Migrant remittances can reduce the potential of local forest transitions—a social-ecological regime shift analysis

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Abstract
We explore how remittances shape the effect of rural out-migration on the potential for local forest transitions. Building on an existing theoretical model of social-ecological regime shifts that links migration, farmland abandonment, and forest regrowth, we incorporate migrant remittances as an additional rural-urban teleconnection. We also extend the ecological dynamics to include a dynamical forest regrowth rate, generating a slowing-down of regrowth once the landscape has undergone extensive agricultural change. We first analyse how these two extensions to the base model reshape the stability of the system, altering the existence and dynamics of alternative agricultural and forested regimes. Then we explore how two different uses of remittances by rural households (hiring agricultural labor or supplementing household income/consumption) affect the potential for local forest transitions in a context of structural economic change, represented as an increasing differential of rural and urban incomes. We find that remittances change the character of forested and agricultural regimes, and increase the resilience of the agricultural regime. This effect is stronger when remittances are used for hiring labor. The findings are consistent with empirical research that highlights the remarkable persistence of rural livelihoods and landscapes in the face of increasing global connectivity and urbanization. Remittances, and possibly other rural-urban teleconnections, are necessary components for an updated ‘economic development pathway’ of forest transitions. With this simple model we show that social-ecological regime shifts offer a useful perspective to study land use transition dynamics and advance land change theory.

Introduction
Migration has always been a central feature of the human experience throughout history. Globally, there are estimated to be 760 million internal migrants (Bell and Charles-Edwards 2013) and 260 million international migrants (UN-DESA 2017). Most of this migration occurs as people move from the countryside to cities, as both a cause and consequence of economic development. Migration poses immense social and environmental challenges, but it also offers opportunities for billions of people to improve their lives sustainably (Martine et al 2008, Seto et al 2010). Moreover, this movement of people implies changes in rural households, livelihoods, and landscapes.

In some parts of the world, rural out-migration has contributed to a reduction in deforestation followed by a net increase in tree cover, a pattern known as the ‘forest transition’ (Rudel 1998, Aide and Grau 2004).

Forest transitions in countries around the world have been attributed to different causal processes, one of which is the so-called ‘economic development pathway’ (Rudel et al 2005, Lambin and Meyfroidt 2010). This causal pathway emphasizes the role of increasing employment opportunities in cities, which attract migrants from the countryside. Agricultural labor scarcity drives landowners to concentrate activities on the most productive pieces of land, allowing forests to regrow in the most marginal ones. This explanation was central in historical accounts of the forest transition in Europe and the United States (Meyfroidt and Lambin 2011), and still is in Latin America (Grau and Aide 2008). However, today’s level of rural-urban connectivity implies that urbanization and economic
development affect land use practices differently than they did a century ago (Perz 2007). Contemporary forest transitions have to be understood in the context of globalization and teleconnections (Schmook and Radel 2008, Meyfroidt and Lambin 2011).

Along with labor reallocation, migration often creates a flow of remittances, the money that migrants send back home. International remittances to developing countries reached $466 billion in 2017, three times the size of official development assistance (World Bank 2018). Although data on internal remittances are extremely scant, they are thought to be at least as large as the international flows, but reaching more people and a poorer segment of the population (Castaldo et al. 2012, Housen et al. 2013). These monetary flows can reshape rural livelihoods and land use decisions (Cole et al. 2015, Hecht et al. 2015). While remittances are sometimes mentioned as a component of the ‘globalization pathway’ of forest transition (Kull et al. 2007, Lambin and Meyfroidt 2010), the emphasis is entirely on international migration. This misses the question of how remittances, whether internal or international, reshape the dynamics of the economic development pathway of forest transitions.

How rural households use remittances can either prevent or accelerate a forest transition. One use is consumption (i.e. supplement household income), covering costs such as home improvements or education (Hecht et al. 2012, Mendola 2012). This can reduce rural households’ dependence on agricultural production, which sometimes leads to farmland deintensification or abandonment (Hecht and Saatchi 2007, Wouterse and Taylor 2008). Alternatively, remittances can be invested in agricultural production, for example to hire additional labor (Hull 2007), purchasing agrochemical inputs (Adger et al. 2002), or acquiring machinery (Mendola 2008). Given these contrasting possible uses of remittances, it is not surprising that empirical evidence on the impact of remittances on rural land change is mixed (Gray 2009). One way of making use of this rich empirical research for theory development is to focus on a few of these insights to develop simple explanatory models of stylized causal mechanisms (Scheffer and Beets 1994, Rodrik 2015). We chose two of these alternative remittances uses (hiring labor and consumption) to explore how they reshape the potential of local forest transitions through the economic development pathway.

