SOCIAL SCIENCE / ARCHAEOLOGY

The Model-Based Archaeology of Socionatural Systems

How should archaeologists and other social scientists tackle the big and little questions about change in socionatural systems? Although fieldwork is certainly the place to start, it alone is not enough to answer troublesome “how” or “why” questions. To make sense of what they find in the field, archaeologists build models—possible explanations for the data. This book is about new developments in applying dynamic models for understanding relatively small-scale human systems and the environments they inhabit and alter. Beginning with a complex systems approach, the authors develop a “model-based archaeology” that uses specific, generally quantitative models providing partial descriptions of socionatural systems that are then examined against those systems. Taken together, the chapters in this volume constitute an argument for a new way of thinking about how archaeology is (and should be) conducted.

Contributors

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Advance praise for *The Model-Based Archaeology of Socionatural Systems*

“This will be *the* book on the simulations of past social systems. The various chapters divide into exploratory efforts and incredibly detailed paleoenvironmental and social systems…. These studies involve the intimate participation of archaeologists, hydrologists, soil scientists, paleoclimatologists, evolutionary biologists, and computer modelers.”

—*George Gumerman, Santa Fe Institute*

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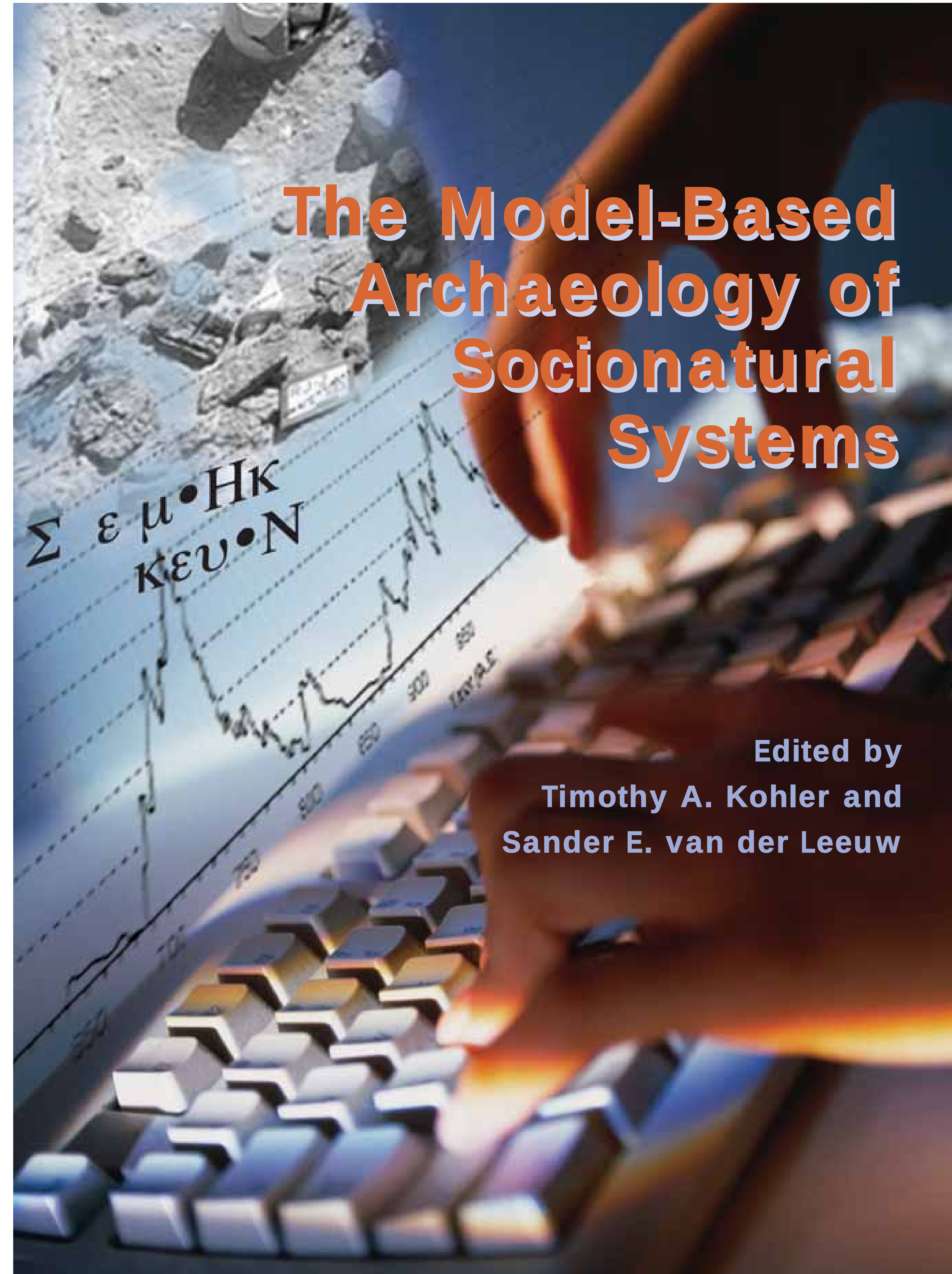
The Model-Based Archaeology of Socionatural Systems

Kohler and van der Leeuw



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CHAPTER 3

Modeling the Role of Resilience in Socioenvironmental Co-evolution

The Middle Rhône Valley between 1000 BC and AD 1000

Jean-François Berger, Laure Nuninger, and Sander van der Leeuw

This chapter discusses part of a research project investigating the spatiotemporal aspects of resilience in complex social systems.[1] That project aims to develop a conceptual model of the dynamics that drive the trajectories of regional socioenvironmental systems by looking at three case studies. We report here on one of those case studies.

The conceptual model combines elements of four research domains. The natural sciences have contributed to the set of ideas that is sometimes called "the science (or theory) of complex systems" (for example, Bak 1996; Kauffmann 1993; Levin 1999; Nicolis and Prigogine 1977). The sciences of organization and information have contributed to our understanding of the dynamics of social organization (for example, Bateson 1973; Beer 1959; Simon 1973, 1981). Some of their ideas on the hierarchical nature of organizations have been taken up and adapted by ecologists (for example, Allen and Hoekstra 1992; Allen and Starr 1982; Allen, Tainter, and Hoekstra 2003; O'Neill et al. 1986; Pattee 1973). Other ecologists (for example, Carpenter et al. 2001; Gunderson 2000; Holling 1973, 1986) have contributed an approach called "resilience theory" to describe the internal dynamics of ecosystems. Finally, some social anthropologists (De Vries, Thompson, and Wirtz 2002; Thompson, Ellis, and Wildavsky 1989) have developed a very similar approach to societal dynamics, which they term "culture theory." The first attempt at a synthesis of these various ideas comes from a collaborative effort of ecologists and social scientists (Gunderson and Holling

2002). McGlade and van der Leeuw (1997), and more recently Redman and Kinzig (2002), have attempted to show the relevance of some of these ideas to archaeology.

The dynamics of socioenvironmental systems oscillate between chance and necessity. In very general terms, one could say that the continued existence of socioenvironmental systems depends on the adequacy of the interaction between their societal and environmental dynamics. This adequacy varies through time with the development of both these domains. At certain times, they are impervious or indifferent to perturbations because their internal dynamics are sufficiently coherent and dominant to be able to ignore them. In such a "robust" state, a system necessarily follows its own trajectory. At other times, such socioenvironmental systems are so vulnerable that any perturbation, large or small, can cause an irreparable loss of coherence. In such a "window of vulnerability," the system will survive only if, by chance, no perturbations occur. The intermediate ("resilient") state, in which the socioenvironmental system survives by adapting, seems to us the most interesting. We will explore it further in order to understand the processes and parameters that impact on the sustainability of socioenvironmental systems.

First, the resilience varies with the connectivity between the system's societal and environmental dynamics. In many areas, the progressive appropriation of nature by society has, little by little, increased that connectivity; in the past few centuries, the slightest climatic or anthropogenic perturbation triggered an oscillation of crisis proportions.

Second is the speed with which the various dynamics that constitute the system can adapt to one another. This depends on the character of the regional environmental dynamics, the constraints inherent in the system, and the rates of change of its temporalities. Also, this depends on the speed at which the society's participants identified and analyzed new circumstances and devised ways to deal with them.

Third, the history of the socioenvironmental system is important. Participants in an evolving social system necessarily use extant elements previously constructed. These elements may be material, such as a road network, but may also be institutional, or sociocultural, as in the case of a society's values or worldview. Often, these are closely integrated, as in the case of technology. The material legacies are usually easier to change than the social or cultural ones, because they are more tangible.

To investigate the interaction between the successive social formations in a region and their environments, we must first understand the following:

- The periodicities of the climate dynamics over the very long term
- The natural dynamics of the landscape in the area
- The societal dynamics involved
- The technologies enabling the interaction between the societies and their environments

Once these are understood, we may hope to identify the respective societal and environmental dynamics by looking at the long-term co-evolution and interaction of both.

And that will finally put us in a position to model these dynamics formally, which is the aim of our project.

Environmental Characteristics of the Middle Rhône Valley

The Mediterranean constitutes a transitional bioclimatic zone between the temperate and tropical zones and between humid and arid zones. It is characterized by a "staged" vegetation (Ozenda 1964) adapted to summer drought and cool winters. This location makes the Rhône Valley vegetation highly reactive to climatic changes and human pressure. The middle Rhône Valley, between the Drôme Valley in the north and the Aygues Valley in the south, is located on the northern edge of the Mediterranean morpho- and bioclimatic systems (figure 3.1b), just south of Alpine climatic influences. Its average annual rainfall ranges between 700 and 1,200 mm. Precipitation is concentrated mainly in spring and autumn; during the two summer months, the area is affected by typical Mediterranean dryness. The river Rhône flows continuously because it is fed by the alpine climate, but the flow in its tributaries in the calcareous southern pre-Alps diminishes considerably in summer.

The two regions dealt with in this study, Valdaine and Tricastin, are juxtaposed but present different geographic contexts (figure 3.1a, c). The Valdaine Basin is characterized by the close proximity of the pre-Alps, and its relief is steeper than that of the Tricastin plain. The former consists primarily of large detritic fans and numerous hills and has a higher average elevation. The Tricastin consists of the Holocene floodplain and fans deposited by the Rhône and its tributaries, surrounded by lower alluvial terraces. Its relief varies between 1 and 3 m.

Global Climate Change...and a Regional Anomaly!

The main environmental events have been summarized in Berger (2003b) and Berger and others (2003). The beginning of the Holocene is marked by diffuse erosion under an expanding vegetation cover, dominated by bioclimatic parameters (9000–6500 cal. BC). Wildfires and erosion cycles are then strictly correlated. During the Atlantic and the "climatic optimum" (6500–3200 cal. BC), we observe biostasis and the first human-induced crises of the landscape in the Neolithic period. Later prehistory (3200–120 cal. BC) is characterized by strong contrasts between the human and the climate dynamics. The end of the Iron Age and the Roman period (100 BC–AD 100) shows an important and extensive weakening of the soil systems, with different morphological consequences. Late Antiquity (AD 100–600) appears more stable until the Early Middle Ages, which witness the return of landscape instability. The High Middle Ages (AD 1000–1500) are marked by a relative stability of the landscape, followed by delayed morphogenetic activity due to earlier human pressure on the vegetation. Finally, the modern and contemporaneous periods (AD 1500 to present) see the conjunction of a multisecular climatic deterioration (the "Little Ice Age") and the Holocene maximum in human pressure on the environment.

To summarize, in the early Holocene, major climate and anthropogenic factors have to act in conjunction to have effects on the landscape. But from the end of the protohistoric period (which saw an increasing intensification of societal impact on the environment), the slightest oscillation in either climatic or societal dynamics had major effects on the landscape. In ten thousand years, the combined system has become hypercoherent, and its tolerance highly compromised.

Overall, the correlation is excellent between these regional data and the global climate change data provided by ocean circulation patterns, glaciers, and lakes, as well as the residual ^{14}C in the atmosphere provided by the Arctic and Antarctic ice cores (figure 3.2). Both globally and locally, two kinds of climatic periodicity may be observed, of 2,500–2,300 and 1,500–1,000 years, respectively (Berger et al. 2003). The geosystems of the northern Mediterranean thus seem to register these millenary oscillations, which are closely related to oceanic and solar fluctuations.

