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Labor markets: A critical link between global-local shocks and their impact on agriculture

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Abstract

Labor markets can shape the impacts of global market developments and local sustainability policies on agricultural outcomes, including changes in production and land use. Yet local labor market outcomes, including agricultural employment, migration and wages, are often overlooked in integrated assessment models (IAMs). The relevance of labor markets has become more important in recent decades, with evidence of diminished labor mobility in the United States (US) and other developed countries. We use the SIMPLE-G (Simplified International Model of agricultural Prices, Land use, and the Environment) modeling framework to investigate the impacts of a global commodity price shock and a local sustainable groundwater use policy in the US. SIMPLE-G is a multi-scale framework designed to allow for integration of economic and biophysical determinants of sustainability, using fine-scale geospatial data and parameters. We use this framework to compare the impacts of the two sets of shocks under two contrasting assumptions: perfect mobility of agricultural labor, as generally implicit in global IAMs, and relatively inelastic labor mobility ('sticky' agricultural labor supply response). We supplement the numerical simulations with analytical results from a stylized two-input model to provide further insights into the impacts of local and global shocks on agricultural labor, crop production and resource use. Findings illustrate the key role that labor mobility plays in shaping both local and global agricultural and environmental outcomes. In the perfect labor mobility scenario, the impact of a commodity price boom on crop production, employment and land-use is overestimated compared with the restricted labor mobility case. In the case of the groundwater sustainability policy, the perfect labor mobility scenario overestimates the reduction in crop production and employment in directly targeted grids as well as spillover effects that increase employment in other grids. For both shocks, impacts on agricultural wages are completely overlooked if we ignore rigidities in agricultural labor markets.

1. Introduction and motivation

One of the important challenges facing researchers analyzing sustainability in a global-local-global framework involves the incorporation of biophysical and socioeconomic processes that arise at the 'meso' level (Hertel *et al* 2021). Several global modeling frameworks resolve processes within individual grid cells (Lotze-Campen *et al* 2008, Valin *et al* 2013, Shin *et al* 2016, Baldos *et al* 2020). However, they tend to overlook processes within regions that span multiple grid cells, i.e. the meso level.

Agricultural labor markets are a meso-level intermediator that can shape impacts in multi-scale frameworks. Farm labor is an essential input into agricultural production, accounting for 40% of production expenses in fruit and tree nut operations in the United States (US) (USDA NASS 2017). Agriculture brings natural as well as human resources into the food system. In this paper, we highlight the critical role of labor markets in governing the effectiveness and distributional impacts of global food price shocks and local sustainability policies targeting land and water use in agriculture. We begin by reviewing the empirical literature on agricultural labor markets. We then offer insights from economic theory regarding the link between the functioning of labor markets and agricultural outcomes. Finally, we build these components into a multi-scale, gridded economic model for US agriculture Simplified International Model of agricultural Prices, Land use, and the Environment—Gridded version ((SIMPLE-G)-CZ). Using SIMPLE-G-CZ, we demonstrate how labor-market responses alter the impacts of global price shocks and local sustainability policies on agricultural production, employment, and land use.

Agricultural labor markets in the US are complex, involving different types of labor with unique characteristics. Field crops such as maize, soy and wheat are largely grown in the Midwest and Great Plains, where mechanization has permitted many farms to operate with a small labor force consisting primarily of family labor, supplemented by hired labor from local communities (USDA 2022). In contrast, in the 'Fruitful Rim,' where the bulk of US fruit, vegetable and horticultural (FVH) farms operate, immigrant labor, particularly from Mexico, is the main source of hired labor. Labor requirements for the FVH sector are highly seasonal. Follow-the-crop migration traditionally has facilitated agricultural production by redistributing agricultural workers across localities and seasons. However, farmworker mobility has decreased significantly over time (Fan *et al* 2015), while the overall supply of farm workers from Mexico has declined (Charlton and Taylor 2016). Because of this, farms are becoming more reliant on workers who have settled in nearby localities and are more likely to compete with nearby non-farm businesses for scarce labor. These trends highlight the importance of representing labor markets in a global-local-global framework.

The growing reluctance of workers to relocate to new regions of the country means that wage differentials can emerge and persist across regions. This was evident in non-agricultural labor markets after China's accession to the World Trade Organization (WTO) and rapid growth in Chinese exports over the past two decades (Autor *et al* 2016). Trade economists analyzing the impacts of WTO accession paid little attention to labor markets (Bhattasali 2004). As a result, few anticipated the slow adjustment of the US manufacturing sector and the depressed regional labor markets that emerged (Autor *et al* 2021).

We bring these recent labor market insights into integrated assessment models (IAMs) by explicitly accounting for the rigidities in the mobility of agricultural workers. We illustrate the importance of labor-market responsiveness by assessing the impacts of the recent commodity price boom as well as local that conserve over-exploited resources from farming. Our emphasis is on how labor market rigidities shape the responses to global and local shocks. We focus on the US, drawing on extensive prior work on US agricultural labor markets. However, these issues are also relevant in developing countries, where agriculture is more labor intensive and labor market rigidities are widespread (Campos and Nugent 2012, Konte *et al* 2022).

2. Agricultural labor markets in the US

Labor is a key input for planting, weeding, harvesting, and post-harvest activities in agriculture. People's willingness to perform farm work at prevailing wages and to engage in follow-the-crop migration determine the availability of labor at particular geographic locations and seasons and thus are key determinants of agricultural production. Environmental stressors and economic conditions affect agricultural labor markets. For example, Jessoe *et al* (2018) and Feng *et al* (2012) show that environmental shocks on crop yields, i.e. rising temperatures and declining precipitation, cause out-migration from rural areas and decrease farm employment. Fan *et al* (2016) show that agricultural wages rise during recessions, due to a leftward shift in labor supply from decreased migration and an inelastic farm labor demand (because people must eat). This contrasts with labor market conditions in other industries with high proportions of immigrant workers (e.g. construction), in which both supply and demand are likely to decline during recessions. In response to conservation policies and economic conditions, the optimal behavior of agricultural producers might be to expand, contract, or relocate production. However, producers' ability to make these changes depends on the availability of workers when and where they are needed.

Historically, the US agricultural workforce has been characterized by a large number of migrant workers willing to travel long distances for employment. Today, there are fewer individuals willing to work in agriculture, and those in the labor pool are more settled (Fan *et al* 2015, Martin 2017a). A variety of factors have contributed to the overall decline in farm labor supply. These include increases in immigration enforcement (Kostandini *et al* 2014, Charlton and Taylor 2016), growing employment opportunities in non-farm sectors (Richards and Patterson 1998, Martin 2017), and relative changes in economic conditions in the US and Mexico (Taylor 2012). These factors contribute to the overall decline in labor supply from Mexico (appendix A) and a reduced willingness to work in US agriculture.

Migrant agricultural workers follow seasonal paths of crop production across large geographic regions. These paths are typically circular—workers begin in the south early in the year, move northward, then head south again, following crops and weather patterns that dictate harvest times (Taylor 1937, Arnedo *et al* 2011)[4]. In recent years, however, agricultural workers have become less mobile (Fan *et al* 2015). More report being settled in a particular location and working nearby (Martin 2017b). The specific causes of this transition to a more settled workforce are not immediately obvious, but the trend correlates with increases in immigration enforcement, which limits historic cross-border migration patterns, and increases in the number of workers with families in the US. It is also linked to the aging of the farm workforce (a consequence of decreasing immigration of young workers from Mexico) and growing employment opportunities in non-farm sectors, which reduce the need to move for employment (Martin 2017b), and possibly welfare policies (Green, Martin and Taylor 2003).

Combined, the decline in agricultural labor supply and reduced intra-US migration have led to a relative scarcity of agricultural labor and widespread reports of worker shortages (Hertz and Zahniser 2013, Bronars 2015, Richards 2018). The implications for US agricultural production are vast. In the short-run, agricultural producers seeking to move or expand their production area might be unable to do so if their operations are not located near where many workers live. Moreover, to attract a sufficient workforce in the long-run, job opportunities (wages, hours, desired skills, etc) must be enticing enough for workers to remain settled in the area.

In sum, employers face stickier labor markets and can no longer rely on having an elastic migrant workforce that arrives at the farm gate when and where they are desired. Models that assume the agricultural labor supply is highly (or perfectly) elastic are likely to give a biased picture of local and global agricultural and environmental impacts of policy interventions. We address this problem by considering a range of long-run labor supply elasticity estimates that are supported by the literature (Hill *et al* 2021).

Shifting migration patterns are also a pivotal element in agricultural labor markets' role in mediating farms' ability to respond to stressors. We expect the decline in mobility of the agricultural workforce to alter the optimal producer response to crop price shocks and groundwater sustainability policies. The extent to which producers expand or relocate production in response to these shocks will be mediated by the availability of workers at specific locations. Thus, models that assume perfect labor mobility are likely to be biased. We geographically restrict labor mobility to areas, or labor sheds, in which modern farmworkers are willing to work, informed by studies of agricultural labor-supply elasticity, and compare the results to those under a perfect-labor-mobility assumption[5].

There are multiple empirical and conceptual challenges to defining agricultural labor sheds. The three most widely-used geographic delineations of US labor markets are the Office of Management and Budget core-based statistical areas (CBSAs), the USDA Economic Research Service (ERS) commuting zones (CZs), and the Bureau of Economic Analysis (BEA) economic areas (EAs). Fowler and Jensen (2020) compare these methods based on the extent to which labor markets represent core EAs, the degree of economic connectivity within areas, and the degree to which individuals live and work within the same areas. They conclude that no labor-market delineation is optimal; it must be tailored to the problem at hand.

