LETTER

Let the farmer decide: examining smallholder autonomy in large-scale land acquisitions with an agent-based model

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Abstract

Large-scale land acquisitions (LSLAs) can facilitate agricultural intensification in low- and middle-income countries, but they frequently dispossess smallholders of their land and thereby generate tradeoffs between market-oriented production and smallholder livelihoods. Given the global prevalence of LSLAs, it is important to understand how they can be structured to reconcile these goals. This paper focuses on contract farming (CF) as a means to reorient LSLAs to more effectively support smallholder land rights and food security. We develop an agent-based model of mixed crop-livestock smallholder livelihoods and calibrate it using household survey data from four LSLAs in Ethiopia. We apply the model to examine smallholder food security and regional productivity under three conditions representing increasing smallholder autonomy over land management: LSLA with smallholder displacement, LSLA with forced CF, and opt-in CF. Our modeling results indicate that supporting smallholder land rights through CF can mitigate the tradeoffs generated by LSLA-induced displacement. LSLAs that implemented a CF scheme improved food security and generated comparable productivity increases to LSLAs with displacement. Further, allowing smallholders to decide whether to participate in a CF scheme (i.e. avoiding land acquisition) resulted in greater alignment between the two outcomes, particularly due to improved food security for poorer households. Our results suggest that to realize these benefits it is important to ensure contract compliance and thereby maintain smallholder trust in the contracting firm. Thus, LSLA governance that fosters smallholder agency, empowerment, and security of land rights could contribute to sustainable development.

1. Introduction

Many food insecure populations rely on agriculture to support their livelihoods, making agricultural development a critical mechanism for reducing global poverty [1, 2]. The dominant paradigm for agricultural development since the Green Revolution has involved intensification, consolidation, and corporatization of agriculture [3]. In recent years this paradigm has precipitated rising levels of large-scale land acquisitions (LSLAs), where states and private investors purchase or lease large tracts of land for agricultural development [4]. Contemporary agricultural LSLAs are inarguably massive in pace and scale, and are estimated to impact up to 33 million ha globally [5, 6].

LSLAs are highly contested. Proponents argue they benefit rural livelihoods by closing yield gaps and prompting infrastructure investments and technology spillovers [7–9]. The creation of policies to facilitate LSLAs is therefore an understandable approach for under-provisioned state actors in the Global South interested in reducing poverty and integrating with global commodity markets. However, ample empirical evidence reveals negative impacts of LSLAs on adjacent socio-environmental systems, frequently due to dispossession of smallholders from their lands and livelihoods (a.k.a. ‘land grabbing’) [10–13], and
increased environmental degradation through deforestation, water extraction, and insufficient environmental monitoring [14, 15].

To reduce the future risks of LSLAs, we need a more nuanced understanding of mechanisms for addressing conflicts between market-oriented agricultural development and local socio-environmental function. In this paper, we focus on contract farming (CF), a smallholder-centric approach to market-oriented agricultural production, to assess how it may affect productivity and food security as compared to LSLAs. Through our assessment of food security, we adopt a broad interpretation of ‘environment’ by conceptualizing food security as a key provisioning service of agroecosystems [16].

CF is an arrangement in which a buyer of agricultural produce (henceforth, ‘firm’) forms contractual relationships with individuals or collectives of small-scale growers ahead of production for a specific crop [17]. Specific contractual terms vary [18], but often guarantee a fixed purchase price and require the small-scale producers to sell specified levels of production from the contracted land to the firm. By providing access to commodity markets, agricultural inputs, credit, and technology, CF reduces institutional and biophysical constraints on smallholder productivity [19, 20]. A growing base of empirical evidence shows that, although context matters, CF can effectively increase smallholder income and food security relative to traditional subsistence arrangements [21–25]. In the context of LSLAs, CF is most relevant in places with considerable existing smallholder agriculture. It allows for increases in market-oriented production while retaining smallholder land tenure and therefore has been praised as a desirable middle ground between traditional subsistence agriculture and large-scale agribusiness [26, 27].

CF poses risks to smallholder livelihoods through several mechanisms. First, and particularly pertinent in the context of land acquisitions, it is possible for smallholders to retain some land rights but be forced to participate in a CF scheme, thus losing autonomy in decision-making and compromising income and food security. This has been observed in Ethiopia, where households forced to participate in a sugarcane outgrower program had significantly lower income and asset stocks than non-participants [28]. The term ‘contract farming’ thus encompasses a variety of levels of smallholder agency [21]. Second, power imbalances can limit accountability if the firm breaches the contract (e.g. does not accept the production at the agreed price), particularly when smallholder side-selling of crops is difficult due to limited alternative output markets [20]. In these contexts, smallholders’ trust in the contracting firm can be an important determinant of their decision to participate [29]. Third, higher labor requirements and production costs for contracted crops may trade off against other livelihood activities that traditionally support food production and income diversification [30–32]. This can generate inequitable effects by excluding resource-constrained farmers from the benefits of participation. Fourth, as CF schemes often produce non-food crops for export markets [33], productivity increases may not improve local food security.

