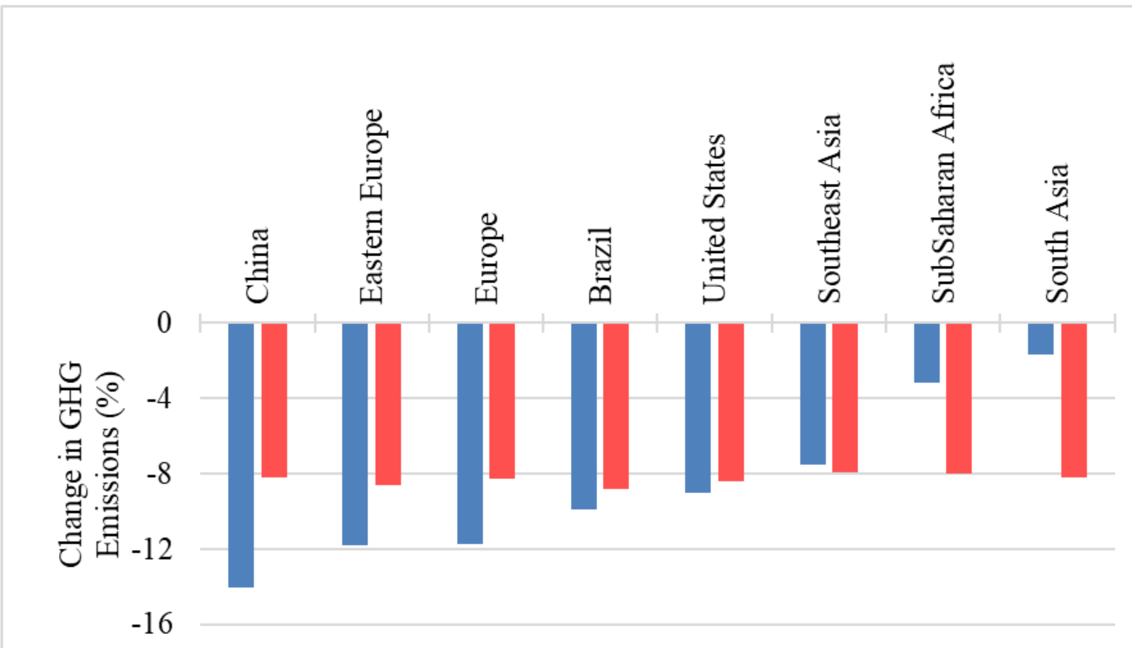

Figure 2. Reduction in Greenhouse Gas Emissions (GHG) due to food waste mitigation. This figure presents the percentage change in greenhouse gas (GHG) emissions under a 50% food waste reduction scenario compared to the 2050 baseline projection. The bars represent the relative reduction in emissions across different global regions. The blue bars correspond to the segmented global market scenario, while the red bars represent the integrated global market scenario. The y-axis indicates the percentage change in GHG emissions, with negative values reflecting reductions in emissions due to decreased agricultural production. The x-axis lists the affected regions.

While the global impacts of FW reduction lead to sustainability gains, these changes also have significant regional consequences, particularly in agricultural labor markets and water use. At the local level, the impact of FW reduction varies significantly across U.S. agricultural production systems, with pronounced effects on irrigation water use and employment in labor-intensive farming regions. The results indicate that total irrigation water use declines by an average of 5.6%, with reductions exceeding 11.6% in water-scarce regions, particularly in California's Central Valley and the Southwest U.S., where irrigation intensity is highest. These reductions are driven by lower demand for water-intensive crops, leading to a contraction in agricultural water withdrawals.

