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How Do Climate and Agrobiodiversity Interact?

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Abstract

The interaction between climate and agrobiodiversity is framed in different ways by different scientific disciplines and researchers. These diverse frames inform climate action by defining the main questions that are being asked and the solutions that are attempted. This chapter explores these frames through select discussion of studies in archaeology, environmental, climate, agricultural, and social sciences. Archaeological and environmental studies frame the interaction between climate and agrobiodiversity as part of a historical coevolutionary process. Agricultural and climate sciences have focused away from systemic interactions between climate and agrobiodiversity, devoting limited attention to genotype–environment interactions and diversification. Another relevant frame is to see agrobiodiversity as an informational resource, which is undermined by climate change as local information about adaptation rapidly becomes obsolete. Knowledge generation then becomes the central engine of economic growth to counteract loss of information due to climate change. Climate action needs to confront climate change and agrobiodiversity management as "wicked problems"—problems that demand attention to the systemic nature of the problem, uncertainty, and the role of human values. Integrated scientific approaches are needed to design processes that explicitly address these aspects, contribute to climate action, and accommodate opposing values.

Introduction

Anthropogenic alterations of the Earth's atmosphere are changing the global climate so fast that this has created one of the most important challenges to humanity. To address climate change, wide-ranging responses are needed to reduce its negative impact, responses which are now often referred to as "climate action." In agriculture, climate action represents an important role for agrobiodiversity, and the intelligent use of biodiversity in agricultural land use is a crucial ingredient in addressing climate change. Mobilization of genetic resources is needed to address new stresses from heat, drought, and new pests

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and diseases induced by climate change. These genetic resources are needed to shift or create crop varieties and animal breeds that produce more, cope better with stresses, and contribute to reducing greenhouse gas emissions per unit of area or unit of product (Jackson et al. 2013). Climate change also requires the redesign of agricultural systems that can cope with higher temperatures or less available water supplies. The use of new combinations of biota that perform agricultural functions with biologically evolved effectiveness can increase resource use efficiency, sequester soil carbon, and decrease the use of fossil energy (Altieri et al. 2015; Branca et al. 2013). However, agrobiodiversity is not solely a tool for climate action: it is also a victim of climate change. Wild and cultivated species and intraspecies diversity may disappear as they lose their habitat to climate change (Bellon and van Etten 2014; Jarvis et al. 2008a).

To explore different views on the interactions of climate and agrobiodiversity, I bring together a range of different disciplinary and theoretical perspectives (see also Chapters 6 and 8): archaeological and environmental studies provide a long-term perspective on these interactions, whereas applied climate and agricultural sciences offer perspectives that focus on informing climate action. A recent generation of studies produces a better understanding of climate and biodiversity from a complex systems perspective. In addition, social science contributes to our understanding of how climate action is shaped by different social forces.

The scope of this essay is not that of a comprehensive review. I have selected studies that explain and illustrate concepts as well as others that provide potentially important insight into how the climate–agrobiodiversity interaction can be reframed. Frames, a term I use rather loosely, define the problem and eventually suggest the solution; hence, they inform climate action (Dorst 2015; Entman 1993). Frames have a strong normative aspect, so discussing research from this perspective involves necessarily a degree of subjectivity and eclecticism. More explicit frames will enable better choices to be made regarding climate action.

Long-Term Perspective

Agriculture emerged in different world regions over a prolonged period of time (Fuller et al. 2015). Whether or not agriculture emerged in response to climate change in different areas is still a matter of discussion. Even if climate change played an important role in specific areas, other aspects as well as demographic and sociocultural causes most likely played an equally important role. Archaeologists have learned that agriculture did not emerge as a sudden invention, but arose gradually from preagricultural land use as prehistoric people exercised selection pressure on plants that they collected and started to manage landscapes in ways that favored their own purposes (Fuller et al. 2015). Through conscious and unconscious selection of plants and animals,

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human populations started to alter a number of traits that favored their agricultural use, leading to a slow process of domestication. Prehistoric people expanded the range of domesticated species by taking plants and animals to new places and sharing them with neighboring human populations as well as through migration. Human populations proficient in agriculture started to grow demographically, expanding their demographic base and occupying more land. As a result, domesticated species radiated out of their areas of origin. The genetic geographies created by prehistoric crop dispersal are still recognizable in today's distribution of crop genetic diversity. As agriculture forced nomadic human populations to settle, they also became more reliant on highly localized resources and, in many cases, broadened the range of plant species they consumed (Brookfield 2001).