Given these risks, there is a need to better understand the conditions under which CF may be a desirable LSLA governance strategy. However, identifying these conditions ex-ante is difficult due to the many mechanisms at play, coevolving outcomes, and heterogeneity of smallholder populations. Process-based simulation models are a promising tool to evaluate such dynamics beyond the range of observable conditions. They have been extensively applied in agricultural policy assessments [34], yet are relatively underutilized in the context of LSLAs. Previous household-level models of LSLAs have primarily focused on ‘representative’ households [35–37] and thus do not incorporate interaction or other behavioral dynamics. Such factors are particularly important for CF, where heterogeneity, trust, and learning are critical determinants of smallholder decisions and outcomes [20, 29].

Ethiopia, the empirical context for our study, has experienced one of the largest rates of LSLAs in Africa [15, 38]. Similar to other countries, LSLAs in Ethiopia have compromised smallholder livelihoods and food security [28, 39–43] and generated insignificant technology spillovers [44]. In contrast to more highly forested regions targeted by LSLAs in places like South America and Southeast Asia, Ethiopia’s dominant agro-pastoral lands hold potential for LSLAs to be implemented using CF schemes. Despite this, little CF has been reported in Ethiopian LSLAs to date. There is therefore an underexplored potential for CF to alleviate some of the concerns of LSLAs in Ethiopia.

For this paper, we leveraged household survey data we collected in four LSLA-affected regions of Ethiopia to develop and calibrate an agent-based model (ABM) of smallholder livelihoods. We applied the ABM to examine how regional productivity and household food security (measured as access to a single, representative staple crop) may change under different LSLA and CF arrangements. Motivated by the tradeoffs that CF may pose, we focused on the following questions:

(a) How do LSLA/CF arrangements that retain different levels of smallholder agency over land management differentially affect regional productivity and household food security?
(b) How are the food security effects distributed across household income levels?
(c) How does contract breaching by the firm affect households’ trust and thereby mediate the food security effects?
Our analysis marks an important step toward reconciling the goals of market-oriented ‘development’ and smallholder livelihoods in the Global South. In places like Ethiopia, where government policies prioritize agricultural development through private sector investment [45, 46] and state actors exert considerable influence over land rights [47], CF is likely more palatable to government agencies than more radical transformations (e.g. agroecology). We use our model as a virtual laboratory to examine how effects might be distributed under different LSLA/CF arrangements, in order to generate hypotheses that could be tested in future empirical studies and pilot programs, as well as using as an input to reorient government development priorities and inform the kinds of investments they seek to attract.

2. Data and methods

2.1. Site selection and empirical data
We focused our assessment in Oromiya (OR), Ethiopia, an LSLA-affected region dominated by smallholder mixed crop-livestock agriculture. Within this context, we selected four ‘sites,’ that we label as OR1–OR4 (figure 1). The sites each comprise an LSLA plus a buffer and were selected to represent the diversity of land uses targeted by LSLAs in OR: OR1 solely on smallholder agriculture; OR2 solely on shrubland; and OR3 and OR4 on a mix of agriculture, shrubland, and forest. Tenure changes included both transitions from previous state farms to foreign ownership (OR2 and OR3) and LSLAs enacted by the Ethiopian government and managed by domestic actors (OR1 and OR4) (table 1). In none of these cases was a CF scheme implemented.

We conducted approximately 100 household surveys at each site in 2018–2019, asking questions about agricultural management and yields, livestock holdings, income, labor allocation, and food security (see details in supplementary material (SM) 5 (available online at stacks.iop.org/ERL/16/105011/mmedia)). Across all sites, most households pursued mixed crop-livestock livelihoods. Agriculture was rainfed and the primary crops were maize, teff, and beans, which were grown for both subsistence and sale to market. Some households engaged in non-farm employment, but this was not a dominant livelihood activity, where crop sales provided the majority of most households’ income.

2.2. ABM
2.2.1. Model overview
A complete model description following the ODD+ protocol [48–50] is provided in SM1. In SM2, we reflect on our positionality as researchers and how it may have affected the research objectives and model design. The purpose of the model is to understand and support generalized conclusions about how alternative LSLA and CF configurations may affect household food security and regional productivity within mixed crop-livestock smallholder systems.

The set of agents in the model represent a community of heterogeneous smallholder households (figure 2; table 2). Each agent manages a fixed amount of agricultural land and an evolving herd of livestock, which they graze on communal rangeland and on their own and others’ crop residues. Agents cultivate a single, staple food crop, which they either consume for subsistence or sell to the market. The agents can also engage in off-farm employment, where they compete for a limited number of jobs.

Each year, the agents make decisions about agricultural management and labor allocation, seeking to satisfy their food needs through their livelihood sources and, if possible, maximize their surplus wealth (livestock and cash holdings). Their livelihood decisions are made under uncertainty about climate conditions, crop prices, and off-farm employment availability, which affect their ultimate livelihood outcomes. The main model processes are described in table 3.

