Land use, migration, and climate uncertainty

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1 Introduction

During the past century the share of the urban population in total population has more than tripled (UN, 2005) and today over half of the world population lives in urban areas (UNFPA, 2007). Although urbanization is a prerequisite for development (World Bank, 2009), it can be harmful, if it is the result of deteriorating rural living conditions forces (push factor) instead of attractive urban conditions (pull factor). An important push factor are environmental changes, which strongly affect living conditions in predominantly agricultural rural areas (World Bank, 2009).

During the next decades, climate change is likely to cause substantial environmental change in many countries, in particular a higher volatility of agricultural output (Parry et al., 2007). As agricultural income and its volatility are key factors in rural-urban migration (Romero-Calcerrada and Perry, 2004; MacDonald et al., 2000), migration caused by deteriorating rural conditions is thus likely to increase. Indeed, induced migration is seen as one of the more costly effects of climate change (Stern, 2006).

Rural-urban migration can be harmful, if it alters land-use patterns in rural regions, which can lead to a loss of species-rich ecosystems as well as a possibly irreversible loss of pasture and crop lands (MacDonald et al., 2000). This holds in particular for developed countries, where such environmental changes have been well documented (Romero-Calcerrada and Perry, 2004). Indeed, many developed countries have devised specific policies to counter rural-urban migration or, at least, the resulting land-use change. A important example is the structural support for less-favored areas in the Common Agricultural Policy of the EU.[1] In contrast, rural-urban migration in developing countries with high population growth may help to reduce population pressure on local rural ecosystems (Cohen, 2006). However, once population growth is reduced, it seems likely that rural-urban migration will cause similar problems as in developed countries.

The reason why rural-urban migration can have detrimental impacts on rural environments is that it leads to a reduction of agricultural activity. Many rural environments are cultivated areas that change rapidly once agricultural activity drops below a certain threshold; pasture and cropland change to bushland or forest, if they are not maintained (Lunt et al., 2010; Burkinshaw and Bork, 2009; Chauchard et al., 2007). This is problematic for several reasons. First, the returning bush or forest often differs from "natural" (primeval) forest and bushland, as some species grow back aggressively and trap the system in an "unnatural" equilibrium. The resulting ecosystem often has a low biodiversity and provides only sparse ecosystem

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[1] In some cases, like Switzerland, countering rural-urban migration is even a explicitly stated objective in the constitution.

services. Second, many pastures and croplands have a high level of biodiversity and yield economically important services, for instance for tourism. Finally, there is a positive feedback effect: a reduced availability of arable land can lead to a decline in agricultural yield and thereby accelerate rural-urban migration, which in turn increases scrub encroachment and thus reduces the amount of arable land further.

But although these processes have been empirically documented in a large set of cases, few economic models exist that link migration and land use dynamics.[2] Furthermore, there are no models that could be used to assess the influence of climate change induced uncertainty on this process and thus to analyze the claim that such uncertainty will indeed increase migration and accelerate land-use change.

In this paper, we set up a simple dynamic model that depicts the interaction between migration and land-use change. To facilitate an analysis of the influence of climate change, we use a model where agricultural yield is subject to an stochastic influence, such as precipitation, the duration of a growing season, or the appearance of pests.

Our model captures stylized facts found in many rural regions. Agriculture is not the only source of income in rural areas. Individuals can have side-jobs in a second sector. This partially stabilizes income against shocks in agricultural productivity. Land is used as a common property, as, for example, for feeding free-ranging livestock. Households have the option to migrate to an urban region, but lose their land-use rights by migrating. As agricultural income is uncertain, migration is thus an irreversible decision under uncertainty, as in Burda (1995). Land can degenerate either by scrub encroachment, which happens in case of a too small density of land use, or by soil erosion, which happens in case of overuse. Consistent with the common property assumption, households do not consider these effects in their land-use or migration decision, implying several forms of externalities in land use.

To depict these features, we use a stochastic model in which land and rural population are dynamic variables. The rural region consists of a two-sector economy (agriculture and a side-job in manufacturing or services) with externalities in land use and an imperfect labor market in the second sector. Migration occurs if the prospective income in the urban region exceeds the achievable income in the rural region plus migration costs and plus an option value, which arises from the irreversibility of migration. Land change is captured by a simple regeneration function.

To assure that there is no predisposition concerning the effect of uncertainty on the system dynamics, we deliberately use assumptions that keep the influence of uncertainty small, such as risk-neutral migration behavior or myopic behavior

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[2] See Section 2.

concerning the dynamics of land change.

We show that despite these assumptions, more uncertainty with regard to agricultural yield leads to a higher probability of strong migration and total land change. Furthermore, we show that, in our model, more productivity in the side-job can temporarily reduce migration (as it increases rural income) but will increase the probability of substantial land change (as less effort is dedicated to agriculture) and thus increase migration in the long run. In contrast, better resource management or a smaller urban-rural income gap will lead to a higher probability of maintaining the productivity of the rural region.

The paper is organized as follows. First, we briefly review the relevant theoretical and empirical literature. Then we present our model. In Section 4, we derive our main results. We discuss their policy implications in Section 5. Section 6 concludes.

2 Literature Review

Labor mobility, and thus migration, plays a fundamental role throughout most of economic theory. Not surprisingly a rich strand of economic literature on migration and especially on rural to urban migration has developed. Standard theory (Harris and Todaro (1970) and Lewis (1954)) on the latter type of migration requires a wage differential, between the high wage industrialized (or modern) urban area and the agricultural rural area, to induce migration. Yet, migration increases (decreases) labor supply in the urban (rural) area and consequently reduces the wage gap. Once the wage gap is eradicated, migration ceases.

However, empirical studies have documented the phenomenon of 'missing migration'. For example Zhao (1999) and Bhattacharya (2002), for China and India respectively, find empirical evidence that migration is a slack process despite existing rural-urban wage differentials.

In order to explain an agent's reluctance to migrate, Burda (1995) applies the real option approach (Dixit, 1989) to the migration decision. In his setup, the agent faces uncertainty about the future wage differential and migration incurs sunk costs and hence has to be seen as an investment. These sunk costs together with the uncertainty can create a positive option value for postponing the migration decision. Consequently, it is possible that no migration takes place despite a wage gap. The same approach is applied by Khwaja (2002) to rural areas in developing countries with the addition that there can be return migration.

That uncertainty is an important factor in the migration decision process, is well established in the empirical literature. For example, Roberts (2001) argues that social networks in Shanghai provide information and thus reduce uncertainty, which leads to more migration. Banerjee and Kanbur (1981) provide similar results in case of India.

A quite different conclusion is obtained by Allen and Eaton (2005). They include uncertainty about the current situation in the destination region into a theoretical framework. Under the assumption of risk-neutral agents, they find that more such uncertainty leads to more migration. This is in line with the static Harris-Todaro model, where a risk neutral rural agent will be more inclined to migrate, given a higher uncertainty. O'Connell (1997) considers two types of uncertainty (about current and future situations) into a migration decision problem. He shows that uncertainty about future conditions and the resulting positive option value of waiting slows migration, but that uncertainty about the current condition might induce speculative migration.

Extending the real option approach by portfolio theory Anam et al. (2007) develop a family-based model, where the portfolio effect provokes migration, whereas the option value effect delays migration. Anam et al. (2007) then present some empirical evidence on migration from Hong Kong to Canada in the course of the reunification of Hong Kong and China. They show that the option value effect was dominating before the reunification, but not afterwards. Further empirical evidence (based on microdata from the German Socio-Economic Panel) for an option value effect in the migration decision is given in Burda et al. (1998).