Agriculture expanded in Europe at an annual rate of 0.9–1.3 km (Fort 2012). This rate not only reflects the speed of demographic expansion of human populations and cultural transmission, but also the ability of crops to adapt to new climates. The dispersal of agriculture from Anatolia to northern Europe or the American tropics to North America is premised on a drastic climate adaptation process. Contemporary climate change can similarly be expressed in a speed rate, as climates shift away from the equator in response to heat accumulation. The prehistoric rate of expansion of agriculture exceeds the contemporary speed of climate change, estimated by Loarie et al. (2009) to be 0.48 km per year as a global average, although locally it could be much higher. In addition, for many systems the required speed of selection may be demanding without the aid of modern plant breeding.

Recent studies of the archaeobotanical record reveal some of the potential costs of climate adaptation. A fair number of species became domesticated and then fell into disuse. Allaby et al. (2015) argue that such false starts may be related to excessive selection pressure that prehistoric people placed on plant populations as they moved into new environments. Cultivated plant populations were often not prepared for human selection pressure as they had already gone through a genetic bottleneck compared to their wild progenitor populations. Prehistoric people removed much diversity as they only propagated small portions of wild populations; this led to genetic drift, the random loss of diversity. Also, they exercised seed selection for traits they found important, leading to so-called selective sweeps across the genome. Likewise, increased selection pressure on crop populations today may reduce their genetic base and the chances of finding traits that help crops adapt to new climates.

The prehistoric past sets the scene for agrobiodiversity in climate action in another way, too. Agriculture, one of the economic sectors most dependent on the natural environment, has typically been viewed as one of the main victims of climate change whereas another economic sector, industry, has been faulted with kicking off the massive fossil fuel use that has increased greenhouse gas concentrations in the atmosphere. It was presumed that agriculture contributes to accelerated climate change only to the extent that

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it is implicated in the Industrial Revolution. Consequently, a return to the "old" ways, with an increased role for agrobiodiversity, was seen as a way of bringing agriculture back on the right track: it would reduce fossil fuel dependency and even act as a redeeming sink, fixing greenhouse gases by converting them to soil carbon.

Recent research, however, challenges this view. Geologist Bill Ruddiman (2013) developed the hypothesis that agriculturally generated greenhouse gases before the Industrial Revolution were significant enough to stave off an Ice Age, which was bound to happen if normal climate cycles had followed their course. Prehistoric farmers cleared forests to plant crops, sending the carbon contained in the trees into the atmosphere. Also, they greatly increased the number of ruminants by domesticating them, keeping them in large herds and protecting them from predators. Given their specific digestion process, ruminants emit much methane, a potent greenhouse gas. Another important source of methane is irrigated rice cultivation. To grow rice, prehistoric people modified the landscape to increase the area that is periodically flooded, thereby creating the anaerobic conditions that favor methane emissions.

There is now a growing body of evidence to support Ruddiman's early anthropogenic hypothesis that agricultural emissions were indeed substantial enough to cause a notable warming of the atmosphere. Prehistoric emissions and concentration gradients predicted from archaeological data on the spread of agriculture match past atmospheric concentrations of greenhouse gases that can be inferred from air bubbles enclosed in Arctic and Antarctic ice cores (Mitchell et al. 2013). Obviously, the increase in greenhouse gas concentration due to preindustrial agriculture is dwarfed by the increase caused by industrial emissions, including those from modern agriculture, but it is not only the quantity of greenhouse gases emitted by preindustrial agriculture that matters. Its timing is also important. The climate system does not respond immediately to the upsurge in greenhouse gases in the atmosphere; it is highly inert and takes several decades to respond to change in greenhouse gas concentrations. The preindustrial buildup of greenhouse gases, although smaller, has had much more time than the industrial contribution to trap energy from the sun into the atmosphere. Simulations reported by Ruddiman (2013) suggest that preindustrial warming is somewhat greater than industrial warming.