We focus on two model outputs: region-level agricultural production and household-level food security status. We calculate regional production as the sum of all agents’ crop production and production within the LSLA. Crop yields are influenced by the exogenous climate as well as agents’ fertilizer decisions. We model household food security using a binary indicator of staple food availability, which represents whether or not an agent meets its food needs through its livelihood sources in a given year. An agent’s ability to satisfy its food needs is influenced by its characteristics (e.g. landholdings, number of livestock) as well as the outcomes of dynamic model processes (e.g. crop yields, success at finding employment), which are driven by agent decision-making and exogenous drivers. We calculate regional food security as the percentage of agents that are food secure. For both outcomes, our use of the term ‘regional’ therefore refers to the modeled region, not the entirety of OR.

The model makes several simplifying assumptions relevant to these outcomes. For food security, we model the production and consumption of a single staple crop because the model analysis aims to differentiate between food crops grown for subsistence and cash crops grown for market. To model multiple food crops would require additional assumptions about crop and dietary choice, which could not be derived through the empirical data. This means that our food security measure does not imply that food secure households have access to adequate nutrients to meet their dietary needs. For crop productivity, we do not model soil fertility dynamics because the household survey provided no empirical data with which to calibrate a baseline. Further, though many scholars
assert that LSLAs can contribute to environmental degradation \cite{11, 14, 51}, limited quantitative data exists.

2.2.2. Calibration and validation
We used the household survey data to initialize, calibrate, and validate the ABM. For the calibration, we used the pattern-oriented modeling approach \cite{52} to evaluate the ABM’s ability to generate sets of empirical patterns from each of the four sites. Once we reached an appropriate level of agreement between the model and empirical data, we conducted a validation experiment that compared the LSLAs’ effects on food security in the ABM against empirical estimates using the household survey data. Our model performed well for all sites in both calibration and validation exercises (see supplementary material). However, given the similarities between the sites and their small number, we utilized a single region-level ABM structure and parameterization to represent all four sites for our main experiments. To account for the uncertainty introduced by the calibration procedure, we identified six plausible model calibrations and estimated scenario outcomes with each plausible model \cite{53}.

2.3. LSLA/CF scenarios and simulation experiments
We designed our simulation experiments to address the three questions outlined in the Introduction. For all experiments, we used the six region-level ABM calibrations with household inputs pooled from the four sites and landcover inputs from the synthetic representative ORX site (table 1). We ran 30 replications of each simulation (SM4).

2.3.1. LSLA/CF scenarios and smallholder agency
We constructed three LSLA/CF scenarios to represent a gradation of smallholder agency in land management (figure 3):

(a) \textit{Displacement}. This represents the observed situation (i.e. no CF), where the LSLA displaces existing land uses and employs laborers on the firm-operated farm.

(b) \textit{CF forced}. Households within the transacted area are forced to participate in the CF scheme. Affected households must cultivate a non-food crop on all land within the LSLA, using inputs provided by the firm on credit, and sell all production to the firm (figure 2).

(c) \textit{CF choice}. No land acquisition occurs. Smallholders can choose their level of participation in the CF scheme each year.

Within these three LSLA/CF scenarios, we examined a variety of implementation and contract configurations (table 4). Because our empirical data did not contain CF, these dimensions were selected to represent variation documented in empirical literature \cite{18, 33, 55} and of relevance to agricultural productivity and food security. We focus on dimensions directly associated with the LSLA/CF schemes, and do not include spillover effects such as infrastructure development or mechanization \cite{36}. Our scenarios therefore provide a lower bound on the effects of
Table 1. LSLA information and effects on land cover within a 2 km buffer of surveyed households.

| Site  | Ownership | Year | Previous use | Crop      | LSLA | Smallholder agriculture | Common land |
|-------|-----------|------|--------------|-----------|------|-------------------------|-------------|
|       |           |      |              |           | % of site | % in smallholder ag. | % of site | % lost to LSLA | % of site | % lost to LSLA |
| OR1   | Domestic  | 2012 | Smallholder  | Sugarcane | 12    | 100                      | 97         | 13           | 3         | 0          |
| OR2   | USA       | 2012 | State farm   | Maize     | 20    | 0                       | 65         | 0            | 35        | 56         |
| OR3   | India     | 2003 | State farm   | Sugarcane | 17    | 19                      | 82         | 4            | 18        | 76         |
| OR4   | Domestic  | 2008 | Forests      | Maize     | 15    | 30                      | 77         | 6            | 23        | 45         |
| ORX   | —         | 2010 | —            | —         | 15    | Variable                | 80         | Variable     | 20        | Variable    |

*This is a synthetic representative site created for the subsequent simulation experiments.*
CF on smallholder livelihoods in reality. We ran the ABM for each valid combination of these factors, which yielded 4644 unique simulation conditions. We measured the effects on regional production and food security relative to the baseline no-LSLA scenario.