We analyse local forest transitions as social-ecological regime shifts shaped by migration and remittances (figure 1). A regime shift is a large, nonlinear, persistent change in the structure and function of a complex system (Scheffer 2009, Biggs et al. 2012). This theoretical lens is useful when the state of a system is not determined solely by external drivers, but rather internal feedback processes can reinforce or dampen externally driven change. Such interactions can produce nonlinear or threshold responses to gradual change in external conditions. When the system is near a critical threshold, small changes can produce systemic reorganization around alternative sets of structures and processes. Multiple geophysical and ecological systems exhibit regime shifts (Lenton et al. 2008, Biggs et al. 2018, www.regimeshifts.org). More recently, a regime shifts perspective has also been used to model qualitative change in coupled social-ecological systems (Lade et al. 2013, 2017, Lansing et al. 2014, Filatova et al. 2016). This perspective has also found its

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**Figure 1.** Two views of local forest transitions according to the type of response of the social-ecological system to external change in urban income: gradual (left) and abrupt and hysteretic (right). The regime shifts perspective emphasizes threshold dynamics and the potential for bistability, i.e. the existence of a range of external conditions in which the system has alternate regimes/equilibria. Both of these features are generated by strong feedback mechanisms.
way into land change science (Hostert et al 2011, Müller et al 2014, Li et al 2017). Ramankutty and Coomes (2016) argued recently that land change science has focused almost exclusively on within-regime dynamics, when land change is relatively slow and largely predictable. They consider land use regime shifts as fundamental but understudied phenomena, and stress the importance of advancing this research area for improving the quality of global change scenarios and forecasts.

Land use change and landscape-level ecological processes operate at different time scales. While extensive deforestation at the agricultural frontier can happen in a matter of years (Rudel and Roper 1997), the recovery of forest cover may require decades (Chazdon 2014). The duration and nature of prior agriculture practices, as well as the properties of local ecosystems shape forest recovery. With reduced forested area, forest recovery can slow down or completely halt, due to a loss of ecological memory (Bengtson et al 2003) or the strengthening of ecological feedbacks, such as fire or grazing, that slow sapling growth (van de Koppel et al 1997, Staver et al 2011). Such slowing of population growth at low population densities is known as the Allee effect in ecology (Turchin 2003) and depensation in fisheries research (Liermann and Hilborn 2001). The Allee effect can generate alternative regimes, fundamentally reshaping ecological dynamics. We include this dynamics in the model, and refer to it as an Allee effect.

In this paper, we present a minimal dynamic social-ecological model that examines how migration and remittances can affect the potential of forest transitions. Our model extends an existing model of social-ecological regime shifts, which links migration, farmland abandonment, and forest regrowth (Figueiredo and Pereira 2011), to include (1) remittance flows and (2) slowing forest recovery rates following extensive agricultural conversion (figure 2). The local forest transition is conceptualized as a shift from an agricultural regime to a highly forested regime, driven by rural-urban teleconnections. We use this ‘forest transition regime shift’ model to address two questions: (1) How do remittances and slowing forest recovery rates affect the potential for forest transitions, and (2) How do two alternative ways of using remittances—hiring agricultural labor and consumption—shape the effect of increasing urban income on the potential for local forest transitions. We address these questions by numerically analysing how different model configurations alter the stability the social-ecological system.
Methods—model development and analysis

In this section we explain the rationale underlying the selection of the base model and describe each of the model components. We then describe three separate ‘experiments’ set up to analyse the model, for which we compare graphically the location of the attractors (equilibrium values of state variables) and size of the domains of attraction (area of the state space in which initial conditions lead to a particular attractor) under different parameter configurations.

The model

Alternative types of models have been developed in the literature for explaining the processes of farmland abandonment and forest regrowth, or the forest transition as a whole. Statistical models using remote sensing data help identifying determinants of farmland abandonment (e.g. Prischepov et al 2013), without specifying causal mechanisms. Simulation models can generate spatially-explicit trajectories under alternative scenarios and assumptions to inform decision making (e.g. Evans and Kelley 2008, Verburg and Overmars 2009). Being place-specific, these models are less suitable for exploring stylized, generic mechanisms. For this purpose, minimal dynamic models are particularly useful. Examples of such models in economics and ecology have a microeconomic foundation driven by competing land values, based on decisions of a single representative agent (e.g. Barbier et al 2017), and can include ecological feedbacks between alternative land uses (e.g. Satake and Rudel 2007). Figueiredo and Pereira (2011) developed a social-ecological regime shifts model focused on migration, farmland abandonment, and forest regrowth. For our study, we adopt this model as our ‘base model’ and extend it by incorporating migrant remittances and slowed forest recovery following extensive agricultural transformation.