To summarize, archaeological and environmental research over the last decade has markedly changed the scientific perspective on how climate and agriculture interact: agriculture is not only a "victim" in the story of climate change, it is also a "villain" contributing to emissions even before industry. Thus, agrobiodiversity is a hybrid product of human and natural forces, and is deeply implicated in anthropogenic environmental transformation over the last 10,000 years. Agrobiodiversity forms the tangible evidence of human environmental transformation over millennia. This transformation has brought us into the Anthropocene—the current geologic period defined by human impacts, such as elevated greenhouse gas levels as well as nitrogen and phosphorous levels, on soil and water systems, especially in estuarine environments (Ruddiman 2013).

These findings undermine the perspective of agrobiodiversity as a "natural" solution, because it predates the Industrial Revolution. Ruddiman's hypothesis and the concept of the Anthropocene suggest a change in our perception of our living environment, challenging the idea that we can go back to an equilibrium situation in which agriculture is "adapted" to its environment. Instead of a simple adaptive process in which agriculture slowly moves to an equilibrium, we are observing a nonlinear, coupled process which may not have a stable equilibrium or optimum (cf. Kauffman 1993). This "frame" suggests a far more active historic role for humans in environmental transformation and, at the same time, urges us to take responsibility for charting the course of the global environment in a forward-looking way. Human decisions about land use, energy, and food consumption will shape global climate. In all of this, agrobiodiversity is highly relevant and can potentially, but not inherently, be used as a positive tool for climate action.

Science and Climate Action

How do disciplines which directly set the climate action agenda in climate science and agricultural science frame the climate–agrobiodiversity interaction? The agriculture chapter of the fifth report of the Intergovernmental Panel on Climate Change (IPCC) summarizes the latest research and provides a sampling of the most influential research (Porter et al. 2014). What is evident, however, is the scant attention given to agrobiodiversity. Most of the agricultural research represented in the IPCC report is limited to the main staple crops, based on data from crop trials as well as crop model studies. Crop models are usually parameterized with data from on-station trials and then used to extrapolate the results to other environmental conditions. This approach is compatible with the model-oriented focus of climate science, but it hampers the understanding of wider interactions in which agrobiodiversity plays an important role (Thornton and Herrero 2015).

To explain the narrow focus of climate science, Demeritt (2001) makes the case that climate science is socially constructed. He does not imply that scientific findings are completely dependent on social relationships or that there is no reality outside of the interactions between scientists, but rather that microsocial relationships play an important role in making choices about what to include and what to leave out in the climate models, and what type of evidence is acceptable or not. For example, global circulation models are a very narrow abstraction of global physical reality and exclude a large number of features, such as cloud formation. This type of reductionism is beneficial because it makes reality analyzable and works toward a strategy that provides a clear focus on the importance of climate change as a global phenomenon. At the

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same time, social factors play a role in the decision-making processes involved in defining what allowable abstractions are in a given scientific domain, and these decisions may limit alternative epistemologies. Demeritt argues that social construction of climate science cannot be circumvented. Even though different mechanisms, such as peer review, can provide checks on the quality of science, trust in science cannot be solely generated with an appeal to correct procedures and abstract principles. In the long term, transparency about the social construction of scientific insights is necessary to generate trust in science, a clearer understanding of its limitations, and reflections on alternative scientific strategies.