We also examined which implementation characteristics (in table 4) most strongly influenced the outcomes in each scenario. We calculated sensitivity for each characteristic $x$ as $E[Y(x = H) - Y(x = L)]$, where $E$ is the expectation operator over all model replications and calibrations, $Y$ is the outcome (either food security or productivity), and $L$ and $H$ are respectively the characteristic’s lowest and highest settings (table 4).

2.3.2. Distributional impacts
To examine distributional effects on household food security, we stratified the agents into quintiles using their simulated cash income under the baseline no-LSLA scenario. We then calculated the change in food security for each quintile under each LSLA/CF scenario.
Table 3. ABM process overview and scheduling. Processes are listed in the order in which they are executed. All processes except ‘Initialize’ are executed at each annual time step. Principal model outputs are in bold. More detailed descriptions are included in supplementary material 1.

| Process                  | Description                                                                                                                                                                                                 |
|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Initialize               | • Read agents’ initial attributes from the household survey data:                                                                                                                                           |
|                         |   • Static attributes—landholding, household size.                                                                                                                                                           |
|                         |   • Dynamic attributes—livestock herd size, fertilizer use, salary labor.                                                                                                                                   |
|                         | • Initialize agent beliefs:                                                                                                                                                                                 |
|                         |   • Agents have beliefs about rainfall, crop prices, and the probability of receiving off-farm employment.                                                                                                  |
|                         |   • Beliefs are represented probabilistically.                                                                                                                                                              |
|                         |   • Beliefs are initially homogeneous across agents and are set using calibrated input parameters (see SM1).                                                                                                 |
|                         |   • Set agent neighbor networks for belief sharing.                                                                                                                                                         |
|                         | • Generate agents’ risk tolerance and their land’s soil fertility from calibrated input parameters (see SM1).                                                                                               |
| Update model environment| • Simulate regional climate condition.                                                                                                                                                                       |
|                         | • Simulate regional crop prices (food crop and cash crop).                                                                                                                                                   |
| Implement LSLA/CF       | • Only run this process in the LSLA/CF implementation year.                                                                                                                                                  |
|                         | • See details in section 2.3.                                                                                                                                                                              |
| Agent decision-making   | • Under baseline conditions, decision options include all feasible combinations of fertilizer purchase (Y/N), invest savings in stocking livestock herd (Y/N), and off-farm salary employment (no change, decrease, or increase). |
|                         | • When agents have the choice to participate in the contract farm, their decision set is expanded to incorporate the CF participation decision (no change, increase by one field, or decrease by one field). |
|                         | • The decision options are evaluated over each agent’s uncertain beliefs about climate, crop prices, and the probability of finding off-farm employment.                                                   |
|                         | • Agents pursue an explicit objective, which is a risk-averse utility function.                                                                                                                              |
|                         | • Utility is calculated on anticipated wealth levels (cash and livestock) after attempting to satisfy food requirements.                                                                                  |
| Allocate regional       | • There is a limited regional availability of off-farm employment.                                                                                                                                            |
| salaried employment     | • Agents can retain salaried jobs over consecutive years.                                                                                                                                                     |
|                         | • Jobs available in the market are randomly allocated between agents that seek them.                                                                                                                         |
| Crop yields             | • Households grow a single staple crop under baseline conditions. With CF, they grow a single cash crop on their fields under contract.                                                                     |
|                         | • Crop yields are calculated using the ‘yield gap’ concept [54], in which yields can be limited by water and/or nutrient availability.                                                                        |
|                         | • Under baseline conditions, crop water is provided exclusively by rainfall (i.e. no irrigation) and is homogeneous each year across all agents.                                                              |
|                         | • Households have heterogeneous levels of soil productivity that are held static throughout the simulation.                                                                                                  |
|                         | • Nutrients available for crop growth depend on an agent’s soil productivity and their inorganic fertilizer application.                                                                                      |
|                         | • We proxy an additional effect of labor on crop yields, in which households with low labor availability relative to their landholdings experience yield reductions.                                              |
|                         | • Finally, the calculated household-level yields are perturbed by a random error term.                                                                                                                      |
|                         | • Crop yields within firm-operated land (i.e. within the LSLA) are calculated using the same procedure, assuming a fixed fertilizer application rate and no labor constraints.                                  |
|                         | • **Total regional crop production** is calculated as the sum of all agents' crop production and (if relevant) the production within the LSLA.                                                           |
Table 3. (Continued.)

