



Research, part of a Special Feature on [Long-term Vulnerability and Transformation](#)  
**Robustness and Resilience across Scales: Migration and Resource Degradation in the Prehistoric U.S. Southwest**

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**ABSTRACT.** Migration is arguably one of the most important processes that link ecological and social systems across scales. Humans (and other organisms) tend to move in pursuit of better resources (both social and environmental). Such mobility may serve as a coping mechanism for short-term local-scale dilemmas and as a means of distributing organisms in relation to resources. Movement also may be viewed as a shift to a larger scale; that is, while it may solve short-term local problems, it may simultaneously have longer term and larger scale consequences. We conduct a quantitative analysis using dynamic modeling motivated by an archaeological case study to explore the dynamics that arise when population movement serves as a link between spatial scales. We use the model to characterize how ecological and social factors can lead to spatial variation in resource exploitation, and to investigate the circumstances under which migration may enhance or reduce the capacity of the system to absorb shocks at different scales.

**Key Words:** *degradation; migration; natural resources; resilience; vulnerability*

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## INTRODUCTION

As the reach of human activity increases and human networks continue to expand, social and ecological processes are becoming linked across an increasing range of spatial and temporal scales. Such linkages expose the global system to an increasing number of shocks and directed change at different scales. The increased exposure of local farmers to competition in international commodity markets and the resulting price fluctuations they experience as they become integrated in global trade networks is an obvious example (O'Brien et al. 2004).

Migration (and other forms of population mobility) is arguably one of the most important processes that link ecological and social systems across scales. Renewed interest in migration in archaeological and other social science research understands migration as a complex process involving donor and recipient populations and ecosystems, sometimes over the course of generations (e.g., Anthony 1990, Kohler et al. 2010). Sometimes migrations are viewed as motivated primarily by push factors, that is, difficult conditions in the donor area, and sometimes by pull factors, that is, particularly attractive conditions in

the receiving area (e.g., Lipe 1995). However, both push and pull processes may be at work simultaneously, and their importance may change as the migration progresses. In the most general terms, migrations can be understood as movement in pursuit of better resources—both social and environmental (Greenwood 1985). This kind of mobility may sometimes serve as a coping mechanism and as a means of distributing organisms in relation to resources. But, particularly when moving involves the relatively permanent dislocation and relocation of populations, it can have culturally, socially, and ecologically deleterious effects. Movement may also be viewed as a shift to a larger scale; that is, while it may solve short-term local problems, it may simultaneously have longer term and larger scale consequences. The research presented here explores the dynamics that arise when population movement serves as a link between spatial scales.

Recent developments in global change research suggest the need to address how the dynamics generated by intricate feedbacks play out across spatial and temporal scales (Folke and Gunderson 2006). Unfortunately, there are few research tools

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up to the task. An alternative to the impossibility of controlled experiments with human societies is to build understanding based on combining basic principles from the natural and social sciences with numerous case studies (Walker et al. 2006a) under the superstructure of a conceptual framework. That is the approach we take. We combine empirical insights (derived from the archaeological record) with mathematical modeling under the conceptual framework of resilience theory, which emphasizes changes across multiple temporal and spatial scales. Resilience theory focuses on the dynamics of social-ecological systems, how they change over time, and especially how they undergo transformations and subsequently reorganize.

The motivation for most research that combines case studies with stylized mathematical models is to better understand critical general features that affect the dynamics of different classes of social-ecological systems, be they lakes (Carpenter et al. 1999), rangelands (Anderies et al. 2002), irrigation systems (Anderies et al. 2006), swidden agriculture (Anderies 1998), or fisheries (Clark 1973, 1990). Such modeling efforts typically do not strive to reproduce detailed patterns associated with a particular case study. Rather, the case studies are used to motivate questions about general patterns, and the stylized models are used to uncover the minimum set of processes that can generate such patterns. The Mimbres archaeological region in the southwestern U.S. has been an important case in research that has linked the deep time of the archaeological record with the conceptual insights of the resilience framework (Nelson et al. 2006, Hegmon et al. 2008). The work presented here is motivated by patterns suggested by the Mimbres case (see Hegmon [2002] for a summary of Mimbres archaeology). First, a minimal model is developed which incorporates basic process governing key features of the Mimbres system, including renewable resource dynamics, resource use, and migration decisions. The model is analyzed and checked for consistency with the details of the Mimbres case to the extent possible. The model is then used to address the following more general questions:

- How is migration associated with spatial variation in resource quality at different spatial and temporal scales?
- How does migration affect the capacity of a system to cope with shocks at different scales?

- How important are social factors in driving or potentially mitigating resource depletion and possible degradation across space? (The distinction between depletion and degradation is clarified below.)

### **THE MIMBRES ARCHAEOLOGICAL REGION, RESOURCE PRODUCTIVITY, AND MIGRATION**

In recent years, archaeologists have increasingly focused on understanding the impacts ancient peoples had on their environments, as well as the environmental and social consequences of those impacts (Redman 1999, McIntosh et al. 2000, Fisher et al. 2009). An important early case study in this work was done in the Mimbres region in southwest New Mexico, where it appears that declines in soil fertility and vegetation cover at a time of drought were associated with (and potentially causal of) the depopulation of major villages and the end of a major cultural tradition known as the Mimbres Classic at about CE 1130 (Minnis 1985, Sandor et al. 1990, Nelson et al. 2010).

Subsequent research in the Mimbres region has complexified this picture considerably, in large part because of multiple spatial and temporal scales that are increasingly being factored into the picture. First, it is now clear that the end of the cultural tradition was not a major collapse or the end of a people. Rather, it is better understood as regional reorganization, in which people shifted among river valleys (Nelson and Anyon 1996), and in some cases moved from the large (and archaeologically highly visible) villages to smaller dispersed hamlets and changed their pottery styles (Hegmon et al. 1998, Nelson 1999, Nelson and Hegmon 2001). Second, there is considerable variability across the region in the availability and productivity of farmland, and also variability in the nature and degree of environmental impacts. Third, more nuanced analyses of productivity suggest that resources were sufficient to maintain populations but that prehistoric peoples' perceptions of declining resources may have been a major cause of change (Schollmeyer 2009). These recent insights fit well with the notion of cyclical change, a key concept highlighted in resilience theory (Gunderson and Holling 2002, Walker et al. 2006b): systems move through stages of growth and consolidation,

transformation and release, reorganization and innovation. These notions suggest that the history of settlement in one area may be better understood in relation to its interaction with other and surrounding areas as part of a cycle that has both spatial and temporal components. What appears as a cycle of growth and decline in one limited area is seen as movement and reorganization when viewed from the perspective of the broader region. The analysis of the model developed here supports this view.

A brief description of the Mimbres region sets the stage for defining a more specific research question and for relating the Mimbres case to resilience issues more directly. At the center of the Mimbres region (Fig. 1, turquoise box) is the Mimbres River Valley, which is, in comparison to many parts of the southwestern U.S., a good place to be a farmer. It receives more rainfall (an average of 44.0 cm/yr at the Reserve Ranger Station [Western Regional Climate Center 2005]) than many surrounding areas because the westerly orographic flow is stopped by a mountain range to its east (Nelson 1999: 29–30). The river flows reliably, creating a broad and manageable floodplain that was probably the locus of many prehistoric fields and is still used for agriculture today. Floodplain fields could have been watered relatively easily using the small-scale irrigation systems that were built prehistorically, and the river would also have periodically replenished these fields. In addition, there are many patches of arable land in the uplands. The Mimbres River Valley was clearly the most densely populated part of the region in the Mimbres Classic period (CE 1000–1130), and there is good evidence that prehistoric farming denuded the floodplain vegetation (Minnis 1985) and degraded the upland soils (Sandor et al. 1990) during the Mimbres Classic period.