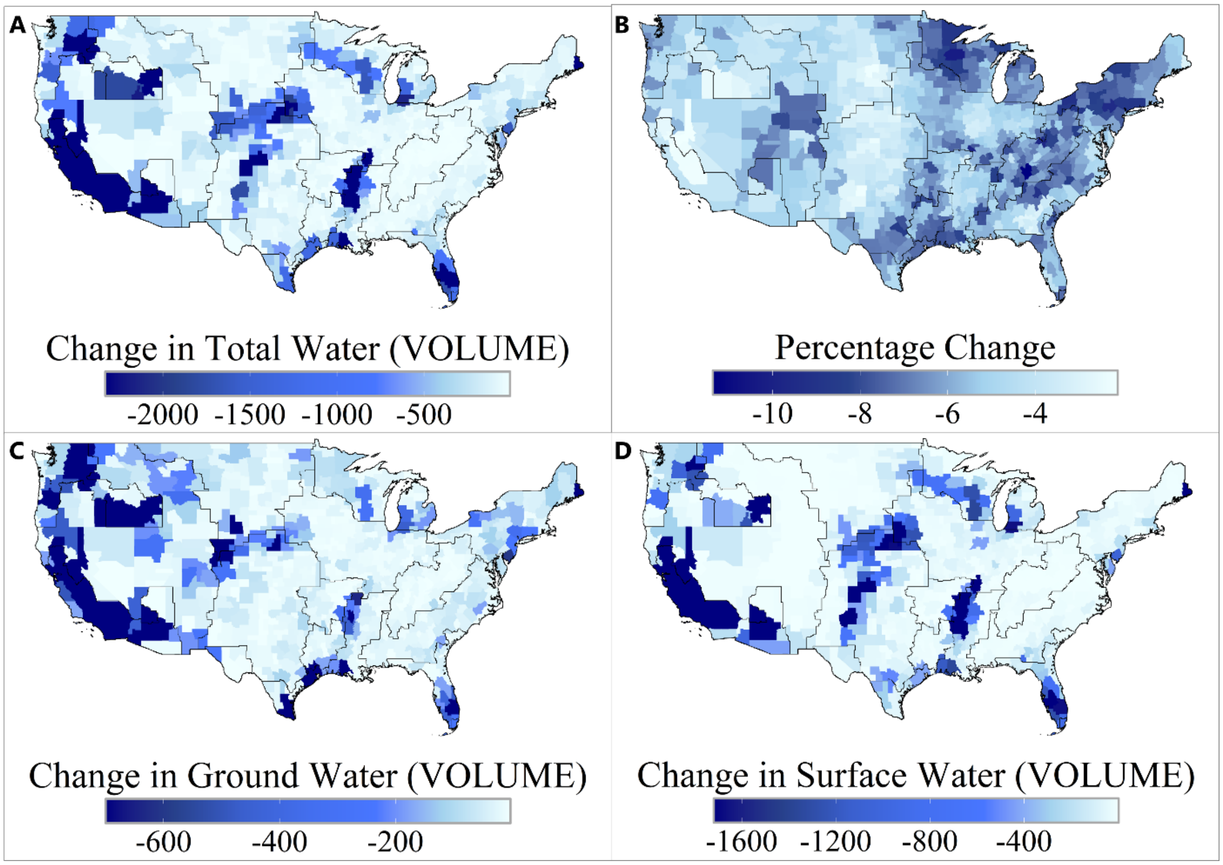

Figure 3: Regional changes in U.S. agricultural water use due to food waste reduction This figure presents the projected changes in agricultural water use across the United States under a 50% food waste reduction scenario compared to the 2050 baseline. Panel A shows the absolute change in total agricultural water use (in volume). Panel B presents the percentage change in total water use relative to baseline levels. Panel C depicts changes in groundwater withdrawals, while Panel D illustrates changes in surface water use. The color gradients in each panel represent the magnitude of reduction, with darker shades corresponding to greater decreases in water use.