Similar social analyses also apply to the agricultural sciences. In a recent study, Baranski (2015b) reexamined the role of environmental variation in the social construction of agricultural science behind the Green Revolution, which started in earnest with wheat breeding in India. She argued that the Green Revolution's focus on yields in high fertility and irrigated conditions was rooted in the institutional landscape of India, which had just centralized its agricultural research program. Of importance was also the belief that fertilizers would soon be widely available in developing countries such as India. Scientifically, the breeding approach was defended with the idea that "wide adaptation," or minimizing genotype–environment interactions, would also favor yield gains in more stressed environments. Baranski argues, however, that the photoperiod insensitivity and responsiveness of the new varieties to fertilizers did little to confer yield stability on the new varieties across a range of environments, including rainfed conditions. Using experimental data from the 1960s, Baranski demonstrated that under rainfed conditions, an important Indian tall variety was more stable and more productive in lower-yielding environments than the Mexican variety that was introduced. Despite this evidence and the more recent emphasis on breeding for drought and heat stress, the same views on wide adaptation still prevail in Indian science; these early choices and strategies are now codified into the wheat breeding program.

The problem with these views is that they obstruct the climate signal in plant breeding. Climate information is generally incorporated into plant breeding only indirectly, primarily through the definition of (widely defined) target production environments and specific insights coming from crop physiology about the relative importance of traits for climate adaptation. It could be argued that even though climate may not be a focus of explicit analysis, the climate signal will be picked up by plant breeding as it affects selection environments. Some breeders argue that a main adaptation response would be to keep a focus on broad adaptation, accelerate breeding, and shorten the time between breeding and farmers' use of the new seeds (Atlin et al. 2017). Ideas around wide adaptation, however, are increasingly being questioned. Desclaux et al. (2008) discuss how new demands placed on agriculture increasingly force plant breeders to rethink their approach to genotype–environment interactions. Some breeders have argued that breeding should be a more decentralized process, working with more diverse populations in "evolutionary breeding," which has been shown to work in favor of resilient crops in marginal conditions (Ceccarelli et al. 2010).

Desclaux et al. (2008) go a step further and expand the concept of genotype–environment interaction to involve other aspects of the environments in which crops grow. Climate change affects these environments not only by increasing plant stress but also by affecting other decisions by farmers on their cropping systems and farms. Breeders can no longer reduce a production environment to a few biophysical aspects. Crop management is not just a factor limiting the genetic potential of varieties but is important in itself and involves multiple trade-offs. In the future, crop physiology needs to play a more important role than just informing the overall setting of priorities. Currently, crop management and its interaction with diverse environments play an increasingly important role in breeding decisions, as environmental sustainability gains in importance, including reducing greenhouse gas emissions from fertilizer use. Desclaux et al. (2008) review several options to subject this expanded view of the environment to analysis and reflection. These authors find, for example, that a broader range of stakeholders needs to be involved in priority setting and that new demands placed on agricultural science can be addressed by increasing transparency and democracy. Demeritt makes a similar point for climate science (see above). New analytical techniques are being developed to tease out the influence of weather and other environmental factors in multiple environment trials. The aim of these analyses is to attempt to predict or address genotype–environment interactions rather than to remove them.

A stimulus for incorporating environmental data in breeding is the trend toward genomic "big data," which has not yet fully been paralleled with a similar effort for environmental big data. For example, Heslot et al. (2014) offer an approach to incorporate weather data into genomic prediction, a technique to predict phenotypic values from genomic information. They derived a range of environmental stress variables from weather data using simple crop growth models. Including these variables in the analysis improved the predictive power of models. This and similar approaches represent important progress, as they enable us to study the interaction between genotypic and environmental variation simultaneously, in a biologically meaningful way, to allow prediction across different environments. This opens up a range of new opportunities to generate physiological insights into plant environmental adaptation directly in breeding experiments.

The role of plant genetic diversity in breeding is likely to become even more important under climate change (see Chapter 5). Heisey and Day-Rubenstein (2015) predict that genetic resources will increase in value as climate change increases the demand for traits that confer stress tolerance. They cannot predict, however, which types of genetic resources will prove to be most useful in the future for breeding for climate adaptation: landraces, crop wild relatives, or nonplant genetic resources (such as useful soil organisms).