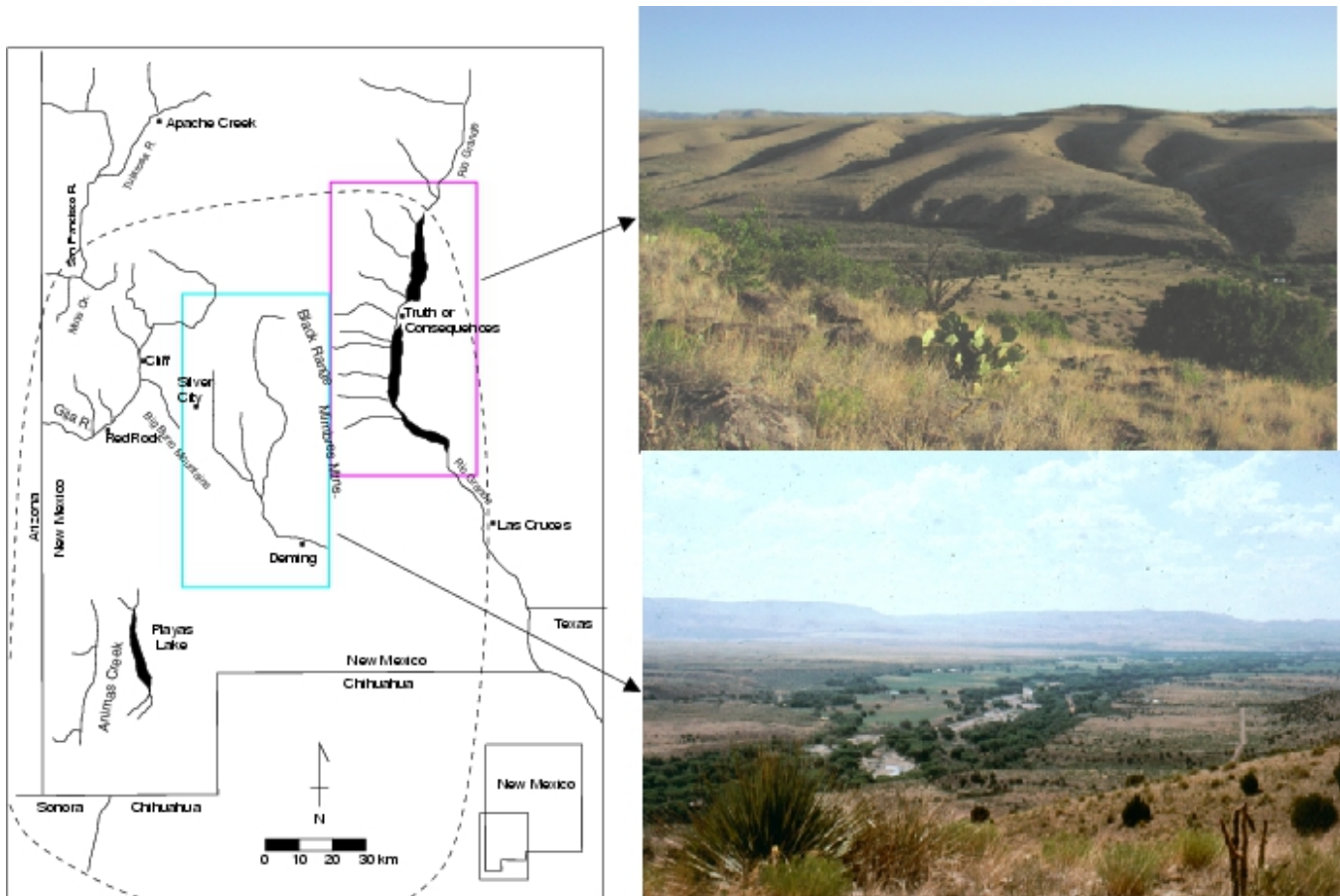
In contrast to the Mimbres River Valley, what is known as the eastern Mimbres area (Fig. 1, magenta box) is a much less likely location for farming. It is in a rain shadow, and rainfall averages only about 31.7 cm/yr (Hillsboro Weather Station [Western Regional Climate Center 2005]), about 72 percent of the amount received in the Mimbres Valley. The eastern Mimbres area has only intermittent streams that flow into the Rio Grande River, which has an unstable and mostly non-arable floodplain that was not suitable for irrigation with prehistoric techniques. Farmers in the eastern Mimbres area

had to rely on small patches of arable land on the terraces of drainages and along small washes. Yet the area had a substantial farming population, and studies of subsistence remains indicate that cultivated foods were equally important in the eastern Mimbres area and the Mimbres River Valley (Nelson and Diehl 1999). When we began paleoenvironmental studies in the relatively poor eastern Mimbres area, we expected to find more evidence of environmental degradation than in the richer, more easily replenished Mimbres River Valley. Instead, we found the opposite: multiple lines of evidence, including studies of various kinds of plants and animals, revealed little and in many cases no evidence of a decline in resources in the eastern Mimbres area during the Mimbres Classic Period, much less any evidence of degradation (Nelson 1999, Hegmon et al. 2006, Schollmeyer 2009).

This apparent paradox led us to formulate an alternative hypothesis that focuses on cultural perceptions of the environment and other factors. Hegmon et al. (2006) suggested that the scarcer resources in the eastern Mimbres area might have prompted people to harvest them more carefully and possibly more sustainably. Furthermore, because the Mimbres River Valley was the location of many large and apparently important villages, it might have been an attractive place to live for social and cultural reasons, even in a situation of declining productivity. That is, people may have become more attached and attracted to the villages in the richer, more fully occupied Mimbres River Valley. This reasoning is not unlike geographers' notion of the gravity effect (larger areas draw more population) or of amenity economies (people move to Portland, Oregon or Boulder, Colorado despite the high cost of living and scarcity of jobs because of the other social and cultural advantages those cities offer [Travis 2007]).

The research we present here was originally designed to test this hypothesis. That is, if people choose to move to more attractive areas, and if attractiveness is based on both economic resources (in this case, arable and irrigable farmland) and public infrastructure (in this case, the larger more prominent sites in the Mimbres Valley), then they will continue to move, even when economic resources become depleted, resulting in further depletion. However, we found that resource depletion and, possibly, associated degradation could develop even in the absence of social drivers.

**Fig. 1.** The Mimbres region. Turquoise and magenta rectangles indicate the Mimbres Valley and eastern Mimbres area, respectively.



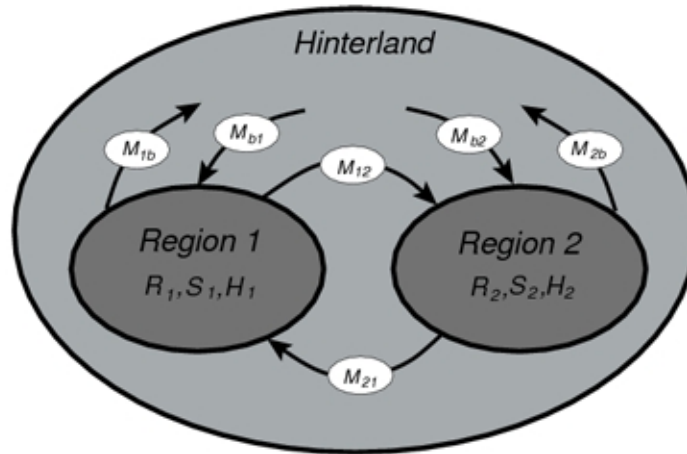
In order to evaluate this hypothesis and investigate the various other ideas that emerged, we developed a stylized model of the Mimbres region that includes an ecologically richer area and a poorer area surrounded by a large hinterland. Actors in the model move among the three areas based on their perceptions of resource productivity potential and socio-cultural factors in those areas. We then used the model to consider the effects of three factors: (1) resource regeneration rate, (2) resource density in relation to harvestability, and (3) social and cultural attractors.

## THE MODEL

We use a simple bioeconomic model to capture the relationships among resource regeneration rate, resource density in relation to harvestability,

cultural attractors, and human migration. Spatial structure was captured using a two-patch metapopulation model to represent natural resource and human population dynamics in the two key regions: the Mimbres Valley (MV) and the eastern Mimbres area (EM). In each patch, we capture three critical elements that influence decisions about resource use and movement: resource availability, population size, and social infrastructure. In reality, the two patches are embedded in a large “hinterland”. The hinterland consists of a very large (relative to the other regions) region that is productive but has much sparser vegetation cover than either the MV or EM (compare hills to valleys in Fig. 1). The archaeological record suggests that this hinterland region was sparsely, and likely intermittently, populated (see discussion of a similar process by Upham [1984]); however, the hinterland becomes important during climate shocks.

**Fig. 2.** Schematic of the two patch model.



At each location there is a density-dependent renewable resource biomass that can be harvested. In reality, agents would have been harvesting resources both through cultivation and hunting and gathering in all three regions. However, we abstract away from this distinction in the model and consider harvesting of a single aggregate resource. We refer to the two patches with subscripts 1 and 2 and to the hinterland with subscript “b” (background). Thus, the renewable resource density is defined as  $R_i$ ,  $i = 1, 2, b$  (see Fig. 2). The simplest formulation for the renewable resource harvesting problem is shown in Eqs. 1, 2, and 3:

$$dR_1/dt = F_1(R_1) - C_1H_1 \quad (1)$$

$$dR_2/dt = F_2(R_2) - C_2H_2 \quad (2)$$

$$dR_b/dt = F_b(R_b) - C_bH_b \quad (3)$$

where  $F_i(R_i)$  describes the regeneration rate,  $C_i$  is the per capita resource consumption, and  $H_i$  is the human population density in the  $i^{\text{th}}$  region, respectively. Note that in the case of agriculture, the renewable resource being harvested is soil fertility. The simplest, biologically meaningful representation for  $F_i(R_i)$  is the logistic, i.e.,  $F_i(R_i) = g_iR_i(1 - R_i/K_i)$  where  $g_i$  is the intrinsic growth rate and  $K_i$  is the carrying capacity. For convenience, we chose  $K_i = 100$  for all  $i$ , which is equivalent to measuring  $R_i$  as percentage of the biomass at carrying capacity; that is, if there is no harvesting,  $R_i \rightarrow 100$  as the  $t \rightarrow \infty$ . We assume that the total rate of resource extraction is proportional to population and resource densities and that per capita consumption,  $C_i$ , satisfies  $C_i =$

$q_iR_i$ , where  $q_i$  is a measure of the productivity of labor in resource extraction ( $1/q_i$ , perhaps more meaningfully, is a measure of how difficult the resource is to extract).

The second major component of the model is the relationship between migration patterns and the resource dynamics defined above. In the case of the prehistoric Mimbres, of course, we do not have data regarding what factors may have motivated migration decisions. However, it is important to note that we are not focused on a detailed study of the determinants of migration but rather on the consequences of migration. Thus, we rely on general principles derived from studies of historic and contemporary migrations and apply them to the Mimbres case. We recognize the dangers in doing so but believe that the principles upon which our model of migration is based are sufficiently general and fundamental as to be broadly applicable to human populations.