Our model considers a fixed land area, with a share of forest cover ($F$) and a share of agricultural land ($1-F$), as well as a fixed human population with a share of migrants ($M$) and a share of residents (non-migrants, $1-M$). Two coupled differential equations representing change in the share of forest cover (equation (1)) and in the share of migrants (equation (2)) constitute the dynamical system. The share of forested land grows logistically and decreases due to land clearing (equation (1a)). The forest growth rate ($\varepsilon(F)$, equation (1b)) introduces an Allee effect (as defined in introduction, Turchin 2003). This growth rate is an increasing function of $F$, with $\varphi$ representing the strength of the Allee effect, and $\varepsilon'$ the maximum growth rate. This effect implies a slower forest recovery rate, once the forest area has been extensively replaced by agriculture. The second term in equation (1a) represents land clearing for agricultural purposes. It depends on the share of rural residents ($1-M$), their capacity to clear the land ($\lambda$) and the hired labor paid for with remittances ($h(M)$, equation (1c)). Remittances are modelled as a proportion ($p$) of the urban wages ($\gamma$) obtained by the share of migrants ($M$). Remittances can increase total land clearing (equation (1a)), if used to hire external agricultural labor ($\beta < 1$, in equation (1c)) at a given agricultural wage ($k$).

$$\frac{dF}{dt} = \varepsilon(F)(1 - F) - \lambda[1 - M + \tau(M)]F$$

Forest dynamics (1a)

with

$$\varepsilon(F) = \varepsilon'(1 - e^{-(\varphi F)})$$

Dynamic forest growth rate (1b)

$$\tau(M) = (1 - \beta)\frac{p\gamma M}{k}$$

Labor hired with remittances (1c)

Migration involves a self-reinforcing process known as the ‘migration network effect’: initial migration facilitates further migration through information feedbacks that increase the ability and aspirations of others to migrate (Massey 1990, Massey et al 1993). We assume that the decision to migrate is defined by the share of migrants ($M$), and that every individual has a different threshold value of $M$ for doing so. The model represents the aggregate threshold of the whole population, and assumes that it has a logistic distribution with average ($\mu$) and variance ($s$). Hence, $\mu$ represents the average threshold in the population, and $s$ represents the level of heterogeneity. We interpret $s$ as the population’s heterogeneity of attitudes toward the risks of migrating. The difference between the cumulative distribution function of the logistic distribution (CDF($M$, $F$), equation (2b)) and the actual value of $M$ indicates the proportion of the total population that chooses to migrate at any given time step (equation (2a)). The scaling parameter $\omega$ in equation (2a) represents the fraction of the population that is at all pondering on the decision of whether or not to migrate at each time step. The $\omega$ parameter is also a simple way of recognizing that there are non-monetary forces, such as ‘attachment to place’ (Adams and Adger 2013) which can be a powerful force slowing-down out-migration.

The average threshold for migrating ($\mu$) is influenced by urban wages ($\gamma$) and agricultural income per unit area ($h$). Total agricultural income is obtained from the total agricultural land ($1-F$), shared among all rural residents ($1-M$). The ratio between urban and agricultural incomes captures the most basic economic driver underlying of rural-urban migration (Taylor and Martin 2001, Black et al 2011). The functional form of equation (2a) comes from the assumption that when agricultural income per capita and
urban income per capita are equal \( \left( \frac{h(1-F)}{1-M} = \gamma \right) \), the decision to migrate depends entirely on social considerations. Following Figueiredo and Pereira (2011), we assume that in this situation the average threshold for migrating would be 50% \( (\mu = 1/2) \). Therefore, \( \mu \) is defined as a function of urban and agricultural income \( (\mu = \frac{h(1-F)}{2\gamma(1-M)}) \). Finally, remittances shape the effect of the rural-urban income ratio on \( \mu \) in two ways. First, irrespective of how remittances are used, the proportion of the urban income that migrants remit \( (p) \) implies a reduction in the urban incomes that migrants keep (equation \( 2c \)). Second, if used for consumption \( (\beta > 1 \text{ in equation } 2d) \), remittances increase the total rural income. These two effects reduce rural out-migration. We assume that agricultural commodities produced in this landscape are part of a globalized market, hence out-migration from this locality does not influence their price.