| Process                                      | Description                                                                                                                                 |
|----------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Income, food consumption, and food security  | • Households have an annual non-food expenditure requirement and an annual food consumption requirement for a single food product, which they can satisfy through their own crop production as well as purchase from the market.  
  • The buying price is higher than the selling price, representing transaction costs.  
  • Agents that are unable to meet their consumption requirements through their livelihood sources are classified as ‘food insecure.’  
  • **Regional food security** is calculated as the probability of food security across all agents (i.e. the percentage of agents that are food secure).  
  • Note: because we model the production and consumption of a single, staple food crop, our measure of household food security represents staple food availability and does not imply that food secure households have access to adequate nutrients to meet their dietary needs. |
| Livestock grazing, reproduction, and stocking | • Each head of livestock represents a large ruminant and has a fixed annual food consumption requirement.  
  • There is no purchase of fodder.  
  • Livestock consumption is preferentially met through on-farm crop residues.  
  • If a livestock consumption deficit remains, livestock are then grazed on neighbors’ leftover crop residues and then on communal grassland, which produces a fixed amount of biomass at the regional level.  
  • Livestock that cannot be supported through these mechanisms are destocked without compensation.  
  • Each year, each animal has an exogenous probability of reproducing. Animal age and sex are not modeled. |
| Agent coping measures                        | • Food insecure agents can reduce their food consumption to a limited extent.  
  • If the severity of food shortage is larger than this threshold, agents resort to two coping measures to (attempt to) make up the deficit.  
  • First, agents seek wage-based off-farm work. There is a limited availability of wage employment, which is allocated randomly between agents on a (pseudo-)daily basis.  
  • Second, if food insecurity remains, agents destock from their livestock herds to raise cash for food purchase. |
| Update agent beliefs                         | • Agent beliefs are updated based on their own and their neighbors’ experiences. Updating is completed using Bayesian conjugate priors. |

Figure 3. Conceptual illustration of land use under baseline conditions and the three LSLA/CF scenarios of increasing smallholder agency. Yellow represents firm-managed cash crop production. Blue represents smallholder-managed cash crop production.
Table 4. Set of LSLA implementation conditions. All conditions are exogenous to the ABM. Bold values denote the default settings used for model calibration and in subsequent experiments. ‘x’ symbols represent the relevant scenario(s) for each implementation condition.

| Condition          | Settings          | Scenario | Description                                                                                                                                 |
|--------------------|-------------------|----------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Implementation     | 0%, 50%, 100%     | x x      | When the LSLA is not fully implemented, displacement occurs but the benefits (through employment or increased productivity) are not experienced. |
| Fraction smallholder | 0, 0.5, 1        | x x      | The fraction of smallholder agricultural land in the LSLA (0 = no agricultural displacement, 1 = full displacement). Equivalent to ‘% in smallholder ag.’ in table 1. |
| Employment         | 0, 0.15, 0.3 jobs ha\(^{-1}\) | x         | Employment is available to all households in the region, including those that are not displaced. |
| Land taking type   | Random field, random percent | x         | This describes the allocation of the site-level land-use change between the agents. Random field: select fields at random. Random percent: randomize the agents, then take a random percent of each agent’s land until the overall land-use change is met. Note: random percent is the default option used in the model calibration as it better approximates the available empirical data (see SM1). |
| Irrigation         | False, True       | x x      | Irrigation removes the water limitations on crop yields. We assume no possibility for irrigation in CF\(_{choice}\) because in this scenario the participating households are conceptually distributed throughout the modeled region (figure 3), making a centralized irrigation system less feasible. |
| Intensification    | 1, 1.5, 2         | x x x   | Fertilizer application for cash crop relative to baseline subsistence conditions. |
| Price premium      | 1, 1.5            | x x     | Average selling price for cash crop relative to food crop. |
| Harvest period     | 1, 2 years        | x x     | Some crops grown under contract (e.g. sugarcane) do not mature until the second year. With a two-year harvest period, agents receive the cumulative crop yield at the end of the second year. |
| Labor requirement  | 1, 1.5            | x x     | Agricultural labor requirement for cash crop relative to food crop. |
| Production costs   | 1, 1.5            | x x     | Fixed costs for production of cash crop relative to food crop. |
| Land requirement   | 0.25, 0.5 ha      | x        | Minimum amount of land in a contract. Each field is 0.25 ha. |
| Trustworthiness    | 0.5, 0.75, 1      | x        | Probability that the firm honors each agent’s contract in each year. |
| Production losses  | 0, 0.25, 0.5      | x        | Fraction of production lost when the firm does not honor the contract. |
| Initial trust in firm | 0, 0.5, 1    | x        | Agents’ initial expected trustworthiness belief. |

\(^{a}\)The site-level values from table 1 were used for model calibration.

2.3.3. Contract breaching and trust
Within the \(CF_{choice}\) scenario, we allowed the firm to breach the contract\(^{4}\). We assume that the firm has an exogenous ‘trustworthiness’, i.e. probability of honoring each contract. If the firm breaches an agent’s contract, the agent must sell their crop at the subsistence market price \([29]\) and incurs some lost production (representing, for instance, losses in transportation or marketing). Each agent has a trust in the firm (i.e. trustworthiness belief), which they update at the end of each time step. 