The literature on human migration is very extensive and often focuses on very specific cases that are driven by data availability (e.g., Walsh 1974, Massey et al. 1994, Constant and Massey 2003). However, in a review of studies of contemporary human migration, Greenwood (1985) highlights two key features of migration decisions: (1) differential characteristics of sending and receiving regions related to employment potential and amenities, and (2) life cycle considerations. In an influential and widely used approach to the study of

human migration based on a neoclassical economics perspective (Massey 1990), the first feature is framed in terms of rational self-interested agents migrating when total benefits are greater than the costs of migration, subject to information constraints (Massey et al. 1993, 1994, Constant and Massey 2003). Benefits include those that are pecuniary (better resource harvesting potential in our case) and cultural (perceptions of social resources in our case), while costs include the direct costs of moving (effort in our case) and psychic costs (attachment to place) (Constant and Massey 2003). Life cycle considerations are a more recent development in migration studies that emphasize the fact that migration decisions are made not by individuals but by larger groups, such as families (Massey et al. 1993), and that the life stage of individuals is important. For example, migration propensities tend to peak in the early to mid-twenties when people are less attached to place and have lower transaction costs, and taper off sharply with age when the opposite is true (Greenwood 1985).

We incorporated these general features of migration decisions into the model by supposing that the average propensity to migrate from region  $j$  to region  $i$  depends on the difference in utilities of consumption between the two regions,  $d_{ij} = U(C_i) - U(C_j)$  according to a function like that shown in Fig. 3. The simple economic rationale for migrating is captured by the fact that the propensity to migrate is small when  $d_{ij}$  is small or negative and increases when  $d_{ij}$  becomes positive and large. The fact that the propensity to migrate first increases slowly as  $d_{ij}$  increases, then rapidly as a threshold is approached, reflects the fact that psychic and real costs of migration must be overcome for migration to occur. Increasing these costs shifts the curve further to the right, as illustrated in Fig. 3 (compare dashed and solid curves). The steepness of the threshold relates to the distribution of the migration cost thresholds across the population and information constraints (compare solid and dotted curves in Fig. 3). For a population of identical agents with perfect information, the threshold would be sharp (e.g., with the threshold located at 1, as for the solid curve in Fig. 3, there would be zero migration for  $d_{ij} \leq 1$ , positive migration for  $d_{ij} > 1$ ). For the solid and dashed examples in Fig. 3, there is still migration for  $d_{ij} \leq 1$  because some individuals have lower thresholds. Finally, some individuals choose to migrate even when  $d_{ij} \leq 0$ , reflecting the fact that they may have imperfect information regarding  $d_{ij}$ . We can control these different features

and explore their impact on the model through varying model parameters as discussed below.

The functional form for the curves shown in Fig. 3 is expressed in Eq. 4:

$$f(d_{ij}, a_m, b_m) = 0.5 + \arctan(a_m(d_{ij} - b_m))/\pi \quad (4)$$

The location and sharpness of the threshold is controlled by the parameters  $a_m$  and  $b_m$ , respectively. Given that  $f(d_{ij}, a_m, b_m)$  lies in the interval  $[0, 1]$  for  $d_{ij} > 0$ , it represents the proportion of the population that will migrate from  $j$  to  $i$  for a given value of  $d_{ij}$ . Thus, if we define migration rates from location  $i$  to location  $j$  by  $M_{ij}$ , as depicted in Fig. 2(A), we have that  $M_{ij} = f(d_{ij}, a_m, b_m)H_i$ . Finally, we assumed that there is endogenous population growth in each region at the per capita rate of  $r_g g(C_i, a_g, b_g)$ , where  $r_g$  is the intrinsic growth rate, and  $g(C_i, a_g, b_g)$  is the consumption dependent growth rate in each region. Again, we assumed that  $g(C_i, a_g, b_g) = \arctan(a_g(C_i - b_g))/\pi$  (see Fig. 3, right-hand y-scale). When  $C_i$  exceeds some minimum nutritional requirement,  $b_g$ , population growth is positive, otherwise it is negative. The parameter  $a_g$  measures how fast the reproduction rate responds to increasing consumption. The population dynamics in the three regions can now be written as shown in Eqs. 5, 6, and 7:

$$dH_1/dt = r_g g(C_1, a_g, b_g)H_1 + M_{21} + M_{b1} - M_{12} - M_{1b} \quad (5)$$

$$dH_2/dt = r_g g(C_2, a_g, b_g)H_2 + M_{12} + M_{b2} - M_{21} - M_{2b} \quad (6)$$

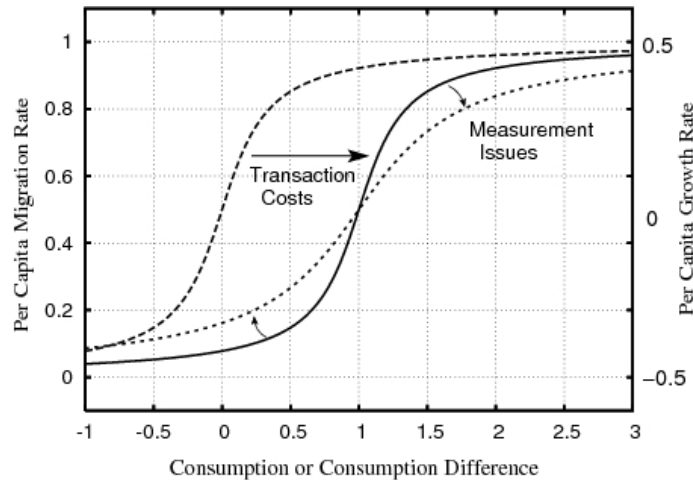
$$dH_b/dt = r_g g(C_b, a_g, b_g)H_b + M_{1b} + M_{2b} - M_{b1} - M_{b2} \quad (7)$$

Given definitions of the resource dynamics in Eqs. 1–3 and population dynamics in Eqs. 5–7, we can now turn to addressing our questions.

## ANALYSIS

The first step in our analysis is to identify the relationship between the parameters and the long-run values of the state variables. This is difficult in the case with migration. However, if we first treat the case with no migration, we can derive these relationships analytically and gain considerable

**Fig. 3.** Examples of the migration function (y-axis scale on left),  $f(x, a_m, b_m) = 0.5 + \arctan(a_m(x - b_m))/\pi$  and  $g(x, a_g, b_g) = \arctan(a_g(x - b_g))/\pi$  (y-axis scale on right) for different values of  $a_m$  and  $b_m$ . The parameters  $a_m$  and  $a_g$  control the steepness of the function, i.e., how well agents can measure and assess differences in consumption possibilities or how rapidly population growth increases with higher food intake, respectively. The parameters  $b_m$  and  $b_g$  shift the functions horizontally. Shifting the function to the right could represent increasing transaction costs to migrate or a higher nutritional threshold before population growth becomes positive.



insight. We can then compare the no migration case to the case with migration (for which we can obtain only numerical results). As shown in the appendix, if we assume no migration ( $b_m$  is extremely large), then Eqs. 5–7 imply that

$$C_1 = C_2 = C_b = b_g \quad (8)$$

given that

$$C_i = q_i R_i \quad (9)$$

By definition, Eq. 8 implies that

$$q_i R_i = b_g \Leftrightarrow R_i = b_g / q_i \quad (10)$$

Substituting the expression for equilibrium consumption in Eq. 8 into Eqs. 5–7 allows the associated equilibrium population densities to be computed, as shown in Eq. 11 (see Appendix):

$$H_i = g_i / q_i (1 - b_g / q_i K_i) \quad (11)$$

Based on Eqs. 8 and 11, we can make several observations. First, for positive populations, Eq. 11 implies that  $b_g < q_i K_i$ , which simply means that the maximum possible sustainable harvest rate must be

larger than the break-even harvest rate or the resource is not productive enough to support a population. If this condition is met, three facts follow. First, Eq. 10 implies that human population dynamics will drive resources to  $b_g / q_i$ , at which time population growth is zero. Second, Eq. 11 demonstrates that equilibrium population increases as  $g_i$  increases. Third, equilibrium population increases as  $q_i$  increases in the interval  $b_g / K_i < q_i \leq 2b_g / K_i$  and decreases for  $q_i > 2b_g / K_i$ . The first observation is obvious: the more productive the resource (in terms of its regenerative capacity — i.e., higher  $g_i$ ), the larger population it can support. The latter illustrates the feedback between population and resources. In the range where resources are relatively difficult to harvest ( $b_g / K_i < q_i \leq 2b_g / K_i$ ), making them easier to harvest increases harvest rates, and increases equilibrium population size. However, if resources become too easy to harvest, ( $q_i > 2b_g / K_i$ ), a population can easily deplete the resource stock. Thus, the long-run equilibrium resource level is lower, and as a result, so is the equilibrium population level. This trade-off provides one possible mechanism by which a more “fragile” ecology with less regenerative capacity could remain in better condition than what appears

to be a more robust ecology. It helps us understand the connection between resource depletion and associated degradation in the richer MV in contrast to the lack of depletion or degradation in the ecologically less productive EM. Specifically, if the condition  $g_1 > g_2$  and  $q_1 > q_2$  holds, then it could easily be the case that Region 1 has a higher population with more severe resource depletion than Region 2, even though it has a higher regenerative capacity. We illustrate a specific example when we explore the role of migration.

In order to explore the role of migration numerically, we must select default parameters. Note that because we are free to choose the units of measurement, the absolute values of the parameters are arbitrary, and only their relative values are important determinants of model dynamics. This general property of mathematical models is especially useful when detailed data are scarce, as is typically the case in archaeological studies. However, the archaeological data can provide rough estimates of relative parameter values, as described below. In our analysis, we explore a wide range of parameter values to illustrate their impact on our results.

In the analysis, we associate Region 1 with the MV and Region 2 with the EM. Based on the ecology of the regions, the resources in Region 1 regenerate roughly 3–5 times faster than in Region 2 and an order of magnitude faster than in the background region (Table 1). In the case of the Mimbres, Regions 1 and 2 cover roughly the same area, and Region b is much larger (10 times, at least—i.e., the size of the present-day state of New Mexico [see Fig. 1 for a sense of scale]). The key impact of scale and density of vegetation in the model is through  $q_i$ , which represents the amount of resources harvested per unit effort (e.g., person-day) per year. For one thing, in a sparser environment, the travel distance between resource encounters is higher, so resource extraction per unit time is lower. This fact is clear in Fig. 1: the valley floors are covered with more dense vegetation in contrast to the dry grass on the hillsides, and the valley floor arable land is more abundant and less patchy than in the upland. These simple considerations allow us to set the default parameters for the model, as shown in Table 1. Note that  $g_1 > g_2 > g_b$  and  $q_1 > q_2 > q_b$ .