One of the weak points of the above theoretical approaches is the oversimplification of the migration decision (Lall et al., 2006). Especially, in case that the economic geography can be decomposed into a dominantly agricultural rural area and an industrialized urban area, it is important to consider the interdependency of resource availability, weather conditions, and the migration decision. Barrios et al. (2006) find that the return to farming is influenced by the perception in the given farming season and thus influences rural to urban migration. To insure against weather shocks, rural population often shifts labor from farming to other sectors, like manufacturing or services (Ito and Kurosaki, 2009). Thus, even though the rural economy is based on agricultural, manufacturing- and/or services are important in rural areas (Lanjouw and Lanjouw, 2001; World Bank, 2008). However, the empirical studies also show that the income stabilization effect will be dampened by a wage decrease induced by the collective shift of labor supply to the non-agricultural sector in case of unfavorable farming conditions (Ito and Kurosaki, 2009). Moreover, land quantity and land quality is limited in the rural area. Hence, a high population density reduces land per capita, and also gives rise to soil nutrient depletion (Drechsel et al., 2001). On the other hand, several studies show that land abandonment leads to a reduction of arable land through structural changes in the natural ecosystems. Chauchard et al. (2007) show, for the case of Europe, that land abandonment led to a loss of arable land through scrub encroachment. Lunt et al. (2010) report that changes in land use/ land management induced scrub encroachment and a resulting loss of arable land in Australia during the last two decades. Similar developments are also recorded by Burkinshaw and Bork (2009) for the rangelands in North America, where scrub land replaces grassland and thus reduces livestock capacity.

3 The Model

To analyze the above questions, we use a stylized model that is designed to capture the essential aspects of rural-urban migration and rural land use, their environmental impacts and their dependency on unpredictable variables, such as precipitation or the duration of a growing season.

Our model consists of a rural and an urban region. In the rural region, there are two sectors: agriculture and manufacturing. In each period, individuals (farmers) can choose to work in one or both of these sectors. The returns in the agricultural sector depend on individual and total effort, on available land, land quality, and on current weather conditions. We assume that this weather shock is global and hence affects the whole rural population in equal terms. By working part-time in manufacturing, income can be stabilized against weather shocks. However, this stabilization is imperfect, as the wage in the manufacturing sector depends on labor supply and thereby indirectly on weather conditions.

Individuals can migrate from the rural to the urban region, where they earn a constant wage. However, migration incurs fixed costs and is irreversible, as land-use rights are lost.[3] The urban region is sufficiently large to absorb all migrants without a decrease in the marginal productivity of urban labor.

The model has two dynamic elements: rural population dynamics and resource dynamics. The population dynamics are determined by population growth and rural-urban migration. The resource dynamics describe the availability of land. They depict two processes: erosion due to overuse and scrub-encroachment caused by underuse.

This setup depicts elements found in many rural areas. Economically, agriculture is an important source of income, but farmers use side-jobs to increase their income and reduce its volatility (Lanjouw and Lanjouw, 2001; World Bank, 2008). If both income options are not sufficiently attractive, individuals will migrate to urban areas. The quality and quantity of farmable land is highly correlated with the population density, a lower rural population density will lead to higher farm profits per agent (Drechsel et al., 2001), and weather conditions influence the return to farming (Barrios et al., 2006). Ecologically, the agricultural system is in a managed equilibrium, that is, land needs maintenance to remain usable (it has to be kept open or irrigation canals or terraces have to be maintained). Thus

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[3] See, for example, de la Rupelle et al. (2009) or Mullan et al. (2011).

underuse reduces the amount of usable land. On the other hand, overuse leads to soil erosion and thereby reduces usable land. As land use depends on the number of the remaining farmers and as the migration decision depends on income from agriculture, and thus on usable land, the migration and resource dynamics are interdependent.

3.1 The rural economy

There are two sectors, denoted by the subscripts A (agriculture) and M (manufacturing). At time t, there are $N(t)$ identical households living in the rural region, each of which is endowed with one unit of labor that can be allocated to farming ($l_A(t)$), or manufacturing ($l_M(t)$). The region is small compared to the markets for agricultural and manufacturing goods, so that the prices of these goods are constant.

The income received from farming at time t depends on $l_A(t)$, usable land $X(t)$, the constant price for agricultural outputs p_A, total farming effort $L_A(t)$, and (stochastic) weather conditions $\theta(t)$ in the following way.

$$y_A(t) = p_A \, l_A(t) \left(X(t)\, \theta(t) - \alpha \, \frac{L_A(t)}{X(t)} \right), \tag{1}$$

where $\alpha > 0$ is a constant parameter that describes rivalry of individual land use. This assumption implies that total agricultural yield equals

$$X(t) \left(L_A(t)\, \theta(t) - \alpha \left(\frac{L_A(t)}{X(t)} \right)^2 \right), \tag{2}$$

which is similar to the logistic yield function that is frequently used in resource economics.

Land is a common property and we assume that $N(t)$ is sufficiently large to disregard the strategic interaction between households. Thus, each household takes $L_A(t)$ and $X(t)$ as given. For simplicity, we denote the maximal marginal productivity of agricultural efforts by $\xi(t) := X(t)\, \theta(t)$.

The manufacturing sector consists of a single firm, which acts as a monopsonist on the rural labor market. The firm's profit is given by

$$\pi_M(t) = p_M \, L_M^D(t)\, \beta - w_M(t)\, L_M^D, \tag{3}$$

that is, labor L_M^D has a constant marginal productivity β. Without loss of generality, we normalize the price of the manufacturing good p_M to one. The wage $w_M(t)$ is determined by the market clearing condition

$$L_M^D(t) = N(t)\, l_M(t). \tag{4}$$

As a monopsonist, the firm takes the influence of its hiring decisions on the wage into account when deciding about job offers.

Finally, we assume that each household allocates its unit of labor so that its income $y(t) := y_A(t) + w_M(t)\, l_M(t)$ is maximized, given observed weather conditions $\theta(t)$, total agricultural effort $L_A(t)$, wages $w_M(t)$, and usable land $X(t)$. For notational simplicity, we denote population density (i.e., population in relation to usable land) by $\nu(t) := N(t)/X(t)$.

3.2 Migration and population dynamics

Households have the option to migrate to the urban region. There, they can earn a wage w_{urban}. We assume that this wage is constant, that is, it does not depend on migration (the rural region is small compared to the urban one) and does not change over time.

Migration is costly. It incurs a fixed cost c_{mig} as well as the loss of land-use rights in the rural area. Due to the latter point, migration is an irreversible decision.

As future weather conditions are not predictable, migration is a decision under uncertainty. For tractability, we assume that $\theta(t)$ follows a geometric brownian motion without drift, that is,

$$d\theta(t) = \sigma\, \theta(t)\, d\epsilon(t), \tag{5}$$

where $d\epsilon(t)$ are the increments of a standard Wiener process. As we intend to capture the uncertainty introduced by climate change, this process is a reasonable compromise between applicability and tractability. It captures not only random fluctuations but also the possibility that expected weather conditions can change.

Households do not discern future changes in land availability, that is, they assume that the currently usable amount of land will also be available in the future. This is consistent but somewhat stronger than assuming that they do not consider their influence on future land availability (as is standard for modeling common property resources). But as only $\xi(t) = \theta(t)X(t)$ matters for land-use decisions and as $\theta(t)$ is a stochastic process, our assumption mainly implies that, from a household perspective, the future productivity of land use is uncertain and that its expected value equals the currently observed value. This is a standard assumption.

Households discount future income at a constant rate r over an infinite time horizon. Migration occurs, if the expected value of staying in the rural area is strictly smaller than the value of the urban income stream minus the fixed migration costs c_{mig}. Thus the migration decision is similar to the market exit decision of Dixit (1989).

If migration occurs, it is instantaneous and households migrate until the migration condition is no longer met. In addition to migration, population changes via population growth. We assume a constant population growth rate g.