That being so, recent geoarchaeological studies (Berger et al. 2003) show that no global climate signal indicates a major climatic "crisis" in the Roman period! Nevertheless, the pedosedimentary sequences observed in southern France seem to indicate that the landscape at this time was highly unstable. This period witnesses an important deterioration of the drainage systems of the lower Rhône Basin. Its impact seems almost equivalent to that of the Early Iron Age (the beginnings of the Sub-Atlantic, 800–600 BC) or the Little Ice Age (AD 1500–1900). This deterioration in Roman times seems principally due to human activity, in particular, to the very widespread and rapid transformation of the countryside from predominantly forest and grassland to intensively cultivated agricultural land.

Identifying the Component Processes of Landscape Change

We have chosen a wide range of indicators to identify the major fluctuations of the geosystems of the region. Among them are the following:

- The fluctuations between meandering and braided river systems that are associated with the relative proportions of solids and liquids in the river system
- The progress of the deltalike formations on the coast and upstream from the detrital cones of the piedmont
- The average accretion rate in the alluvial plains
- The variation in particle sizes of the high water deposits of the rivers
- The origin of the sediment flows (petrography of the detrital sediments)
- The fluctuation of the water level in the aquifers (as identified by analysis of the soils and microalgae, as well as malacological analyses)
- The micromorphological study of the structural stability of the soils (the state of their surface, the degree of destruction of their structural stability, their conductivity to water)
- The form and intensity of runoff on the slopes

- The structure and composition of the vegetation
- The fire regime and the intensity of wildfires
- The ways in which the soils were exploited by the inhabitants (Berger et al. 2003)

The torrential and sometimes excessive nature of the indicators observed in our area of study is due to its mountainous topography, its lithology (mainly soft rocks), and, above all, its subhumid climate, known to be one of the most erosive in the world. Soil micromorphological studies across the area enabled us to characterize its pedoclimatic features, to determine the spatial extent of all stages of soil degradation, erosion, and regeneration, and therefore to understand the combined effect of people and climate over the long term.

A recent regional chronostratigraphic synthesis of six river basins in the middle Rhône Valley, based on 300 soundings and cores and 250 ^{14}C dates, distinguished a hundred archaeological levels, combining into twenty-four hydrological and pedological phases between 1000 BC and AD 1000 (Berger 2003a; Berger and Brochier n.d.). Three main states of the landscape dynamics were observed (figure 3.3). The first is associated with a stable optimum (see figure 3.3a): the soils are well drained, in and of themselves, with good agricultural potential; frequent wildfires occur, both natural and anthropogenic in origin. Many Neolithic to Bronze Age sites in the plains are associated with this kind of environment.

The second corresponds to maximum instability of the landscape, with a dominance of North Atlantic air currents (figure 3.3b). The annual and multiyear water balance is often positive. This leads to high instability of the river systems (braided styles) and rising water tables. Before people knew how to drain the landscape, these phases strongly limited subsistence in the lower plains and humid areas—only herding was possible. As a result, from the Neolithic to the Gaulish period there are very few settlements on the plains in these phases.

The third configuration is associated with short periods of high instability, dominated by tropical air currents (figure 3.3c). Flash floods and fires were common in these situations, but the alluvial plains do not show much evidence that these conditions imposed serious constraints on the prehistoric and early historic economies.

The Overall Evolution of Settlement Systems from the Late Bronze Age to the Middle Ages

Settlements reflect ancient choices about the landscape. In the Tricastin and Valdaine, intensive field walking, soundings, and rescue excavations have identified eight hundred sites, dating from the Late Bronze Age to the beginning of the Middle Ages (see figure 3.1a, d; figure 3.4). Because surface surveys are more representative of ancient settlement densities in certain periods or regions than in others, we corrected for the biases of the surface surveys with respect to certain cultural horizons by taking into account subsequent soil erosion and deposition. Next, the total probable number of sites in any one landscape unit was determined statistically (see Verhagen and Berger

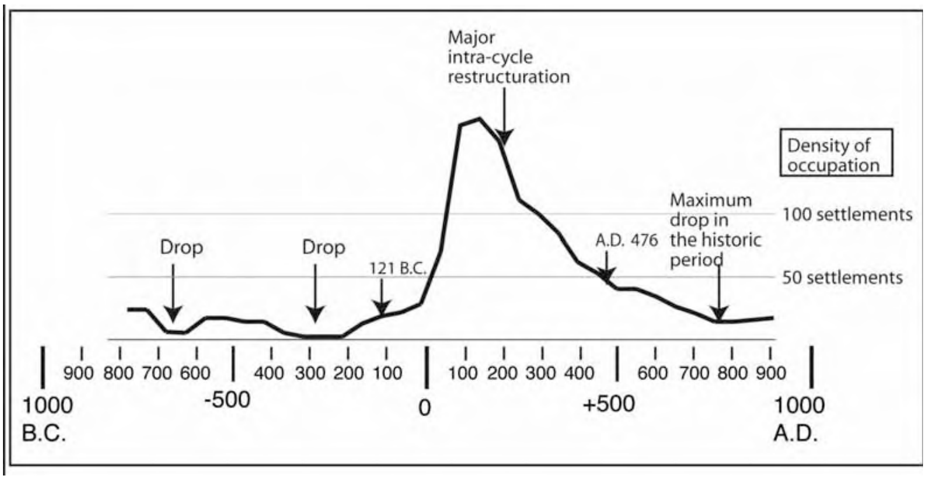

Figure 3.4. The evolution of settlement density between 800 BC and AD 800. Note that the Roman Empire constitutes only part of the cycle because it is riding on the back of a longer-term socioenvironmental expansion.

2001). The results indicate variation in settlement density between 800 BC and AD 800, marked by a first maximum at the end of the Bronze Age (ca. 800 BC), a first abrupt decrease during the seventh century BC, followed by another peak between 600 and 400 BC and a second drop in numbers during the fourth and third centuries BC. The third and most important peak in occupation density begins around 200 BC and culminates during the first century AD. It thus begins before the arrival of the Romans in *Gallia Narbonensis* (ca. 120 BC). A major intracycle restructuration occurs in the course of the second century AD. More than a third of the settlements are then abandoned in less than a century. This decrease continues during the following centuries, but more slowly. A brief respite in this trend can be observed in the fifth and sixth centuries AD, but it continues throughout the seventh century. Finally, a minimum settlement density is reached in the eighth and ninth centuries AD. The Roman Empire constitutes only part of the cycle, riding on the back of a socioenvironmental expansion.

But the number of settlements per period does not assess the real impact of settlements on the landscape. We have therefore calculated the total surface occupied by all establishments occupied in any century (figure 3.5a). For the Iron Age, the occupied total surface in the Valdaine and Tricastin is relatively variable, pointing to an unstable settlement system.[2] Moreover, there are considerable differences between the two areas. First, the total surface of the settlements occupied in the Tricastin during the first Iron Age is proportionally large, whereas that of the settlements in the Valdaine is almost negligible. Because the number of establishments in the Tricastin is almost zero in the seventh century BC and relatively low in the sixth and fifth centuries BC, settlement must have been agglomerated. In the Valdaine, the situation is clearly dif-

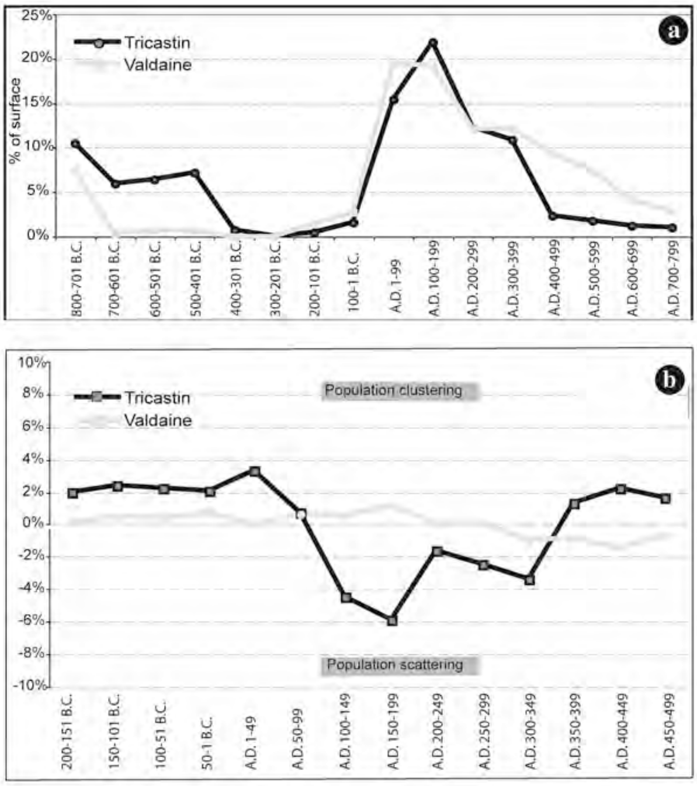

Figure 3.5. Aggregation and disaggregation of settlement: (a) graph of the total surface occupied per century in the Tricastin and Valdaine between 800 BC and AD 800 and (b) evolution of clustered/scattered systems of settlement in the Tricastin plain and the Valdaine Basin from 200 BC to AD 500.

ferent. There, in the sixth century BC, the number of establishments is relatively significant, but their total surface is not. Most individual settlements must have been very small.

Both the number and the surface of settlements in the third century BC is relatively low, as is the case in the nearby lower Ardèche (Durand 2002) or in the east Languedoc where big *oppida* (large hilltop forts) were still dynamic (Bertoncello and Nuninger in press; Nuninger 2002). The area seems to be almost depopulated. Many oppida are temporarily abandoned, and few smaller settlements are found. At the scale of the northwest Mediterranean region, an apparent decline in trade in the fourth and third centuries BC is also observed. But we observe a marked progression in the number of settlements during the second and first centuries BC, even though the total settlement surface increases very little. Roman colonization begins in small, relatively dispersed settlements.

At the height of the Roman Empire, the total settlement surface and the number of settlements increase hand-in-hand in both areas. But in Late Antiquity and at the beginning of the Middle Ages (fifth to eighth centuries AD), in spite of a general reduction in the number and surface of settlements, the Valdaine Basin seems to be doing a little better than the Tricastin. In the Tricastin, the major reduction in total settlement surface that accompanies a much less marked decrease in the number of settlements suggests settlement dispersal.

An Example of Analysis at High Chronological Resolution

To understand the dynamics behind these oscillations, we shall now focus on a shorter period (200 BC–AD 500), for which better documentation exists. Figure 3.5b shows the difference between the change in the surface occupied and that of the number of establishments. A positive difference indicates a clustered settlement system (fewer, larger sites), and a negative difference indicates a scattered system (more, smaller sites) (Nuninger 2002). The graph clearly contrasts the relative stability of the settlement pattern in the Valdaine (with fluctuations of less than 2 percent) with the more dynamic development in the Tricastin. But even in the Tricastin case, the greatest oscillation (which occurs over one century) does not exceed 10 percent. It clearly indicates the passage from a clustered settlement pattern to a dispersed one at the beginning of the second century AD (see figure 3.5b). This change accompanies the peak in new creations of agricultural establishments in the Rhône Valley during the first century AD (see figure 3.4). The return of the settlement system to a form close to that of its early days occurs in two stages, the first in the first half of the third century AD and the second in the second half of the fourth century AD. In Late Antiquity, the settlement pattern is clustered again, and that tendency continues into the Middle Ages, until the creation of the typical villages of the High Middle Ages (tenth to twelfth centuries AD) (see Favory et al. 1999).

We explain these differences in the development of settlement systems between these two nearby areas with reference to their geoeconomic history. The Tricastin plain is nearer to the regional capital (*Augusta Tricastinorum*) and to the major communication routes of the Rhône Valley (the *via Agrippa* and the river). Its soils are favorable for the establishment of vineyards (on the vast alluvial terraces), and viticulture led to large financial investments (wine-growing *villae*) during the first century AD (Jung et al. 2001). The area thus felt the full force of a crisis in viticulture that hit most of *Gallia Narbonensis* at the end of the second century AD (Buffat and Pellecuer 2001; Jung et al. 2001). The Valdaine, farther from the main economic networks and with more contrasted landscapes, is less dependent on viticulture (except for the quaternary terraces of the Rhône in its western part). Its economic profile is polycultural and less sensitive to economic fluctuations. Hence, during the Roman period it maintains stable settlements networks.