We use CZs as the geographical areas over which we delineate the pool of available workers because, among existing labor market delineations, they are most consistent with our research objectives. The CZ methodology, first developed by Tolbert and Sizer (1996), is based on central place theory, assigning counties to nodes based on a hierarchical cluster algorithm that groups counties with strong commuting ties (Carpenter *et al* 2022). CZs are widely used in population and labor-economic analyses of areas sharing a common labor-market. They are an alternative to counties, which are problematic because they are largely arbitrary political units, and Metropolitan Statistical Areas (MSAs) or CBSAs, which by definition *exclude* non-metropolitan places and do not span the entire United States. Agricultural workers often cross county- and state-lines, and the CZ approach is well suited to deal with this (ref appendix A for additional evidence).

3. Insights from economic theory

In this section we provide insights from a stylized, two-input theoretical framework to assess impacts from a global price shock and a sustainable groundwater policy shock. We demonstrate the importance of accounting for agricultural labor markets by comparing the model under two contrasting assumptions—perfect mobility and restricted mobility of labor. In this framework, we model the profit maximizing behavior of a producer combining natural resources (A), consisting of land and water, with agricultural labor (L) to produce output (Q). We focus on the local 'grid' level impacts of the global

[4] One historic route of agricultural laborers on the West coast was to begin harvesting truck crops in California's Imperial Valley, next to the Mexican border, in the winter; moving to the Los Angeles or San Bernardino county areas in the spring; then spending most of the summer and fall in central California near Bakersfield and Fresno (Taylor and Rowell 1938).

[5] One can think of agricultural labor markets as 'labor sheds' in much the same way as hydrologists think about water sheds. Watersheds are shaped by geological features. Labor sheds are shaped by farm workers' willingness to move from one place to another in response to changing labor demands.

price shock and the wider labor market impacts of the groundwater policy shock.

Equations (1) and (2) contrast the *percentage change* in crop output under the two shocks assuming perfect and restricted labor mobility, respectively (see appendix C for derivations). The global price shock is implemented as an exogenous crop price increase ($p > 0$). The sustainable groundwater policy shock is implemented as a percentage restriction ($\phi_A > 0$) on the cultivation of irrigated land following the withdrawal of underlying overexploited groundwater resources. Since resources are taken out of production under this policy, there is an indirect increase in commodity price ($\phi_A > 0 \,\&\, p > 0$). Therefore, the groundwater policy's effects on production depend on the magnitude of the policy intervention, which is grid specific, as well as the subsequent crop price increase (equal for all producers), which results in spillover effects on grid cells not directly affected by the shock.

$$q = \frac{p}{\theta_A}\left(\nu_A + \sigma\theta_L\right) - \phi_A \quad (1)$$

$$q = \frac{p}{\theta_A}\left(\nu_A\Gamma_A + \sigma\theta_L\Gamma_\sigma\right) - \phi_A\Gamma_A, \quad (2)$$

where $\Gamma_A = \frac{\theta_A(\nu_L+\sigma)}{\theta_A(\nu_A-\nu_L)+(\nu_L+\sigma)}$ and $\Gamma_\sigma = \frac{\theta_A(\nu_L-\nu_A)}{\theta_L(\nu_A-\nu_L)+(\nu_L+\sigma)}$

Absent local groundwater restrictions ($\phi_A = 0$), producers expand production when crop prices increase. The magnitude of this production increase depends on two possible margins of response (the terms in parentheses in equation (1) and (2)). The first, termed the *extensive margin of supply response*, refers to the additional land and water resources brought into crop production, depending on the price elasticity of resource supply (ν_A). The second, termed the *intensive margin of supply response*, is the producer's ability to change the input mix by substituting away from the relatively scarce resource inputs (e.g. by hiring more workers). It depends on the input substitution (intensification) parameter (σ) and the cost share of labor inputs(θ_L).

If inputs A and L are not substitutable ($\sigma = 0$), the impact of the crop price change on total production is determined fully by the extensive margin response. When both inputs are substitutable, a relatively small cost share of labor ($\theta_L \to 0$) can suppress the intensive margin response. The natural resource input constrains the supply response; thus, the economic importance of this input relative to labor is key. If the cost share of natural resources is relatively small ($\theta_A \to 0$), the total supply response (sum of intensive and extensive margins) will be relatively large. Since $\theta_A = 1 - \theta_L$, as the cost share of land shrinks, the intensive margin of supply response strengthens.

When labor market rigidities are introduced, we see that both the intensive and extensive margin responses are modified by the terms Γ_A and Γ_σ, respectively, which are both less than one. Labor market rigidities diminish the grid cell's responsiveness to the commodity price change. In a 'stickier' labor market, Γ_A and Γ_σ are smaller, leading to higher wages and a diminished production response.

Further examination of terms Γ_A and Γ_σ reveals the crucial role that the labor supply elasticity, ν_L, plays in governing local responses to a commodity price boom, in particular, the size of this elasticity relative to the land supply response ν_A. Given the geographic immobility of land, we expect $\nu_A$to be lower than the labor supply response, $\nu_L > \nu_A$, and therefore $\Gamma_\sigma > 0$. The larger the difference in labor and resource supply elasticities, the larger the intensification component of supply response. If the factor supply elasticities are equal, i.e. $\Gamma_\sigma = 0$, there is no incentive to intensify production in response to the commodity price hike.

When commodity prices increase, the returns to both inputs increase (by p_A and p_L). If $\nu_L > \nu_A$, natural resources capture a greater share of the increase in crop prices ($p_L < p_A$), since producers are willing to pay a higher price for the relatively scarce input. Thus, the relative price elasticity of labor determines the distribution of gains from the higher crop price between the two inputs. In the extreme case of perfect labor mobility—as assumed in most IAMs—wages are constant in spite of the increased production. In this case, all of the gains accrue to land owners.

In the case of the groundwater policy shock, as with the commodity market boom, the presence of inelastic labor markets mediates the production impact of the resource conservation policy. The maximum impact of the policy would be realized under perfect labor mobility ($\Gamma_A \to 1$ as $\nu_L \to \infty$). We saw that the production impact of the crop price boom is smaller when labor market rigidities are introduced. However, in the case of the groundwater conservation policy, the ramifications of ignoring imperfect labor mobility are ambiguous. The direct impact of the policy shock on production is negative (resources are forced out of production in targeted grid cells), but the spillover effects are positive (labor moves to untargeted cells). Both of these effects are over-estimated when we ignore labor market rigidities. Therefore, whether ignoring labor market rigidities causes the aggregate effect of the groundwater policy to be over- or under-estimated varies by grid cell, depending on the grid level parameters.

4. Modeling framework: SIMPLE-G and SIMPLE-G-CZ

We developed a gridded economic framework to capture the spatial heterogeneity of environmental shocks and conservation policies along with labor market responses to such changes. This paper expands SIMPLE-G, (Baldos *et al* 2020). SIMPLE-G is a multi-scale economic equilibrium model with global markets for agricultural commodities, regional and sub-regional markets for mobile production inputs (e.g. fertilizer), and gridded local markets for immobile or imperfectly mobile production inputs (e.g. land and water). The model permits the integration of economic and biophysical determinants of sustainability, using fine-scale geospatial data and parameters within a gridded decision framework. This study introduces SIMPLE-G-CZ by building on the SIMPLE-G framework and the literature on CZs (Fowler *et al* 2016).

SIMPLE-G-CZ models agricultural labor markets at the fine-scale gridded level and incorporates labor market rigidities. Equilibrium agricultural employment in each grid-cell is determined by the interaction between the demand and supply of agricultural labor. Labor demand in each grid-cell is the result of producers' profit maximizing behavior. The supply of agricultural labor in a grid-cell is jointly determined by an upward sloping agricultural labor supply curve at the CZ level and an additive constant elasticity of transformation (ACET) function at the grid cell level. The ACET function has similar attributes as a standard constant elasticity of transformation (CET) function, however, it preserves the total labor quantity via additivity (Mensbrugghe and Peters 2016). This approach has been previously used in land use modelling by Zhao *et al* (2020). The agricultural labor supply curve determines the responsiveness of agricultural labor to changes in the wage differential between agriculture and the non-agricultural sectors, and thus, the availability of agricultural labor in each CZ. The ACET function models the mobility of agricultural workers across farms (grid cells) within a CZ (ref figure F.1). We use estimates of the agricultural labor supply elasticity on the extensive margin (0.7) from Hill *et al* (2021) to parameterize the agricultural labor supply equation for each CZ. Since the ACET function determines the mobility of farm workers across agriculture *within* a CZ, we set the ACET parameter at twice the labor supply elasticity. Given uncertainty over these parameters, highlighted in the review paper, we conduct a bounding analysis on this parameter (appendix D). The SIMPLE-G framework, models crop production at the grid-cell while the livestock and food processing sectors are national industries. Building on this, the SIMPLE-G-CZ model, focusses on labor for crop production (for direct consumption as well as for other industries). Labor for crops does not explicitly compete at the grid-cell level with labor used in other industries, such as livestock.

At the regional level, the food consumption module determines the demand for each commodity as a function of prices, income, population, and dietary shift parameters. The global module governs international trade, for which a market clearing condition determines world prices. Consumers in each region choose between imported and domestically produced commodities (Armington 1969). Domestic producers can sell their products into the world market or domestically, depending on relative prices. At the grid cell level, there are more than 75 000 production units in the continental US at 5 arc-min resolution[6]. Crop production within each grid cell can involve irrigated and rainfed activities. Crop production is a function of labor, water (surface & ground water), land, fertilizer, and other inputs. The demand for each input depends on input prices, the production scale, and production technology. Each production function has parameters specific to the grid cell and activity. The gridded equilibrium quantities are shaped by biophysical limits and likely economic responses. SIMPLE-G-CZ determines equilibrium prices considering local biophysical and economic features, regional interconnections, and global linkages (model details in appendix B).