Note that the migration decision is based on income, not on utility. Thus we assume that it is the result of risk neutral behavior. We use this assumption to avoid any predisposition that uncertainty increases the propensity to migrate. Indeed, we will show that even under risk-neutral migration behavior, more uncertainty leads to a higher probability of depopulation, due to resource-migration interaction. As risk-aversion would amplify this effect, the risk-neutrality assumption can thus be seen as a deliberate choice intended to increase the robustness of our results; we do not have to rely on risk aversion to get our main results.

3.3 Environmental dynamics

Finally, we have to characterize the resource dynamics, that is, the change in available land in dependency on land use. As this part of the model will depend strongly on the specifics of the ecosystem in question, we use a stylized model that captures only the essential points.

These points are the following. First, the resource is double-limited, that is, too much or too little land use reduces the amount of usable land. This is characteristic for ecosystems that have to be shifted from their "natural equilibrium" (i.e., their state in the absence of human use) to become agriculturally usable. A typical example is the removal of forest or bush to get pasture or cropland. Such converted land is often in a rather fragile state. As the soil is not optimal for pasture or crops, it erodes easily under overuse, such as a too high stocking density. On the other hand, forest or bush will grow back, if the stocking density is too small (so that the livestock does not trample or eat a sufficient amount of tree or bush saplings).

Second, we assume that if land is used "properly", that is, within the above boundaries, then "lost" land will be slowly recovered.[4]

For tractability, we use the following resource dynamics.

$$\dot{X}(t) = \begin{cases} -\underline{\gamma}\, X(t) & \text{if } \frac{L_A(t)}{X(t)} < \underline{L}, \\ 0 & \text{if } \frac{L_A(t)}{X(t)} = \underline{L}, \\ \gamma^R\, X(t) & \text{if } \underline{L} < \frac{L_A(t)}{X(t)} > \bar{L}, \\ 0 & \text{if } \frac{L_A(t)}{X(t)} = \bar{L}, \\ -\bar{\gamma}\, X(t) & \text{if } \frac{L_A(t)}{X(t)} > \bar{L}. \end{cases} \tag{6}$$

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[4] For simplicity, we do not impose an upper limit to this recovery. But this could be done without much change to our results.

Here, $\underline{\gamma}, \bar{\gamma} > 0$ denote the constant rate of land loss due to scrub encroachment and erosion, respectively, and $0 < \underline{L} < \bar{L}$ describe the stock density at which scrub encroachment and erosion set in, respectively. The quantity γ^R denotes the rate of land recovery.

4 Model Analysis

To analyze our model, we first derive the short-run equilibrium for each period. Then, we analyze the migration decision. Finally, we characterize the dynamics of land use and migration and derive our main results. In Section 5, we discuss the policy implications of our results.

4.1 The short-run equilibrium

We begin by analyzing the households' labor allocation. At every time t, each household maximizes total income $y(t) = y_A(t) + w_M(t)\, l_M(t)$, which derives from farming effort $l_A(t)$ and working in manufacturing $l_M(t)$. The household can allocate one unit of labor, so that $l_A(t) + l_M(t) = 1$. By using Eq. (2) and the equilibrium condition $L_A(t) = N(t)\, l_A(t)$, we get the following candidate for an internal income maximum

$$l_A^*(t) = \frac{p_A\, \xi(t) - w_M(t)}{\alpha\, p_A\, \nu(t)}. \tag{7}$$

Thus, for an internal optimum, total labor supply to the manufacturing sector equals

$$L_M(t) = X(t) \left(\nu(t) - \frac{p_A\, \xi(t) - w_M(t)}{\alpha\, p_A} \right). \tag{8}$$

The manufacturing firm maximizes its profit (3) taking Eq. (8) into account. This yields the equilibrium wage (again for an internal optimum of the households' labor allocation decision)

$$w_M^{eq}(t) = \frac{1}{2} \left(\beta + p_A \left(\xi(t) - \alpha\, \nu(t) \right) \right). \tag{9}$$

With Eq. (9), the equilibrium values of total agricultural effort in relation to usable land and individual income can be written as

$$\frac{L_A^{eq}(t)}{X(t)} = \frac{p_A \left(\xi(t) + \alpha\, \nu(t) \right) - \beta}{2\, \alpha\, p_A}, \tag{10}$$

$$y^{eq}(t) = \frac{1}{2} \left(\beta + p_A \left(\xi(t) - \alpha\, \nu(t) \right) \right). \tag{11}$$

This characterization of the short-run equilibrium highlights some features of our model.

First, individual agricultural effort in equilibrium depends positively on usable land, as more usable land increases the marginal productivity of labor allocated to agricultural activity. Due to rivalry in land use, it depends negatively on rural population. It also depends on weather conditions, so that agricultural effort will fluctuate over time, even if population and land availability remain unchanged.

Second, due to this fluctuation, labor supply in manufacturing is also changing randomly. Caused by the market power of the manufacturing firm, the equilibrium wage will be smaller than the marginal productivity of labor, but the difference depends on labor supply and thus on how productive agricultural activity is.

Consequently, individual income is smoothed by the option of working in manufacturing, but still fluctuates with weather conditions. It depends positively on the maximal marginal productivity in agriculture (which is uncertain) and negatively on the population density. In contrast, total agricultural effort per unit of usable land depends positively on both of these variables; individual agricultural effort decreases with population, but the larger number of active individuals outweighs this effect.

The above characterizations hold, if the households are in an internal optimum. As Eqs. (8) and (10) show, this is not the case, if $\xi(t) < \beta/p_A - \alpha\,\nu(t)$ or $\xi(t) > \beta/p_A + \alpha\,\nu(t)$. However, as we will show below, within the interesting range of the endogenous variables, a plausible parameter constraint implies that these conditions will not be met, so that we can focus on internal optima.

4.2 The migration decision

The household can decide between staying in the rural region, where income has a random component due to unpredictable weather conditions, and migrating to the urban region, where income is constant over time. As noted above, migration is irreversible and incurs fixed costs c_{mig}.

The following result characterizes the migration decision.

Proposition 1. *Define*

$$\delta := \frac{\sigma^2 + \sigma\,\sqrt{8\,r + \sigma^2}}{4\,r}. \tag{12}$$

A household migrates if and only if $\xi(t) < \bar{\xi}$, *where*

$$\bar{\xi} := 2\frac{w_{urban} - r\,c_{mig} - \frac{1}{2}\,(\beta - p_A\,\alpha\,\nu(t))}{p_A\,(1+\delta)}. \tag{13}$$

Proof. The urban wage is constant and each household is endowed with one unit of labor. Thus the present value of the migration option equals

$$V^{urban} = \frac{w_{urban}}{r} - c_{mig}. \tag{14}$$

The present value of staying in the rural region (V) depends on $\xi(t)$ and thus on the random shocks to the agricultural productivity θ. By Itô's Lemma and Eq. (5), we have

$$d\xi(t) = \Big(\theta(t)\,\dot{X}(t)\Big)\;dt + \sigma\,\xi(t)\,d\epsilon(t). \tag{15}$$

As assumed above, a household does not perceive its influence on land availability and on wages and does not consider a time-trend in $X(t)$. Thus we have $\dot{X}(t) = 0$ in Eq. (15) and, from the perspective of the individual, the value V depends only on $\xi(t)$. This value is thus a solution of the following Hamilton-Jacobi-Bellman equation.

$$r\,V(\xi) = y^{eq} + \frac{\sigma^2}{2}\,\xi^2(t)\,V''(\xi), \tag{16}$$

where y^{eq} is given by Eq. (11). This problem is similar to the exit problem studied in Dixit (1989), so that we use the solution concept employed there.