\(^{4}\) In reality, smallholders sometimes can breach their contract by ‘side selling’ their produce to alternative markets \([20]\). For simplicity, we do not include this behavior in our analysis.
of each year based on both their own and their neighbors’ experiences with the firm [56]. Trust factors into the agents’ decision-making by reducing the expected returns to CF. For this experiment, we systematically varied the firm’s trustworthiness and smallholders’ initial trust in the firm.

3. Results

3.1. Smallholder agency and LSLA/CF characteristics

The three LSLA/CF scenarios generate distinct patterns of effects on regional food security and productivity (figure 4). LSLAs involving displacement lead to the strongest tradeoffs—the ‘paradox’ of LSLAs [5]—with potential increases in regional productivity (ranging from −15% to +35% relative to the baseline subsistence scenario) often at the expense of smallholder food security (between −10% and +2%). Involving smallholders within the acquired land as outgrowers (CF_{forced}; figure 4(B)) provides comparable productivity increases (up to +35%) while better supporting smallholder food security (up to +7%). CF\_forced also reduces the risk of decreasing regional productivity, as observed the Displacement scenario. Finally, allowing smallholders to decide to join the CF scheme (CF\_choice; figure 4(C)) generates substantially larger potential food security benefits (up to +14%), but lower productivity increases relative to the other scenarios (up to +17%). Under this CF\_choice arrangement, the food security effects are more strongly positively correlated with regional productivity gains (figure 4), suggesting a closer alignment of firm and smallholder preferences.

Within each LSLA/CF scenario, the effects are mediated by a number of implementation characteristics (figure 5). Under the arrangements involving LSLA (Displacement and CF_{forced}), high levels of implementation in non-smallholder land generate the largest productivity increases. This is because these conditions bring non-agricultural land into production (i.e. entail agricultural expansion; figure 3). In contrast, the CF\_choice scenario does not allow for agricultural expansion and so does not provide as large benefits to regional productivity (figure 4). Under CF\_choice, the level of intensification exerts the largest effect on regional productivity (figure 5(C)).

For smallholder food security, the amount of displacement in the Displacement scenario (through ‘% in smallholder ag.’) is much more important than the amount of employment offered by the LSLA (figure 5(A)). This implies that LSLA-based employment does little to offset the negative effects of displacement. Within the CF_{forced} scenario, the largest food security benefits are experienced when the LSLA is fully implemented in smallholder land with high levels of intensification, large price premiums, and using a crop with a single-year harvest period (figure 5(B)). The same general patterns are seen for food security under the CF\_choice scenario, where both firm trustworthiness and agents’ initial trust also support better outcomes (figure 5(C)).

For some implementation characteristics, the direction of sensitivity changes between LSLA/CF scenarios. This is most clearly illustrated by the cash crop harvest frequency (‘CF harvest period’ in figure 5). Within the ABM, cash crops with a two-year harvest period (representing, e.g. sugarcane) increase income variability and thereby increase food insecurity in non-harvest years. This effect is particularly strong for households that are forced to contribute a large fraction of their land (SM4). Under CF\_forced, the harvest frequency has little influence on the regional productivity (figure 5(B)). However, when smallholders can choose to participate (CF\_choice), a two-year harvest period is associated with smaller regional productivity increases (figure 5(C)), as fewer smallholders decide to join (SM4). In this case, allowing the smallholders to choose to join internalizes the negative effects of the two-year harvest period to the firm.

3.2. Distribution of effects

Under the default settings (table 4), the Displacement scenario negatively affects food security across the entire population (figure 6(A)). Yet, the poorest households are least strongly affected. This is for two reasons. First, due to the empirical data, approximately 45% of these agents do not own any land and so are not directly affected by the LSLA-induced displacement. Second, the poorer agents, with less land on average and hence a larger dependence on off-farm income, benefit from the employment generated by the LSLA. Further inspection reveals that levels of employment above 1.0–1.5 jobs ha\(^{-1}\) begin to offer net-positive effects on average (figure 7(A)), which are experienced primarily by the poorest group of households (figure 7(B)).

Under the scenarios involving CF, food security effects are non-negative across all quintiles and the CF\_choice scenario yields better effects than CF\_forced (figures 6(B) and (C)). In both scenarios, poorer households generally experience larger benefits. This is for two reasons. First, poorer households have higher food insecurity under baseline conditions and so there is more room for improvement. Second, the richest households are less likely to join the CF scheme (SM4) because they already experience high utility under baseline conditions and so the relative utility of joining is not as high. Yet, the lowest income quintile does not as strongly benefit from CF, which is due primarily to the land constraints described above (i.e. 45% of this group are landless, so cannot participate in CF).
Figure 4. Spread of region-level food security and productivity outcomes under the three LSLA/CF scenarios, relative to baseline subsistence conditions. Each point represents the mean region-level output under a single model calibration and set of LSLA/CF implementation conditions (from table 4). All six model calibrations are included in this plot and did not generate discernably different patterns of effects.