Nonetheless, gene bank collections have more value if information about their biology and environment of origin is available. Little hard data is available, however, about the economics of the use of plant genetic resources in breeding (for an overview, see Heisey and Day-Rubenstein 2015). Studies show that the costs of searching for accessions with biotic resistance traits are lower than the benefits these accessions give to breeding. In addition, they argue financial support for gene banks relative to the total revenue of the seed sector seems small. As a source of agrobiodiversity, the importance of gene banks will increase for climate adaptation; new breeding technologies will not undermine their function but rather expand it.

While climate is being factored explicitly into agrobiodiversity management for technology development and introduction, agrobiodiversity is also relevant for farm management strategies (see Chapters 6 and 8). Thornton and Herrero (2015) argue that interactions between components in farming systems can be managed to respond to climate change, with their study emphasizing interactions between livestock and crops. Branca et al. (2013) summarize some of the evidence for agrobiodiversity-based practices that are providing both adaptation and mitigation benefits, including agroforestry practices and nitrogen-fixing species. Still, little is known about the exact yield effects of many of these practices or how interactions within farming systems are affected by climate change. Consequently, farming system assessments have been largely absent from IPCC reports. Thornton and Herrero (2015) argue that to analyze the agricultural system, we need better models, scenarios, and indicators. Models are needed for a broader range of crops for which detailed crop models are currently unavailable. In addition, more data is needed to assess whole farm strategies. This requires consistent data across a range of metrics, including productivity, livelihood strategies, and nutrition. Thornton and Herrero argue that different data collection strategies are needed, using modern technologies and citizen data collection, to meet these needs. Hammond et al. (2016) present a relatively “light” electronic survey instrument that collects a large number of simple indicators. Agrobiodiversity is taken into account explicitly in this instrument (crop diversity, diet diversity) and can be analyzed in conjunction with indicators on greenhouse gas emissions, poverty, gender, and food security, among others, to assess the trade-offs and synergies in different agricultural systems and livelihood strategies.

Within agricultural systems, diversification is arguably an important risk management strategy and an important role for agrobiodiversity management. This is less controversial for mixed crop–livestock farming (Seo 2012) than it is for crop diversification (Lin 2011). For example, Barrett et al. (2001) have suggested that crop diversification is of limited importance as a strategy for risk management because yields of different crops are, in general, positively correlated. From plant modeling results, Gilbert and Holbrook (2011) suggest that diversification within grain crops does not contribute much to risk management, but that growing crops of different functional types or diverse physiologies (such as vegetables) does help to spread risk.

Empirical evidence on the role of crop diversification in risk management is rare because microstudies with detailed time series of crop yields require significant investments in repeated field data collection. One such long-term field study was reported by Matsuda (2013). He studied the upland farming systems of central Myanmar, which face very large interannual variation in rainfall. Myanmar farmers have a diverse agricultural system: pigeon peas, cotton, and sesame are the main crops. Each of these crops responds in different ways to climate variation, buffering the impact of drought. Yields between the main crops in central Myanmar farming systems showed a weak or even slightly negative correlation over the seven-year study period, which means that together they form a good portfolio for risk management.

Matsuda (2013) compared these findings with the farming systems in northeast Thailand, where interannual variation of rainfall is also high. In this area, rice is the predominant field crop and there are very few other crops, except in home gardens. Rice is grown under rainfed conditions and yields vary highly between years. In some years, the harvests are low or fail completely. Agrobiodiversity plays a very minor role in risk management in this area. Risks are mitigated between years through rice storage. Off-farm labor also provides an important buffer against income variation. This comparison demonstrates how risk management can take different shapes in different agricultural systems, depending on the actual configuration of farming systems, livelihoods, and institutions (see Chapter 8).