The Main Landscape Units and Their Relation to the Settlement Pattern

In order to define the main landscape units, we included in a geographic information system (GIS) a range of information on the middle Rhône Valley landscapes, including their lithology, soils, geomorphology, and pedosedimentary data (Verhagen and Berger 2001). Nine landscape units were defined and mapped by automated reclassification. We then positioned the settlements in their landscape and calculated their relation to the surrounding soils, the hydrology, and the lithological, morphostructural, and topographical parameters of their environment. That enabled us to identify the most probable vegetation surrounding them.

Calculating for each century the distribution of the settlements within the nine landscape units enabled us to compile regional diagrams (figure 3.6a) showing the principal tendencies in soil exploitation. The diagrams show a clear preference for fluvial soils and wetlands during the Late Bronze Age (800–700 BC). The total exploited surface in these rich alluvial plains and the wet basins of the piedmont is markedly reduced during the Early Iron Age (700–500 BC). An expansion of settlement begins again in the Late Iron Age (ca. 200 BC), in the same areas as before.[3] Settlement expansion reaches its maximum in Roman Antiquity (AD 1–500). At that time, a wider range of soils is exploited than ever before. In the third and fourth centuries AD, a restructuring of the settlement system occurs, which manifests itself in a brief period of increase in the number of hilltop settlements. It is followed by two centuries of partial recolonization of settlements in lower areas that had been abandoned a few centuries earlier. Finally, in the sixth century AD, Roman society (and its settlement system) begins to disintegrate. Hence, at the analytical scale of the physiographic unit (figure 3.6b), the tendencies observed above, including the abrupt rupture of the Early Iron Age, are confirmed. We observe the same dynamics in the eastern Languedoc (Favory et al. 1999; Nuninger 2002; Tourneux 2000).

The cumulative diagrams (see figure 3.6a, b) show a complete settlement cycle of fifteen centuries. They clearly highlight an abrupt break in the organization of the settlement of Valdaine and Tricastin around 700 BC, that is, during the Bronze/Iron Age transition.[4] The eighth century BC undoubtedly corresponds to the end of a settlement cycle that began at the end of the Middle Bronze Age (Berger and Vital, study in progress). The new cycle is marked by a progressive descent of settlements from the tops of the hills to the fluvial soils of the lower plains. The largest number of sites, the largest total settlement surface, and the widest range of exploited environments are reached in the middle of this cycle (first and second centuries AD); at the beginning of the Middle Ages, people move back to hilltops and similar locations. But the new settlement pattern is different: rather than scattered, it is now nucleated.

The second major rupture observed occurs in a much more progressive way during the second part of Classical Antiquity. It begins in the second century AD with a slow but constant reduction in the settlement of alluvial plains and humid areas and with a corresponding increase in the number of settlements on Pleistocene terraces and alluvial fans, as well as at the base of hill slopes. From the fourth century AD, the settlements are mainly distributed on hills and plateaus. This tendency culminates during the eighth century AD, marking the end of this cycle of settlement.

The Evolution of Settlement Systems

To monitor, insofar as possible, the main tendencies in territorial management over the period concerned, we carried out a correspondence analysis (AFC).[5] In the resulting plot (figure 3.7a), axis 1 separates the relief associated with sedimentary rocks from the other forms of relief, and axis 2 opposes the highlands and the lowlands. The projection of the archaeological settlements on these two dimensions reveals an almost perfect relation between their position in space (landscape units) and their chronology (figure 3.7b). The two periods characterized by a tendency to settle on, and exploit, heights (700–500 BC and AD 400–800) show clearly on axis 2, but they occur on opposite ends of axis 1, which distinguishes between different lithologies. The dynamics of the soil occupation, even when occupied geographical space contracts, is in perpetual movement on a secular scale (figure 3.7c).

The period 700–600 BC is characterized by exploitation of resistant limestones, karstic relief and hydrology, and not very thick Mediterranean red soils. Settlements are predominantly located on the hills and plateaus. Defensive concerns seem to take precedence over agropastoral production. In effect, this period sees important socioeconomic and political disturbances associated with migrations in both the Rhône Basin and in Switzerland (Vital 1990). But the possible contribution of simultaneous, abrupt climate change, on the scale of the Rhône Valley (or even the northern hemisphere; see figure 3.2), cannot be ruled out. From the end of the ninth century BC, we also see a strong and sudden increase in levels of the circum-alpine lakes and the lakes in the Jura (Van Geel and Magny 2002).

The second period of occupation of the high points in the landscape (Late Antiquity to the Early Middle Ages) is particularly interesting because it indicates a different choice of soils at the lithological level (with consequences at the level of landscape morphology, hydrology, and agricultural potential). At the end of Antiquity (fifth century AD), the settlements are concentrated at the base of the slopes, where thick colluvial soils dominate, and higher up on soft rocks, mainly marls and molassic substrates. During the sixth and seventh centuries, settlements are preferentially found on soft rocks and somewhat later on intermediate rocks. This concentration of sites in the highlands is due to the same processes that occurred during the first Iron Age (climate change and sociopolitical constraints), but the human communities responded in different ways. They chose soils that were easier to exploit and more productive (milder slopes; thicker soils; not very stony, lighter soils that are easier to work; better water availability). The eighth century AD sees a more marked retraction of agropastoral territories and their concentration on intermediate geological substrates (marno-limestones and sandstone). This period therefore resembles the seventh century BC in many respects, but concern with defense may be more marked in the Early Middle Ages, following the emergence of feudal society (see figure 3.7c).

The correspondence analysis shows that in the periods between these two extremes of the cycle, the sites located on the fluvial soils are of primary importance, and a maximum is reached in the diversification of the exploited landscape units.

Land Management Strategies and the Evolution of Agriculture

Although historical information about Roman agriculture and land management strategies exists, such information does not take the specifics of this region into account. Hence, we base our arguments in this section on both on-site and off-site paleoenvironmental data.

The data concerning the morphosedimentary and pedological evolution of the area have been published, and they are summarized above. The chronostratigraphical context is still being refined (Berger and Brochier n.d.). For the moment, we can conclude that the period we are covering here has witnessed three major periods of climatic degradation, around 700–650 BC, around the beginning of our era, and around AD 550. Other, shorter or more localized phases of degradation appear around 350–300 BC, AD 200–250, and AD 750. Stable phases—in which soils regenerated, streams cut deeper into sediments, and fluvial plains were exploited—appear around 900–800 BC, 200–150 BC, AD 350–450, and after AD 900 (see figure 3.3a). The Gaulish-Roman expansion cycle is then coinciding with the middle of a stable hydroclimatic phase (figure 3.8).

Our information about agriculture comes from various sources: palaeosols, ancient river courses and ditches in the landscape, and storage structures and hearths in archaeological excavations. The history of hydraulic technology and of the fluctuations in hydraulic regimes has been reconstructed by analyzing approximately one hundred fossil channels (Berger 2001; Berger and Jung 1999) and a score of ditches in a marsh near the villa of Vernai (upper Rhône Valley; Berger et al. 2003). Two kinds of interacting dynamics affect the costs and benefits of the region's water infrastructure for agriculture: (1) the form of the rivers, which determine both the level of the aquifers (and the need to extend the drainage systems) and the frequency of inundations (impacting on the speed with which irrigation channels fill up with sediment) and (2) the maintenance of drainage channels by the agrarian communities, which depends on the availability of manpower, the constraints imposed on agriculture by local, provincial, or imperial authorities, and the occurrence of sociopolitical unrest (see Berger 2001).

Paleobotanical data have been obtained from the sieving residues obtained from about thirty off-site geoarchaeological soundings and twenty recent excavations (Delhon 2005). The fill of agrarian structures has also been used. Charcoal and phytolith analysis of these residues has provided the bulk of the information, because pollen is poorly preserved in the region (Berger and Jung 1999). The vegetation dynamics and the pressure of agriculture on the Rhône landscapes are exemplified in a diagram (see figure 3.8) obtained in the southern part of the Tricastin plain (Delhon 2005). Several agropastoral cycles appear in the course of the sixteen centuries studied here. Human impact is in evidence in the development of vineyards and orchards, the exploitation of gallery forests, the increase in (mainly *garrigue*) species associated with the degradation of the climactic oak forest, changes in the relative proportions of *Graminaeae* and *dicotyledons* in the phytolith spectra, fluctuations in the numbers of light-seeking plants in preforest vegetation associations, and, finally, fluctuations in frequency of pubescent oak and its undergrowth varieties (Delhon 2005).

The Long Term

From a long-term perspective, the various kinds of information obtained from independent sources point to a coherent picture that reinforces the hypotheses discussed here and enables us to understand landscape change in terms of human impact, climate impact, and/or the combined impact of climate and human population. These are the kinds of information concerned:

- Fluctuations in the extent of total plant cover and in the crops harvested (vine, olive and other tree crops)
- Oscillations in the composition of oak forests between deciduous oak forest, evergreen oak forest, and boxwood
- Indications of soil erosion and sediment deposition in the streambeds
- Fluctuations and reorganizations in land use in the Rhône Valley
- Changes in the periodicities of use, maintenance, and cleaning of the drainage and irrigation networks

The spatial reorganization of the settlement pattern in the seventh century BC is accompanied by a decrease in the agricultural exploitation of riverine and marshy environments during a phase of high hydrosedimentary activity associated with braided river systems. These probably are transformed into pastures. But other landscape units continue to be cultivated (Berger 2003a; Delhon 2005). Never is there a total retreat from the exploitation of the landscape. Activities shift to those parts of the landscape that are better protected from fluctuations in the hydrosedimentary equilibrium, or they change in nature (reduction of cultivation and increase in herding) in periods of major restructuring, such as the seventh century BC and the eighth–ninth centuries AD.

All paleoenvironmental and hydraulic data confirm the expansion of agriculture and its impact on the vegetation, particularly in the very low areas of the region where we see the development of drainage systems from the fifth century BC onwards. From the beginning of the second century BC (cf. infra), the area witnesses the colonization of the fluvial domain, as is evident from the impact of agriculture on the riverine forests (figure 3.8). This phenomenon finds an equivalent in the eastern Languedoc (Lunellois, Vaunage), where intensive colonization of lower areas is documented (Nuninger 2002) and well correlated to an attack on the riverine forest (Chabal 1997). This leads to changes in the rhythm of agriculture, causing an increase in the pressure it exerts on the landscape from the second century BC onwards. Pressure is heaviest from the first century BC to the third century AD.

These new data, which are still subject to interdisciplinary discussions (Berger and Brochier n.d.), confirm in a remarkable way the tendencies observed in the simultaneous and independent analyses of the settlement pressure and the changes in hydrology. In fact, studies in the upper Rhône Valley (Berger and Royet 2003) and the Limagne

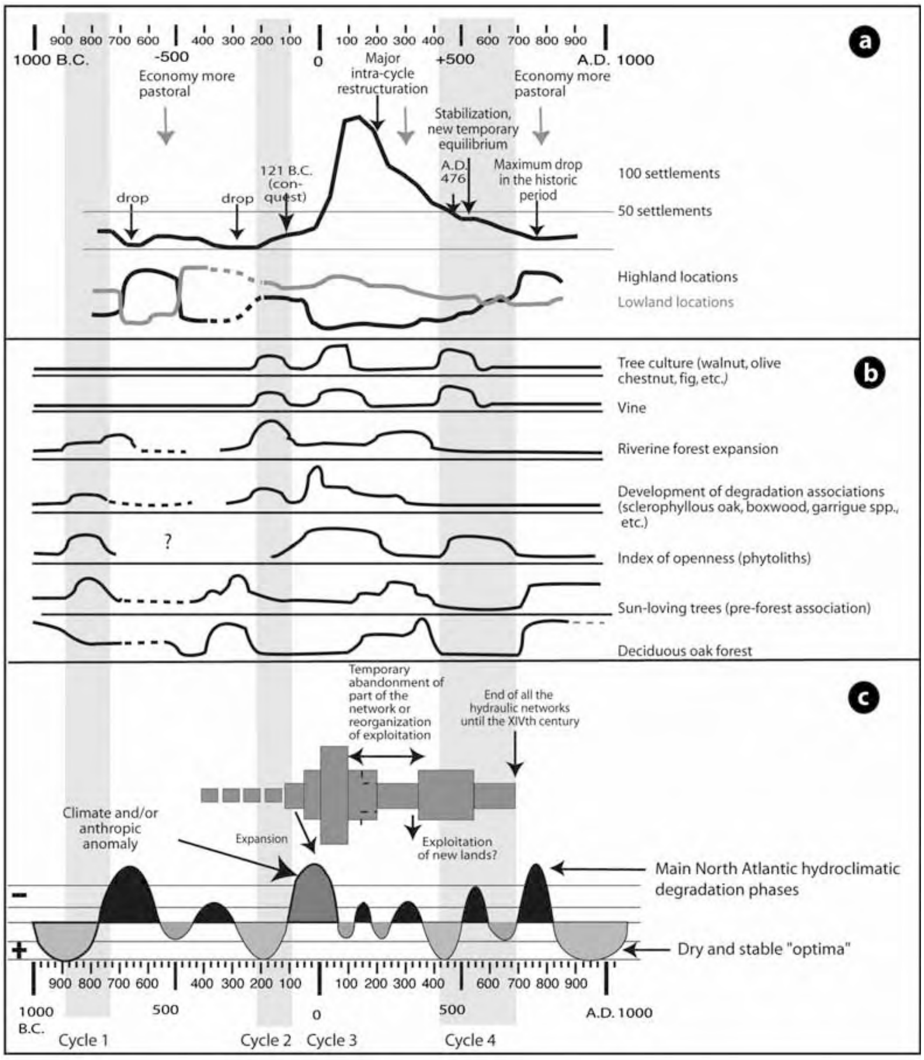

Figure 3.8. Correlation among the evolution of the vegetation in the southern Tricastin (adapted from Delhon 2005), the antique hydraulic system in the Tricastin-Valdaine region (adapted from Berger 2001), and the settlement patterns between 1000 BC and AD 1000. On the basis of these data, we propose a series of agropastoral cycles.