A general solution of Eq. (16) is

$$V(\xi) = \frac{\beta + p_A\,(\xi - \alpha\,\nu)}{2\,r} + C_1\,\xi^{\frac{\sigma+\sqrt{8\,r+\sigma^2}}{2\,\sigma}} + C_2\,\xi^{\frac{\sigma-\sqrt{8\,r+\sigma^2}}{2\,\sigma}}, \tag{17}$$

with some constants C_1, C_2. As in Dixit (1989), we discard the term that increases more than proportionally with ξ (i.e., we set $C_1 = 0$). The boundary (13), below which migration occurs, follows from setting $V(\xi) = V^{urban}$ and from using the smooth pasting condition $V'(\xi)|_{\xi=\bar{\xi}} = 0$.[5] □

So, whenever $\xi(t) < \bar{\xi}$, migration occurs. As migration increases the income of the remaining households via reducing ν and thus increasing both agricultural income and the wage in the manufacturing sector, there will usually be a migration equilibrium, that is, some but not all households will migrate if $\xi(t) < \bar{\xi}$ at some time t.

The following lemma provides some characteristics of the migration boundary.

Lemma 1. *Assume that* $w_{urban} \geq r\,c_{mig} + \beta\,(2+\delta)/2$. *Then* $\bar{\xi}$ *is strictly decreasing in* σ. *Furthermore under this condition, there exists a* $\tilde{\xi} \geq \beta/p_A$, *so that for* $\xi(t) \leq \tilde{\xi}$ *all individuals will migrate, whereas there can be a migration equilibrium with* $N(t) > 0$, *for* $\xi(t) > \tilde{\xi}$.

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[5] See Dixit (1989).

Proof. The first assertion follows directly from Eqs. (12) and (13). The second assertion follows from solving $\bar{\xi} = \beta/p_A$ at $\nu = 0$ (which implies that all individuals migrate) for w_{urban} and from the fact that $\bar{\xi}$ is increasing in ν and w_{urban}. $\square$

Lemma 1 shows that higher uncertainty leads to a smaller propensity to migrate. This is intuitive, because we have assumed risk-neutral migration behavior and irreversibility of migration. Thus there is a strictly positive option value of staying in the rural area and this value increases with the uncertainty.

The second part of Lemma 1 shows that, under a reasonable condition, the corner solution, where individuals stay in the rural region without working in agriculture, is not relevant. All individuals will migrate, before individual agricultural effort becomes zero. The sufficient condition simply states that the wage achievable in the urban region exceeds the per-period value of the migration costs plus the maximal wage achievable in rural manufacturing by a sufficient amount. Given that labor productivity in rural manufacturing is often small, due to a lack of capital investments and due to poor infrastructure, this assumption should hold in many interesting cases.[6]

4.3 Dynamics and long-run equilibria

The migration boundary Eq. (13) and the assumed constant population growth rate determine the population dynamics in our model. The resource dynamics follow from Eqs. (6) and (10). To depict the model dynamics, it is helpful to consider them in the space spanned by the dynamic variables $(\nu(t), \xi(t))$.

The migration dynamics can be described by the linear relation

$$\nu^{mig}(\xi) = \frac{1+\delta}{\alpha}\,\xi - 2\,\frac{w_{urban} - r\,c_{mig} - \frac{\beta}{2}}{\alpha\,p_A}. \tag{18}$$

This relation separates the $(\nu(t), \xi(t))$-plane into two regions. Combinations of $(\nu(t), \xi(t))$ with $\nu < \nu^{mig}(\xi)$ imply a population growth at the constant rate g. In contrast, combinations of $(\nu(t), \xi(t))$ with $\nu > \nu^{mig}(\xi)$ lead to migration and, as migration is instantaneous, this implies that ν is instantaneously reduced to $\nu = \nu^{mig}(\xi)$.

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[6] Note that considering corner solutions would still induce some minor changes in the model, as the option value changes. To derive the exact migration boundary, a slightly different Hamilton-Jacobi-Bellman equation has to be analyzed. As this equation is non-differentiable at the point where a corner solution of the labor allocation is reached, a generalized solution (a viscosity solution) needs to be derived. This solution has the same characteristics as the solution described in Proposition 1, only there is some non-linearity in the vicinity of the switching point to the corner solution. Under the the condition of Lemma 1, this change is mostly contained to the infeasible part of the state-space, so that we get the same qualitative conclusions with this generalized solution. For simplicity, we thus work with the much simpler linear expression (13).

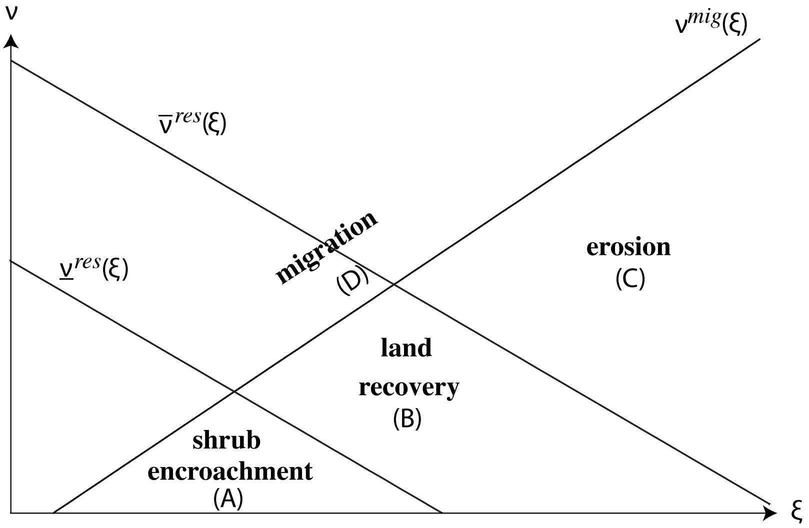

Figure 1: Regions in the (ν, ξ)-state-space of the model. The variable $\nu = N(t)/X(t)$ denotes the population pressure and $\xi(t) = \theta(t)X(t)$ is the maximal productivity of agricultural labor efforts.

The resource dynamics can be captured in a similar way. The boundaries in Eq. (6) together with equilibrium land use as given by Eq. (10) suggest the following definitions.

$$\underline{\nu}^{res}(\xi) = -\frac{\xi}{\alpha} + \frac{\beta}{\alpha\, p_A} + 2\,\underline{L}, \tag{19}$$

$$\bar{\nu}^{res}(\xi) = -\frac{\xi}{\alpha} + \frac{\beta}{\alpha\, p_A} + 2\,\bar{L}. \tag{20}$$

Eqs. (6) and (10) imply that for combinations of $(\nu(t), \xi(t))$ with: (A) $\nu < \underline{\nu}^{res}(\xi)$, we have a constant land-loss rate of $\underline{\gamma}$ due to scrub encroachment; (B) $\underline{\nu}^{res}(\xi) < \nu < \bar{\nu}^{res}(\xi)$, there is a land recovery at rate of $\gamma^R(X(t))$; (C) $\nu > \bar{\nu}^{res}(\xi)$, there is land loss at the constant rate $\bar{\gamma}$ due to erosion. Figure 1 depicts this situation. It shows that there are four regions of the state-space with qualitatively differing dynamics.

Eqs. (18)–(20) provide a convenient characterization of the migration/land-use dynamics. In particular, the stochastic component $\theta(t)$ influence only the state variable $\xi(t)$. The boundaries (18)–(20) do not depend directly on this stochastic variable. Therefore, we can analyze the model dynamics by focusing on the regions depicted in Figure 1; the stochastic shocks induce only displacements in the ξ-dimension.