Figure 5. Sensitivity of the food security and productivity outcomes to the LSLA/CF implementation characteristics. Bars indicate the direction (bar color) and magnitude (bar length) of an outcome’s sensitivity to an implementation characteristic. Sensitivity magnitudes are scaled between zero and their maximum value for each outcome.

Figure 6. Distribution of food security effects under each LSLA/contract farming (CF) scenario, relative to the baseline subsistence conditions. Households are grouped into income quintiles under the baseline no-LSLA simulation, where quintile 1 contains the poorest households. Each line plots the mean response under a different model calibration.
3.3. Trust and contract breaching
Varying the firm’s trustworthiness and smallholders’ initial trust reveals distinct patterns of sensitivity; moderate declines in smallholders’ initial trust do not substantially affect the food security outcomes, whereas small declines from perfect firm trustworthiness have comparatively large effects (figure 8). The lower sensitivity to declines in agents’ trust is because trust is repaired over time, assuming the firm consistently honors the contract. In contrast, moderate reductions in the firm’s trustworthiness generate a feedback between food security and trust: by the model’s design, contract breaches degrade both food security and trust, consequently reducing smallholders’ subsequent likelihood of participation in CF. At very low levels of trustworthiness, food security outcomes are worse than under baseline conditions (figure 8). This is due to the mismatch between the firm’s trustworthiness and smallholders’ initial trust, which causes agents to still enter the CF scheme despite it being welfare-reducing.

4. Discussion
4.1. Supporting smallholder agency for pro-poor development
The main message emerging from our analysis is the potential benefits of supporting smallholder land rights and agency in LSLA policy and design. By shifting the locus of decision-making toward the smallholder through CF, we observed comparable regional production but substantially larger food security benefits. These results compare favorably to previous modeling research, which has found outgrower schemes to more strongly improve smallholder economic outcomes than state farms [35, 37, 57]. Sim-

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**Figure 7.** How much employment is required to offset the negative effects of displacement? Effect of the LSLA on food security in the Displacement scenario, under different levels of LSLA employment. (A) shows the effect over all agents, where each line represents the mean response under a different model calibration. (B) shows the effect for each income quintile, where each line represents the mean over all model calibrations.

**Figure 8.** Impact of varying smallholder trust in the firm (solid lines) and the firm’s trustworthiness (dashed lines) on regional food security. Outcomes are scaled between the baseline subsistence arrangement (the lower bound, conceptually representing ubiquitous contract breaches) and the CF choice arrangement with perfect trust (the upper bound). The smallholder trust experiments (solid black) assume that the firm always honors the contract. The firm trustworthiness experiments (dashed black) assume an initial smallholder trust level of 1. Each line plots the mean response under a different model calibration.
ilarly, the empirical study most comparable to ours found that households with more land rights over CF participation effectively improved their asset stocks, income, and food security [28]. Other empirical evidence has separately shed light on the tradeoffs generated by LSLAs with displacement [5] and the potential welfare benefits of opt-in CF schemes [25]. Our study is the first to investigate this continuum within a consistent framework. Beyond the context of LSLAs, stable land rights are a key facet of food sovereignty [58] and foster productivity-enhancing investments (e.g. conservation activities [59]), which can translate to food security benefits [60].

The hypothesis that higher smallholder agency leads to better alignment of smallholder and firm outcomes merits further scrutiny in both modeling and empirical research. Future simulation-based studies could expand the scope of smallholder decisions—such as input intensity [18], side-selling of production [20, 29], or other forms of resistance to LSLAs [61]—to understand the importance of agency over what in affecting CF outcomes. Beyond this, contract breaching by the firm may undermine the empirical plausibility of the win-win outcomes we observed. Because smallholders will not accept a welfare-decreasing contract, allowing smallholders the choice to join theoretically incentivizes firms to support smallholder welfare. Yet, contract breaching is a pertinent concern in CF schemes worldwide [20], and our results demonstrate its potential feedbacks to smallholder trust and food security. As far as the authors are aware, there has been no empirical investigation of either this feedback or the implications of the balance of agency in contract structure on firm behavior. Future research on this topic could contribute to understanding on the most important CF conditions for smallholder welfare [25].

Our results also show that opt-in CF schemes (\(CF_{\text{choice}}\)) could increase regional productivity, though the maximum increases were smaller than under conditions of land acquisition (figure 4). This is because productivity increases in \(CF_{\text{choice}}\) occurred solely through agricultural intensification and not expansion, as in Displacement and \(CF_{\text{forced}}\) (figure 3). Beyond these results, empirical research on out-grower schemes in Ethiopia has found higher crop yields on smallholder-managed fields than factory-operated fields [62], and more generally there is convincing evidence of higher productivity of small farms [63]. Therefore, there could be large productivity benefits to opt-in CF and enhanced smallholder agency without the need for agricultural expansion. Yet, in any case, there are financial costs and risks involved in contracting with a large number of independent smallholders [20] and production volumes must be sufficient to ensure firm profitability. Future work could expand the modeling scope to include the firm’s profits [29] to understand how profitability constraints mediate the results observed in this study.