(Guichard 2000; Trément et al. 2004) indicate that the Romans conquered only lands that had been "prepared" by autonomous structuring.

The crisis of the landscape in the Late Republican period and the Early Empire (100 BC–AD 100) (see figures 3.2 and 3.8) was initially interpreted by many, including Berger (1996; Bravard, Verrot-Bourrely, and Salvador 1992; Bruneton et al. 2001; Provansal et al. 1999), as a phase of climatic degradation. But that hypothesis needs to be reconsidered in view of two observations. First, there is no sign of any major global climatic deterioration during Classical Antiquity (see figure 3.2). Second, the study area witnessed the installation and development of a kind of preindustrial, very intensive agriculture that heavily impacted the environment and fundamentally changed the behavior of the hydrological system. This caused the geosystems to become extremely fragile and increased water activity and erosion, all associated with the cumulative effects of the Roman agricultural system coupled with an irregular pluviometry (Berger 2003b; Berger et al. 2003). This protoindustrial, intensive kind of agriculture is characterized by

- The maximum spread of rural settlement and landscape exploitation in the first century AD (see below).
- The occupation and exploitation of all landscape units of the middle Rhône Valley (see below).
- The appropriation of the landscape by the imposition of Centuriations (land registers) associated with rectangular road and drainage systems (Berger and Jung 1999; Chouquer 1995).
- A significant reduction of the vegetation cover that serves to protect the soils coupled with the spread of regressive plant communities (evergreen oak and boxwood scrub) at the expense of those based on deciduous oak (see figure 3.8). The frequency of wildfires increases, and the proportion of tree pollen regularly dips below 20 percent (Berger 1995; Berger and Jung 1999; Delhon 2005).
- A significant increase of cereal cultivation (Berger and Jung 1999; Leveau 1998) and of the cultivation of crops that do not cover the soil very densely, such as vine and tree crops (Delhon 2005; Jung et al. 2001) (see figure 3.8).
- The progressive eradication of riverine gallery forests beginning in the Late Iron Age (figure 3.9), which removes an important element of protection against inundations from the landscape. Currents increase in speed, and riverbanks are undermined (Berger 2003b; Delhon 2005).
- The increased human control of the hydraulic system, which becomes artificial (Berger 2001; Berger and Jung 1996; Chouquer 1995) (see figure 3.8).
- The systematic drainage and drying out of humid zones (Berger and Jung 1996; Leveau 1998) (see figures 3.8 and 3.9).
- The destruction of structural stability of the soils and acceleration of rill formation, due to intensive agriculture (Berger 2003a; figure 3.10).

The fundamental change in the distribution of the settlements that occurs at the height of the Roman Empire (reorganization of land holdings, new ways to manage water, changes in agropastoral management) (Berger 2001, 2003b; Berger and Jung 1999; Delhon 2005; Jung et al. 2001) has an impact on the environment. The increased emphasis on pastoralism and polyculture, to the detriment of large-scale agriculture,

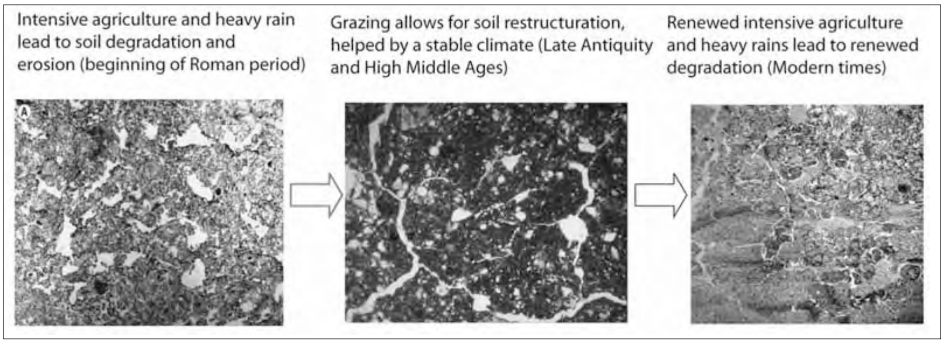

Figure 3.10. Resilience is based on the regenerative capacity of certain kinds of geological substrates. Soil micromorphology allows us to spatialize all stages of soil degradation, erosion, and regeneration and thus to spatialize the combined effect of people and climate.

engendered more stable landscapes and led to the recurrence of brownish paleosols until the end of the fifth century AD (Berger 2003a; see figures 3.3a and 3.9). This restructuring of agriculture led to the agri deserti described by the classical authors. Such temporarily fallow lands were probably grazed by herds, but in no way should this be seen as a major reduction in agricultural activity, such as occurs in the Late Roman Empire.

The vegetation history of this area registers this reduced human pressure on the countryside (see figure 3.8), but the reduction seems less important than during the first part of the Iron Age or the second part of the early Middle Ages. A critical analysis of texts by Jaillette (1996) has shown that this process is part of a strategy of dissimulation adopted by the farmers in the face of increasing fiscal pressures. This phase of soil regeneration could explain the development of one last agrarian cycle from AD 400 to 700 (see figure 3.8), because it led to good natural drainage in the lower plains (initially at least) and optimal agrological conditions of the soil cover (requiring less investment and yielding high profits). A small number of ditches dating between the end of the fourth century and the sixth century AD (see figure 3.8) could represent a new occupation of the landscape, which corresponds to the brief respite in the diminution in settlement observed around the fifth to sixth centuries AD (see figure 3.4). Quantitative data on the evolution of total settlement surface suggests that, at this time, settlement was dispersed in the countryside.

Although this is less easy to document, the end of Antiquity and the beginning of the Middle Ages do not correspond to a total disintegration of agrarian society and a return of the forest after AD 476. Rather, recent paleoenvironmental and hydrological data point to the continuity of the Roman exploitation system and its control over the vegetation until the end of the sixth or the middle of the seventh century AD (see above). And that is the case not only in the middle Rhône Valley. A similar process is documented by advanced palynological, sedimentological, and spatial analyses in the upper Rhône Valley (in the so-called Isle Crémieu between Lyons and Geneva) (Berger et al. in press; Salvador et al. 2005), as well as in the Paris Basin and the lower Loire

Basin in northwestern France (Barbier 1999; Leroyer 1997). The Merovingian tribes that merge with the Gallo-Romans at the end of the fifth century maintain the Roman agricultural system for almost two centuries, while in the Mediterranean Basin and the Rhône Valley an important erosive crisis sets in (see figures 3.3c and 3.8).

We are inclined to ascribe this Mediterranean landscape crisis to tropical rather than oceanic phenomena. It is associated with an increase in the frequency of wildfires and a developed evapotranspiration (concentration of $CaCO_3$ nodules in the soil) (Berger and Brochier n.d.). These short-lived geomorphological phenomena may have an impressive impact locally, but they do not durably limit exploitation (see above and figure 3.3). The last humid hydrosedimentary fluctuation identified in the soils of the Rhône during the eighth century AD corresponds to the lowest human pressure on the landscape (see figure 3.8). Archaeological and paleoeconomic data are still so few during this time in the Rhône Valley that it is difficult to determine whether this retraction should be interpreted as due solely to a major North Atlantic influence on the northern Mediterranean Basin or whether the sociopolitical dynamics of the "Dark Ages" played an important role. It is possible that the settlement system shows centers or microareas of economic development and demographic concentration during this period at the scale of southern France, as happens along the eastern coast of the Languedoc (Raynaud 1990).

Paleoenvironmental data for the "Dark Ages" show a humid phase in which numerous lowlands in temperate and Mediterranean Europe became marshy (Berger and Brochier n.d.; Provansal et al. 1999). But human pressure was relatively weak and limited the effect of this climatic deterioration on slopes and river systems (Berger 2003a; Berger and Brochier n.d.). Erosion was limited, and the episode is mainly in evidence through the positive water balance in the aquifers, as well as an extension of hydromorphous soils (gley or peat).

Perception and Reaction of the Roman Actors in the Drama

It appears that the Romans did not measure the secondary effects of their agriculture on the soil cover, on erosion, and on the dynamics of the water system. The environmental transformations observed in the course of the Early Roman Empire are due, in part, to choices made by politicians and administrators, farmers, and engineers. Their perception of the landscapes of *Gallia Narbonensis* and their dynamics at the time of Roman conquest (the late second and first centuries BC) determined the spatial organization, the agricultural techniques, and the infrastructure (roads and drainage systems) that we still encounter. These people were not aware of the long-term hydrological dynamics and the effect that the drainage systems they installed had on these. Indeed, they were unaware of the need to maintain the long-term resilience of the geoecosystems involved until their system proved unable to deal with new environmental dynamics, for which they were to a great extent responsible.

The Gallo-Romans nevertheless attempted to respond appropriately to these transformations. They tried to protect themselves against the risk of inundation: in the towns, by regularly topping up the surfaces on which they lived with thick layers of debris, and in the countryside, by improving water management (see figure 3.9). But these measures often were insufficient in the face of the ever-higher water levels (figure 3.11).

This belated awareness of environmental changes—in part, due to secondary economic effects of the environmental transformations, which are difficult to monitor archaeologically—may explain the cadastral and fiscal reforms undertaken by the Emperor Vespasian in the second half of the first century AD, as well as Domitian's measures to protect Italian vineyards a few years later. And the rapid changes in the organization of rural settlement in *Gallia Narbonensis* at the beginning of the second century AD undoubtedly reflect local responses to the risks inherent in extensive monoculture (see Favory and van der Leeuw 1998). In fact, the climatoanthropogenic phenomena and problems with which Romans were confronted, and their solutions, appear highly similar to our own.

Summary

The 10,000 years of the Holocene, and, in particular, the period since the Neolithic, have seen major transformations of the northern Mediterranean landscapes. One observes climate cycles of 2,300 to 2,500 years and settlement cycles of shorter duration (two to five centuries), corresponding to phases of increasing and decreasing impact of society on its environment.

Interdisciplinary studies show that the prehistoric and protohistoric societies were heavily dependent on climatic conditions, which determined the size of exploitable soil surfaces, as well as annual agricultural productivity (Arbogast, Magny, and Pétrequin 1995; Berger et al. in press; Tinner et al. 2003). During climatic deteriorations (which were mainly of North Atlantic origin), suitable agricultural and pastoral soils were found only in the plains. Up to the Gaulish period, agricultural societies cultivating cereals are thus not very resilient and depend strongly on the state of the climate. Pastoral societies appear better armed to resist climatic changes, as in the case of the middle Neolithic "Chasséen" (Berger 2003a; Delhon 2005).

The new data presented here for the middle Rhône Valley show a significant rupture in the resilience of the agrosystems in the Middle Iron Age (600–400 BC) (figure 3.12). This crash leads to major transformations in all aspects of social organization. In the following centuries, we see the development of protourbanism, the intensification of economic exchanges (Py 1993), the extension of tree cultivation, and the introduction of Roman water-management technology in southernmost Gaul. As a result, the Roman socioenvironmental system is for some time impervious or indifferent to perturbations because its internal dynamics are sufficiently coherent and dominant to be able to ignore them. And even when it is not, the next two transitions are much more gradual (ca. 200–50 BC) and (AD 300–700). In both these later cases, the system does not crash, but reorganizes the structure shaped during the period 400–200 BC.