5. Experimental design

Our experiments consider two cases that allow us to highlight the significance of labor markets in a multi-scale, integrated socioeconomic-biophysical framework. The first case examines a global commodity price boom. The second case considers a local sustainable groundwater policy. We simulate the impacts of these two shocks on both local and national production, wages, and employment. For each case we consider two labor market scenarios i.e. (a) perfect labor mobility across the US, in keeping with traditional IAMs, and (b) restricted mobility, as discussed in section 2.

5.1. Global commodity boom

Agricultural commodity prices are notably volatile, and crop producers must continually form expectations about prices prior to harvest. Commodity prices began a sharp rise at the onset of the Ukraine conflict in early 2022. This was particularly notable for wheat and oilseeds, for which Ukraine and Russia account for a large share of global exports. Due to substitutability in use as well as production, crop commodities tend to move in tandem, and the prices of other crops rose during this period. While they have subsequently declined, agricultural commodity prices remain above forecasts prior to the conflict, and the future for agricultural prices is uncertain. Similar shocks to the global food system occurred in the 2006–2013 period, when a combination of rapid growth in biofuel demand, low commodity stocks, and adverse weather events resulted in a series of commodity price spikes (Abbott *et al* 2011). Of course, the price that matters for producer profits is the one prevailing at time of sale, but this is unknown at time of planting; hence the importance of expectations. For longer-term decision-making, prices in subsequent

[6] At this latitude, 5 arc-min corresponds to approximately 6–8 km -wide grid cells with the US.

years are also relevant. For example, the price of maize prevailing in the spring of 2022 was 19% higher than in the spring of 2021 (World Bank 2022). Price increases varied by crop, and it is unclear whether farmers took this to signal persistently higher prices. For this reason, we study the effect of a commodity price boom using a stylized, 10%, price hike.

5.2. Sustainable groundwater policy in the Western US

Water scarcity is one of the major challenges facing states in the Western US, where there is widespread unsustainable use of groundwater. Extraction of groundwater is expected to increase in the coming decades as a key adaptation mechanism in the face of a warming climate and diminishing surface flows.

We consider a groundwater sustainability policy that restricts groundwater extraction rates to average recharge rates in each grid cell (see figure E.1). This policy ensures that the groundwater table does not decline over the long run. Viewed from a local perspective, the implications of this policy are dramatic, implying up to a 90% reduction in groundwater pumping at some locations. In total, the policy imposes a 66.7% reduction in total groundwater withdrawals in the US. (A more detailed discussion of this sustainability scenario is provided in a companion paper in this special issue.)

6. Results

In this section we explore the implications of the two policy shocks. In both cases, we assume that the perturbation to the system is permanent, as the model is designed to elicit long-run, equilibrium responses to shocks. Thus, producers assume that the groundwater sustainability policy will not be reversed, despite political pressures that inevitably emerge from such policies. In the case of the commodity price boom, we assume that there are structural features causing prices to be persistently higher, relative to baseline expectations, so that farmers adjust their land, water and labor usage accordingly. If the commodity price boom is perceived as being temporary (as is typically the case with commodity booms), then the supply response will be smaller than portrayed here.

6.1. Impacts of an agricultural commodity price boom

The price boom has an expansionary effect on crop output as well as all underlying inputs used (figure 1). However, the extent of the expansionary effect is starkly different depending on agricultural labor mobility. When labor is perfectly mobile, the 10% crop price increase leads to a 12.8% increase in total crop production (1a) and a 23% increase in employment (1b). This supply response is implausibly large, considering estimates in the literature (Lee and Helmberger 1985, Keeney and Hertel 2009). By contrast, total crop production and employment increase 9.9% and 9.5%, respectively, when there are labor market rigidities (1d and 1e).

Under the imperfect labor mobility scenario, expansion in land use occurs along the margins of the Corn Belt as well as regions in the Southern and Eastern US, where agriculture is less reliant on scarce groundwater than in the Western US (1f). This is consistent with recent observations in the wake of the biofuel boom (Lark *et al* 2015). In contrast, there is almost no change in land use in the Western US. The smaller increase in land use under restricted labor mobility is associated with a smaller increase in groundwater use: 6.9%, compared with 8.7% under perfect labor mobility (appendix D, figure D.1). Differences in land use between the two labor market scenarios are small compared with differences in production and employment because, based on empirical estimates, the mobility of natural resource inputs is limited in both models (Villoria and Liu 2018).

Agricultural labor markets mediate the regional impacts of the global crop price boom on agricultural workers. With perfect labor mobility, agricultural wages do not change, whereas with more realistic sticky labor market assumptions, wage increases are evident (appendix D, figure D.2). In the presence of sticky labor markets, agricultural wages increase by 20%–30% across labor sheds in the Corn Belt.

6.2. Impacts of a sustainable groundwater conservation policy

The sustainable groundwater policy affects primarily the Western US, where irrigated agriculture relies on severely over-exploited groundwater resources. Figure 2 shows impacts on production, wages, and employment in the Western US, along with inserts showing national impacts. The change in national crop production (figures 2(a) and (d)) is not very sensitive to labor market assumptions. However, if we ignore labor market rigidities, the national-level reduction in employment is over-estimated, at 3.7% (2c) compared with 1.6% (2f).

Due to the reduction in national crop production following the groundwater conservation policy, there is an increase in US crop prices under both sets of labor-market assumptions (roughly 2%, appendix D). This crop price increase affects all producers, leading to spillover effects in grid-cells that are not directly targeted by the policy. These spillover effects could contribute to an over-exploitation of groundwater resources in the non-targeted regions. Under both labor market scenarios, there is a 54% reduction in national groundwater use (appendix D, table D.1). While the simulation reduces groundwater withdrawals by 66.7% in the directly-affected cells, the national crop price increase stimulates more intensive groundwater use in cells not targeted by the policy. Thus, the net reduction in groundwater use, accounting for the spillover effects, is lower.

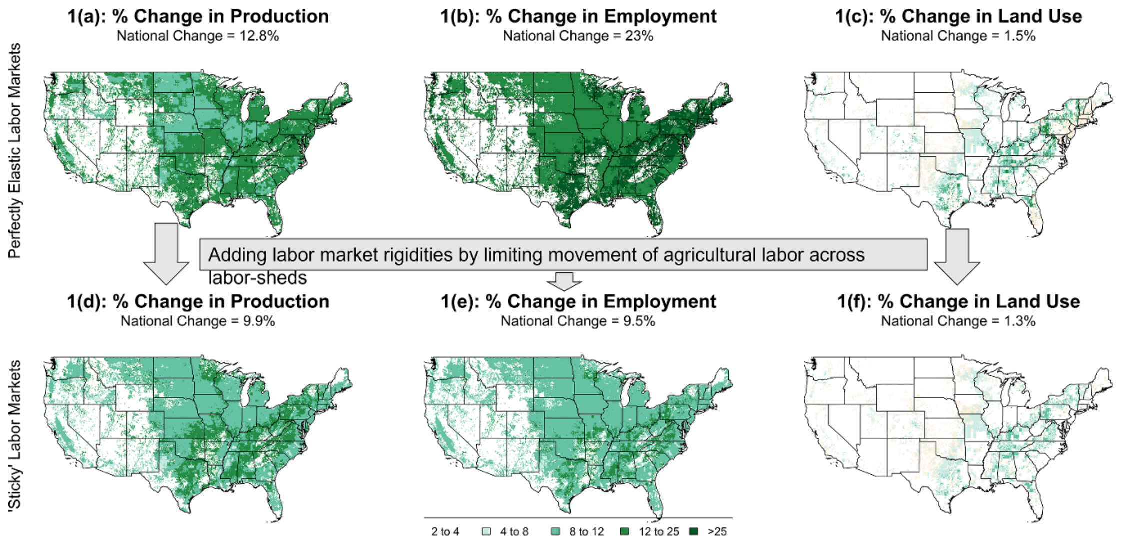

Figure 1. Impact of crop price shock under perfect vs. restricted labor mobility. The top panel reports production, employment and land use changes by grid cell in response to a permanent, 10% price hike, assuming perfect labor mobility. This contrasts sharply with the same responses under restricted labor mobility (bottom panel).