To illustrate the impact of migration, we first compare the equilibrium state with and without

migration. For the parameter set in Table 1, the long-run steady state of the system is shown for various cases in Table 2. Note that with no migration, Region 2 is in considerably better condition in terms of biomass, and supports a little more than a quarter of the population of Region 1. Also note that the population in the hinterland region is zero because the condition  $b_g < q_i K_i$  is not met—that is, maximum harvest is below the minimum required for population growth. This choice of parameters generates the situation described above in which even though Region 1 has a higher resource regeneration rate (i.e., is more productive), resource biomass is lower than in the region with a lower resource regeneration rate. When agents are allowed to migrate based on resource consumption opportunities, the long-run state of the system is shown in the third row of Table 2.

Compared to the case with no migration, we see that migration can reduce pressure (i.e., reduce the population and increase the resource stock) on the most productive region (1) and has the opposite effect on the other regions (third row, Table 2). This is somewhat counter intuitive, but it makes sense after reflecting on the shape of the migration curve in Fig. 3. Specifically, the larger the values of  $a_m$  (ability to measure differences accurately) and  $b_m$  (transaction costs or attachment to place), the less impact migration has; that is, equilibrium values approach those for the no migration case (see dashed curves in Fig. 4). On the other hand, the lower these values, the more impact migration has. Thus, if agents make errors in assessing conditions between regions and face low transaction costs in moving, migration rates increase. The net direction of migration is related to the overall numbers of individuals making such mistakes. In the most populous region (1), just by virtue of fact that more individuals are making migration decisions, there is a higher chance individuals will migrate, and this leads to net out-migration. This necessarily results in a lower population and higher resource stock than without migration (see Appendix). Likewise, the regions with lower populations are impacted in the opposite direction, with higher populations and lower resource biomass in equilibrium than without migration. Thus, proximity to a densely populated area can generate deleterious consequences for local resources due simply to migration based on (mis) perception of resource differences.



**Table 1.** Parameter definitions and default values.

Symbol(s)	Definition	Default value(s)
$g_i$	Resource regeneration rates	$g_1 = 1, g_2 = 0.33, g_b = 0.1$
$K_i$	Resource carrying capacities	$K_i = 100$ for all $i$
$q_i$	Resource harvestability	$q_1 = 0.1, q_2 = 0.07, q_b = 0.03$
$a_m$	Migration sensitivity to consumption	$a_m = 4$
$b_m$	Migration transaction cost threshold	$b_m = 1$
$a_g$	Population growth sensitivity to consumption	$a_g = 1$
$b_g$	Consumption threshold for positive population growth	$b_g = 5$
$r_g$	Intrinsic population growth rate	$r_g = 0.01$

These results depend, of course, on parameter values. Although the parameter choices in Table 1 are reasonable for the Mimbres case, it is important to explore the robustness of our results. In order to determine the sensitivity of the model to different parameter choices, we compute how the equilibrium state changes as parameters are varied. There are 14 parameters. As mentioned above, several simply set the units of measurement, e.g.,  $K_i$ , and the temporal scale, e.g.,  $r_g$ . The most important six parameters relate to key assumptions regarding migration decisions ( $a_m$  and  $b_m$ ), the relative productivity of the different regions ( $g_2$  versus  $g_1$ ), and resource harvestability ( $q_2$  versus  $q_1$ ). These parameters are the focus of our sensitivity analysis.

Fig. 4 shows the equilibrium resource biomass in Regions 1 and 2 as  $b_m$  varies between 0 and 100 for  $a_m = 4$  (solid) and  $a_m = 20$  (dashed). The figure illustrates that intermediate values of  $b_m$  generate considerable deviations from the case with no migration, while for extreme values, the deviation approaches zero. This highlights the fact that migration effects depend critically on perceptions. Given the biophysical characteristics of the system, the equilibrium consumption levels in the different regions are on the order of 1 to 5. Because Region 1 is most productive, the difference between it and the other regions is negative, so the agents will be sampling the migration curve to the left of zero where it is very low. Shifting the migration curve

to the right (increasing  $b_m$ ) has little effect on migration—it just reduces a small positive number further. However, there is still a tendency to migrate out due to mistakes. For Regions 2 and b, on the other hand, agents will perceive a positive difference between their regions and Region 1 and will sample the migration curve to the right of zero. If  $b_m$  is at the nominal value of 1, differences between consumption opportunities of 1 or 2 may generate high per capita migration rates (i.e., 0.5 or 0.9), while differences of -1 or -2 (as perceived by agents in Region 1) generate rates an order of magnitude smaller. Thus, increasing  $b_m$  has a dramatic downward effect on out-migration from Regions 2 and b and a very small effect on Region 1. Given this fact, when  $b_m$  is at the nominal value, out-migration from Regions 2 and b based on a correct assessment (in the sense that the difference is positive) of consumption differences counters the out-migration from Region 1 based on errors (out-migration even though the difference is negative). As  $b_m$  increases, this compensating out-migration from Regions 2 and b drops rapidly, and the net effect is an increase in the net out-migration from Region 1 into Regions 2 and b. This reduces pressure on resources in Region 1 (increasing portion of blue solid curve, Fig. 4) and increases pressure on resources in Region 2 (decreasing portion of solid red curve, Fig. 4). As  $b_m$  increases further, the tendency to migrate goes to zero for all regions, and the equilibrium system state approaches those for

**Table 2.** Summary of equilibrium population and resource densities with and without migration.

Region	Resource density			Population density			
	1	2	b	1	2	b	Total
No migration	50	71.4	100	5	1.35	0	6.35
Migration	51.6	65.5	97.3	4.85	1.62	0.09	6.56
Migration and cultural factors	49.3	90.9	98.7	5.07	0.43	0.04	5.54

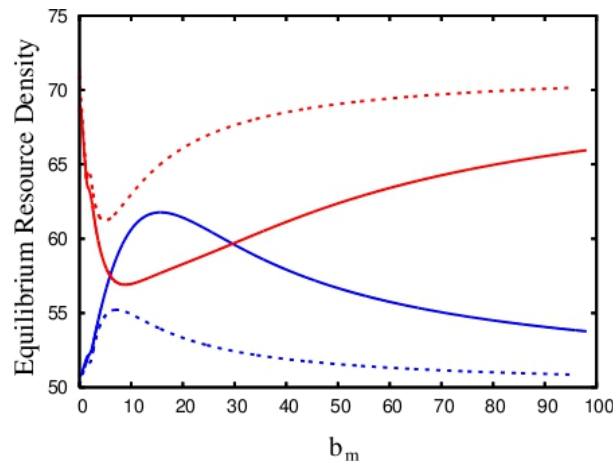
the case with no migration, obviously. As  $a_m$  increases (dashed curves), the values of  $b_m$  at which this effect drops off is reduced because there is a sharper transition in the migration function (agents make fewer mistakes). Imagine shifting the solid and dashed curves in Fig. 3 to the right and observing the intersection of these curves with the vertical line at a consumption difference of 1. The intersection point will drop faster (downward effect on out-migration) for the solid curve (larger  $a_m$ ). Finally, note that as  $b_m$  decreases to zero (no transaction costs) and  $a_m$  increases, the equilibrium resource densities again approach those for the case without migration (intersection point of dashed curves with the y-axis, Fig. 3). This is consistent with the concept of “ideal free distribution”. If organisms have perfect information about resource availabilities in different patches and face no transaction costs, resource consumption opportunities will be equalized across patches and migration will cease.

Fig. 5(A) shows how equilibrium resource density changes as  $g_2$  is varied while all other parameters are held constant with (dashed) and without (solid) migration. Fig. 5(B) is the equivalent for human population density. Figure 5(B) makes it clear that migration has very little impact on the relationship between population densities and regeneration rate. Put another way, changing characteristics of one patch does not strongly affect other patches, even though they are linked through migration; local processes are the strongest drivers of population and resource dynamics in equilibrium. However, for the reasons discussed above, Fig. 5(A) shows that migration can have considerable effects on the way local characteristics affect local equilibrium resource abundance (the difference between the

solid red and dashed red lines becomes large as  $g_2$  decreases). Fig. 5(C) and Fig. 5(D) summarize a similar analysis for  $q_2$  and confirms that this is true for  $q_2$  as well. Note that for the parameter choices in Table 1, the analytical results imply that the population in Region 2 will be 0 for  $q_2 < 0.05$ , will increase for  $0.05 < q_2 < 0.1$ , and will decrease for  $q_2 > 0.1$ . The population density (red) curve in Fig. 5(D) conforms to these analytical results, but migration induces spillover from Region 1, which shifts the analytical results to the left; that is, there is positive population in Region 2 when  $q_2$  is less than 0.05 and the population density begins to decrease when  $q_2$  is around 0.09 rather than 0.1.

The information contained in Figs. 4 and 5 constitutes a comprehensive analysis of model equilibrium behavior for a wide range of reasonable parameter values. This information, along with our analytical results, helps identify conditions under which we might expect a more productive landscape to be more depleted in the long run than a less productive one, even in the absence of social factors (which might exacerbate this situation if the more productive landscape becomes the site of desirable public infrastructure). The analysis also suggests that migration, somewhat counter-intuitively, does not amplify or exacerbate this situation, but rather, serves to dampen it. However, this assumes that the system is in long-run equilibrium and that agents are making decisions based purely on resource availability. This sets the foundation for the remaining two foci of our analysis: the effect of migration on the system when it experiences shocks, and the effect of social and cultural factors that may drive migration decisions.