From Eqs. (18)–(20) we get the following equilibria.

$$\begin{pmatrix} \nu_1^{eq} \\ \xi_1^{eq} \end{pmatrix} = \begin{pmatrix} \frac{\beta}{\alpha\, p_A} + 2\,\frac{1+\delta}{2+\delta}\,\underline{L} - 2\,\frac{w_{urban} - r\,c_{mig}}{\alpha\, p_A\,(2+\delta)} \\ \frac{2\,\alpha}{p_A\,(2+\delta)}\,\underline{L} + 2\,\frac{w_{urban} - r\,c_{mig}}{p_A\,(2+\delta)} \end{pmatrix}, \tag{21}$$

$$\begin{pmatrix} \nu_2^{eq} \\ \xi_2^{eq} \end{pmatrix} = \begin{pmatrix} \frac{\beta}{\alpha\, p_A} + 2\,\frac{1+\delta}{2+\delta}\,\bar{L} - 2\,\frac{w_{urban} - r\,c_{mig}}{\alpha\, p_A\,(2+\delta)} \\ \frac{2\,\alpha}{p_A\,(2+\delta)}\,\bar{L} + 2\,\frac{w_{urban} - r\,c_{mig}}{p_A\,(2+\delta)} \end{pmatrix}. \tag{22}$$

Outside these equilibria, the dynamics differ among the regions (A)–(D) depicted in Figure 1. As $\nu(t) = N(t)/X(t)$, we have $\dot{\nu}(t) = \nu(\dot{n}(t)/n(t) - \dot{x}(t)/x(t))$. Together with the assumed growth rates, this implies:

$$\text{Region A: } \frac{\dot{\nu}(t)}{\nu(t)} = (\underline{\gamma} + g), \qquad d\xi(t) = -\underline{\gamma}\,\xi(t)\,dt + \sigma\,\xi(t)\,d\epsilon, \tag{23}$$

$$\text{Region B: } \frac{\dot{\nu}(t)}{\nu(t)} = (g - \gamma^R), \qquad d\xi(t) = \gamma^R\,\xi(t)\,dt + \sigma\,\xi(t)\,d\epsilon, \tag{24}$$

$$\text{Region C: } \frac{\dot{\nu}(t)}{\nu(t)} = (\bar{\gamma} + g), \qquad d\xi(t) = -\bar{\gamma}\,\xi(t)\,dt + \sigma\,\xi(t)\,d\epsilon, \tag{25}$$

$$\text{Region D: } \frac{\dot{\nu}(t)}{\nu(t)} = -\infty, \qquad d\xi(t) = 0. \tag{26}$$

These dynamics lead to the following result.

Proposition 2. *Assume that*

$$\frac{\beta}{p_A\,\alpha}\,\frac{2+\delta}{\delta} \leq \underline{L} < \frac{\beta}{p_A\,\alpha}\,\frac{2+\delta}{\delta} + \bar{L}, \tag{27}$$

$$r\,c_{mig} + p_A\,\alpha\,\underline{L}\,\frac{\delta}{2} < w_{urban} < r\,c_{mig} + p_A\,\alpha\,\bar{L}\,\frac{\delta}{2} + \beta\,\frac{2+\delta}{2}. \tag{28}$$

Then for all combinations (ν, ξ) *with* $0 \leq \xi \leq \xi_2^{eq}$ *and all* $0 \leq \nu \leq \nu^{mig}(\xi)$*, the households' labor allocation is an interior optimum, that is, Eqs.* (7)–(11) *hold.*

Furthermore:

0) *The equilibrium* $(\nu_0^{eq}, \xi_0^{eq}) := (0, 0)$ *is asymptotically stable and absorbing.*

1) *The equilibrium* (ν_1^{eq}, ξ_1^{eq}) *is unstable.*

2) *The equilibrium* (ν_2^{eq}, ξ_2^{eq}) *is asymptotically stable.*

Proof. By Eq. (10), the households allocate some labor to agriculture if $(\nu, \xi) \geq (0, \beta/p_A)$. Lemma 1 implies that if $w_{urban} \geq r\, c_{mig} + \beta\,(2 + \delta)/2$, then we have $(\nu, \xi) \geq (0, \beta/p_A)$ in all possible migration equilibria. This condition is met, if the left-hand sides of Conditions (27) and (28) hold.

Similarly, all households supply labor to manufacturing, if $(\nu, \xi) \leq (\nu_2^{eq}, \xi_2^{eq})$ and if the right-hand sides of Conditions (27) and (28) hold. Furthermore, by Eqs. (21)–(22), we have $(\nu_1^{eq}, \xi_1^{eq}) > (0, 0)$ and $(\nu_2^{eq}, \xi_2^{eq}) > (0, 0)$, whenever Conditions (27) and (28) apply.

Assertions a), b), and c) follow directly from Eqs. (23)–(26). □

Proposition 2 shows that there are two states to which the system can evolve. First, there is Equilibrium 2, which is characterized by a strictly positive population, strictly positive usable land, and a land-use intensity that keeps the resource system close to a state of soil erosion. Second, there is Equilibrium 0 at which all individuals have left and all land has been changed by scrub encroachment (and become unusable for agricultural purposes).

Obviously, the probability that the system is in the absorbing state is high probability for very large t. However, if t is not too large, the probability that the system is in the basin of attraction of Equilibrium 2 can be substantial; as Figure 1 shows, this basin can be much larger than the basin of attraction of Equilibrium 0. In the following, we investigate how the model parameters influence the probability of being in the basin of attraction of Equilibrium 0 at a finite time t.

The first and most interesting question is how the uncertainty influences this probability. As noted above, we have been careful not to include a predisposition concerning how the uncertainty influences the system dynamics; indeed, as Proposition 1 shows, more uncertainty leads to a higher option value and thus to a smaller propensity to migrate to the urban region. However, the following result shows that, despite this point, more uncertainty leads to a higher probability of depopulation and total land loss.

Proposition 3. *Assume that the conditions of Proposition 2 apply and that the initial state* $(\nu(0), \xi(0)) > (0, 0)$ *is feasible, that is,* $\nu(0) \leq \nu^{mig}(\xi(0))$. *Furthermore, assume that* $\sigma^2 \geq 2 \max\{\underline{\gamma}, \bar{\gamma}\}$ *and let* $\underline{t} = \max\{2\, \frac{\beta + 2\,\alpha\, p_A\, \underline{L}}{\sigma^2 - 2\,\underline{\gamma}}, 4\,\alpha\, \frac{\bar{L} - \underline{L}}{\sigma^2 + 2\gamma^R}\}$. *Then a marginal increase in uncertainty (i.e., in* σ*) increases the probability that the system is in the basin of attraction of Equilibrium* 0 *at time* $\underline{t} \leq t < \infty$.

Proof. As shown in the left plot of Figure 2, the basin of attraction of Equilibrium 0 is reduced by an increase in σ but only by points that were not feasible before the change. Furthermore, any process starting at an originally feasible point that would have led from the basin of attraction of Equilibrium 2 to that of Equilibrium 0 before the change still does so after the change.

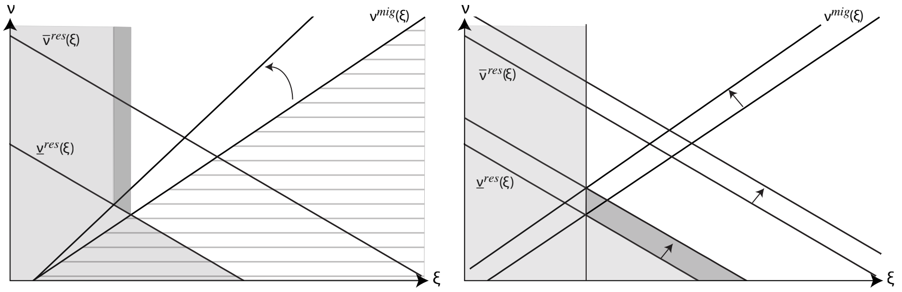

Figure 2: The basin of attraction of Equilibrium 0 (light grey area) and the change to this basin caused by a higher σ (left plot, dark grey area is lost) or a higher β (right plot, dark grey area is gained). The striped area in the left plot indicates the set of feasible initial states $(\nu(0), \xi(0))$.