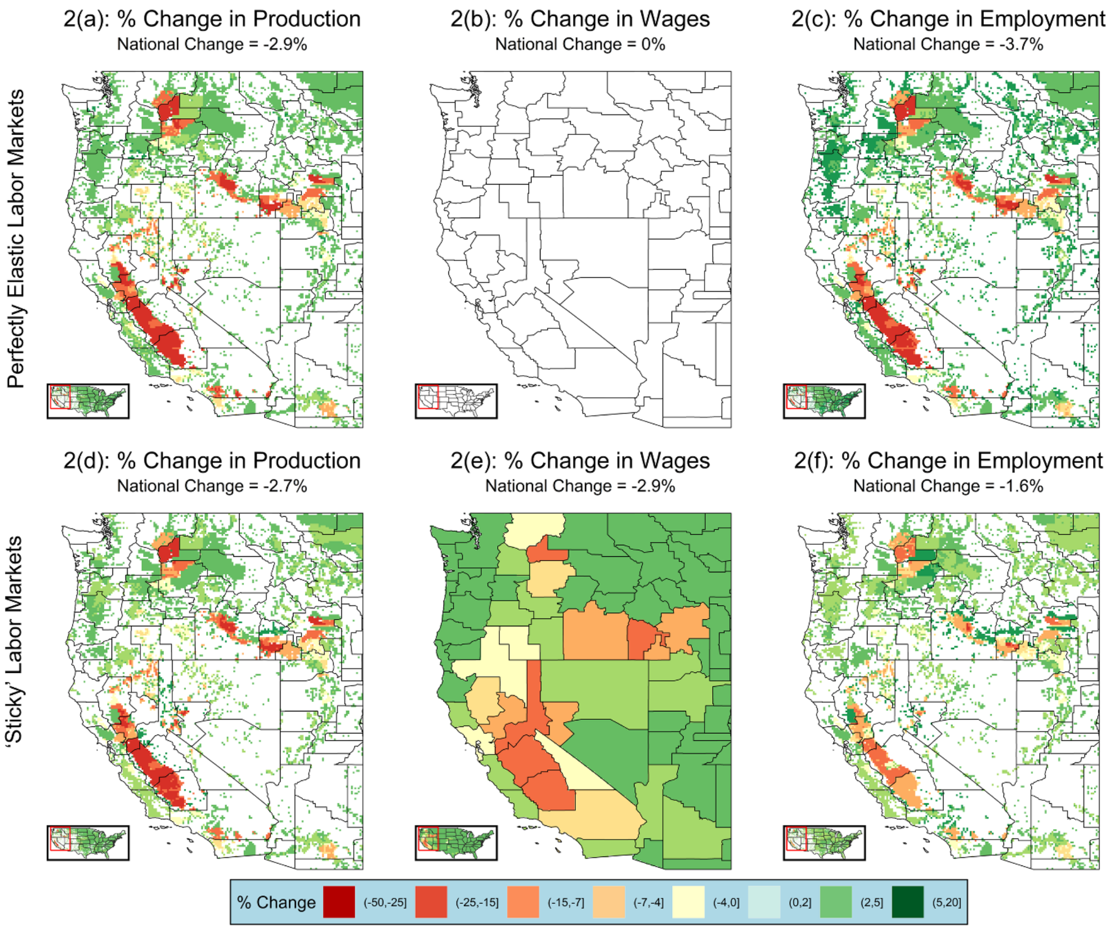

Figure 2. Impact of sustainable groundwater policy shock on crop production, employment and wages in the Western US under perfect vs. restricted labor mobility. The figure shows the impacts of the US groundwater sustainability policy on crop production, wages, and agricultural employment in the perfectly mobile (2a, 2b, and 2c, respectively) and restricted mobility (2d, 2e and 2f) labor scenarios in Western US with insets for the US. Figure (b) is blank because there is no change in wages, by construction, in the perfect mobility scenario. Borders within the wage change maps show the CZ delineations across the Western US. Figure D.4 shows the sensitivity of wage changes to the labor supply elasticity parameter.

From equations (1) and (2) it is evident that, if we assume perfect labor mobility when labor markets are sticky, we overestimate the expansionary (contractionary) effect of a crop price increase (decrease). In the case of the sustainable groundwater policy shock, we overestimate the local reduction in production in the targeted grid cells *and* increases in production in other grid cells, resulting from the spillover effect. Thus, while the net impact on some outcome variables appears insensitive to labor market assumptions at the national level, this masks significant local-level differences.

With imperfect labor mobility, the water policy leads to decreases in grid-cell production by as much as 25%–50% at some locations targeted by the policy (dark red grids in 2d) and increases of up to 5% in areas bordering the targeted grids (shown in green), due to spillover effects. These changes are overestimated under perfect labor mobility (darker reds and greens in 2a).

Figures 2(e) and (f) show wide variation in the sustainable groundwater policy's impacts on labor-shed-level wages and grid level employment. Local employment falls by as much as 15%–25%. Wages fall by as much as 25% in California's Central Valley. Some CZs in Oregon, Washington and Idaho also face job losses and wage reductions. CZs that are not directly impacted by the policy offset some of the reduction in wages and employment due to the expansionary (spillover) effects of the crop price increase. A comparison of figures 2(b) and (e) shows that the impact of the policy on wages and the spatial distribution of this impact would be completely lost in the perfect labor mobility scenario, which allows for no wage changes whatsoever.

As anticipated by our conceptual framework, the impact of the policy on employment is also overestimated under the perfect labor-mobility scenario. This is the case for decreases in employment in the targeted grid-cells and increases in employment in other grid- cells due to spillover effects (darker reds and greens in 2(c) relative to 2(f)). Further disaggregation of these results, within each grid cell, into irrigated and rainfed activity shows that, when labor market rigidities are ignored, the reduction in irrigated employment is overestimated, at 12.6% compared with 4.9%, and the increase in rainfed employment is overestimated, at 4.9% compared with 2.1% (appendix D.4). This trend is also observed in the change in overall crop production (appendix D.3).

7. Discussion

This work represents a first step towards integrating labor markets into multi-scale sustainability analyses. We detail conceptually why agricultural labor markets are increasingly likely to influence agriculture's ability to respond to a variety of factors, including changes in global commodity prices and local conservation policies. US agricultural workers have become less mobile in recent years, contributing to geographically smaller and more contained labor market sheds. Our simulations demonstrate that labor markets can be crucial determinants of how agricultural production changes over time and across space in response to economy-wide, sectoral, or regional shocks.

Incorporating labor market responses can improve the accuracy and utility of IAMs. Challenges remain, however, and future research should be directed towards addressing them. A top priority is to develop better estimates of the underlying parameters used in the gridded models. Given the importance of factor supply response within this framework, estimating the agricultural labor supply response within and across labor sheds, as well as agricultural and non-agricultural sectors, is a priority for future research. Reliable agricultural labor-supply elasticity estimates are few and far between (Hill *et al* 2021). Land and groundwater supply elasticities can also be improved upon. Work is currently underway to estimate cropland supply elasticities at the grid cell level and use those elasticities to validate the model's predictions over an historical period (Villoria *et al* 2022).

The CZ methodology is not designed to depict the journey of migrant agricultural workers nor 'follow-the-crop' migrants, who represent an important subset of the agricultural workforce and are crucial to ensure a sufficient labor supply when and where it is needed. Further research to delineate labor sheds specifically pertaining to agricultural labor is necessary for future work to build on our framework.

An important adaptation to groundwater restrictions involves changes in crop mix that imply changes in the labor intensity of production. Although incorporating dozens of crops into a gridded model of agriculture would be appealing, such an endeavor would pose major challenges due to the absence of necessary data and parameters. However, the proposed framework approximates the interplay between multiple crop types, with different water needs, by estimating an aggregate relationship between the water intensity of all crops grown in a given region and water availability. Crop mix also plays a role on the demand side of this analysis, where we have assumed a single, national crop price. In a companion paper in this special issue (Haqiqi *et al*), the authors implement consumer differentiation of the composite crop by USDA production region.

There are potential limitations to using CZs as geographical restrictions on labor mobility. The CZ methodology is based on commuting patterns for the general US population, the majority of whom do not regularly move for employment throughout the year. Most workers commute from their homes to nearby workplaces, for example, living in a suburb and commuting to a city center. The CZ methodology is not designed to depict the journey of the follow-the-crop migrant. While this type of worker movement has grown less common in recent years, follow-the-crop migrants still represent an important subset of the agricultural workforce, crucial to ensure that there is a sufficient labor supply when and where it is needed.

One emerging solution to the decline in migrant workers is the H-2A visa program for temporary agricultural workers. H-2A visa holders are beholden to specific agricultural employers for a duration that is agreed upon prior to the workers' arrival. As these workers cannot move from employer to employer, we omit them from our current analysis as, in effect, their labor market area encompasses the home country and a single US employer (usually a farmer or farmer association, but in some cases a labor contractor). All of this points to the need for future work to build on our framework and explore the implications of richer delineations of agricultural labor markets.

In summary, we believe there is considerable potential for explicitly modeling agricultural labor markets to improve our understanding of the impacts and distributional implications of global food price shocks, local conservation policies, and other shocks. The results of this study show that the assumption of a less-than-perfectly-elastic labor supply can significantly alter conclusions from multiscale sustainability modeling regarding the effectiveness and distributional consequences of global shocks as well as local conservation policies. We see this work as a first step towards understanding how labor markets mediate between local and global spheres and hope it will serve as an impetus for the development and refinement of IAMs with richer representations of labor markets.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. An archived version of model results and R-code for replicating the analysis is available at MyGeoHub. To access it use doi:10.13019/5C15-K630. For more information please contact the corresponding author.

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Appendix A. Agricultural labor supply and market delineations

Data from the National Agricultural Workers Survey (NAWS) support anecdotes and statistical evidence that US crop workers are becoming less mobile. The NAWS is a repeated cross-sectional survey of US crop workers, administered by the US Department of Labor with the intent of monitoring the terms and conditions of agricultural employment and tracking demographic characteristics of crop workers. It is, to the best of our knowledge, the most useful data source for studying migratory and living patterns of US agricultural workers. The NAWS includes a work grid with detailed information on each interviewed worker's employment and unemployment history over the two years prior to their interview. This grid includes the country, state, and county (if in the US) in which that each worker worked (for farm and non-farm jobs) or lived (for periods of unemployment). These data paint a compelling picture of the declining supply and mobility of US agricultural workers.