**Fig. 4.** Equilibrium resource densities as a function of  $b_m$  in Regions 1 (blue) and 2 (red) for  $a_m = 4$  (solid) and  $a_m = 20$  (dashed).



Before turning our attention to these questions, it is important to make a distinction between “resource depletion” and “resource or environmental degradation”. Most bioeconomic models like the one presented here focus on resource exploitation and often refer to “resource depletion”, which is often used synonymously with “resource overexploitation”. The resource is typically a stock such as a fish population or a forest stand, and exploitation equates to removing a portion of this stock. Typically, as is the case with the logistic growth model used here, regeneration depends on the standing stock size. Thus, overexploitation or depletion refers to a case where the stock size has been driven below the level that produces the maximum flow of biomass (Maximum Sustainable Yield in fisheries). Depending on the resource dynamics, depletion may or may not lead to degradation, which typically implies a very long lasting or permanent reduction in the productivity of the resource system. In the case of a resource that behaves logistically, in which exploitation affects only the stock size, degradation is not possible because there is no permanent loss in productive potential (unless the stock is driven to extinction). In order to introduce the possibility of degradation (at positive stock levels), we must assume that exploitation either directly affects the structure of the system (e.g., physical damage caused by fishing gear in coral reefs, changes in physical soil structure from cultivation) or that there is a feedback between stock size and system structure (e.g., changing trophic structure induced by harvesting of target

species). In this case, depletion can lead to degradation. Thus far, we have discussed only depletion, but we consider the potential for degradation below.

### Robustness, resilience, and migration responses to climate shocks

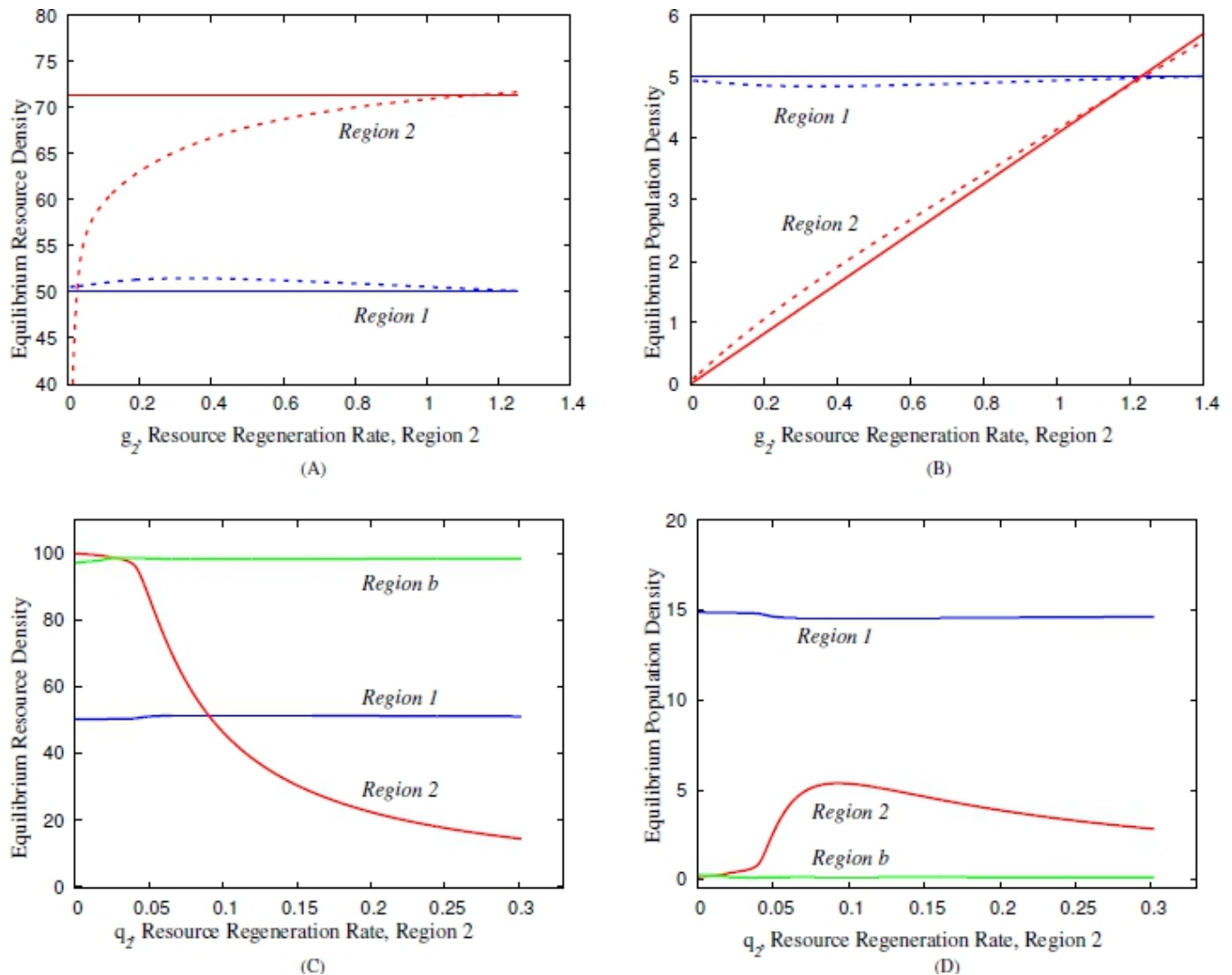
As illustrated above, the effect of migration based on assessment of differences in resource consumption potential on the equilibrium configuration of the system is relatively minor and is due mainly to misperception of these differences. We now turn to the question of the impact of migration on the system when it is out of equilibrium (e.g., following an exceptional drought event). We evaluate the impact of migration both in terms of robustness (low robustness = high vulnerability) and resilience. Robustness refers to the sensitivity of a particular desirable system output (human welfare in our case) in response to external variation (a climate shock in our case). Resilience, on the other hand, refers to the size of shock a system can sustain and still maintain its structure and function.

To include the possibility for a shock, we modify Eqs. 1–3 to read as

$$dR_i/dt = F_i(R_i) - C_i H_i - \sigma_i s(t) R_i \quad (12)$$

where  $i = 1, 2$ ,  $b$ ,  $s(t)$  is the stress profile (top, Fig. 6), and  $\sigma_i$  is the stress factor for region  $i$ . Thus, stress

**Fig. 5.** (A): Equilibrium resource density in Regions 1 and 2 (blue and red lines, respectively) as a function of  $g_2$  with and without migration (dashed and solid lines, respectively), with all other parameters held constant. (B): Equilibrium human population density as a function of  $g_2$ , with all other parameters held constant (same color and line type interpretation as in A). (C)–(D): Equilibrium resource and population density, respectively, in Regions 1 (blue), 2 (red), and b (green) as a function of  $q_2$  with migration.