These reorganizations allow it to exhibit resilient behavior in the face of environ-

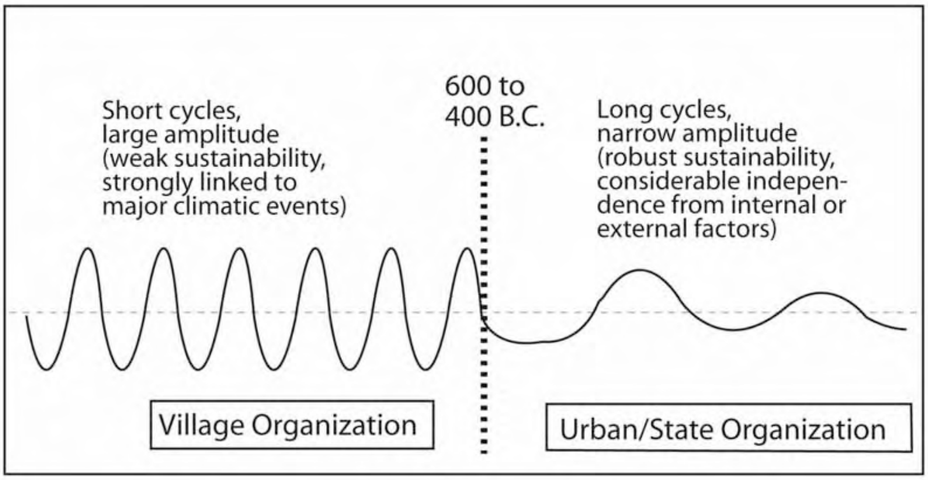

Figure 3.12. Rhythms of change in a sequence of settlement cycles in the middle Rhône Valley, from the Neolithic (village organization) to the Roman period (urban/state organization).

mental perturbations (that is, several hydrosedimentary crises, in part, generated or amplified by agrarian exploitation of the landscape), as well as societal ones (that is, the political, military, or socioeconomic changes that characterize the second part of Antiquity). Its resilience may be due to the buffer effect inherent in the particular form of organization of Roman society (relatively loose, horizontal couplings between regions and vertical ones between the regions and the Empire's administration, diversification of agrarian exploitation during Late Antiquity, and so forth), as well as to the Romans' technical and management skills in the area of agricultural exploitation (mastery of hydraulic management, manuring, adaptation of soils to cultivation) (see figure 3.8).

The new balance achieved after these reorganizations resists the severe sociopolitical crises that characterize the last centuries of the Roman Empire. The barbarian invasions do not seem to disturb the system at all. Either the newcomers adapted rapidly by amalgamating with the Gallo-Roman substrate of the countryside, or they quickly adopted the Roman technology. Altogether, the agropastoral and economic system is thus even more resilient than the political system (which collapses at the end of the fifth century AD). It does not disappear until the beginning of the Middle Ages (towards AD 700), more than two centuries after the official fall of the Western Roman Empire.

A cycle of between nine and twelve centuries can therefore be defined (depending on whether one sees its beginnings around 200 or 500 BC). It appears much longer than earlier cycles and can be compared to the cycle that starts in the Early Middle Ages (tenth century AD) and continues until the beginning of the twentieth century, resisting one period of major climatic degradation (the Little Ice Age) (see figure 3.8c).

Conclusion

As this example illustrates, the crossing of interdisciplinary information does not simplify our vision of the co-evolution of social formations and their environments over the long term. On the contrary, it shows us the complexity of the natural phenomena and their close connection with the socioenvironmental processes that guide the evolution of the landscape.

How can we improve our theoretical understanding of these complex dynamics? One way would be to conceptualize different successions of robustness, resilience, and vulnerability in a framework that is applicable to all kinds of interactive socioenvironmental dynamics, at different spatial and temporal scales. It is argued here that the collective effort of the resilience alliance, as represented in works by Holling, Folke, Perrings, Gunderson, and others (see http://www.resalliance.org), has laid the basis for such a framework. But even though it does take the dynamics of interaction between social formations and their environments into account, it does not provide a model to conceptualize societal change itself. In part, this seems due to the fact that the time frame of the case studies used in this context is too short (at most, a century or two), so the (slow) evolution of the societies involved, and of their perspective on their environment, is not sufficiently in evidence. That gap is, to some extent, filled by the work of Thompson on "culture theory." The two approaches are very closely related, both historically and substantively (De Vries, Thompson, and Wirtz 2002). Our next step will be to link the two approaches and model the Rhône data in that light.

Notes

1. The project was funded by the McDonnell Foundation of the United States at the request of principal investigators A. Kinzig, C. Redman, and S. E. van der Leeuw (all at Arizona State University). Much of the work on which this chapter is based has been funded in the context of several other research projects, among which are the ARCHAEOMEDES Project (funded by DG Research of the European Union) and the French high-speed railways' (TGV) archaeological rescue operation between Lyon and Marseille.

2. The area differs in this respect from others, such as the Eastern Languedoc (Nuninger 2002).

3. Our data relativize, but do not contradict, the traditional emphasis on fortified hilltop sites (*oppida*) in this period, at least for this area.

4. This cannot be ascribed to a taphonomic bias of the archaeological sample used, because the major surveys revealed the concentration of the majority of Late Bronze Age settlements to be near the rivers, which drain the two areas. They are identified today under 1 to 3 m of alluvium.

5. The analysis that was carried out, according to a method developed by Benzecri (1979), combines elements of correspondence analysis and factor analysis and is called in French "Analyse factorielle des correspondences" (literally, factor analysis of the correspondences). It is mostly unknown in the Anglo-Saxon world but, in our opinion, more effective than the statistical methods commonly used in Anglo-Saxon archaeology.

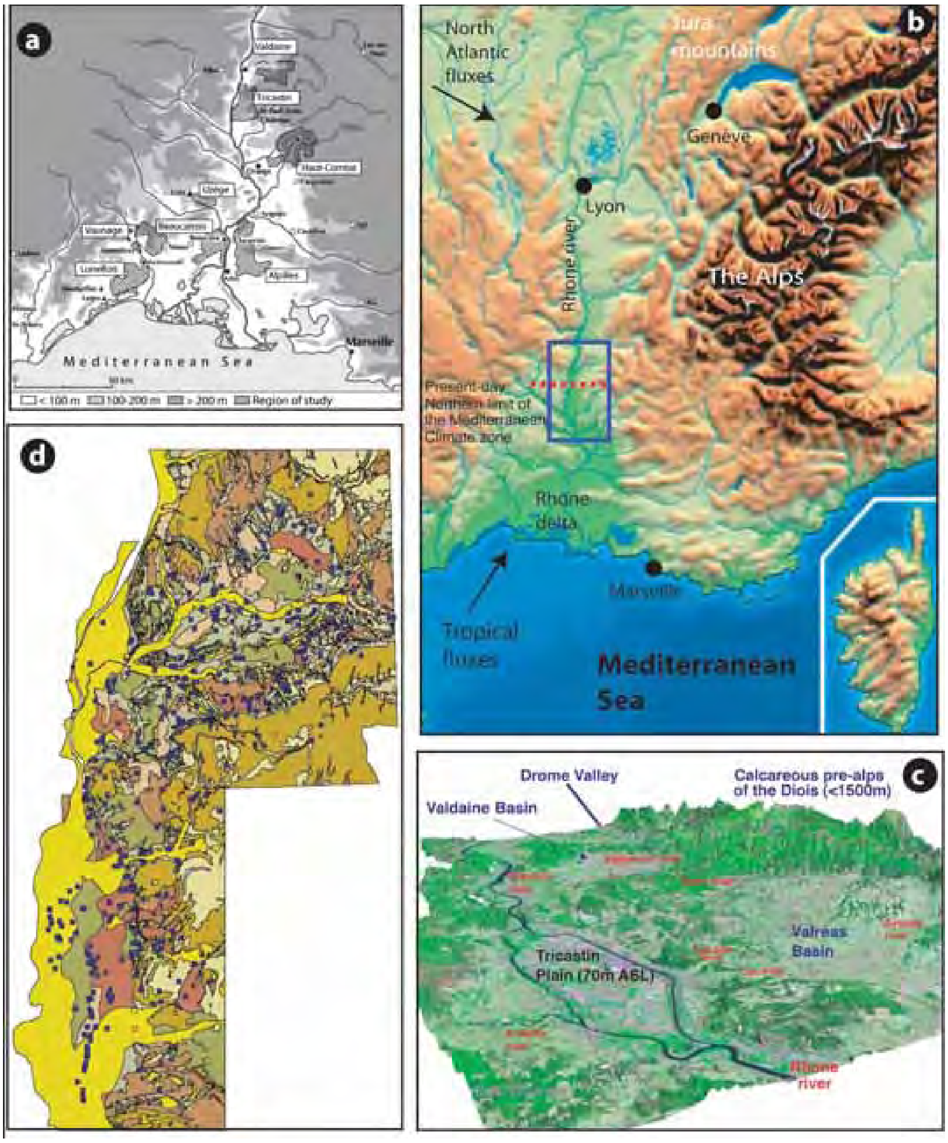

Figure 3.1. The middle and lower Rhône Valley: (a) location of the study areas in the Archaeomedes project; (b) location of the areas studied and the main bioclimatic characteristics; (c) three-dimensional view of the middle Rhône Valley from the southwest (SPOT satellite image over DEM)—in dark green, the spread of the forest cover since the beginning of the twentieth century (which is strictly located on plateaus, hills around the Rhône River, and more distant mountains); and (d) map of the sites in the Tricastin and Valdaine projected on the nine landscape units we distinguished.

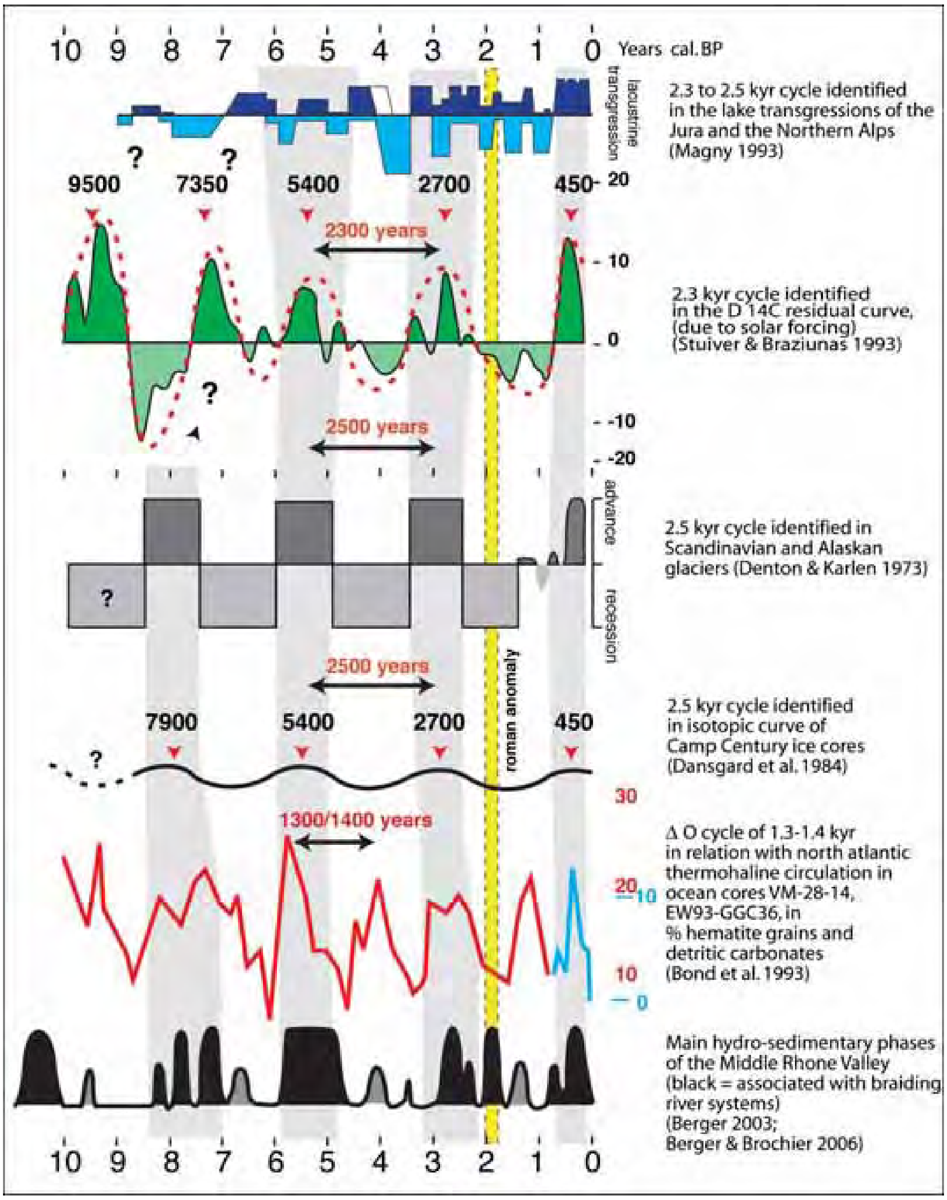

Figure 3.2. Global climate change curves at the global and regional scale. At the global scale, during the Holocene, two kinds of periodicities dominate, of 2,500–2,300 and 1,500–1,000 years, respectively. But at the regional scale, we find anomalies in the Bronze Age and the Roman Imperial period.