The NAWS data consistently show that Mexico is the primary source of hired farm workers in the US. In the most recent NAWS data, 94% of foreign-born workers (who constitute 68% of the sample) moved to the US from Mexico. However, workers having recently lived or worked in Mexico, including those who commute across the border, have been in decline in recent years. Figure A.1 shows the percentage of hired farmworkers who reported living or working in Mexico in the two years prior to their NAWS interview[7]. In the 1999/2000 survey round, nearly 40% of workers reported traveling across the border to Mexico in the prior two years. In the 2011/2012 and subsequent survey rounds, only 10% of workers did. These shifting patterns of agricultural worker movement reinforce findings from other studies suggesting that the geographic areas, or labor sheds, in which farmworkers are willing to work over the year have shrunk.

Data from the NAWS also support that CZs are a reasonable geographical area for delineating agricultural labor markets. We use the NAWS to compare the extent to which workers report living and working across three possible labor market delineations—counties, ERS CZs, and BEA EAs. Note that we exclude MSAs and CBSAs as these exclude non-metropolitan areas which are important for defining labor markets in rural areas. Figure 2 shows the percentage of workers who reported living or working in more than one US county, CZ, or EA[8]. In comparison to the shifts in cross-border migration patterns shown in figure A.1, movement across these three geographical delineations is more stable. In the 1999/2000 survey round, roughly 25% of crop workers reported having lived or worked in more than one county in the prior two years and roughly 20% reported this

[7] Because workers are interviewed at their current place of work, all NAWS respondents have worked in the US during this timespan-time span. Mexico is the only other country workers reported working or residing in during the prior two years.

[8] There are multiple versions of both CZ and EA delineations. Here we use 2010 CZ delineations developed by Fowler et al (2016) and 2004 EA delineations developed by the BEA. Both are available here: https://sites.psu.edu/psucz/data/.

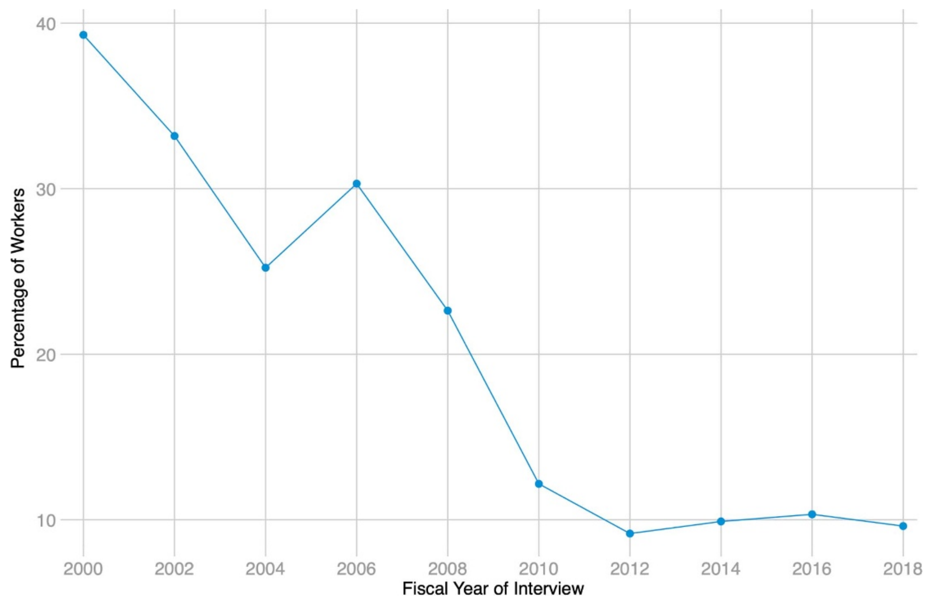

Figure A.1. The percentage of workers who live or work in both the US and Mexico is falling. Figure shows the percentage of crop workers who are working in the US at the time of the interview and report living or working in Mexico in the prior two years. Estimates are weighted using NAWS sampling weights and are summarized for each two-year NAWS cycle.

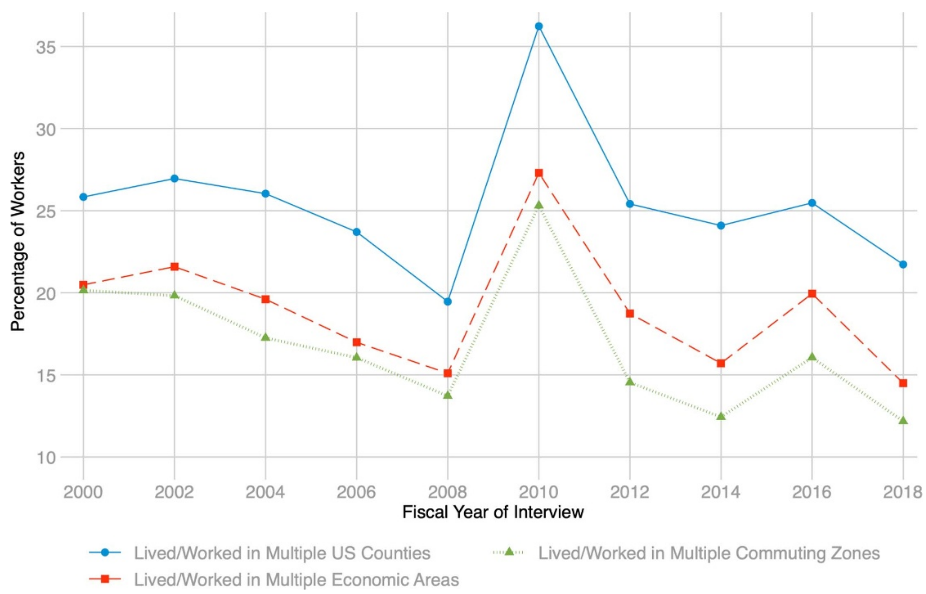

Figure A.2. Percentage of US Crop Workers Living or Working Across Labor Market Areas. It shows percentage of crop workers who report working in more than one county (blue, solid line), CZ (red, dashed line), or economic area (green, dotted line) in the prior two years. Estimates are weighted using NAWS sampling weights and are summarized for each two-year NAWS cycle.

for CZs or EAs. Movement across each of these delineations declined until 2008, when 20% of respondents worked in more than one county and 15% worked in more than one CZ or EA. In the 2009/2010 NAWS, movement across these delineations experienced a temporary increase but has been declining since. From this figure alone, both CZs and EAs appear to be more appropriate delineations of agricultural labor market areas. In the most recent survey round, 22% of workers reported having lived or worked in multiple counties, whereas 15% reported this for CZs and 13% for EAs. The proportion of workers living and working across CZ and EA delineations are similar over time, however they are generally lower for EAs. This makes sense as EAs are larger than CZs—there are 625 CZs with each including an average of 5 counties, and 179 EAs with each including an average of 18 counties.

Because CZs and EAs perform similarly in terms of the percentage of workers who live or work outside of the areas, we turn to two additional criteria in determining which to use as our delineation of agricultural labor market areas. Figure A.3 shows the mean percentage of counties within each CZ and

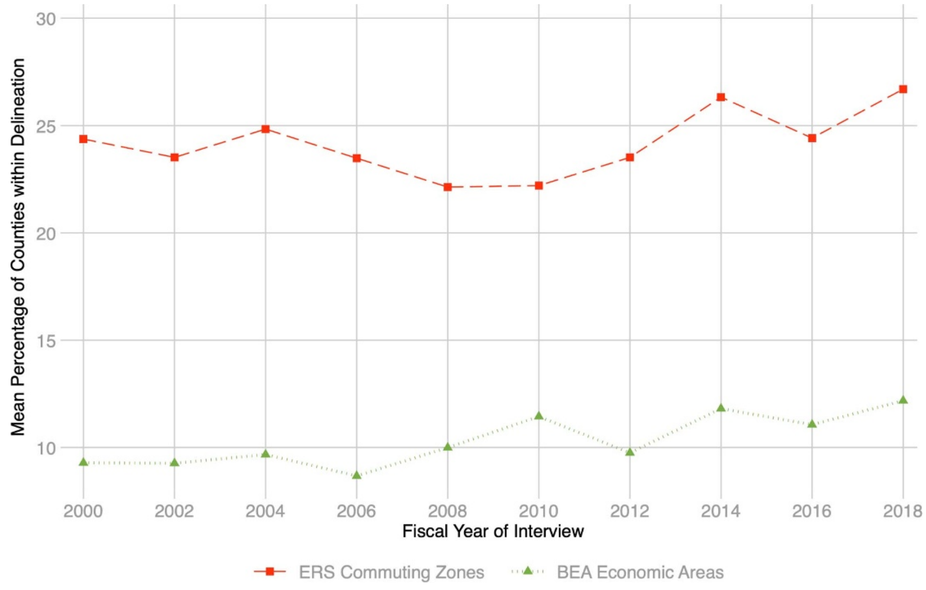

Figure A.3. Percentage of Counties within CZs and EAs in which Workers have Lived or Worked. It shows the mean percentage of counties within a CZ (red, dashed line) or economic area (green, dotted line) that workers have lived or worked in during the prior two years. Estimates are weighted using NAWS sampling weights and are summarized for each two-year NAWS cycle.