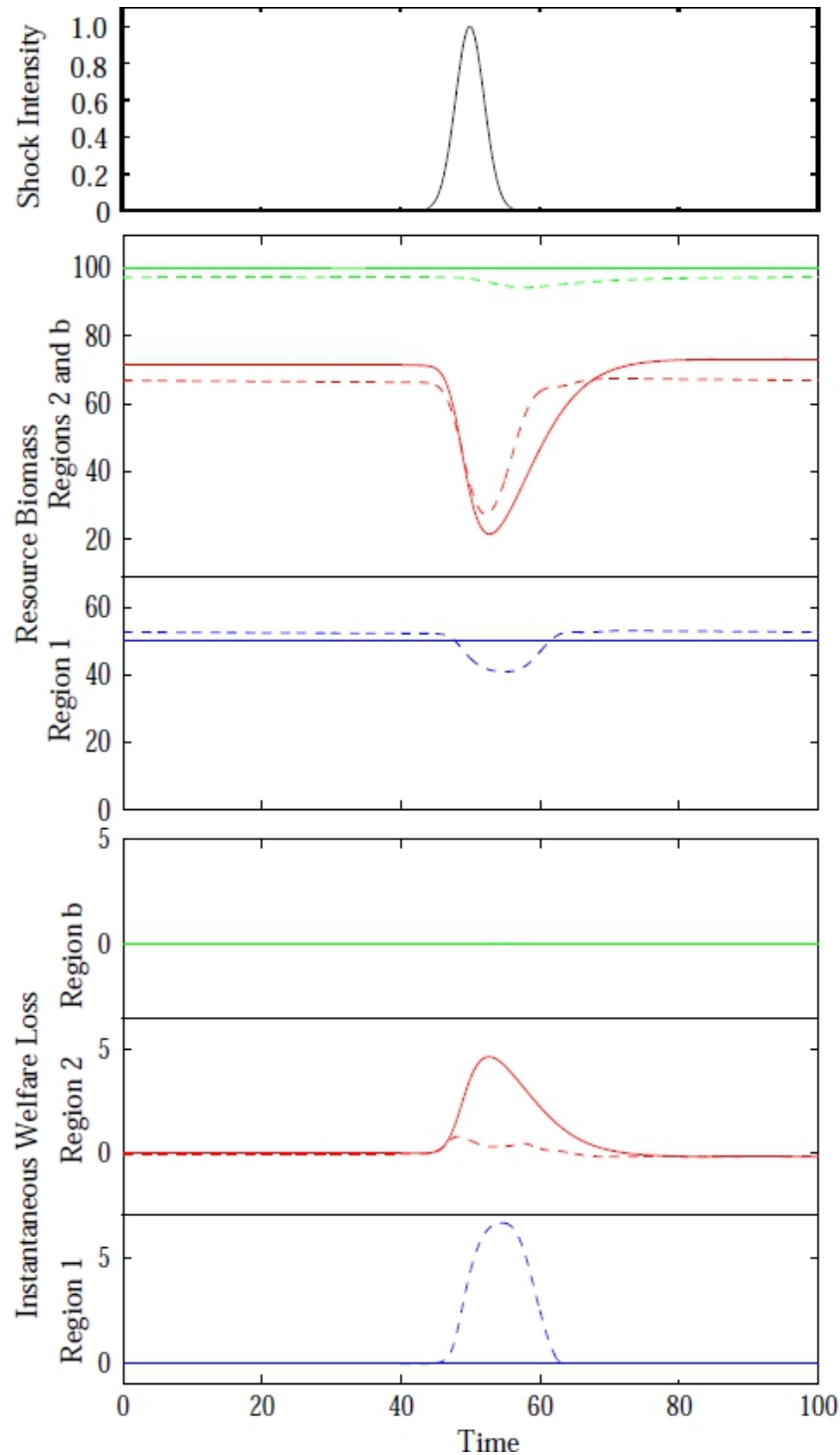


reduces biomass proportionately. The parameter  $\sigma_i$  allows us to control the impact of stress in different regions. For example,  $\sigma_1 = 0, \sigma_2 = 0.4, \sigma_b = 0$  means the stress (intense drought of relatively short duration) event impacts only Region 2, and only up to a maximum of 40% rate of reduction in biomass. In the numerical experiments that follow, the following four scenarios were studied: (1)  $\sigma_1 = 0,$

$\sigma_2 = 0.4, \sigma_b = 0,$  (2)  $\sigma_1 = 0.4, \sigma_2 = 0, \sigma_b = 0,$  (3)  $\sigma_1 = 0.4, \sigma_2 = 0.4, \sigma_b = 0,$  and (4)  $\sigma_1 = 0.4, \sigma_2 = 0.4, \sigma_b = 0.4.$

Fig. 6 illustrates the impact of migration after a shock in Region 2 on resources (top) and welfare loss (bottom). The dashed and solid curves show the

**Fig. 6.** Resource density (center) and welfare loss (bottom) as a function of time after a high-frequency weather variation (top) that reduces resource densities in Region 2. Solid lines show the case without migration, dashed with migration. Colors correspond to those in Fig. 5. Note that there are multiple scales on the y-axis.



time responses with and without migration. Without migration, Regions 1 and b are unaffected. With migration, all regions are affected, and it is clear that the impact of the shock on Region 2 is reduced via migration. Obviously, the impact on the other two regions is increased. Does migration increase the robustness of the system in terms of reduced sensitivity of the maximum welfare loss during a climate shock? The instantaneous welfare losses shown in Fig. 6 are computed using the expression in Eq. 13 for each of the three regions:

$$(C_i^{eq} - C_i)H_i \quad (13)$$

This is a measure of how far consumption has fallen below its equilibrium value weighted by the number of people who must suffer the loss. From the dashed lines in Fig. 6 it is clear that the welfare loss is moved from Region 1 to Region 2 (solid red hump is flattened and dashed blue hump appears). However, has the net sensitivity of welfare in the system been reduced overall?

Consideration of per capita consumption suggests that such a reduction did occur. Note that the per capita consumption shown in Fig. 7 (top) in Region 1 falls much less due to migration than it would have fallen in Region 2 without migration. That is, with migration, a larger number of people suffer a slight reduction in consumption, while without migration, fewer people suffer a much greater reduction. Fig. 7 (bottom) shows the net effect of this trade-off (the sum of the area under the curves in Figure 6 [bottom]) up to time  $t$ , i.e., if

$$W_i(t) = \int_0^t (C_1^{eq} - C_1(\tau))H_1(\tau) + (C_2^{eq} - C_2(\tau))H_2(\tau) + (C_b^{eq} - C_b(\tau))H_b(\tau)d\tau \quad (14)$$

Fig. 7 (bottom) shows  $W_i(t)$  versus  $t$ .

Again, the cases with and without migration are shown with dashed and solid curves, respectively. From this figure, it is clear that migration leads to a cumulative loss of welfare. However, this is due to the fact that in the model welfare is directly proportional to consumption. In reality, the relationship is nonlinear. That is, a drop in per capita consumption from 5 to 4 in Region 1 in the case with migration would not induce nearly as much suffering as would a drop from 5 to 1.5 in Region 2 without migration. Under this assumption, the dashed curve in Fig. 6 (bottom) would fall below the solid one; that is, migration would reduce net

loss in welfare. In summary, migration can obviously increase the robustness (reduce vulnerability) of human welfare of individuals in Region 2 to shocks in Region 2. Further, it also can increase robustness of cumulative human welfare at the system scale to shocks in Region 2. This analysis highlights the subtle issue of the distribution of costs and benefits associated with present-day global environmental change challenges.

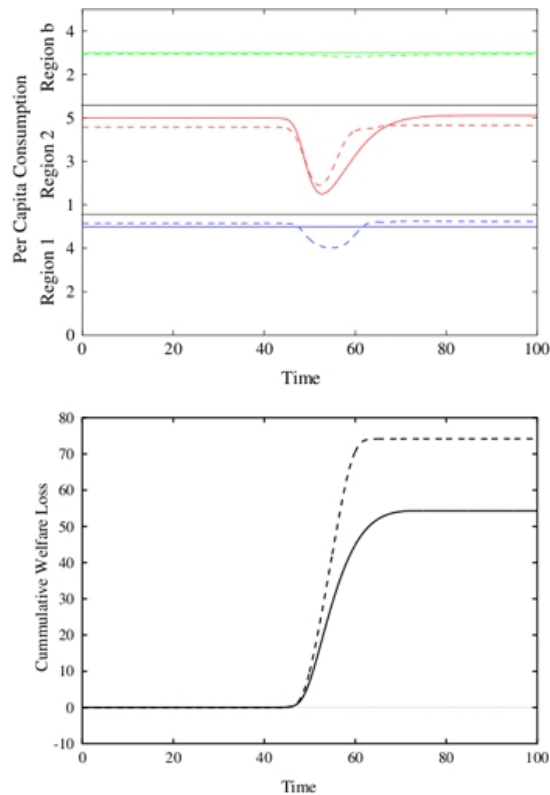
Now we consider issues of resilience. If a system does not exhibit multiple basins of attraction, the concept resilience does not add anything to the analysis above; that is, resilience and robustness (reduced sensitivity to shocks) are similar. The model as specified above does not exhibit multiple equilibria (although the real system may). The possibility of multiple equilibria in ecological systems can be generated by mutual interdependence of at least two systems. In our case, the interactions between two such systems would be between plants and soil communities. One example is the rangeland model developed by Anderies et al. (2002), in which plant growth depends upon below-ground processes. In our case, extending the model in this direction can be easily achieved by introducing a dependence of the intrinsic regeneration rate on plant biomass; that is, the health of the soil community and with it, soil fertility depends on processes related to plant biomass (see Anderies et al. [2002] for details). Mathematically, we would replace the parameter  $g_i$  with a state variable  $g_i(t)$ , whose dynamics evolve according to Eq. 15:

$$dg_i/dt = G_i(g_i, R_i) \quad (15)$$

where  $G_i(g_i, R_i)$  describes the dependency between  $g_i$  and  $R_i$ . Because such dynamics are well understood (see Carpenter et al. [1999] or Anderies et al. [2002]), it is not necessary to explicitly introduce this additional level of mathematical complexity here other than to note that it can generate a threshold biomass level below which the system cannot recover (i.e., can become permanently degraded). Put another way, in this case depletion can lead to degradation. For our purposes, it is sufficient to simply consider the model under the assumption that such a threshold exists (which would be implicit in the mathematics, regardless).

Suppose such a threshold existed at  $R_2 = 25$ . Without migration, the climate shock would push the system across the boundary (minimum  $R_2 = 21.55$ ), while

**Fig. 7.** Per capita consumption (top) and cumulative welfare loss (bottom) as a function of time after a high-frequency weather variation (shock) that reduces resource densities in Region 2. Solid lines show the case without migration, dashed with migration. Note that there may be multiple scales on the y-axis.



with migration, this boundary would not be crossed (minimum  $R_2 = 27.2$ ). Thus, migration allows the system to absorb the same shock yet not move into a new basin of attraction (i.e., it does not become degraded as long as the thresholds for Region 1 and the hinterland are below 40.3 and 93.9, respectively). Thus, migration can increase the resilience of the system to climate shocks. Note, because the equilibrium resource level in Region 2 is lower with than without migration, if the threshold were high, migration might reduce the resilience of the system. For the shock in the example, migration will increase the resilience of the system as long as the critical threshold is below 55 in Region 2. An extensive analysis of the model could generate relationships between shock types and maximum critical threshold values for which migration increases resilience. Such an analysis is beyond the scope of this paper. We make a final comment concerning our assumptions about migration. If  $b_m$

$= 0$  (zero transaction costs), and  $a_m = 40$  (agents assess resource differences very accurately), migration may increase the resilience of the system even further. In this case, the minimum value of  $R_2$  reached during the shock is 30.9. Interestingly, agents do not make mistakes and migrate to the hinterland; they instead go to Region 1 and put more pressure on resources there. Thus, the threshold for Region 1 must be less than 38.5 (as compared to 40.3) for migration to increase the resilience of the overall system in this case.

A similar analysis was conducted for each of the cases above, as summarized in Table 3. When a shock hits Region 1, the same general principles just discussed apply. However, because Region 2 is less heavily exploited in equilibrium, it can absorb more temporary population influx than can Region 1. In this case, migration significantly reduces welfare losses in Region 1 with only moderate impacts on

Region 2 and negligible impacts on Region b. Unlike the case above, not only are the impacts of the shock distributed, overall welfare losses are significantly reduced by migration (from 94.3 to 63.3). This makes sense: Regions 2 and b serve as buffers for the most densely populated area. This makes it clear that whether migration increases robustness and resilience depends on where the shock occurs.