This plot also shows that, for a marginal increase in σ, the border to the basin of attraction of Equilibrium 2 increases only by a marginal amount. Thus a process that begins in or enters the basin of attraction of Equilibrium 0 and stays there for the original value of σ will almost surely also stay there for a marginally increased value of σ.

Now consider a process that starts in Region B at some point (ν_0, ξ_0). Within this region, $\xi(t)$ and $\nu(t)$ change independently and $\xi(t)$ follows a geometric brownian motion with positive drift γ^R, cf. Eq. (24). Thus, for all $T > 0$, the probability that $\xi(t)$ hits a lower boundary $\xi^{low}(\nu(T))$ before or at time T follows from a log-normal distribution.

$$P\left(\xi(T) \leq \xi^{low}(\nu(T))|\xi_0\right) = \frac{1}{2}\left(1 + \text{Erf}\left(\frac{T\,(\frac{\sigma^2}{2} - \gamma^R) + \ln(\xi^{low}(\nu(T))) - \ln(\xi_0)}{\sigma\,\sqrt{2\,T}}\right)\right). \tag{29}$$

The derivative of this probability with respect to σ is

$$\frac{\partial P\left(\xi(T) \leq \xi^{low}(\nu(T))|\xi_0\right)}{\partial \sigma} = C_0\,\left(T\,(\frac{\sigma^2}{2} + \gamma^R) + \ln(\xi_0) - \ln(\xi^{low}(\nu(T)))\right), \tag{30}$$

with some constant $C_0 > 0$. As, by construction, $\xi_0 \geq \xi^{low}(\nu(T))$, this derivative is strictly positive. Thus an increase in σ leads to a higher probability that the process hits a lower boundary. As this holds for any lower boundary, this implies that with a higher σ, a process is more likely to change from the basin of attraction of Equilibrium 2 to the basin of attraction of Equilibrium 0.

The probability that a process starting in Region A hits an upper boundary $\xi^{up}(\nu(T))$ before or at time T equals $1 - P\left(\xi(T) \leq \xi^{up}(\nu(T))|\xi_0\right)$, where $P\left(\xi(T) \leq \xi^{up}(\nu(T))|\xi_0\right)$ follows from Eq. (29) with γ^R being replaced by $-\underline{\gamma}$ and $\xi^{low}(\nu(T))$ being replaced by $\xi^{up}(\nu(T))$. The derivative with respect to σ is thus a positive constant times $-T((\sigma^2/2) - \underline{\gamma}) + \ln(\xi^{up}(\nu(T)) - \ln(\xi_0)$. With the assumption $\sigma^2 \geq 2\underline{\gamma}$ and with $\xi(0) \leq \xi^{up}(\nu(T))$ (which holds by construction), this derivative is non-positive for $T \geq 2\, \frac{\beta + 2\,\alpha\, p_A\, \underline{L}}{\sigma^2 - 2\,\underline{\gamma}}$.

Altogether, the basin of attraction of Equilibrium 0 changes due to a marginal increase in σ in a way that each particular process that would have entered Region A from Region B without the increase does so with the increase and that each particular process that stays in Region A without the increase almost surely does so with the increase. Furthermore, processes that enter A from B become more likely and processes that enter B from A less likely.

The argument can be repeated for Regions B and C, showing that switches from Region C to Region B become more and from Region B to Region C less probable for a marginal increase in σ if $\sigma^2 \geq 2\bar{\gamma}$ and $T \geq 4\,\alpha\, \frac{\bar{L} - \underline{L}}{\sigma^2 + 2\gamma^R}$. Thus the probability to find a state that was initially feasible in the basin of attraction of Equilibrium 0 at some time $t > \underline{t}$ increases with a marginal increase of σ. ☐

Given Proposition 1, this result is somewhat astonishing; although individuals are less likely to migrate under higher uncertainty, the probability of depopulation increases. The reason is that more uncertainty shifts the migration boundary upward but leaves the land-use boundaries unchanged. Therefore every initial point that has been feasible and in the basin of attraction of Equilibrium 0 remains in this basin of attraction after the change. In addition, higher uncertainty implies (under the condition on σ) that the probability increases that a shock moves the system moves from the basin of attraction of Equilibrium 2 to that of Equilibrium 0.

Another interesting question is how a higher marginal productivity of labor in rural manufacturing influences the system behavior. The following Proposition shows that, again, we get a somewhat surprising result.

Proposition 4. *A marginal increase of β (i.e., the marginal productivity of labor in rural manufacturing) increases the size of the basin of attraction of Equilibrium* 0*, as long as the conditions of Proposition 2 apply before and after the change.*

Proof. By Eqs. (18)–(19), a marginal increase in β shifts both $\nu^{mig}(\xi)$ and $\underline{\nu}^{res}(\xi)$ upward by the same distance. This increases ν_1^{eq} without changing ξ_1^{eq} (cf. Eqs. (21)–(22)). The resulting change is depicted in the right plot of Figure 2. As this figure shows, the basin of attraction of Equilibrium 0 increases. ☐

A higher productivity in rural manufacturing increases rural income and thus reduces the incentives to migrate to the urban region. However, it also alters

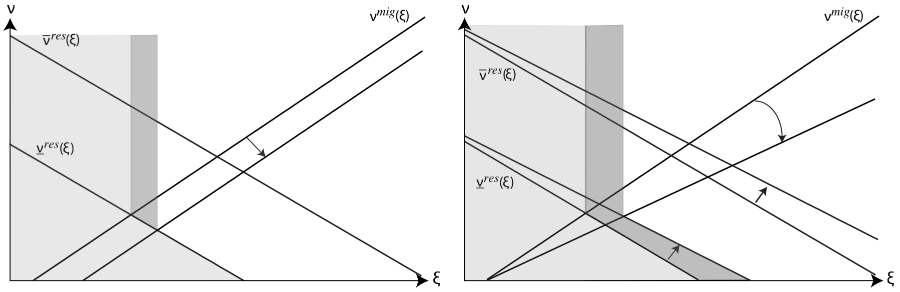

Figure 3: The basin of attraction of Equilibrium 0 (light grey area) and the change to this basin due to a higher w_{urban} or lower c_{mig} (left plot, dark grey area is gained) or a higher α (right plot, dark grey area is gained).

the labor allocation in the rural region in favor of manufacturing. Thus we may have more individuals in the rural region but, individually, they exert less effort in agriculture. This implies an upward shift of the resource boundaries $\underline{\nu}^{res}, \bar{\nu}^{res}$ and thereby, as Figure 2 shows, a larger basin of attraction of Equilibrium 0. As the stochastic process remains unchanged, this implies that it becomes more likely that a process enters this basin of attraction.

Note however, that this result applies only as long as the conditions of Prop. 3 are met. If productivity in rural manufacturing increases drastically, income from this sector alone can be sufficient to deter individuals from migrating. Thus for a large increase of β, it is possible that we get complete scrub encroachment (as no labor is allocated to agriculture) but no total depopulation; there is no more agricultural activity, but some people stay in the rural region.

Finally, the following lemma collects the influence of the other relevant parameters on the land-use/migration dynamics.

Lemma 2. *A marginal increase of w_{urban} (urban wage), a marginal reduction of c_{mig} (fixed migration costs), or a marginal increase of α (rivalry of resource use) increase the size of the basin of attraction of Equilibrium 0, as long as the conditions of Proposition 2 apply before and after the change.*

Proof. By Eqs. (18)–(19), an increase in w_{urban} or a reduction of c_{mig} leads to a downward shift of $\nu^{mig}(\xi)$ without changing $\underline{\nu}^{res}(\xi)$. Consequently, they reduce ν_1^{eq} and increase ξ_1^{eq} (cf. Eqs. (21)–(22)). The resulting change is depicted in the left plot of Figure 3. It shows that the basin of attraction of Equilibrium 0 becomes larger.