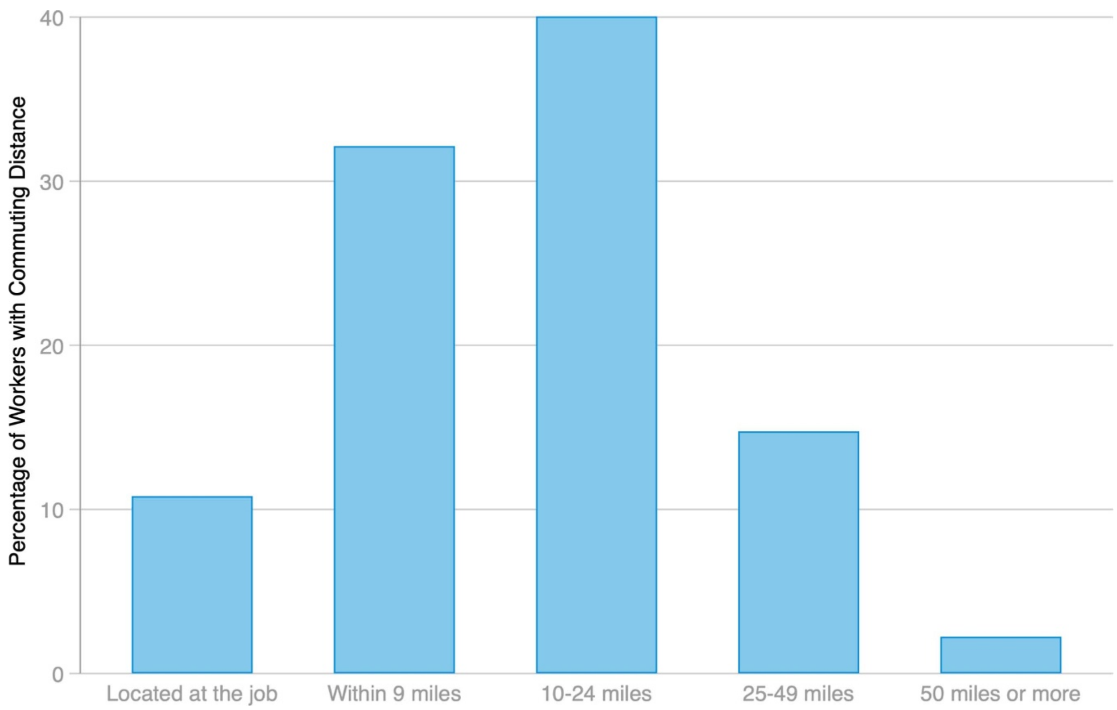

Figure A.4. Commuting distance from residence to current job for US crop workers. It shows responses to NAWS question D37 for all survey respondents from 2015–2018. Reported proportions are weighted using NAWS sampling weights.

each EA in which each worker reports having lived or worked. For example, if a CZ consists of five counties and a worker reports living or working in only one of these counties, they are recorded as having lived or worked in 20% of the counties in the delineation. Figure A.3 shows the average of this statistic for all workers within each NAWS cycle. By this standard, CZs perform better than EAs. Workers report, on average, living or working in 22% to 27% of counties within each CZ and living or working in 8% to 12% of counties within each EA.

Finally, the NAWS does not collect information on workers' county of residence, but it does ask each worker to report approximately how far they travel from their place of residence to their place of work. Figure 4 summarizes responses from this question in recent years (2015–2018). Most respondents (83%) report traveling fewer than 24 miles from their home to their current farm job and very few (2%) report traveling 50 miles or more. Each CZ is on average nearly 5 620 sq. miles in area, with the median area being 3 750 sq. miles. Each EA is on average 19 620 sq. miles in area, with the median area being 11 470 sq. miles. Were CZs and EAs perfect squares, this would equate with sides equal to 61–75 miles long for CZs and 107–140 miles long for EAs. Given responses to the commuting distance question in the NAWS, CZs appear to be a reasonable area within which to assume agricultural workers are traveling on a daily basis (figure A.4).

Appendix B. A note on data availability

The model code, input data, and simulation outputs for this study will be open-source and publicly available on myGeoHub. Currently, a previous version of SIMPLE-G with multiple simulation outputs are available on https://mygeohub.org/tools/simpleus.

Appendix C. Two input model theoretical model

In this section we develop a stylized two input partial equilibrium model to understand the theoretical implications of the perfect labor mobility assumption in the presence of labor market rigidities. This framework can be implemented at a national level market as well as at a higher resolution of the 'grid-cell' level. The only distinction is that at the grid-cell level we assume that the agricultural producer is a price taker, i.e. the commodity price (p) is determined in the national market, and individual producers respond to changes in this (for them, exogenous) price. In the global agricultural commodity price experiment, we assume that the percentage change in commodity price is $p = 10$.

Agricultural production (Q) is represented by a constant elasticity of substitution (CES, σ is the CES parameter) function of two inputs, agricultural labor (Q_L) and irrigation-augmented land (Q_A), comprising non-labor inputs such as land and water resources as well as seeds, fertilizer and machinery in a relevant spatial unit. Gohin and Hertel (2003) derive the conditional aggregate input demand equation $\left(q_j^D\right)$ for input j in percentage terms (1). Change in input supply $\left(q_j^S\right)$ is a function of the input price (p_j) and price elasticity of supply (ν_j), net of any policy shock such as the sustainable groundwater policy shock $(\emptyset_j)$. In the absence of a policy shock, $\emptyset_j = 0$.

$$q_j^D = q - \sigma\left(p_j - p\right) for j = L or A \quad (C1)$$

$$q_j^S = \nu_j p_j - \phi_j \quad (C2)$$

In order to arrive at the long run equilibrium, we impose the zero-profit condition (C3), which implies that any change in prices is distributed to the input owners according to the cost share of the relevant input (θ_j)

$$p = \sum_{j=L,A} \theta_j p_j, \text{ where } \sum_{j=L,A} \theta_j = 1. \quad (C3)$$

Using (C1)–(C3), we arrive at (C4), which refers to the percentage change in optimized agricultural supply.

$$q^S = \varepsilon p - \Gamma_A \phi_A, \text{ where}$$
$$\varepsilon = \left[\sum_{j=L,A} \theta_j \left(\nu_j + \sigma\right)^{-1}\right]^{-1} - \sigma,$$
$$\Gamma_A = \theta_A\left(\nu_L + \sigma\right)\left[\sum_{j,k=L,A} \theta_j\left(\nu_k + \sigma\right)\right]^{-1}. \quad (C4)$$

Using (C1)–(C4), we derive the equilibrium changes in input use and output for a given $p = p^*$

$$\text{% Change in input } L \text{ use: } q_L = p^* \frac{\nu_A}{\theta_A}\Gamma_L + p^* \frac{\sigma}{\theta_A}\Gamma_L - \phi_A \Gamma_L \quad (C5)$$

$$\text{% Change in input } A \text{ use: } q_A = p^* \frac{\nu_A}{\theta_A}\Gamma_A - \phi_A \Gamma_\phi \quad (C6)$$

$$\text{% Change in price of input } L\text{: } p_L = \frac{p^*}{\theta_L}\left(1 - \Gamma_A\right) - \theta_A \phi_A \left[\sum_{j,k=L,A} \theta_j\left(\nu_k + \sigma\right)\right]^{-1} \quad (C7)$$

$$p_A = \frac{p^*}{\theta_A}\Gamma_A + \theta_L \phi_A \left[\sum_{j,k=L,A} \theta_j\left(\nu_k + \sigma\right)\right]^{-1} \quad (C8)$$

$$\text{% Change in production : } q = p^* \frac{\nu_A}{\theta_A}\Gamma_A + p^* \frac{\sigma\theta_L}{\theta_A}\Gamma_\sigma - \phi_A \Gamma_A \quad (C9)$$

$$\text{where } \Gamma_L = \frac{\theta_A \nu_L}{\sum_{j,k=L,A} \theta_j\left(\nu_k + \sigma\right)}, \Gamma_\phi = \frac{\theta_A\left(\nu_L + \sigma\right) + \theta_L \sigma}{\sum_{j,k=L,A} \theta_j\left(\nu_k + \sigma\right)},$$
$$\Gamma_\sigma = \frac{\theta_A\left(\nu_L - \nu_A\right)}{\sum_{j,k=L,A} \theta_j\left(\nu_k + \sigma\right)}$$

for $\nu_A < \nu_L$, $0 < \Gamma_\sigma < \Gamma_L < \Gamma_A < 1$.

Given this framework, we can contrast the impact a policy shock on the outcome variables (C5)–(C9) when labor supply is perfectly elastic $(\nu_L \to \infty)$ verses the prevalence of labor market rigidities $(\nu_L \ll \infty)$.

Appendix D. National and grid level impact of commodity price boom and groundwater sustainability policy

Table D.1. National change (%) in crop production, employment, wages, land use, groundwater use and crop price in the US. The table shows the national level changes in the different outcome variables as a result of the two experiments studied in this paper, a crop price boom and groundwater sustainability policy in the Western US, under two different labor market scenarios.