Appendix A lists and describes the state variables and parameters of the model.

\[
\frac{dM}{dt} = \omega \left[ \text{CDF}(M, F) - M \right] \quad \text{Migration dynamics} \quad (2a)
\]

with

\[
\text{CDF}(M, F) = \frac{1}{1 + e^{-(\mu(M,F)-M)/\gamma}} \quad \text{Cumulative distribution function} \quad (2b)
\]

\( \text{CDF} \) with \( \mu \) as in \( 2a \). The curves representing situations when forest stock (green curve) and migration (orange curve) do not change.

\[ \mu(M, F) = \frac{h(1-F)}{2(1-p)\gamma(1-M)} \quad \text{Average migration threshold} \quad (2c) \]

\[ r_c(M) = \beta p \gamma M \quad \text{Remittances used for consumption} \quad (2d) \]

The coupled dynamics of migration and forest can produce alternate agriculture or forest dominated social-ecological regimes. Figure 3 illustrates how the system can evolve towards either an agricultural regime (low forest cover and low migration) or a highly forested regime with some agricultural land and a high share of migrant population. Specific parameter values determine which type of system is possible, while relatively small differences in the initial conditions can generate very different outcomes (trajectories starting at A–C in figure 3).

**Analysis**

We address two questions: (1) How do remittances and slower rates of forest recovery following extensive agricultural conversion affect the potential for forest transitions, and (2) How do two alternative ways of using remittances—hiring agricultural labor and consumption—shape the effect of increasing urban income on the stability of the system, and hence, the potential for local forest transitions.

We addressed these questions by numerically analysing how different model configurations alter the character and stability of forest transitions. For the first question we illustrate four parameter configurations, varying \( \varphi \) and \( p \) (table 1, A), and for the second question we represent nine more parameter configurations, varying \( p, \beta \) and \( \gamma \) (table 1, B). For these two

![Figure 3](image-url)

Three system trajectories represented in a time series plot (left) and a phase portrait (right). The phase portrait also shows the zero-isoclines for forest (green curves), \( \frac{dF}{dt} = 0 \), and migration (orange curves), \( \frac{dM}{dt} = 0 \), two attractors (full black circles), two domains of attraction corresponding to alternate social-ecological regimes: agricultural regime with low migration (yellow background) and highly forested regime with high migration (light green background). The three trajectories (black curves) with different initial conditions (A, B, C) in the phase plot correspond to the time series plot for forest and migration (left). Parameter values used are shown in table A1. A version of the phase portrait that shows vector field and full trajectories is presented in appendix B.

![Diagram](image-url)
Table 1. Overview of model and parameter comparisons to evaluate the effect of: (A) model extensions and (B) remittances and structural economic change. See all other parameter values in table A1.

| (A) Model extensions | No remittances | With remittances |
|-----------------------|----------------|-----------------|
| No Allee effect       | $\varphi > 999 p = 0$ | $\varphi > 999 p = 0.1$ |
| With Allee effect     | $\varphi = 10 p = 0$ | $\varphi = 10 p = 0.1$ |

| (B) Remittances and structural economic change | Increasing urban income |
|----------------------------------------------|-------------------------|
| No remittances                               | $p = 0 \gamma = 1.1$     |
| Remittances used for consumption             | $p = 0.1 \beta = 0 \gamma = 1.1$ |
| Remittances used for hiring labor            | $p = 0.1 \beta = 1 \gamma = 1.1$ |

*The base model (Figueiredo and Pereira 2011) is a particular case of our extended model in which extreme values for the Allee effect term and share of remitted urban income are selected.*

comparisons, we assessed the existence of different social-ecological regimes (i.e. agricultural or high forest cover), the location of their respective attractors, and the size of their domains of attraction. Structural economic change is akin to a 'slow variable' (sensu Walker et al 2012), an external change that can trigger a regime shift.

All the analyses were conducted with the R packages deSolve (Soetaert et al 2010) and phaseR (Grayling 2014). For more detailed explanations see appendices A–C.