By Eqs. (18)–(19), a marginal increase of α leads to a reduction of the absolute value of the slopes of $\nu^{mig}(\xi)$ and $\underline{\nu}^{res}(\xi)$. Furthermore, it increases the value of ξ

at which $\underline{\nu}^{res}(\xi) = 0$, leaving the corresponding value for $\nu^{mig}(\xi) = 0$ unchanged, and increases $\underline{\nu}^{res}(0)$. Finally, under the conditions stated in Prop. 2, it increases ν_1^{eq} as well as ξ_1^{eq} (cf. Eqs. (21)–(22)). The resulting change is depicted in the right plot of Figure 3, which shows that the basin of attraction of Equilibrium 0 increases with a marginal increase of α. □

Again, the stochastic process remains unchanged, so that an increase size of the basin of attraction of Equilibrium 0 implies that it becomes more likely that a process enters this basin of attraction.

These results of Lemma 2 are intuitive. If migration becomes more attractive due to higher urban wages or reduced migration costs, the range of settings increases under which total depopulation occurs. Similarly, a smaller α, that is, less rivalry in resource use, renders agricultural activity more attractive and thus leads to a smaller probability of depopulation.

5 Policy implications

The above results have important policy implications. To discuss these implications, it is helpful to assume that a policy aims at avoiding a high probability of a depopulation of the rural region. Even without a welfare analysis, there are several reasons, why this might be a rational strategy in many cases. First, Equilibrium 0 is absorbing and implies the depletion of a once productive resource. Thus a path that approaches this equilibrium will often not be sustainable, in the sense of Krysiak and Krysiak (2006), as it significantly reduces future production options.

Second, there is a positive externality in land use as soon as scrub encroachment begins. This positive externality becomes increasingly important for low values of ν compared to the negative externality caused by land being a common property. So individual incentives for land abandonment are too strong in case of substantial scrub encroachment. Thus from a welfare perspective, total scrub encroachment will not be socially optimal in many cases.

Finally, reducing land abandonment is a political objective in many countries, sometimes to stabilize agricultural output, sometimes to prevent land changes, like scrub encroachment. In the following, we consider policy instruments aimed at meeting this objective.

One implication of our results is that higher uncertainty with regard to agricultural income increases the probability of land abandonment. It is important to note that this result holds, although the model is based on assumptions, such as risk-neutral individuals and myopic behavior with regard to land change, that assure that uncertainty has not per se a positive effect on migration. Even under these assumptions, the system dynamics imply that uncertainty is detrimental to reducing land abandonment. We thus expect this result to be fairly robust against model changes.

This result indicates that climate change, if it induces higher uncertainty, as for example envisioned in Stern (2006) or in Parry et al. (2007), will lead to more migration and thus to more land abandonment if it is not countered by policy measures. But finding such measures is not straight forward, as our results show.

An instrument that is widely discussed is investing in rural sectors that can offer side-jobs and thereby provide and insurance against weather shocks. Our results show that such investment will not always produce the desired effect. Although it reduces migration, it also reduces the incentives for agricultural activity. If agricultural land needs to be used in order to be kept open, reduced agricultural activity can lead to land degeneration and thus to a further reduction in income from agriculture. Eventually, the latter effect dominates a one-time increase of the labor productivity in rural manufacturing, because there is a positive feedback effect: less usable land shifts labor towards rural manufacturing, which assures future land loss, which reduces agricultural activity further, and so on.

This process can be avoided, if the investment is sufficiently large, that is, if it increases productivity in rural manufacturing so much that the maximal achievable rural wage comes close to the urban wage. In this case, migration will not end with a total depopulation. However, a complete land change will occur. Whether this is desirable, depends on the political objectives: if migration is the problem, this might be a useful approach; if land change is to be avoided, investment in rural side-jobs is not a helpful instrument. In either case, our results imply that it is not reasonable to invest sparingly in rural manufacturing, as this will only increase the set of cases in which total depopulation and complete land change occur.

A more potent approach would be a direct insurance against shocks to agricultural output, which could reverse the negative impact of uncertainty. Another feasible approach would be to improve land-use management, as, for example, proposed by Ostrom (1990); Mwangi and Ostrom (2009); Trawick (2001). Even if myopic behavior is not overcome, a better management could reduce rivalry in land use; rendering an individual's output less dependent on the land-use decisions of others. As Lemma 2 shows, this would reduce the basin of attraction of the depopulation equilibrium.

Finally, an interesting implication of our model is that too strict measures to reduce soil erosion can be harmful in the long run. In a double-limited resource system, one of the limits will become binding in the long run. An equilibrium in which land is on the brink of scrub encroachment will often be unstable, as in our model, because a temporary reduction of land productivity will reduce land use, which increases scrub encroachment and thus leads to a further deviation from the equilibrium. Thus the system will either tend to total scrub encroachment or to an equilibrium at the brink of erosion.

As argued above, the latter equilibrium will be socially preferable in many cases. In a system that is subject to random shocks, this implies that, whenever the system is close to the "benign" equilibrium, it is likely that erosion is observed at least temporarily. Addressing such temporary erosion can be a bad idea, because such intervention will often increase the probability that a negative shock drives the system to a path that leads to depopulation and scrub encroachment.

6 Conclusions

Rural-urban migration is a salient characteristic of economic development found both in industrialized and developing countries. Due to its implications for rural land use, it can have strong environmental repercussions, such as, soil erosion or scrub encroachment. As climate change is expected to increase the uncertainty of agricultural income, an acceleration of rural-urban migration is expected implying, possibly, substantial land change in rural environments. However, despite numerous empirical studies, the drivers in the interaction between migration and land use and the potential impact of uncertainty are poorly understood.

In this paper, we have addressed the question of how rural-urban migration and land change interact and how this interaction is influenced by a higher uncertainty of agricultural yields. We have presented a simple model that presents a reasonable complete picture of the migration/land-change dynamics under uncertainty with regard to agricultural output. This model encompasses several features that are frequently found in applications, such as the possibility of income-stabilizing rural side-jobs, irreversibility of migration, and common property management of rural land. However, it has been kept simple in order to gain an intuitive understanding of the main drivers in the land use/migration nexus. Furthermore, we have deliberately set up the model in a way that is likely to understate the negative impacts of uncertainty, for example, by assuming that households are risk-neutral and do not anticipate the positive feedback effects inherent in land loss.

We have shown that, in this model, the migration/land use dynamics have two stable equilibria; one equilibrium where land is used at the brink of erosion and one equilibrium characterized by total land loss (due to scrub encroachment) and a corresponding strong migration. Higher uncertainty increases the probability that the system will be in the basin of attraction of the land-loss equilibrium after a finite time. As we have assumed risk-neutrality, which implies a lower propensity to migrate for higher uncertainty, this result is a somewhat surprising consequence of the system dynamics. It results from the positive feedback effect of scrub encroachment: too little land use leads to encroachment, which reduces the income from agricultural activity and thereby future land use. Given that our model is set up to underestimate the consequences of uncertainty for migration and land use, this result should be robust.

A second important results is that investing in rural side-jobs might reduce migration in the short run but increases the likelihood of total land loss and the resulting strong migration in the long run. The reason is that higher productivity does not only reduce migration but also shifts rural labor from agriculture to the side-job. This increases the probability of scrub encroachment and thus the probability that the above positive feedback process starts, which eventually leads to a total land loss. If the investment in rural side-jobs is strong enough, rendering rural labor productivity sufficiently close to urban labor productivity, migration might be avoided. However, it seems questionable whether the land loss is socially desirable.