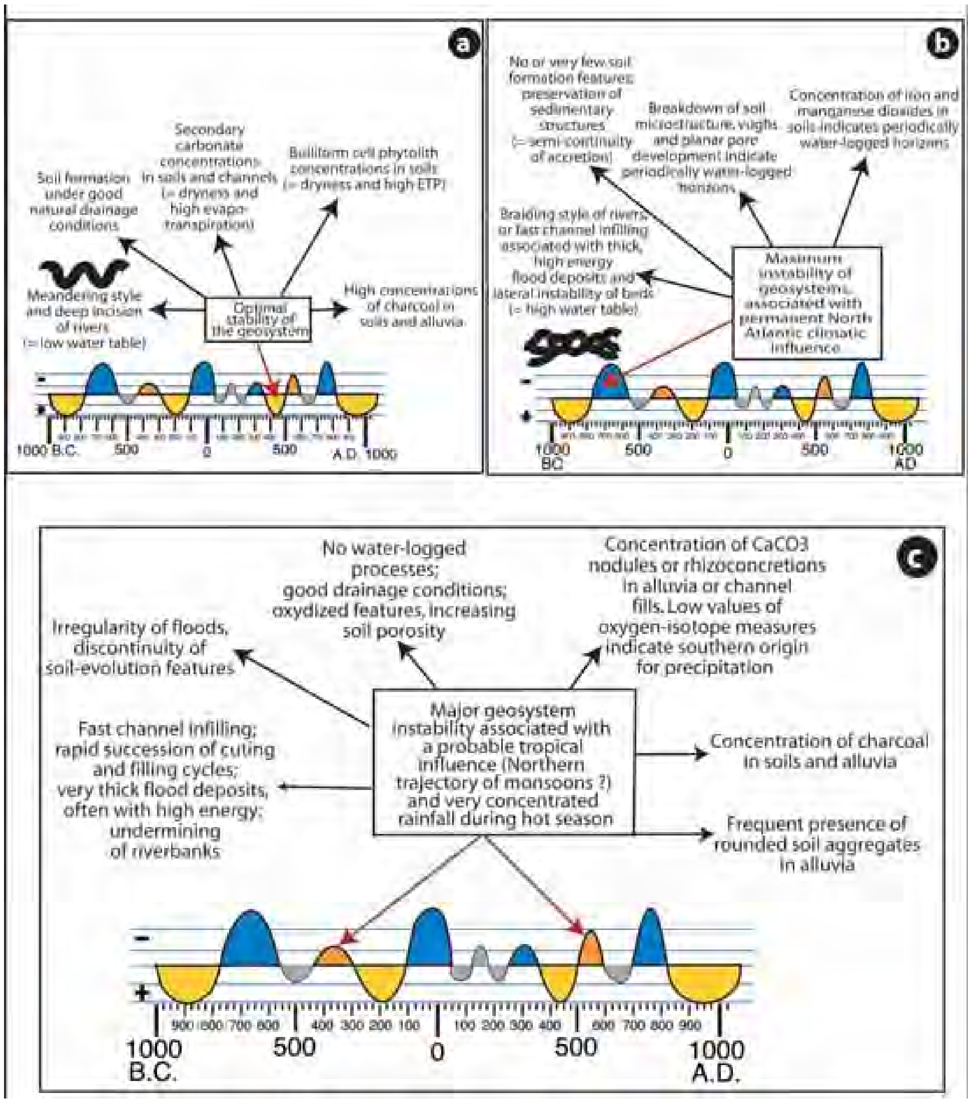

Figure 3.3. Different configurations of landscape-climate dynamics in the middle Rhône Valley: (a) optimal stability of the geosystems; (b) optimal instability of the geosystems, associated with a permanent North Atlantic climatic influence; and (c) major instability of the geosystems, associated with a probable tropical influence.

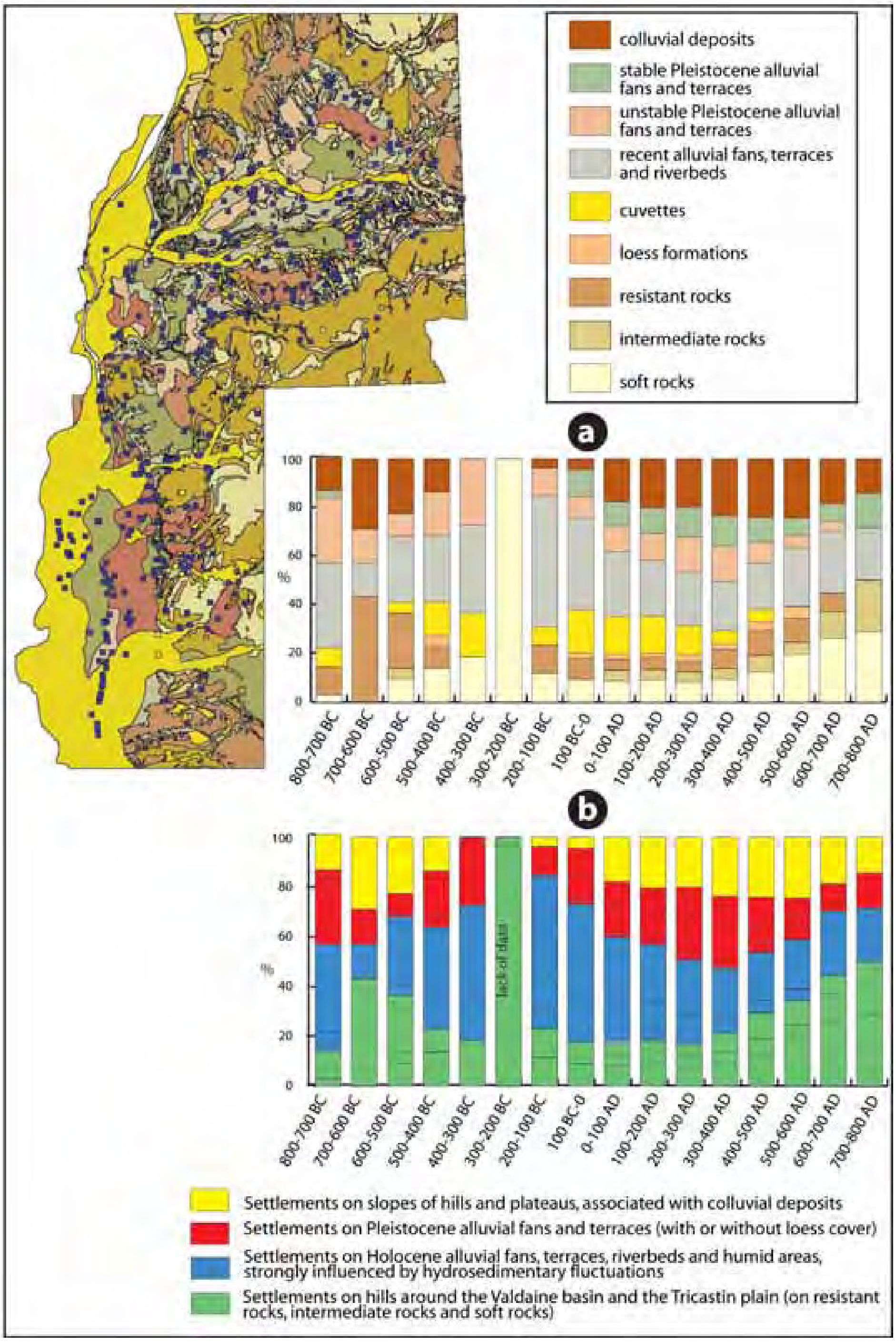

Figure 3.6. Landscape and site distribution: (a) calculation (per century) of the site distribution over the nine landscape units of the Tricastin and Valdaine, from 800 BC to AD 800, and (b) reclassification of settlement locations in the main physiographic units of the region.

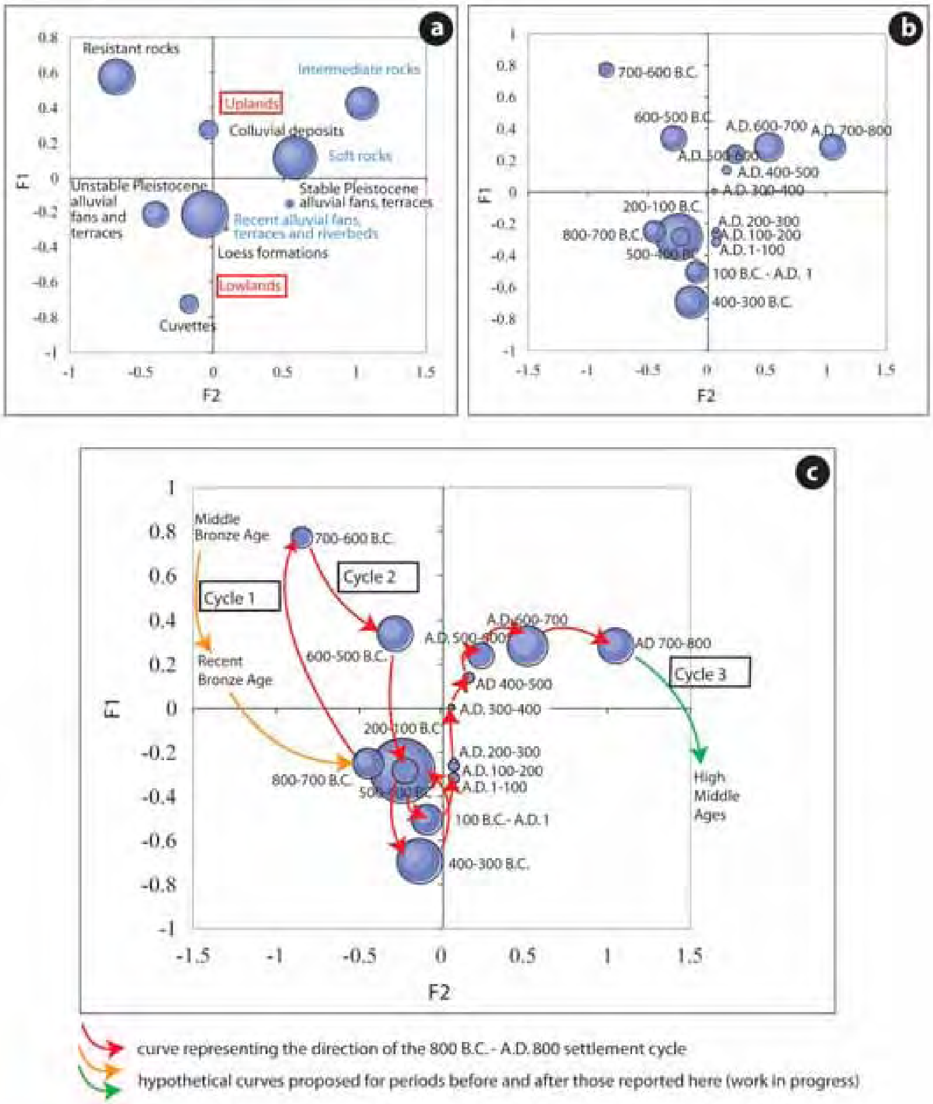

Figure 3.7. Choosing settlement location: (a) correspondence analysis showing the respective importance of various landscape units in choosing settlement location (800 BC–AD 800) (the principal contributing units are in blue); (b) correspondence analysis of the relative weight of each century in the total settlement load, relative to the location of settlements in the landscape. The Guttman effect is distorted, but the chronological factor is dominant and exceeds the current cycle (Braudel's "très longue durée"); and (c) the same graph, but with an indication of the potential trajectory of a settlement cycle.