Results

Remittances and Allee effect
The Allee effect in forest growth has a conspicuous effect on the coupled dynamics of forest cover and migration. The forest cover zero-isocline (figure 4, green curve) shifts from a linear relationship (figure 4, top panels), to a sharp concave–convex shape (figure 4, bottom panels) that stabilizes the agricultural regime (no forest cover). Remittances introduce a subtler change, shifting the migration zero-isocline to the right (figure 4, orange curve), resulting in a change in the location of the attractor for high forest cover regimes. The full forest cover and full migration attractor (figure 4, left panels), is replaced by an attractor of mixed forest-agriculture with a small resident population (figure 4, right). Remittances also widen the domain of attraction of the agricultural regime and lower its attractor toward a smaller migrant population (figure 4, bottom–right).

Remittances and structural economic change
For this part of the analysis, we focused on the parameter space defined by intermediate levels of the two key social and ecological parameters described in the previous section ($s$ and $p$), as the system’s bistability is most noticeable in this parameter space (figure C1).

At low levels of urban income, remittances generate a single agricultural regime with low migration, while in their absence the system is bistable, adding a regime of full forest cover and full migration (figure 5, left column). As urban income increases, the systems with remittances become bistable as well (figure 5, centre column), yet the domain of attraction of the agricultural regime is wider when remittances are present. Noticeably, the use of remittances for hiring labor reduces the equilibrium level of forest cover for the high forest cover regimes much more than when remittances are used for consumption (figure 5, centre column). At even higher levels of urban income (figure 5, right column), the domain of attraction of the agricultural regime with remittances used for consumption is almost as narrow as in the system with no remittances (figure 5, middle–right panel). Very small ‘shocks’ to the system or stochastic variability changing the level of forest cover, would make the system shift to the high forest cover regime. Moreover, when remittances are used for hiring labor instead, another bifurcation occurs so that the high forest cover regime disappears (figure 5, bottom–right panel).

Discussion
Our minimal model of social-ecological regime shifts captures some of the complexities of the interaction between migration and land use change, and suggests that migrant remittances can reduce the potential for local forest transitions. The dynamic forest regrowth rate we introduced becomes slower after extensive agricultural transformation. This is more sensible from an ecological point of view and introduces the potential for a stable agricultural equilibria. Hence we could better assess the effects of migration and remittances on forest regrowth. While rural out-migration can drive a shift from an agricultural to a forested regime via a labor scarcity mechanism (Figueiredo and Pereira 2011), our model shows how remittances can have a countervailing effect through two different mechanisms (figure 6).
Remittances landscapes

Contrary to what the traditional economic development pathway of forest transitions suggest, agricultural landscapes and livelihoods have been found to persist despite significant out-migration (Jockisch 2002, Radel and Schmook 2008, Böhme 2015). This is related to an increase in the intensity and character of rural-urban teleconnections, which reshape the relation between urbanization, economic development, and rural land use. Across the developing world, the sharp distinction between rural and urban is being increasingly blurred (Hecht 2010, Seto et al. 2012). One example is the rise of ‘multi-local’ or ‘multi-sited’ households (Padoch et al. 2008) comprised of members living in distant locations yet economically reliant on each other. Rural household income sources are increasingly diversified away from agriculture, relying more on off-farm activities, within small rural villages or away in urban centres (Hecht et al. 2015). Migrant remittances are a key rural-urban teleconnection that fundamentally reshapes social-ecological dynamics (Kramer et al. 2009, Güneralp et al. 2013). In particular, as our model and multiple case studies have shown (Adger et al. 2002, Taylor et al. 2003, Gray 2009, Gray and Bilsborrow 2014), remittances can dampen the effect of labor scarcity created by rural out-migration, and in this way help explain the resilience of rural livelihoods and the persistence of inhabited rural landscapes. In our model, remittances shape the effect of structural economic change on the stability of the social-ecological system, but do so differently depending on how they are used (figures 5 and 6). When used for consumption, remittances affect the migration decision itself. The utility of non-migrants is increased through the remittances they receive, while the utility of migrants is reduced by the remittances they send. Hence, this remittances mechanism dampens the effect of the ‘migration network’ positive feedback.