A more detailed breakdown of water use reductions reveals important regional disparities. Panel A of Figure 3 shows that the largest absolute declines in total water use occur in states with expansive irrigated farmland, such as California, Texas, and Nebraska, where reductions exceed 2,000 million cubic meters in some areas. Panel B highlights the percentage reductions in total water use, showing moderate declines in the Midwest and Southeast, while the Southwest and Western states exhibit the most substantial reductions.

The distinction between groundwater and surface water reductions provides further insights into how different regions are affected. Panel C illustrates that groundwater withdrawals decline most sharply in the Western U.S., particularly in California and parts of the High Plains Aquifer, which have long faced challenges of aquifer depletion. Panel D reveals that surface water withdrawals decline most notably in the Midwest and along major river basins, such as the Missouri and Mississippi River systems, indicating that reductions in irrigation demand could also lessen pressures on surface water sources.

These findings highlight geographic differences in how FW reduction affects water use, with variations in absolute and percentage reductions depending on regional irrigation patterns and water source dependencies.

Despite these sustainability benefits, FW reduction also negatively affects agricultural employment in the U.S., particularly in regions reliant on labor-intensive fruit and vegetable production. The results show that employment in agriculture declines between 4.25% and 11.8% nationwide, with the largest reductions concentrated in states with high agricultural employment, including California, Florida, and Texas.