	SIMPLE-G (Perfect labor mobility)	SIMPLE-G-CZ (Restricted labor markets)
	Crop price boom	
% Change in Crop production	12.8	9.9
% Change in Employment	23	9.5
% Change in Wages	0	12.8
% Change in Land use	1.5	1.3
% Change in Groundwater use	8.7	6.9
	Sustainable groundwater policy	
% Change in Crop production	−2.9	−2.7
% Change in Employment	−3.7	−1.6
% Change in Wages	0	−2.9
% Change in Land use	0.26	0.03
% Change in Groundwater use	−54.3	−53.8
% Change in Crop price	2.2	2.1

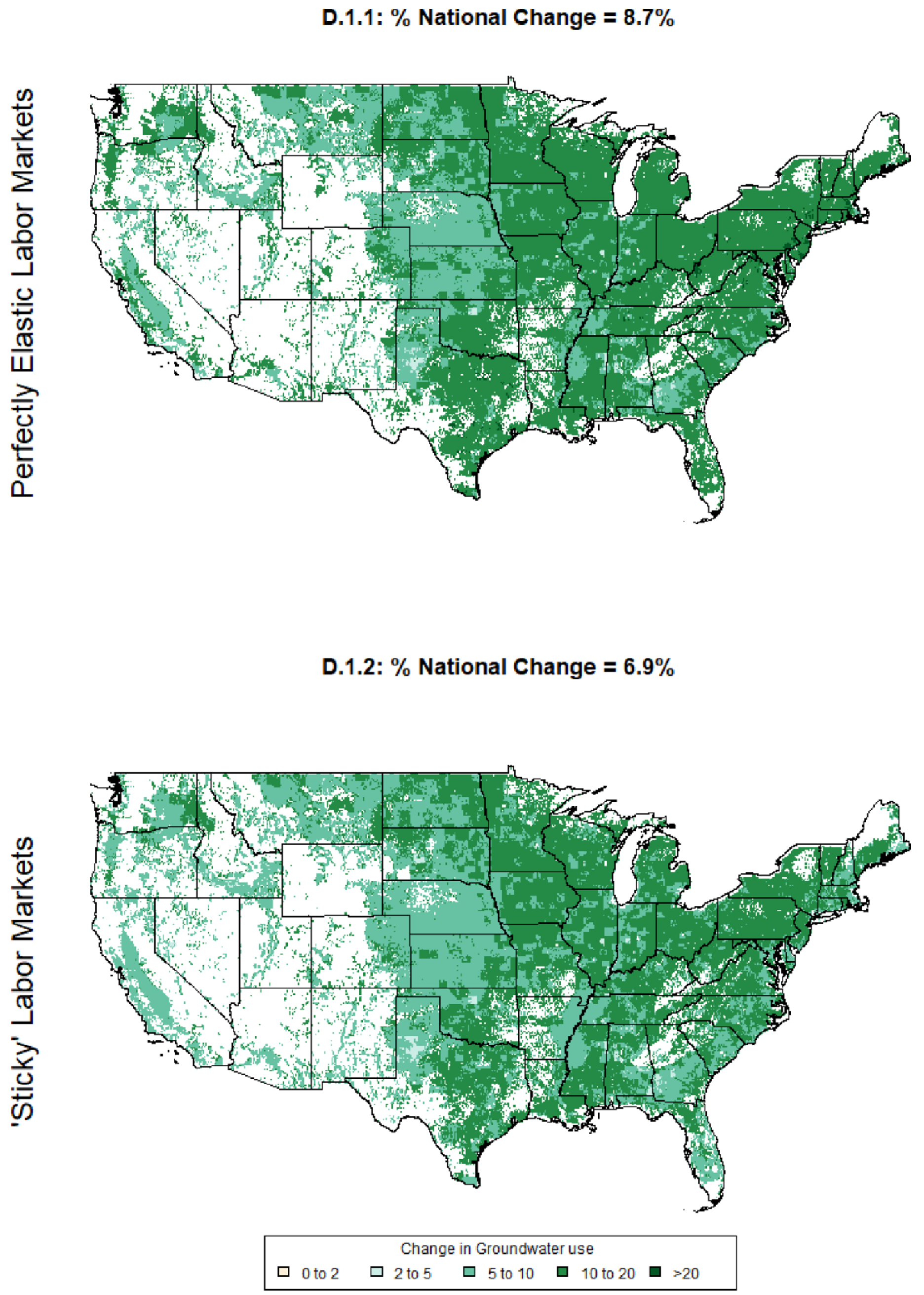

Figure D.1. Impact of crop price shock on groundwater use (perfect vs. restricted labor mobility). The figure shows the impact of the crop price boom on groundwater use under both labor market scenarios. The increase in groundwater use is overestimated under the perfect labor mobility scenario.

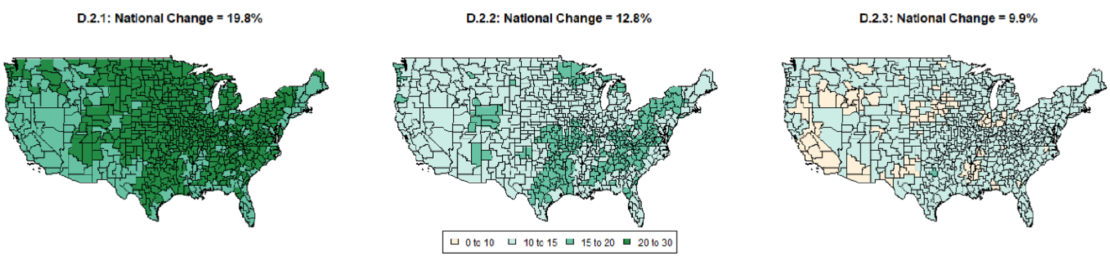

Figure D.2. Impact of crop price shock on wages at the CZ level (restricted labor mobility model) with the bounding analysis. Figure D.2.2 shows the changes in CZ level wages due to the crop price shock, where the CZ level agricultural labor supply elasticity is 0.7. Figures D.2.1 and D.2.3 show results of the bounding exercise for the crop price shock, using the lower (0.2) and higher (1.1) value of the agricultural labor supply elasticity at the CZ level. It shows that the sensitivity to the agricultural labor supply elasticity parameter is higher for a lower (i.e. relatively inelastic) parameter value.

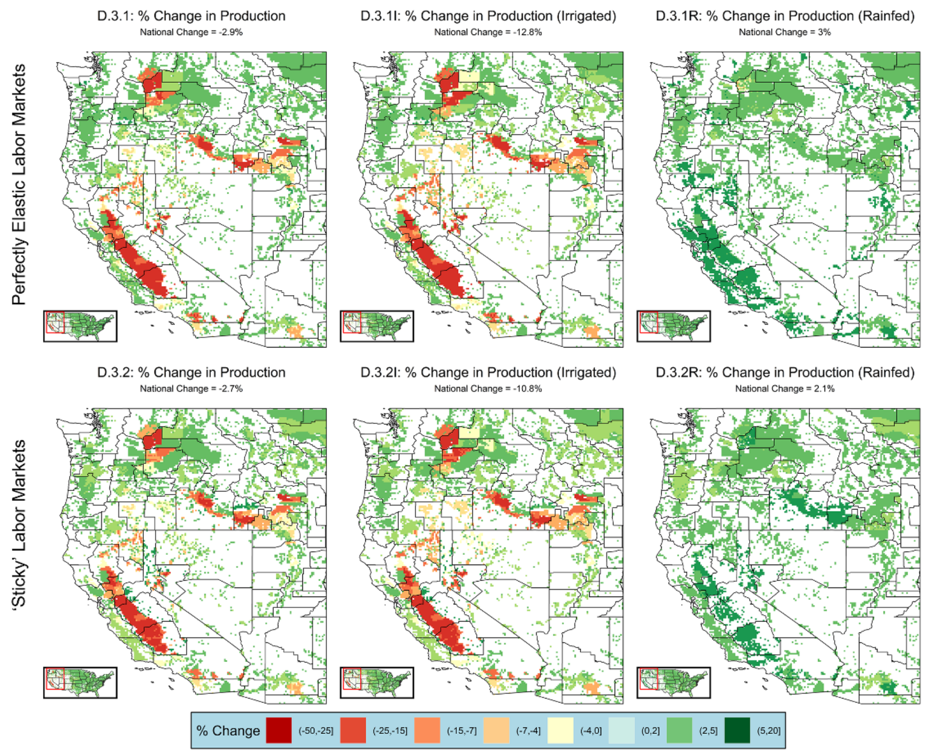

Figure D.3. Impact of sustainable groundwater policy shock on crop production disaggregated into irrigated and rainfed sectors in the Western US. The top and bottom panels in this figure disaggregate (figures 2)(a) and (d), respectively. They show that the changes in crop production in irrigated (Figures D.3.1I and D.3.2I) and rainfed (figures D.3.1R and D.3.2R) sectors are over-estimated when one assumes perfect mobility of agricultural workers (red and green are darker in the top panel). The net impact on crop production in each grid (figures D.3.1 and D.3.2) is an aggregate of both sectors.

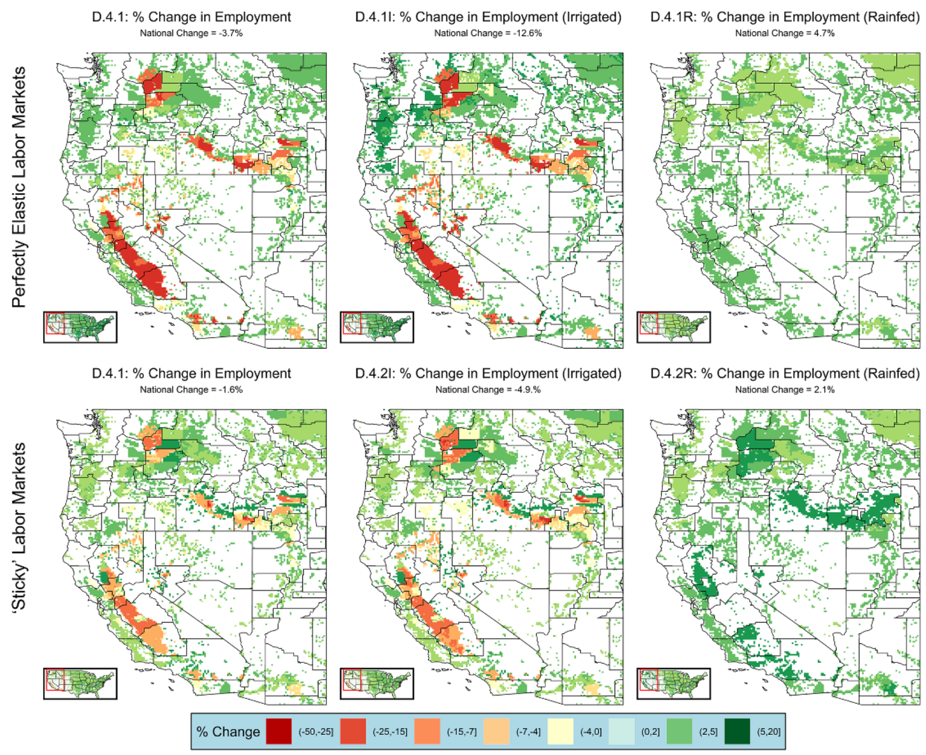

Figure D.4. Impact of sustainable groundwater policy shock on employment disaggregated into irrigated and rainfed sectors in the Western US. The top and bottom panels in this figure disaggregate (figures 2)(c) and (f), respectively. They show that the changes in employment in irrigated (figures D.4.1I and D.4.2I) and rainfed (figures D.4.1R and D.4.2R) sectors are over-estimated in the case of perfect mobility of agricultural workers (red and green are darker in the top panel). The net impact on employment in each grid (Figures D.4.1 and D.4.2) is an aggregate of both sectors.