The use of remittances to hire agricultural labor can counteract the effects of labor lost to migration (e.g. Hull 2007 in Thailand, Jokisch 2002 and Gray 2009 in Ecuador). This points to another condition that can prevent the dynamics described by the traditional economic development pathway: the persistence of an agricultural labor surplus (Rudel et al. 2002). Landless peasants or sharecroppers are a common feature in many developing countries (Deininger and Feder 2001, Griffin et al. 2002). Due to their lower economic assets, they are less likely to migrate, and hence they provide a stable source of agricultural labor. When remittances are used for hiring
agricultural labor in our model, land clearing occurs at a higher rate, lowering the equilibrium level of forest cover and even preventing the existence of a high forest cover regime (figure 5, bottom-right panel). In other words, farmland abandonment and forest regrowth might not happen at all, even when a substantial fraction of the land users have migrated to urban areas. By dampening the migration network effect and preventing agricultural labor scarcity, remittances effectively constitute novel mechanisms that can stabilize agricultural landscapes and rural livelihoods. The notion of ‘remittance landscapes’ (McKay 2005) comes to mind for describing this type of teleconnected social-ecological system.

While our focus is on the implications of remittances through these different mechanisms, it is essential to assess these impacts with a more realistic representation of forest dynamics. In particular the Allee effect model extension introduces the possibility that forest recovery can slow down or completely halt when the forested area is substantially reduced. As a result agricultural regimes can become persistent below a minimal forest cover threshold, a property that is absent in a model with a constant regrowth rate. The agricultural regime reflects a situation in which the capacity of labor (whether from residents or external hired laborers) to keep the land cleared, surpasses the rate of forest regrowth. Intuitively, this applies for virtually any transformed agricultural landscape: once it has been cleared and cultivated, it takes substantially less work to keep it like that, than it took to clear it in the first place. In other words, beyond a threshold of forest loss, the positive feedback that drives forest regrowth is severely weakened. The important

![Figure 5. Effect of two alternative uses of remittances on system stability as urban income rises. Phase portraits show (1) zero-isoclines for forest (green curve) and migration (orange curve) dynamics, (2) attractors (full black dots), and (3) domains of attraction corresponding to alternate social-ecological regimes: two agricultural regimes with high level of migration (orange background) and low level of migration (yellow background), one fully forested regime with full migration (dark green background), and one highly forested regime (or mixed forest-agriculture) with some agriculture and a high level of migration (light green background). See all remaining parameter values in table A1.](image-url)
Implication for our analysis is that the Allee effect generates bistability in the system for a much wider range of social and ecological conditions, and even when the rural-urban income differential is very high (figure 5). In this wider range of bistable conditions the effects of remittances can be examined more clearly.

Future research priorities
The power of minimal models derives from their simplicity. Simplicity enables them to be used to isolate specific mechanisms and reveal their role in generating complex systems dynamics. These mechanistic insights can be developed through further investigations using complementary approaches: in-depth single-case studies, large-N statistical analysis, and more complex empirically-grounded simulation models. Our model provides concrete propositions, which can be further refined into empirically-testable hypotheses. For example, our model suggests that higher levels of forest recovery would be found in contexts in which remittances are used mainly for consumption, and that forest recovery would be less likely, even with a large difference between urban and rural incomes, in contexts in which remittances are mainly used to hire additional labor. Retrospective and scenario analysis using socioeconomic survey data and remote sensing data have already been employed to explore land use regime shifts (Hostert et al 2011, Müller et al 2014). This work suggests that land systems can be fruitfully conceptualized as undergoing regime shifts, and methods to analyse regime shifts could be usefully applied in land systems theory, such as searching for signatures of regime shifts in multi-modal land use data (Staver et al 2011) and identifying places and times that are more or less likely to experience regime shifts (Staal et al 2018).

Our analysis focused on some aspects of the model, but other relevant aspects could be explored. While we focused on forest recovery (the final stage of the forest transition), the model can also represent deforestation (the initial stage of the forest transition). For example, an uninhabited forested landscape (initial conditions $F = 1$ and $M = 1$) with no wage differential ($h = γ$) would exhibit a trajectory leading to a fully agricultural inhabited landscape. Similarly, while we focused on remittances from urban to rural settings ($p > 0$), this flow can go in the opposite direction and this can be represented in the model as well ($p < 0$). Future modelling would benefit from considering explicit decision making processes, geographical heterogeneity, and alternative uses of remittances:

(1) How does variety of human decision making shape the forest transition regime shifts? Which types of variety have the greatest impact on these shifts and how do these impacts vary across contexts? Differences in land ownership and wealth are known to shape people’s decisions to migrate and send remittances back to their families (Taylor and Martin 2001, Mendola 2012), and they influence how people make land use decisions (Coomes et al 2016, Sant’anna 2017). In our model all rural residents share the benefits obtained from agricultural land. This reflects situations where land is held in common, but does not represent appropriately cases with very unequal land distribution patterns. Moreover, while we represented landless peasants as an external source of labor to be hired, the interactions among people with different assets, through land and labor markets, would shape the possibilities for migration or land use in ways that our
model cannot capture. Similarly, gender and ethnicity also influence the mechanisms linking migration and forest regrowth (Rudel et al 2002, McKay 2005). These are particularly important in Latin America, where there is substantial inequality in land access, gendered agricultural activities, and ethnic differences in access to jobs.