Padulosi et al. (2011b) argue that agrobiodiversity could play a larger role in climate adaptation through the expanded use of crop species that are currently underutilized. They hold that many underutilized species adapt to a wide range of environments and are tolerant to a range of stresses. Little information, however, is available on how these crops would function in new, adapted cropping and farming systems. From the perspective of climate action, prior evidence on the potential contribution of these species to production and livelihoods would be needed to justify targeted investments in research and development before their use is expanded. Systems analysis, however, has its own drawbacks: system modeling approaches often require a large amount of data, propagate uncertainties, and may provoke “analysis paralysis.” Addressing this complexity is the main challenge.

Information, Networks, and Diversification

Scientific understanding of the interaction between climate and agrobiodiversity may have been limited by path-dependent historical choices in agricultural research, the need for closure in research strategies, and selective policy support. A number of alternative strategies have been suggested that

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are methodological in nature. What would be the corresponding theoretical perspective? To encourage a broader perspective, one approach would be to focus the discussion around concepts of *information*.

Utilizing the insight of Quiggin and Horowitz (2003), one of the main effects of climate change is to *destroy information*. For agriculture, this means that local knowledge about how to manage plant, animals, and environments becomes increasingly less valid, as conditions change. Under new conditions, well-known practices no longer work: species, varieties, and breeds are no longer adapted to local conditions; environmental observations no longer lead to reliable predictions; and well-honed skills become obsolete. Agrobiodiversity is arguably one of the most important forms of information in agriculture: it involves the genetic information contained in the biota that constitute agriculture as well as information (held by farmers, consumers, and institutions) about the functions of these biota that organize agrobiodiversity in time and space. Adapting to future climates and reducing emissions will involve creating new information at an accelerated pace. Even though the capacity of farmers to generate new information is important and needs to be strengthened, it cannot be assumed that the historical capacity of farmers to adapt to extreme climates or socioeconomic change will guarantee adaptation under highly accelerated, nonlinear, or disruptive change. While some aspects are visible to farmers (e.g., yield), others are highly invisible or not of immediate influence to their livelihoods (e.g., landscape degradation, emissions). Creating new information will be very challenging: it is often not codified but rather held as part of tacit knowledge gained through experiential learning; it is also embodied in artifacts or evolved populations of domesticated plants and animals. New information will need to be generated that is accessible at all levels.

In his book *Why Information Grows,* Hidalgo (2015) presents a new concept of information. Building on previous work by Kauffman (1993) on “complex systems,” Hidalgo argues that biological evolution and economic growth processes are characterized by the growth of information. In this context, information is not the usual “entropy” of information theory (the Shannon index, which has no relation to meaning or function). Instead, information is defined as a measure of *order*, a concept in which function plays a role. This idea of information is actually much closer to the meaning of information as used in common language. Information growth in these studies is the product of functional diversification in both biological and economic systems.

An important implication of the theoretical work of Hidalgo, Kauffman, and others is that the growth of information or diversity depends on the size of interaction networks. In the industrial sector, for example, complex, less ubiquitous artifacts are created through the collaboration of a number of producers who specialize in certain components, which are then assembled. Economic growth is to a large extent the outcome of the ability to create and participate in such networks. In policy terms, this would mean that stimulating diversity, complementarity, and connectivity of economic activities are main ingredients

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of economic growth. Hidalgo (2015) shows the relation between economic diversification and economic development using data on international trade, but the theory would predict similar effects at other scales and for other sectors.

In parallel to this research, a small but growing number of studies explore how human networks underpin the ability to manage agrobiodiversity for climate adaptation. Bellon et al. (2011) show that for maize farming in a Mexican landscape with altitudinal gradients, farmers may have access to genetic materials adapted to future climates within the current geographic scope of their networks. Mwongera et al. (2014) did a detailed comparative study of two communities that occupy similar environments on Mt. Kenya. One community has been able to adapt to drought conditions much better than the other community. The community with better adaptive capacity has more intensive seed exchange with the drought-prone lowlands.