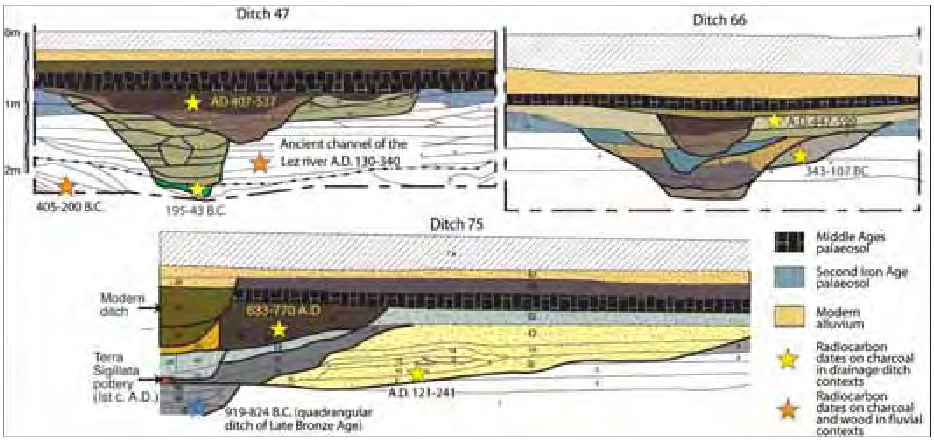

Figure 3.9. An example of drainage ditches that were used from the end of Iron Age to the beginning of the Middle Ages at the site of Brassiere, in the southern Tricastin plain.

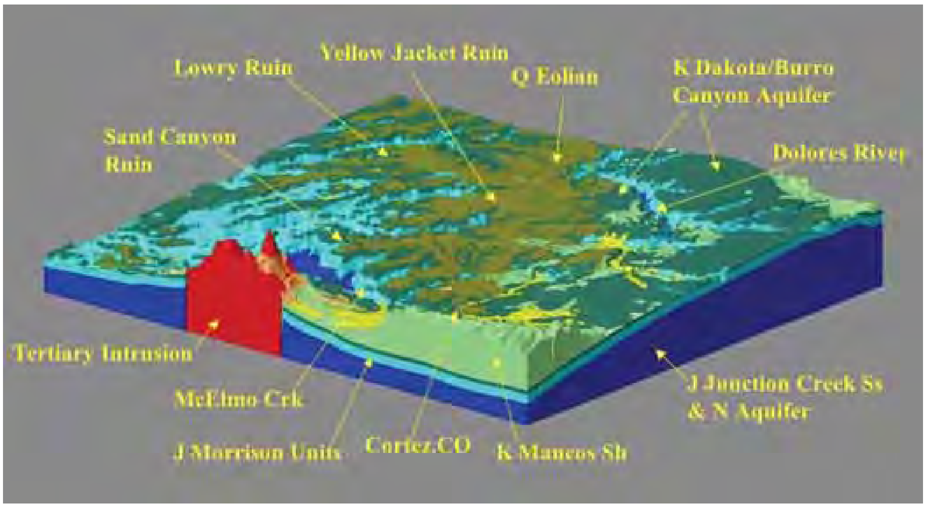

Figure 4.3. A 3D hydrogeologic block model of the study area at 200 m resolution.

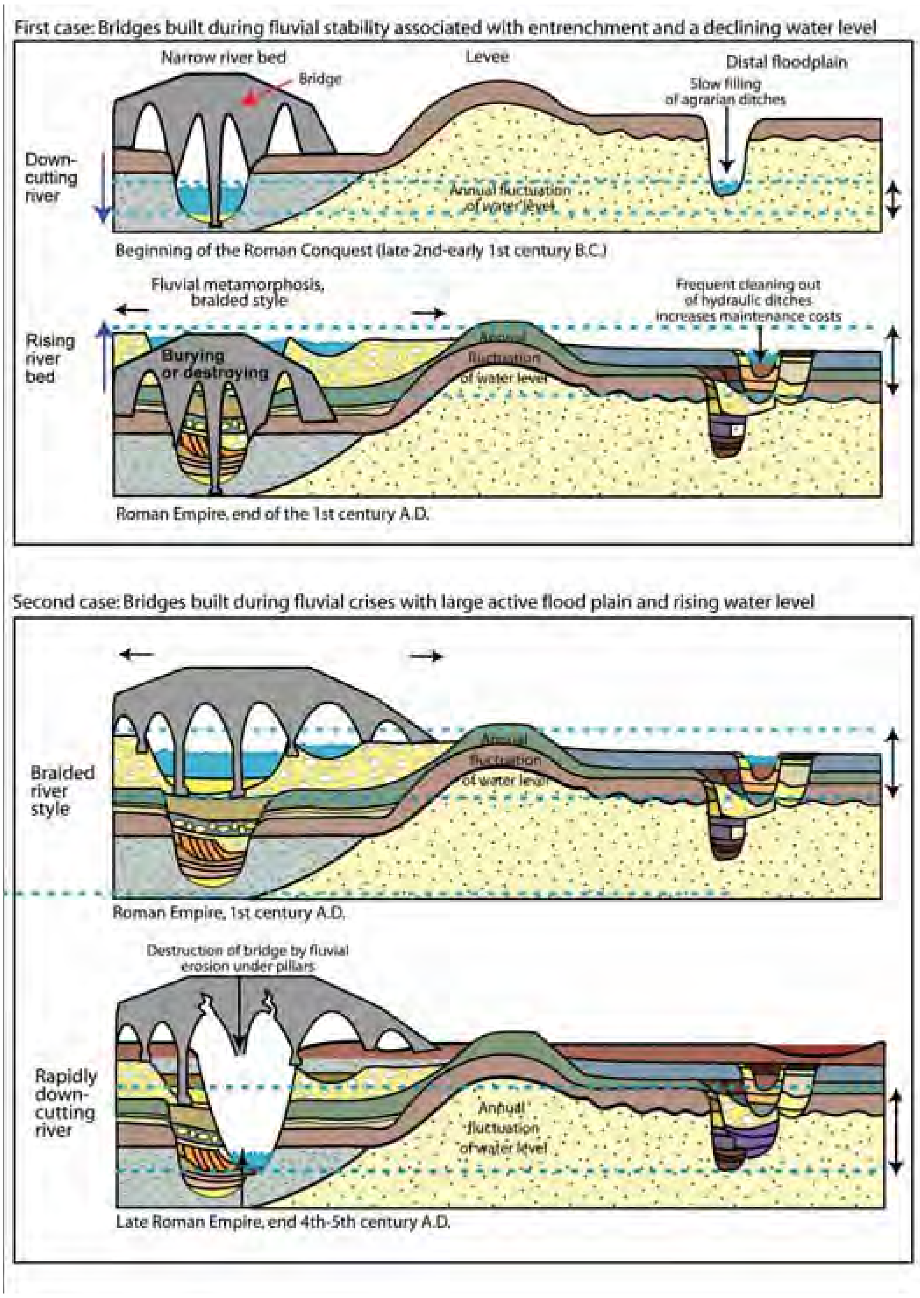

Figure 3.11. The influence of fluctuations in fluvial dynamics on infrastructure such as bridges and aqueducts.

remplacer aqueducts par canals ou ditches

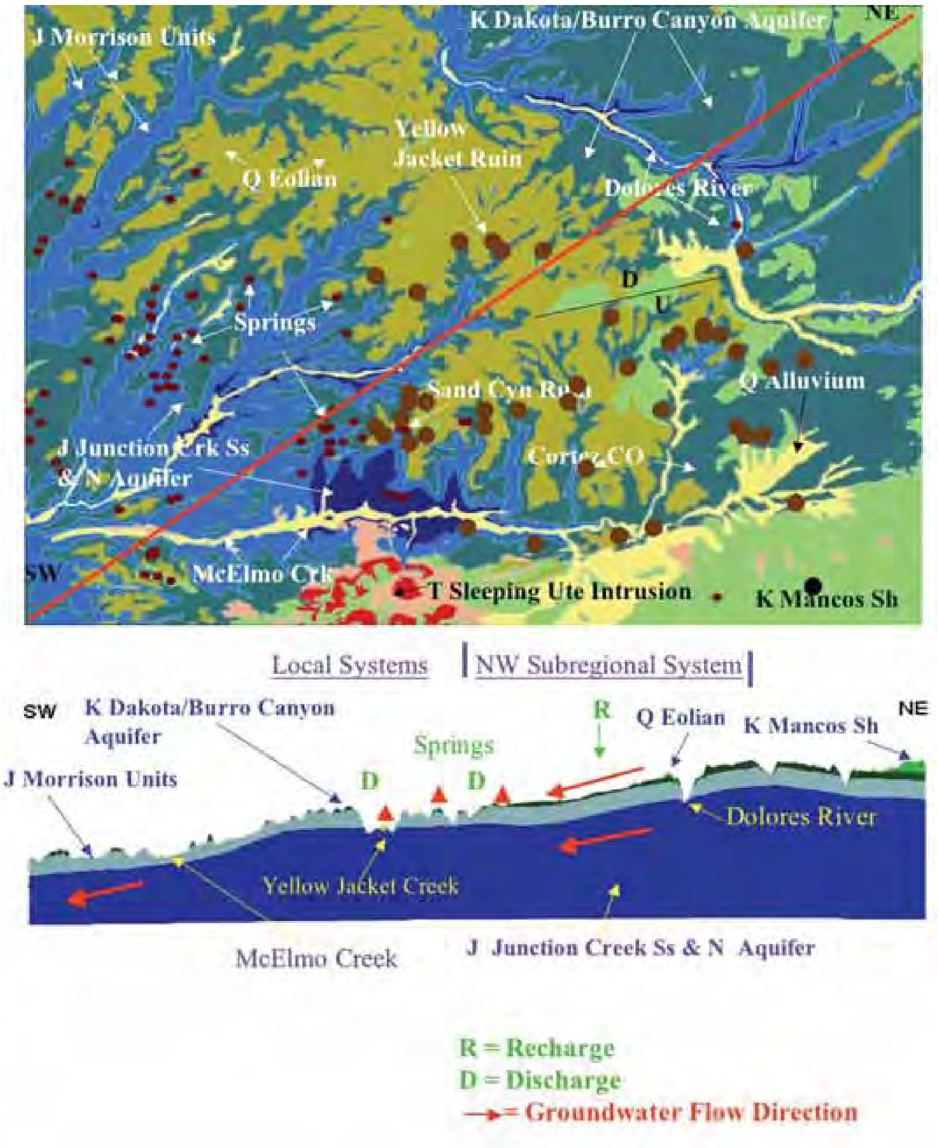

Figure 4.4. Top: *(a) Distribution of hydrogeologic units and springs.* Bottom: *(b) Subregional hydrologic cross-section showing groundwater flow paths with subregional and local systems.*

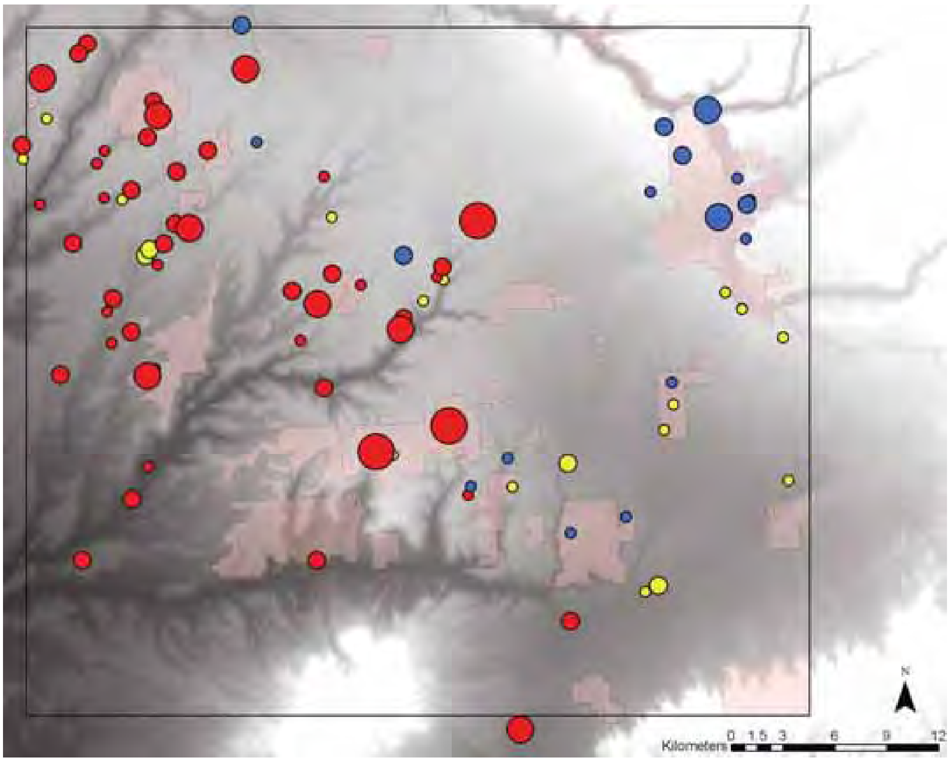

Figure 4.8. Distribution of community centers in the project area by size, class, and time period of peak population: blue, Pueblo I (AD 725–920); yellow, Pueblo II (AD 920–1140); and red, Pueblo III (AD 1140–1280). Lighter background shading indicates increasing elevation; block survey areas are shaded.