(2) How does geography and ecology shape forest transition regime shift dynamics across regions? Our model represents a landscape as a homogeneous area. It does not distinguish between abandoned farmland where forest can regrow and degraded lands where forests cannot regrow. Sources of ecological memory for any particular abandoned plot change in relation to the spatial patterns of forest remnants (e.g. connectivity for seed dispersion), and the intensity of its previous use (e.g. remaining seed bank) (Bengtsson et al 2003). Exploring the interactions between these and the way migration and remittances shape land use/management is an interesting research avenue that could build on substantial theoretical and empirical work on ecological memory (Johnstone et al 2016) and tropical forest regeneration (Chazdon 2014).

(3) How do additional ways of using remittances reshape forest transition regime shifts? Our model considered two types of common remittances’ uses (consumption and hiring labor), but agricultural investments for intensification are an alternative use with critical implications for land use/management, particularly in developing countries (Stark and Bloom 1985, Taylor and Martin 2001). For example, investments in agroforestry can accelerate other forms of tree cover growth, while investments in intensification, expansion of agricultural uses, or cattle can prevent it and enable other qualitative changes in the landscape and livelihoods. Understanding these more complex uses of remittances requires model extensions, which would include alternative investment opportunities, and even the flow of ‘social’ remittances (knowledge, ideas, contacts) (Levitt 1998, Montefrio et al 2014).

Conclusions

We presented a model that represents local forest transitions as social-ecological regime shifts, driven by migration and remittances, two kinds of rural-urban teleconnections. Our analysis shows how the labor scarcity mechanism, through which migration generates farmland abandonment, can be weakened when remittances are used for consumption or hiring labor. Therefore, the model suggests that remittances can reduce the potential and magnitude for local forest transitions. This is a contribution toward updating our understanding of the economic development pathway of forest transitions for an era of intense and diverse forms of rural-urban connectivity. The remittances mechanisms in the model also help to understand the resilience of rural landscapes and livelihoods in the context of broader urbanization and structural economic change.

Our aim with this work was to contribute to bridging regime shift and resilience theory with land systems theory, as called for by Ramankutty and Coomes (2016). This model provides a mechanistic description of how competing feedback processes can generate regime shifts, and shows how these reorganizations are shaped by both local and distant conditions. We hope that this work will stimulate more research on the effect of specific teleconnections on social-ecological regime shifts, as well as further work on the mechanisms underlying forest transition at different scales, that can better illuminate how the Earth system functions in the Anthropocene.

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Appendix A

The default value for parameters $s$, $\gamma$, $h$, $\lambda$, and $\omega$ come from Figueiredo and Pereira (2011), to help comparison. For parameter $\varepsilon'$, we used the value of parameter $\varepsilon$ in Figueiredo and Pereira (2011). The values for the share of remitted urban income ($p = 0.1$) and agricultural wages ($k = 0.5$) represent common real-world proportions. For $\varphi$ we choose a value between the extremes which creates a relation between $F$ and $\varepsilon$ that is not a linear increase (when $\varphi = 0$ nor a constant $\varepsilon$ ($\varphi > 999$), but rather a concave downward increasing function (when $\varphi > 999$), but rather a concave downward increasing function (when

\[ 4 \quad \text{For international migrants in the United States, Cervantes (2016) estimated that in 2014 the average of remittances among migrants from 63 countries in the United States was around 10\% of their income. Regarding wage differentials, Clemens et al (2009) estimate that the median wage ratio for migrants moving to the US was 2.7 (but it can be as high as 15.5). Martinez-Chaparro (2014) found that the difference between agricultural wages and those of low skilled urban-industrial workers, ranged between a factor of 2 (construction) and a factor between 4 and 8 (industry employees), while in the US this range was between 1.5 and 2.5.} \]
### Table A1. State variables and parameters in the model.