The data also suggest that interactions between scales are important in determining whether migration can increase the robustness of the system. As discussed above, when there is a shock only in Region 2, migration drastically reduces per capita welfare losses in Region 2 from 41.6 to 21.2 while increasing them in Region 1 from 0 to 11.6. Region b is only mildly affected because things never get bad enough for it to become very attractive for migration. However, migration increases the net welfare loss from 54.3 to 74.7 at the system scale. This net welfare loss, when spread across the entire population, is mild and is a reasonable trade-off against severe losses at the scale of Region 2. The case for a shock in Region 1 is similar.

Compare these to the case when there is a shock in both Regions 1 and 2. In this case, conditions in Regions 1 and 2 become bad enough to induce migration to Region b. Migration, again, dramatically reduces per capita welfare losses in Region 2 (from 41.6 to 25.2), and only mildly increases welfare losses in Regions 1 and b (from 19.2 to 21.2 in Region 1 and from 3.5 to 7.8 in Region b). Here, the role of the hinterland is critical. Although it regenerates slowly, it is a large store of resources (because it is very sparsely occupied most of the time) that can be temporarily exploited for a short time during infrequent shocks. Because there are so few people there, aggregate welfare is not reduced significantly. As a result, unlike the case with a shock only in Region 2, aggregate welfare loss is reduced (from 148.6 to 120.4) for the system as a whole. Likewise, the resilience of the system is likely increased. The minimum biomass reached during the shock is slightly higher with migration than without except in Region b (which reaches 80.1 with migration as compared to 100 without). Unless Region b is very fragile with a critical minimum biomass threshold above 80, the overall resilience of the system is increased slightly by migration. Given that it is conditioned for very harsh, dry conditions, it is likely that the flora in Region b would have a critical threshold well below 80.

Finally, note the outcomes when there is a shock in all regions. Here, the aggregate welfare loss increases with migration. Again, Region 2 is the beneficiary of migration, which reduces per capita welfare loss from 41.6 to 29.4. Region b is unaffected by migration. Because its resource base is reduced along with the other two regions, it never becomes attractive for migration. Note that the aggregate welfare loss in Region b is very small (4.9) versus the per capita loss (60.0) because the population is so low. As with the case when there is only a shock in Region 2, per capita welfare losses increase in Region 1 due to migration (from 19.2 to 26.7), but this increase is much less than the benefits to Region 2. Again, migration helps spread the impact of a shock over a larger population so that, overall, a significant number of individuals experience considerably lower welfare losses while others experience a minor increase in welfare losses. Resilience, on the other hand, suffers across the board; the minimum resource level in all regions is lower with migration than without.

In summary, several general themes emerge from the analysis. First, the intermediate patch (in terms of resource productivity—Region 2) benefits most from migration. Second, the scale of the shock is an important determinant of whether migration improves robustness and resilience of the system. For shocks at the smallest scale (Region 2 only), migration causes an overall welfare loss but likely increases resilience in the sense that the system is less likely to flip into an alternate domain of attraction. The alternate domain of attraction in this case is a completely degraded Region 2 with little or no population (i.e., one population center versus two). For shocks at the intermediate scale, the impact of migration is most pronounced. Migration significantly reduces welfare losses in Region 2 and for the system as a whole with negligible negative impacts in Regions 1 and b. Unless Region b is extremely fragile, migration increases the resilience of the system. For shocks at the largest scale, although migration still benefits Region 2 somewhat, at the system level there is a net welfare loss, and the resilience of the system is reduced. Taken together, these results suggest that migration increases robustness and resilience of the system to shocks at the intermediate scale but decreases robustness to shocks at the smallest and largest scales (in aggregate). We conclude the analysis by exploring how cultural factors impact these results.



**Table 3.** Summary of system response to shocks.  $R_m$  and  $C_m$  refer to the minimum resource and consumption levels reached during the shock, respectively.  $W_l$  refers to the cumulative welfare loss suffered during the shock in each region (per capita shown in parenthesis), and  $W_T$  shows the cumulative welfare loss for all three regions, i.e., the quantity defined by Equation 14. NM = no migration, WM = with migration, WM&C = with migration and cultural (social) factors.

Shock scenarios	Region 1			Region 2			Region b			Total
	$R_m$	$C_m$	$W_l$	$R_m$	$C_m$	$W_l$	$R_m$	$C_m$	$W_l$	$W_T$
1–NM	23.4	2.34	94.3(19.2)	71.4	5	0(0)	100	3	0(0)	94.3
1–WM	33.4	3.34	45.6(12.1)	47.0	3.29	17.5(7.9)	93.9	2.82	0.21(1.32)	63.3
1–WM&C	32	3.2	144.0(31.5)	64.8	4.54	0.04(0.03)	98.3	2.95	0(0)	144.1
2–NM	50	5	0(0)	21.6	1.51	54.3(41.6)	100	3	0(0)	54.3
2–WM	40.3	4.03	66.9(11.6)	27.2	2	7.6(21.2)	93.9	2.82	0.24(1.5)	74.7
2–WM&C	46.7	4.67	19.3(3.65)	33.9	2.37	5.2(38.2)	98.1	2.94	0.02(0.3)	24.5
1,2–NM	23.5	2.35	94.3(19.2)	21.6	1.51	54.3(41.6)	100	3	0(0)	148.6
1,2–WM	25.8	2.58	100.9(21.2)	22.7	1.59	16.0(25.2)	80.1	2.40	3.5(7.8)	120.4
1,2–WM&C	23.6	2.36	95.4(19.4)	31.9	2.23	10.3(40.4)	94.8	2.84	0.2(1.7)	105.9
All–NM	23.5	2.35	94.3(19.2)	21.6	1.51	54.3(41.6)	20.2	0.61	0.1(60.8)	148.7
All–WM	23.3	2.33	140.9(26.7)	20.5	1.44	29.2(29.4)	19.35	0.58	4.9(60.0)	175.0
All–WM&C	23.0	2.3	105.0(20.8)	31.4	2.2	12.6(41.2)	19.9	0.6	2.3(60.4)	119.9

### Cultural factors and migration decisions

Recall that in the analysis so far, migration decisions are based on perceived differences in utility between patches  $i$  and  $j$ ,  $d_{ij}$ , given by  $d_{ij} = U(C_i) - U(C_j)$ . We have assumed so far that  $U(C_i) = C_i$ . Including cultural factors in migration decisions entails extending our utility model so that  $U = U(C_i, S_i)$ , where the variable  $S_i$  is some measure of such factors. The simplest possibility is to assume  $U(C_i, S_i) = C_i S_i$ . Obviously,  $S_i$  would depend on levels of investment in public infrastructure, and is thus a dynamic variable. However, in small-scale societies, sense of place is often quite strong, which suggests that it is reasonable to represent  $S_i$  as a fixed

parameter, meaning that each location has a fixed social attractiveness. If we assume that  $S_1 > 1$  and  $S_2 = S_b = 1$ , we have the Mimbres situation. The larger  $S_1$ , the greater the cultural drawing power of the MV.

First, we consider equilibrium conditions. Interestingly, migration based on such a social premium attached to the most productive region has the opposite effect of migration based purely on resource consumption potential. As  $S_1$  increases from 1 to approximately 1.5, the equilibrium resource density in Region 2 increases monotonically from around 66 to 91, while equilibrium population density drops from 1.62 to

0.43. Equilibrium population and resource densities in Region 1 remain virtually unchanged compared to the case with no migration. Per capita resource consumption in Region 2 increases from 4.6 to 6.36, while in Region 1 it drops from 5.15 to 4.93. Aggregate population drops from 6.56 to 5.54. Taken together, these results suggest that cultural factors can set up a source-sink population dynamic with Region 2 as the source. Namely, such factors significantly reduce equilibrium populations in the more fragile region, even though resource consumption potential is very high. People in that region lead a good life in terms of resources, and have a positive reproduction rate (since  $C_2 > 5$ ). This surplus population, which is drawn to Region 1 by cultural factors, puts more pressure on resources there. However, density dependent factors prevent depletion of the resource base much below 50 (the equilibrium level with no migration), but the reproduction rate is negative (since  $C_1 < 5$ ) so that deaths exceed births and the population is held constant from in-migration from Region 2. Thus, life in Region 1 is slightly worse than in Region 2 in terms of resources but, at least in the situation modeled, its cultural appeal compensates. This abstract description mirrors the Mimbres situation quite well.

It turns out that the equilibrium conditions induced by cultural factors significantly increase robustness except when a shock occurs only in Region 1. In every other case, the welfare loss is lowest with migration based both on consumption possibilities and cultural factors. This is because the cultural draw of Region 1 lowers population density and resource stress in Regions 2 and 3. Density dependent factors limit population growth in Region 1 (i.e., population growth rates are suppressed), so even though people are drawn to it for cultural reasons, the population does not increase significantly compared to the case without migration. Thus, culturally induced migration reduces population at the system level, and in so doing, enables the system to better cope with shocks than without migration. In the case where a shock occurs only in Region 1, cultural factors decrease robustness for two reasons. The first is related to the fact that utility is modeled as a product of consumption and social considerations. As such, increasing the importance of social factors will amplify the impact of losses in consumption; that is, people used to a high quality of life in an attractive location may be less able to cope with hardship than those living in less attractive places and who are

accustomed to a harsher existence overall. The second reason relates to the fact that social factors tend to make people less willing to migrate during a shock. Notice in Table 3 that with social factors, Regions 2 and b are less impacted during the shock in Region 1 than in the case with only migration. However, this effect is small; the minimum resource density and consumption levels are only slightly below the case with migration only.