4.2. Alternative approaches to development of smallholder agricultural systems

Both LSLAs and CF have the potential to play important roles in broader rural development processes [64]. Although our model is not a predictive tool, the levels of employment required to offset the negative effects of displacement (figure 7(A)) are considerably larger than previous empirical estimates, which extend to at most 0.7 jobs ha\(^{-1}\) [4, 35, 57]. Our results therefore suggest that LSLAs involving displacement likely need to be coupled with other forms of rural development or value addition to succeed as a pro-poor strategy [13, 65]. Unfortunately, such investments are not usually made [15] and spillover effects on adjacent smallholders are frequently insignificant [44]. If LSLAs with displacement continue, there is therefore a need to identify strategies for stimulating such investments.

CF, in contrast, approaches rural development by more directly connecting smallholders to commodity markets. In our model, this led to improved food security outcomes. Similar effects have been empirically observed in Ethiopia [66], but opportunity costs can exist if cash crops displace subsistence food production or livelihood diversification [28, 30]. Furthermore, market integration can generate complex spillover effects on other livelihood components and outcomes [67], for instance hiring and allocation of labor [25, 43] and subsistence crop yields [68]. Our model did not include such spillovers, and their net effects on food security and productivity are likely context dependent.

All of our scenarios represent transitions toward agricultural intensification and commodity production. Such approaches to development have been criticized for furthering integration into exploitive market-based economies and legitimizing agribusiness under the guise of smallholder inclusivity [69–72]. CF can result in other kinds of losses to smallholder agency, leading to relations of dependence and compromising food sovereignty [71, 73]. Moreover, agricultural intensification can undermine underlying ecosystems and contribute to environmental degradation [51, 74]. Future empirical and modeling work could expand the scope of processes and outcomes to contrast rural development through intensification with alternative paradigms, such as sustainable intensification or agroecology, and contribute to broader debates about land sparing versus land sharing [75].

4.3. Generalizability of findings

Our model is a simplification of LSLA and CF processes, and does not include all the social-ecological complexity that qualitative and ethnographic approaches tend to articulate [33, 71, 76]. A ‘win-win’ outcome as observed in our model therefore does not imply that effects are strictly positive,
especially for dimensions not included in our simulation. With this in mind, we have used our model results to identify hypotheses and patterns that warrant further empirical and model-based investigation and for assessing generalizability across contexts.

We calibrated the model using empirical data from four LSLA sites in Ethiopia. The surveyed households are not necessarily representative of all households within these regions, and our questioning may have missed some factors important to food security (e.g., intra-household food allocation). Further, we did not consult with local community members during the model’s design, so our process representation may miss aspects of the affected households’ lived experiences (SM2). Mixed crop-livestock systems represent at most two thirds of the areas targeted by LSLAs globally [78]. The question remains as to how our results generalize to LSLAs implemented in forested landscapes. In such contexts, processes other than displacement of agricultural land (e.g., deforestation and agricultural expansion) dominate [79] and the LSLA/CF scenarios we tested are not as directly relevant.

Beyond this, the ABM necessarily excludes processes that may be important in some real-world agricultural systems. For example, our model did not include land degradation, which is a major challenge facing smallholder agriculture globally [80]. CF could either exacerbate soil degradation [51] or help to prevent natural resource-based poverty traps [81, 82], thereby affecting the relative benefits of CF over time. Smallholder agricultural systems face many other challenges that we did not consider but often intersect with the drivers and effects of LSLAs (e.g., climate change [83]).

5. Conclusions

There is a need to better align the development preferences of large-scale actors with the wellbeing of smallholder populations. LSLAs present a globally pertinent conflict between these objectives [5]. In this study, we examined the potential for CF as an alternative implementation of LSLA to generate outcomes beneficial to both regional productivity and smallholder food security. We developed an ABM of smallholder livelihoods and calibrated it using household survey data from OR, Ethiopia, a region representative of many areas targeted by LSLAs globally. Our simulation-based approach enabled us to cover a large set of experimental conditions and to examine distributional effects across the smallholder population.

Our results show that CF offers potential to simultaneously increase agricultural productivity and support smallholder livelihoods in mixed crop-livestock systems. In particular, arrangements that gave smallholders greater agency over their land led to better food security outcomes that aligned more closely with productivity increases. CF therefore should be seriously considered as an alternative to forms of intensification by dispossession enacted by LSLAs. Nevertheless, we neither claim that CF is ‘the solution’ nor seek to promote the proliferation of ‘sustainable’ LSLAs through CF. Rather, we suggest that moving the needle toward enhanced smallholder agency is a step toward greater smallholder benefit, within the paradigm of commodity agricultural production.

Data availability statement

The code and data that support the findings of this study are available on ComSES.net via the link: https://orcid.org/0000-0001-5642-728X.

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