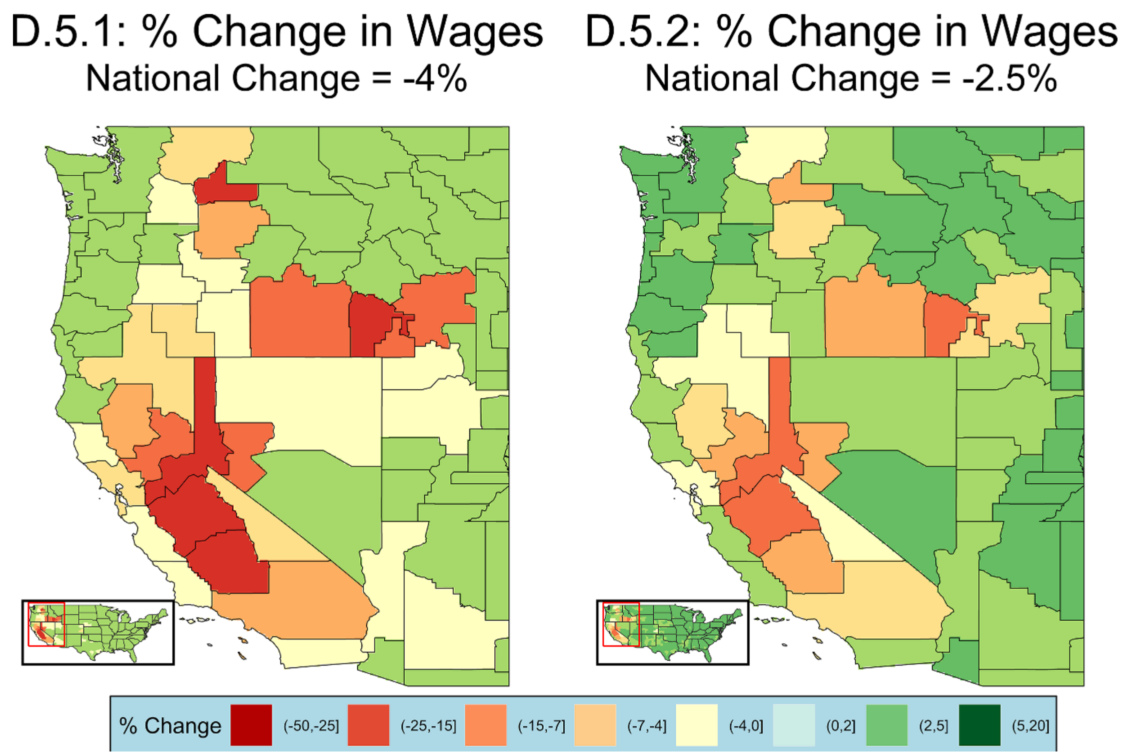

Figure D.5. Sensitivity check on the effect of labor supply elasticity on the simulated impact of sustainable groundwater policy shock on agricultural wages. In the paper we use $\nu_L = 0.7$. This figure presents the impact of the groundwater policy shock on agricultural wages at the upper and lower bound values for $\nu_L = [0.2, 1.1]$, based on the comprehensive review article by Hill *et al* (2021). The left (right) panel shows that under greater (lesser) labor market rigidities, the reduction in wage in the directly targeted CZ (orange—red polygons) is likely to be greater (smaller) than in figure 2(e).

Appendix E. Groundwater sustainability shock

The percentage change in groundwater extraction required to achieve close to sustainable levels, calculated to ensure groundwater withdrawal is limited to recharge rates. The recharge rates are obtained at 100-meter resolution from USGS Earth Resources Observation and Science (EROS) Center from Reitz *et al* (2017). Reitz *et al* (2017) used the irrigation data by county averaged from the USGS Water Use datasets for 2000 (Hutson *et al* 2004), 2005 (Kenny *et al* 2009), and 2010 (Maupin *et al* 2014). This does not show variation in the extraction to recharge ratio. To consider the differences between wet and dry years in recharge and pumping, we employed outputs from the Water Balance Model for the CONUS for 2007–2012 at 2.5 arc-min resolution, introduced from (Haqiqi *et al* 2021).

The recharge rates are linked to irrigated areas of the United States obtained from the 250-meter moderate resolution imaging spectroradiometer (MODIS) irrigated agriculture dataset (MIrAD) (Wardlow and Callahan 2014). This is linked to cropland data in SIMPLE-G, aggregated using 30-meter resolution information from multi-year National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) data (Boryan *et al* 2012).

Appendix F. Agricultural labor markets in SIMPLE-G-CZ

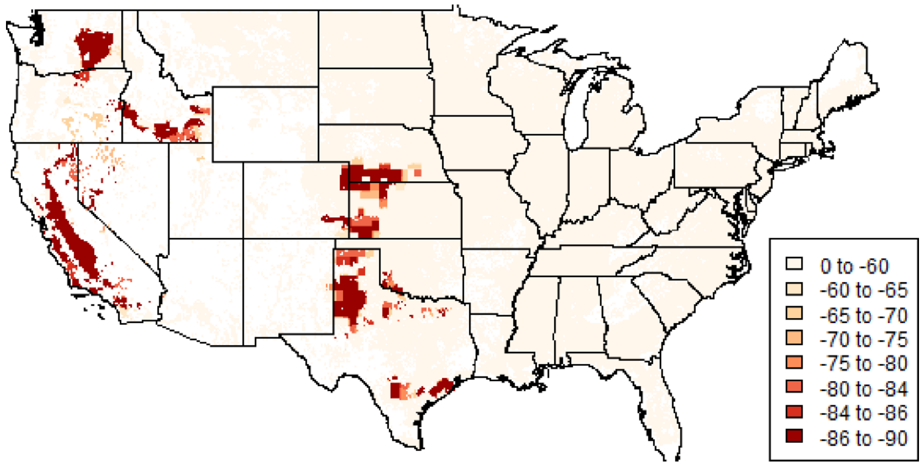

Figure E.1. Sustainable groundwater policy. Figure shows the grids targeted by the sustainable groundwater policy in terms of the percentage reduction in groundwater use. It shows that 3 watersheds in the Western US are primarily targeted by the policy, namely: Central Valley, Snake River Basin and Rio Grande River Basin.

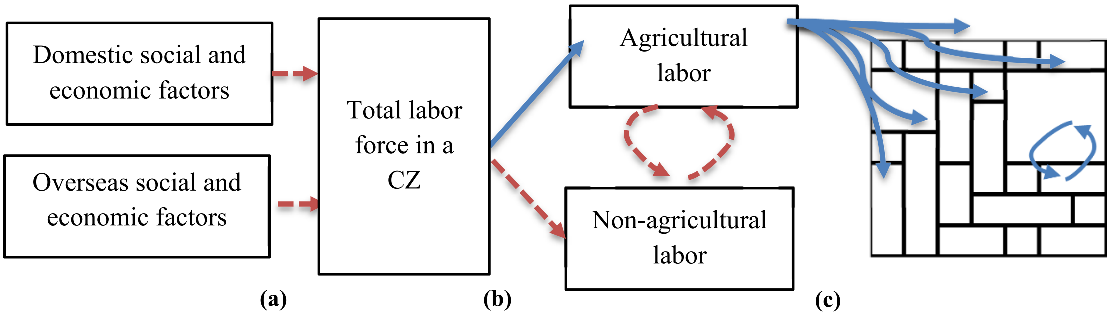

Figure F.1. Conceptual framework for modeling labor markets in a gridded economic framework. (a) Social and economic factors determine the total labor force in a CZ. (b) Total labor then is allocated to agricultural and non-agricultural activities in a CZ. This is determined by the upward sloping agricultural labor supply curve, which captures the responsiveness of agricultural workers to the wage differential between the agricultural and non-agricultural sectors. (c) Then, labor is allocated to different locations or grids. The square at the extreme right represents a CZ that consists of grids with varying labor force sizes. Each grid generates labor demand as a result of profit maximization by agricultural producers. Supply of agricultural labor at the grid level is determined jointly by the agricultural labor supply curve at the CZ level and a ACET function that represents frictions in the movement of labor between grids within a CZ. The agricultural labor supply curve is parameterized based on estimates of long-run extensive margin labor supply for U.S. agricultural workers from the literature summarized in Hill *et al* (2021). The ACET parameter, which determines the mobility of agricultural workers within a labor-shed, is set to twice the labor supply parameter. The allocation of labor in each grid is therefore determined by the intersection of grid level labor demand and supply. In the current study, the blue lines are modeled explicitly. The dashed red lines are not modeled but are embedded in the agricultural labor supply. This figure is based on Woo (2018).

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