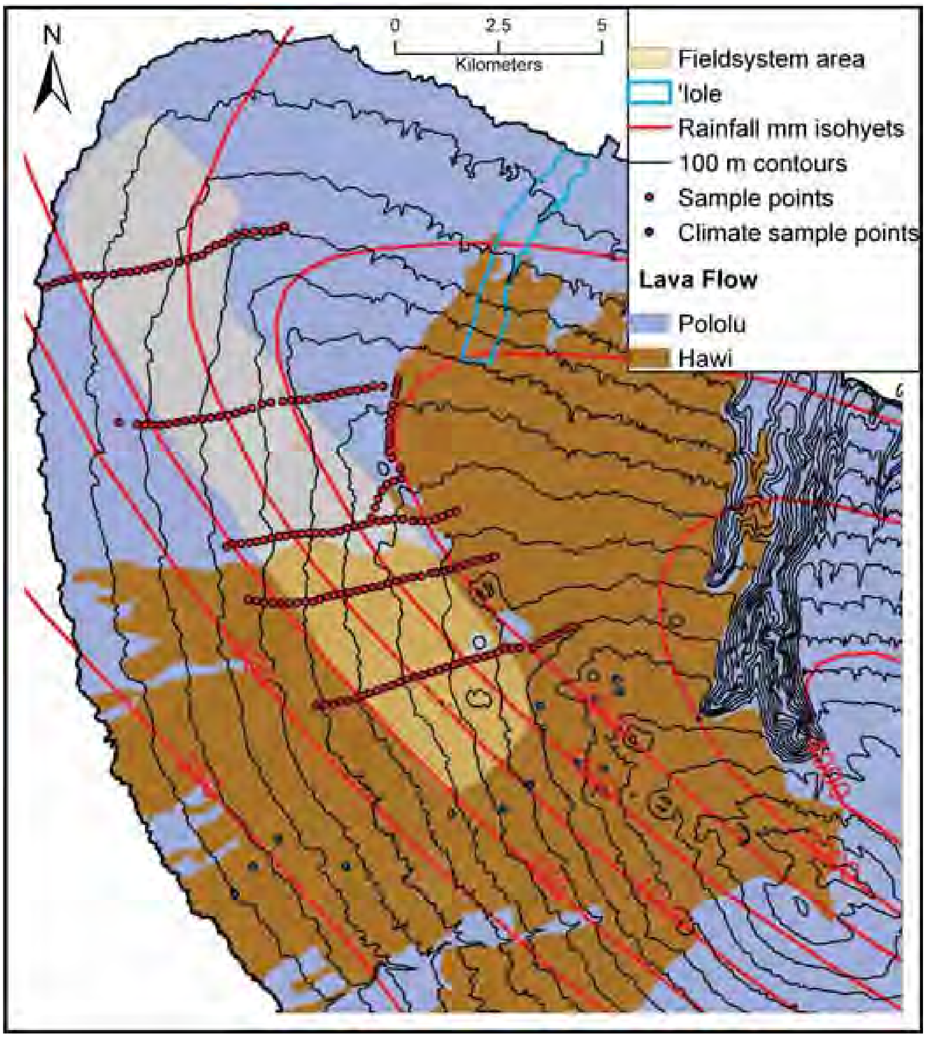

Figure 6.2. Map of Kohala showing the dryland field system in relation to rainfall and elevation, as well as the locations of soil sampling transects (Vitousek et al. 2004).

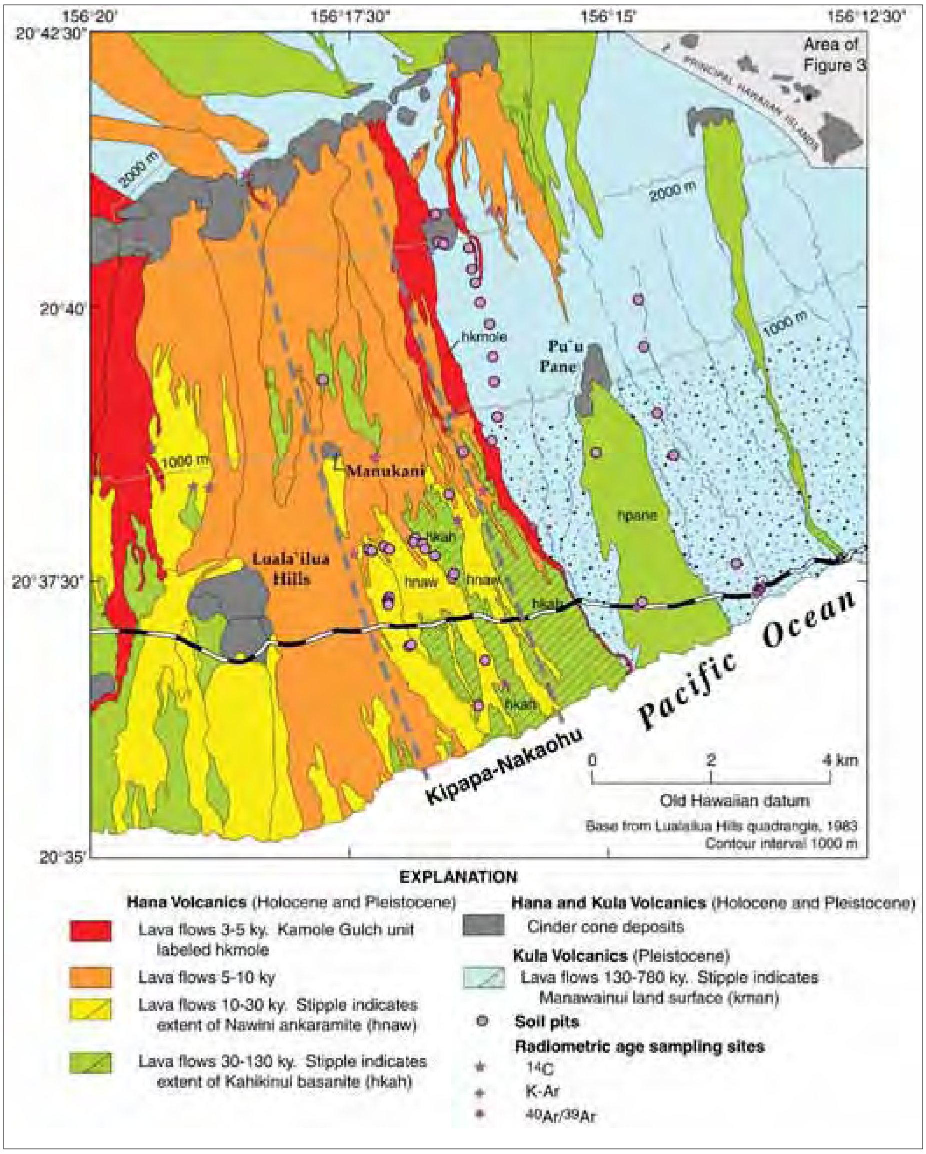

Figure 6.4. Map of the Kahikinui study area showing the geological mosaic of different substrate ages and soil sampling transects (Kirch et al. 2004).

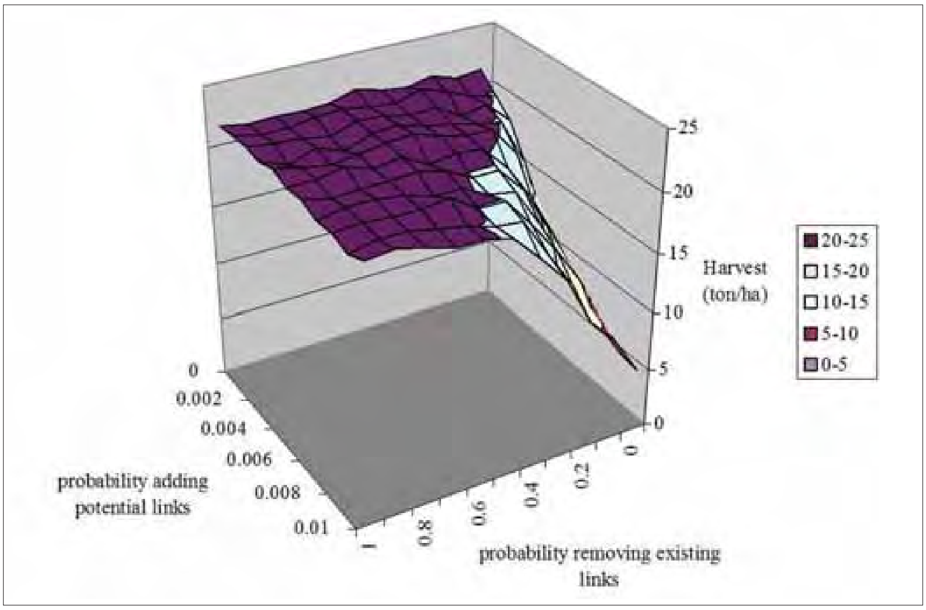

Figure 8.3 Average harvest per subak (per hectare) for various degrees of perturbation of links among subaks that disperse pests and are conditional imitators.

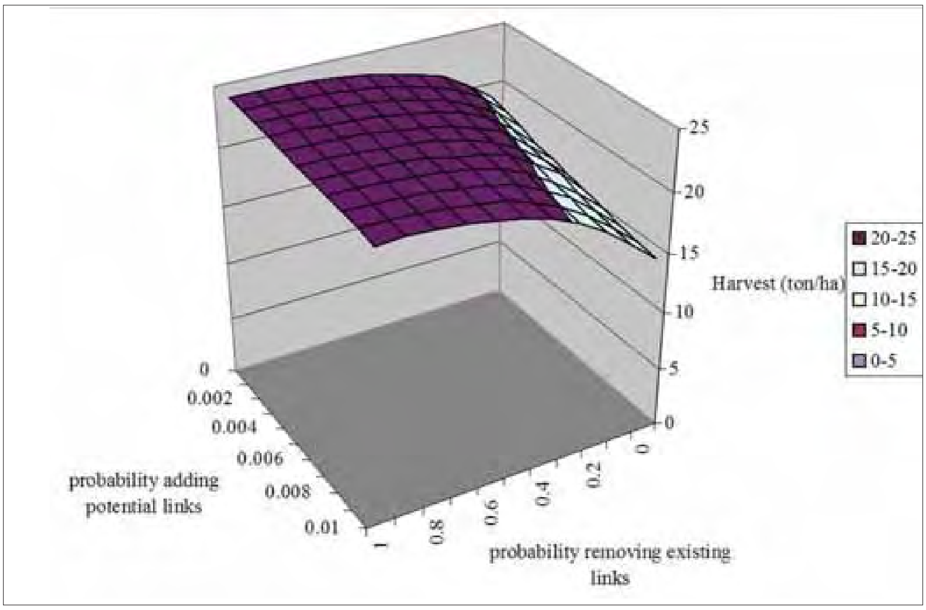

Figure 8.4. Average harvest per subak (per ha) for various degrees of perturbation of links among subaks that disperse pests and are conditionally adaptive.