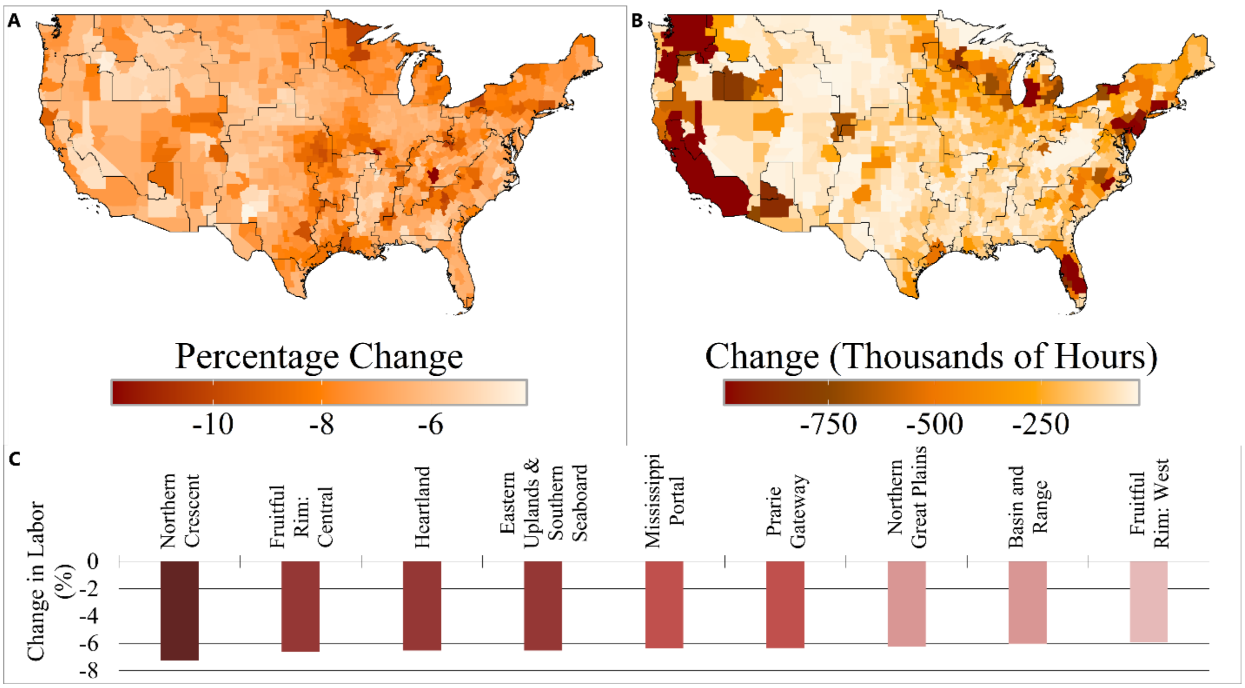

Figure 4. Changes in U.S. agricultural labor demand due to food waste reduction. This figure presents the projected changes in agricultural labor demand across the United States under a 50% food waste reduction scenario compared to the 2050 baseline. Panel A shows the percentage change in agricultural labor demand across U.S. counties, with darker shades indicating larger percentage reductions. Panel B illustrates the absolute change in labor demand, measured in thousands of hours, with darker colors representing greater decreases. Panel C provides a regional breakdown of labor demand changes, showing the percentage decline across major agricultural production zones. The color gradients in each panel indicate the magnitude of change, with darker shades corresponding to greater reductions.

Panel A of Figure 4 presents the percentage change in agricultural labor demand at the county level, showing widespread declines, with the most substantial reductions in coastal and southern agricultural regions. Panel B illustrates the absolute change in labor demand, measured in thousands of hours, with the most significant reductions occurring in California's Central Valley, parts of the Mississippi Delta, and agricultural zones in the Midwest and Southeast. Some of these areas experience cumulative losses exceeding 750,000 labor hours, indicating a substantial contraction in total farm labor requirements. Panel C provides a regional breakdown of labor demand reductions across key agricultural production zones. The Fruitful Rim and Mississippi Portal regions experience the highest percentage declines in labor demand, with multiple areas showing job reductions exceeding 16%. Other regions, including the Prairie Gateway, Northern Crescent, and Basin and Range, also see measurable declines, though to a lesser extent.

The decline in agricultural labor demand is accompanied by a significant reduction in farm wages, particularly in the same regions experiencing the largest contractions in employment. Wages in the agricultural sector decline between 6% and 16% nationwide, with the highest reductions occurring in states with large agricultural workforces.