## CONCLUSIONS

We developed a model that allowed us to investigate, conceptually, a landscape in which there are two areas, one relatively richer (i.e., with more resources and a faster regeneration rate) than the other, and both are surrounded by a poorer hinterland. In the archaeologically known case that was the basis for this model, the richer Mimbres River Valley was considerably more degraded than the less rich eastern Mimbres area. Our initial assumption was that if people chose their location based on ecological factors alone, population would be distributed to match resource abundance in the patches, somewhat analogous to the ideal free distribution in ecology (Fretwell and Lucas Jr. 1969). In this case, populations in patches scale with resource availability, and resource abundance is equalized across patches. As such, there would be no reason to expect one patch to be more degraded than another patch, especially the more productive one. Our analysis explored possible reasons, both social and ecological, for the observed departure from this expectation in the Mimbres case.

Using the simple model, we derived conditions under which ecological factors can produce a situation in which patches with different resource productivity have different resource abundance in equilibrium; that is, one in which a more fragile area (slower resource regeneration rate) is less degraded (higher equilibrium resource biomass) than a less fragile area, as observed in the Mimbres case. The model suggests that at least two factors are needed: differences in regeneration rates and harvestability. In the case without migration, we derived the necessary condition:  $g_1 > g_2$  and  $q_1 > q_2$ . The key issue is how "resource abundance" is defined (often vague in definitions of the ideal free distribution). To be sensible, it must be defined as the net resource flow, which is the flow of resource biomass production (measured by  $g_i$ ) less the effort to harvest the resource (measured by  $q_i$ ). Thus, if in a more

productive patch the resource is easier to harvest, “resource abundance”, as measured by equilibrium biomass, can be lower than in the less productive patch. Such conditions are consistent with the resource characteristics in the MV and the EM, and could give rise to the situation observed in the Mimbres case, even without migration.

Next we explored the role of migration. First, we focused on migration based on ecological factors alone. We found that such migration has little effect on the long-run configuration of the system but generates additional welfare in the system overall. Thus, contrary to our expectation that social factors (i.e., more public infrastructure making the richer area even more attractive) would have to be invoked to create a situation in which the richer area was more depleted, we found that even without social factors, the richer area (MV) experienced more resource depletion than the less rich area (EM). Second, we explored the role cultural factors might play. We found that, in fact, cultural factors can also generate a situation in which a more fragile area is less degraded than a less fragile area, and will amplify differences in equilibrium resource density. Interestingly, the amplification occurs not through further degradation in Region 1 but reduced degradation in Region 2. Finally, we explored the capacity of migration to enable the system to recover from a shock. Depending on the scale and location of a particular shock, migration based on consumption possibilities alone can spread the impact of the shock and reduce welfare losses for the system as a whole, as we have shown for a shock in Region 1 alone or in Regions 1 and 2. Finally, because of the equilibrium situation induced by migration based on social factors, migration can increase the robustness of the system as a whole. Likewise, depending on the spatial distribution and level of potential thresholds of resource density, migration can increase the resilience of the system as well (measured in terms of the minimum resource density reached during a shock). One stark exception is the case when there is a shock in Region 1 only. The minimum resource density in Region 2 during the shock is reduced from 71.4 to 47.0 by consumption-based migration. Thus, the resilience of the system could be reduced to a specific pattern of shocks: a shock in Region 1 and then in Region 2.

These results have several implications for the questions we posed at the beginning of this article. First, migration can be viewed conceptually as a link among spatial and temporal scales. It may, in some

ways, solve a short-term local problem by distributing it across spatial and temporal scales but with larger scale or longer term consequences. The extent to which movement in space lessens or exacerbates the problem depends on the resource characteristics, particularly regeneration rates and harvestability and the nature of the shock, as detailed above. Second, social factors may have a role in exacerbating or mitigating resource degradation processes, but depletion and degradation can occur even in the absence of social factors. The model suggests that ecological factors set the absolute levels of degradation in the most productive patch, and social factors amplify differences between this patch and less productive patches. Thus, social factors that may have made the MV more attractive may have reduced pressure on the EM, allowing it to remain above the MV in terms of net resource productivity. As such, the social attractiveness of the MV could have protected the EM from further resource degradation, thereby increasing its resilience.

These conclusions have several general implications for future work in this area. Herein, we have focused primarily on robustness—the increase or decline in the quantity of available resources (equilibrium biomass) and welfare. Although we investigated the extent to which such depletion might constitute degradation (a switch into a condition in which the ability of the resource to continue to reproduce itself is compromised) by assuming the existence of a threshold, a more thorough investigation of how this occurs is warranted. The effects of public infrastructure depend strongly on where the infrastructure is located with respect to the distribution of resources on the landscape. Depending on this spatial relationship, it may exacerbate or possibly mitigate population resource imbalances and situations of resource decline. More careful treatment of public infrastructure is a very important area for future work. Finally, the effects of migration may be interpreted in terms of a robustness vulnerability trade-off. That is, migration, by mitigating a short-term local problem, creates robustness at one level by distributing it at a larger spatial and temporal scale. In our model, migration increased the ability of the system to absorb a high-frequency shock. However, this “solution” may also increase vulnerability in the long run by depressing resource densities and increasing overall population densities. Although the model presented here is not rich enough to rigorously explore trade-offs associated with

mobility strategies, it hints at their importance. Models such as this one, combined with empirical case studies, are a means of investigating trade-offs that are (relatively) satisfactory at a variety of spatial and temporal scales and could meaningfully contribute to modern sustainability debates.

Responses to this article can be read online at:  
<http://www.ecologyandsociety.org/vol16/iss2/art22/responses/>

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## Brief Mathematical Appendix

Here we derive the equilibrium conditions for the model system:

$$\frac{dR_1}{dt} = F_1(R_1) - C_1H_1 \quad (1)$$

$$\frac{dR_2}{dt} = F_2(R_2) - C_2H_2 \quad (2)$$

$$\frac{dR_b}{dt} = F_b(R_b) - C_bH_b \quad (3)$$

$$\frac{dH_1}{dt} = r_g g(C_1, a_g, b_g)H_1 + M_{21} + M_{b1} - M_{12} - M_{1b} \quad (4)$$

$$\frac{dH_2}{dt} = r_g g(C_2, a_g, b_g)H_2 + M_{12} + M_{b2} - M_{21} - M_{2b} \quad (5)$$

$$\frac{dH_b}{dt} = r_g g(C_b, a_g, b_g)H_b + M_{1b} + M_{2b} - M_{b1} - M_{b2}. \quad (6)$$

- **Equilibrium with no migration:**

No migration implies  $M_{ij} = 0 \forall ij$ , thus,

$$\frac{dH_i}{dt} = 0 \Rightarrow r_g g(C_i, a_g, b_g)H_i = 0. \quad (7)$$

Given that  $g(x, a_g, b_g) = \arctan(a_g(x - b_g))/\pi$ , we have

$$\arctan(a_g(C_i - b_g))/\pi = 0 \quad (8)$$

so that

$$(a_g(C_i - b_g))/\pi = \tan(0), \quad (9)$$

which, because  $\tan(0) = 0$ , implies that  $C_i = b_g$  in equilibrium. Note that  $C_i = q_i R_i$  by definition so we have

$$R_i = \frac{b_g}{q_i} \quad (10)$$

in equilibrium. The equilibrium population levels are determined by setting

$$\frac{dR_i}{dt} = F_i(R_i) - C_i H_i = 0 \quad (11)$$

thus

$$g_i R_i (1 - R_i/K_i) - C_i H_i = 0 \quad (12)$$

but since  $R_i = \frac{b_g}{q_i}$  and  $C_i = b_g$  we can solve for  $H_i$  thus

$$H_i = \frac{g_i}{q_i} \left( 1 - \frac{b_g}{q_i K_i} \right). \quad (13)$$

If we choose  $q_1 > q_2$ , Equation 10 implies that  $R_1 < R_2$ , i.e. region 1 will be more “degraded” in equilibrium, as measured by standing biomass. Then if we choose  $g_1 > g_2$ , we have constructed a case in which the more productive region (as measured in terms of regeneration

rate) is more degraded in equilibrium. All else being equal, Equation 13 implies that for a given choice of  $q_1$  and  $q_2$ ,  $g_1$  and  $g_2$  can be chosen so that the condition  $H_1 > H_2$  will hold in equilibrium. This exercise illustrates that it is possible to choose ecological conditions in which a more productive region can be more heavily populated and more degraded than a less productive one, independent of migration.

- **The effect of migration on the equilibrium state:** If we define the net migration *into* region  $i$  as

$$M_i = M_{ji} + M_{ki} - M_{ij} - M_{ik} \quad (14)$$

where  $j$  and  $k$  are indexes for the other two regions, then in equilibrium we have

$$\arctan(a_g(C_i - b_g))/\pi = -M_i \quad (15)$$

or

$$C_i - b_g = \frac{1}{a_g} \tan(-\pi M_i). \quad (16)$$

If net migration is out of region  $i$ , then  $M_i < 0$ , and  $\tan(-\pi M_i) > 0$ . This implies that  $C_i - b_g > 0$  or  $C_i > b_g$ . Recall that with no migration,  $C_i = b_g$  in equilibrium. Thus, since

$$R_i = \frac{C_i}{q_i} \quad (17)$$

in equilibrium, it is evident that because  $C_i$  is larger with net out-migration than with no migration,  $R_i$  will be as well. The same argument shows that with net in-migration,  $C_i < b_g$  and  $R_i$  will be lower than in the case with no migration. In summary, net out-migration (in equilibrium) increases equilibrium biomass and *vice versa*.