Finally, we have shown that better land management (a reduction of rivalry in land use) can reduce the likelihood of substantial land change and the accompanying migration. A similar effect could be reached by providing insurance against shocks to agricultural income.

Compared to the literature, our paper is in line with the existing theory on migration (Burda, 1995) in that increasing uncertainty leads to more reluctance to migrate, because it increases the option value in the migration decision. However, due to the interaction with the resource dynamics, uncertainty increases the probability of migration and land abandonment. This provides a theoretical argument as to why a higher volatility of weather conditions will lead to more migration in the long run, which is assumed, for example, in Stern (2006).

Although our paper is based on a highly stylized model, it has several implications that are likely to be relevant in applications. The depicted double-limited resource system, where land needs to be kept open by agricultural use but where the soil is susceptible to overuse, is typical for many agricultural regions, ranging from former forest areas in Africa, Asia, and North and South America to mountain regions in Europe. The modeled rural economy, where households combine agricultural activity with side-jobs in manufacturing or tourism and can migrate to an urban area with higher wages, is ubiquitous in industrialized and common in developing countries. Our analysis shows that, in such a system, higher uncertainty with regard to agricultural income is likely to cause more land change and rural-urban migration. Thus climate change may have substantial effects on the development of these areas. Furthermore, combating these effects is difficult. Commonly discussed counter-measures, such as investing in rural sectors beside agriculture, can be ineffective or even detrimental, as they withdraw labor from agriculture, accelerating land change.

Our analysis is purely descriptive and thus cannot offer strong policy conclusions. However, if avoiding land change and land abandonment is a political objective, as is the case in many industrialized countries, it seems clear that appropriate measures are necessary to counteract the influence of climate change.

In particular, providing direct insurance against income uncertainty in agriculture and improvements to land management practice could be among possible adaptation options.

References

Allen, J. M., and B. C. Eaton, 2005, Incomplete information and migration: The grass is greener across the higher fence, Journal of Regional Science 45, 1–19.

Anam, M., S. H. Chiang, and L. Hua, 2007, Uncertainty and international migration: An option cum portfolio model, Journal of Labor Research 29, 236–250.

Banerjee, B., and S. M. Kanbur, 1981, On the specification and estimation of macro rural-urban migration functions: With an application to Indian data, Oxford Bulletin of Economics and Statistics 43, 7–29.

Barrios, S., L. Bertinelli, and E. Strobl, 2006, Climatic change and rural-urban migration: The case of sub-saharan Africa, Journal of Urban Economics 60, 357–371.

Bhattacharya, P. C., 2002, Rural-to-urban migration in LDCs: A test of two rival models, Journal of International Development 14, 951–972.

Burda, M. C., W. Härdle, M. Müller, and A. Werwatz, 1998, Semiparametric analysis of german east-west migration intentions: Facts and theory, Journal of Applied Econometrics 13, 525–541.

Burda, M. C., 1995, Migration and the option value of waiting, Economic and Social Review 27, 1–19.

Burkinshaw, A. and E. Bork, 2009, Shrub encroachment impacts the potential for multiple use conflicts on public land, Environmental Management 44, 493–504.

Chauchard, S., C. Carcaillet, and F. Guibal, 2007, Patterns of land-use abandonment control tree-recruitment and forest dynamics in mediterranean mountains, Ecosystems 10, 936–948.

Cohen, B., 2006, Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability, Technology in Society 28, 63–80.

de la Rupelle, M., D. Quheng, S. Li, and T. Vendryes, 2009, Land rights insecurity and temporary migration in rural China, IZA Discussion Papers 4668, Institute for the Study of Labor (IZA).

Dixit, A., 1989, Entry and exit decisions under uncertainty, Journal of Political Economy 97, 620–638.

Drechsel, P., L. Gyiele, D. Kunzea, and O. Cofie, 2001, Population density, soil nutrient depletion, and economic growth in sub-saharan Africa, Ecological Economics 38, 251–25.

Harris, J. R, and M. P. Todaro, 1970, Migration, unemployment & development: A two-sector analysis, American Economic Review 60, 126–42.

IPCC (2007) *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, UK: Cambridge University Press).

Ito, T., and T. Kurosaki, 2009, Weather risk, wages in kind, and the off-farm labor supply of agricultural households in a developing country, American Journal of Agricultural Economics 91, 697–710.

Khwaja, Y., 2002, Should I stay or should I go? Migration under uncertainty: A real options approach, Public Policy Discussion Papers 02-10, Economics and Finance Section, School of Social Sciences, Brunel University.

Krysiak, F. C. and D. Krysiak, 2006, Sustainability with uncertain future preferences, Environmental & Resource Economics 33, 511 –531.

Lall, S. V., H. Selod, and Z. Shalizi, 2006, Rural-urban migration in developing countries : A survey of theoretical predictions and empirical findings, Policy Research Working Paper Series 3915, The World Bank.

Lanjouw, J. O., and P. Lanjouw, 2001, The rural non-farm sector: Issues and evidence from developing countries, Agricultural Economics 26, 1–23.

Lewis, A. W., 1954, Economic development with unlimited supplies of labor, Manchester School of Economic and Social Studies 22, 139–91.

Lunt, I. D., L. M. Winsemius, S. P. McDonald, J. W. Morgan, and R. L. Dehaan, 2010, How widespread is woody plant encroachment in temperate Australia? Changes in woody vegetation cover in lowland woodland and coastal ecosystems in victoria from 1989 to 2005, Journal of Biogeography 37, 722–732.

MacDonald, D., J. R. Crabtree, G. Wiesinger, T. Dax, N. Stamou, P. Fleury, J. Gutierrez Lazpita, and A. Gibon, 2000, Agricultural abandonment in mountain areas of Europe: Environmental consequences and policy response, Journal of Environmental Management 59, 47–69.

Mullan, K., P. Grosjean, and A. Kontoleon, 2011, Land tenure arrangements and rural-urban migration in China, World Development 39, 123–133.

Mwangi, E. and E. Ostrom, 2009, Top-down solutions: Looking up from east Africa's rangelands, Environment: Science and Policy for Sustainable Development 51, 34–44.

O'Connell, P. G. J., 1997, Migration under uncertainty: "Try your luck" or "wait and see", Journal of Regional Science 37, 331–347.

Ostrom, E., 1990, Governing the Commons: The Evolution of Institutions for Collective Action (Cambridge University Press, New York).

Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, eds., 2007, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007 (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA).

Roberts, K. D., 2001, The determinants of job choice by rural labor migrants in Shanghai, China Economic Review 12, 15–39.

Romero-Calcerrada, R. and G. L. W. Perry, 2004, The role of land abandonment in landscape dynamics in the spa 'encinares del río alberche y cofio, central Spain, 1984–1999, Landscape and Urban Planning 66, 217–232.

Stern, N., 2006, The Economics of Climate Change: The Stern Review (Cambridge University Press, Cambridge, UK).

Trawick, P., 2001, Successfully governing the commons: Principles of social organization in an andean irrigation system, Human Ecology 29, 1–26.

UNFPA, 2007, State of world population 2007: Unleashing the Potential of Urban Growth (New York: United Nations Population Fund).

UN, 2005, World Population Prospects: The 2005 Revision (United Nations, DESA, Population Devision).

World Bank, 2009, World Development Report 2009: Reshaping Economic Geography (World Bank, Washington, D. C.).

World Bank, 2008, World Development Report 2008: Agriculture for Development (Washington D.C.: World Bank).

Zhao, Y., 1999, Leaving the countryside: Rural-to-urban migration decisions in China, The American Economic Review 89, 281–286.