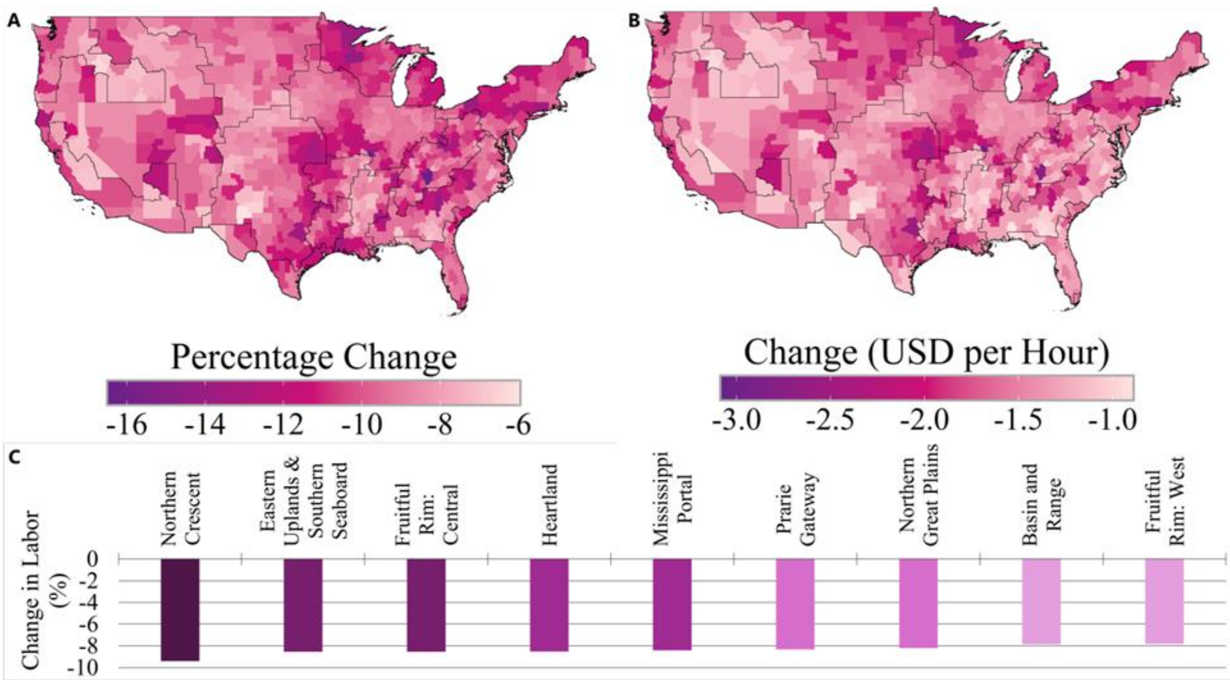

Figure 5. Changes in U.S. agricultural wages due to food waste reduction. This figure presents the projected changes in agricultural wages across the United States under a 50% food waste reduction scenario compared to the 2050 baseline. Panel A shows the percentage change in agricultural wages across U.S. counties, with darker shades indicating larger percentage reductions. Panel B illustrates the absolute change in wages, measured in USD per hour, with darker colors representing greater declines. Panel C provides a regional breakdown of wage reductions, showing the percentage decrease across major agricultural production zones. The color gradients in each panel indicate the magnitude of change, with darker shades corresponding to greater wage reductions.

Panel A of Figure 5 shows that the largest percentage declines in wages are concentrated in California, Florida, and Texas, as well as parts of the Midwest and Southeast. Panel B illustrates absolute wage reductions, with losses exceeding $3 per hour in California's Central Valley, sections of the Mississippi Delta, and other high-production agricultural regions. Panel C provides a regional breakdown, showing that the Fruitful Rim, Mississippi Portal, and Northern Crescent experience the largest declines, aligning with the regions most affected by labor contractions. Other agricultural zones, including the Prairie Gateway, Basin and Range, and Northern Great Plains, also exhibit measurable wage decreases.

Discussion and conclusions

The findings from this study highlight both the global sustainability benefits and the localized economic challenges associated with food waste (FW) reduction. At the global scale, a 50% reduction in FW significantly enhances resource efficiency by decreasing cropland use and mitigating greenhouse gas (GHG) emissions by approximately 1.5 gigatons of CO_2-equivalent annually. These environmental gains are coupled with improved food security, particularly in Sub-Saharan Africa and South Asia, where reductions in global crop prices lead to notable declines in undernourishment. These results underscore FW reduction as a viable strategy to support multiple Sustainable Development Goals (SDGs), including SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). However, these global benefits come with important trade-offs at the regional level, particularly in labor-intensive agricultural economies.

At the local scale, FW reduction leads to significant declines in both agricultural employment and wages across the United States, with the most pronounced effects in labor-intensive farming regions such as the Fruitful Rim and Mississippi Portal. Employment in agriculture declines between 4.25% and 11.8%, with corresponding wage reductions of up to $3 per hour in highly affected areas. These findings raise important equity concerns under SDG 8 (Decent Work and Economic Growth), as FW reduction, while beneficial for sustainability, disproportionately affects regions and workers reliant on labor-intensive agricultural production. Additionally, while reductions in irrigation water use, particularly in water-scarce areas, contribute to conservation goals, they also reflect shifts in economic activity that may impact rural communities dependent on agricultural livelihoods.

These results suggest that FW mitigation policies should be designed with a balanced approach that maximizes environmental and food security benefits while addressing potential economic disruptions. Policies that integrate FW reduction with labor transition programs, regional economic diversification, and support for affected agricultural workers will be critical to ensuring an equitable transition. Additionally, targeted strategies that align FW reduction with sustainable land and water management can further enhance resource efficiency while minimizing unintended consequences. Moving forward, a coordinated policy framework that considers both sustainability and economic resilience will be essential to harnessing the full benefits of FW reduction without disproportionately burdening vulnerable agricultural communities.

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