| Symbol in equations | Meaning | Unit | Default value | Range |
|---------------------|---------|------|---------------|-------|
| $F$                 | Forest cover share of total area (1- $F$ corresponds to the share of land cleared for agricultural purposes) | Proportion of total area (dimensionless) | | [0–1] |
| $M$                 | Migrant share of total population (1- $M$ corresponds to is the share of rural resident) | Proportion of total population (dimensionless) | | [0–1] |
| $\mu$              | Population’s average threshold for value of $M$ deciding to migrate | Proportion of total population (dimensionless) | | [0–1] |
| $\varepsilon$      | Forest growth rate (subject to and Allee effect given $F$ and $\varphi$) | Area$^{-1}$ yr$^{-1}$ (Dynamic) | 0.02 | [0–1] |
| $\varepsilon'$     | Maximum forest growth rate | Area$^{-1}$ yr$^{-1}$ | 0.02 | [0–1] |
| $\lambda$          | Land clearing rate | Person$^{-1}$ yr$^{-1}$ | 0.02 | [0–1] |
| $s$                 | Variance in the population’s threshold for migrating. It represents the heterogeneity of attitudes to the risks that migration involves | (Dimensionless) | 0.1 | (0–1) |
| $\gamma$           | Urban wages | Utils person$^{-1}$ yr$^{-1}$ | 2 | [0–∞) |
| $h$                | Agricultural income | Utils area$^{-1}$ yr$^{-1}$ | 1 | [0–∞) |
| $p$                | Share of urban wage remitted by migrants | Proportion of utils (dimensionless) | 0.1 | [0–1] |
| $k$                | Cost of hired labor (agricultural wage) | Proportion of utils (dimensionless) | 0.5 | [0–∞) |
| $\beta$           | Share of remittances used for supplementing rural household income (consumption as opposed to hiring labor) | Proportion of utils (dimensionless) | 0.5 | [0–1] |
| $\varphi$         | Strength of the Allee effect (lower values generate a linear change) | (Dimensionless) | 10 | [0–∞) |
| $\omega$          | Share of the population who even consider the choice of whether or not to migrate at each time step | Proportion of total population (dimensionless) | 0.1 | [0–1] |
For parameter $\beta$, we tested values of 0 and 1, representing either all remittances used for hired labor or all used for consumption, respectively.

**Appendix B**

The phase portraits presented in the results section do not include the vector field in order to simplify the figures. Figure B1 shows the same dynamic system as figure 3 with the vector field (gray arrows), and showing the entire trajectory from initial conditions (A, B, C) to the attractors (full back dots). The direction and length of the vector field arrows indicate the direction and relative speed of change throughout the entire area of the state space.

**Appendix C**

We explored how the stability of the system would change in broadly different social and ecological contexts. We did so by identifying bifurcations that would either generate new steady states or make some disappear when some parameter values changed. The search for bifurcations was informed by a mathematical analysis of the steady states. When possible, we solved the steady states values and identified threshold parameter values that would generate changes in the number of possible steady states. These calculations are standard and are available on demand from the authors. When the expressions for steady states did not provide enough information on the bifurcation points we instead gradually changed the relevant parameter values to investigate whether this would trigger bifurcations. The different phase portraits in figure 3 right hand side and figures 4 and 5 illustrate representative cases that we were able to identify. The curves in the diagrams represent zero-isoclines, i.e. points in space (combinations of forest cover and migrant population values) where migration (orange curves) respectively forest cover (green curves) do not change. At the intersection of the two types of curves are the equilibria of the system (attractors). The background colours illustrate the different domains of attraction for the different steady states (in other words, the location of initial conditions such that the system would finally end up in the steady state present in that region).

In addition to the tests presented in figures 4 and 5, we tested the impacts of change in other parameter values. We illustrate the different cases we identified by showing six parameter configurations that were compared, varying $\varepsilon^\prime$ and $s$. The maximum forest regrowth rate ($\varepsilon^\prime$) has a clear effect on whether alternate social-ecological regime exist, as well as the size of the domains of attraction. When the maximum forest growth rate is low, only agricultural regimes exist. In contrast, when the maximum forest growth rate is intermediate or high, the system is bistable with an agricultural regime and a high forest cover regime. However, the domains of attraction of the agricultural regimes are much smaller when the maximum forest regrowth rate is high. The figure below also shows how the heterogeneity of attitudes toward migration ($s$)
influences the equilibrium level of migration, in a particularly strong way for the agricultural regimes.

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