In a study on cotton seed acquisition behavior in Andhra Pradesh, India, Stone et al. (2013) show a case of maladaptation. They found that farmers' observations on the phenotypic performance of different cotton varieties hardly influenced their seed choices. Instead, farmers tend to imitate others and seek out new trends. As a result, there is a fast turnover of with cyclical fads sweeping through diffusion networks, but no detectable improvement of the varieties selected over time. Thus, varietal selection lacks environmental learning, which makes it very difficult for the seed system to pick up any climate signal. Stone et al. explain this as the result of a process of cotton farmers' gradual loss of agricultural skills of seed selection, which became superfluous when farmers started to depend on commercial seeds. The "wisdom of the crowd" principle points to the degree of independence between observations as a necessary property for networks to generate true information in response to external signals (Surowiecki 2004).

Complex agricultural systems can be regarded from the same perspective as complex industrial artifacts: both embody human interactions and knowledge. Agricultural diversification, including crop diversification, is important from a climate perspective (see above). Increased integration into financial and labor markets can, however, substitute the "natural insurance" function of agrobiodiversity, leading to the abandonment of certain species, varieties, and breeds (Baumgärtner and Quaas 2010). Partially replacing the natural insurance function of agrobiodiversity does not necessarily entail a net destruction of "information" from Hidalgo's (2015) perspective. The focus of climate information and financial service provision is on expanding the information network in which farmers are embedded. The effect of these interventions is to partially replace one type of information—agrobiodiversity in agricultural systems—with other types of information, embedded in new financial and information services. Brookfield (2001) introduced the concept of *agrodiversity*, which encompasses agrobiodiversity but also diversity of other elements that underpin agriculture institutions, management, and culture. It could be argued that within agrodiversity, different types of information or diversity may partially

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substitute each other in the "growth of information" during economic development. Likewise, different types of agrobiodiversity may replace each other. Duvick (1984) has described the development of a commercial seed sector as the replacement of diversity in space by diversity in time, from the diversity of landraces in different niches, to the quick turnover of crop varieties over larger areas. It is clear, however, that the substitutability between more and less "embodied" types of agrobiodiversity information is far from perfect. Material genetic resources (e.g., seeds in gene banks) and nonmaterial genetic information (e.g., gene sequences in digital format) are becoming more exchangeable as genomics, bioinformatics, gene editing, and developments toward synthetic life increasingly shape the way that breeding is being done. Even so, many aspects of agrobiodiversity as information remain embodied as they are associated with agricultural skills tied to specific places or knowledge about plant or animal performance and interact with managed environments that are difficult to transfer to new situations.

Even though different types of diversity can partially substitute each other, the theories discussed above suggest that a balanced climate action strategy should focus on diversification across various domains and scales, and that a narrow strategy of institutional and productive specialization should be avoided (see also Chapters 6 and 8). Highly developed agricultural systems are knowledge intensive and make smart use of agrobiodiversity, not only for its risk insurance function but also for many other purposes. For example, greenhouse horticulture in Europe, perhaps the most highly technological agricultural subsector, provides strong biological solutions to pest and disease problems, such that agrobiodiversity use makes chemical pest control no longer necessary (van Lenteren 2000). Agrobiodiversity creation should therefore keep pace with overall agricultural development and compensate the loss of information due to climate change. For example, modern crop variety development will only contribute to resilience if it has wide access to genetic resources, if it can periodically release genetically diverse, adapted varieties (cf. Duvick 1984), and if farmers have the capacity to purchase seeds and replace varieties over time based on reliable information (cf. Stone et al. 2013).

Current policies of developing countries and development donors, however, tend to stifle diversification. Pingali (2015) has documented the extent to which policies support staple grains to the exclusion of other crops. This reflects historical concerns about calorie supply; however, this policy focus fails to support diversification as a risk management strategy and is also incompatible with other policy goals, such as the fight against micronutrient malnutrition and child stunting as well as overweight and obesity. Pingali calls for a "crop neutral" policy instead, one that supports farmers' crop choices in response to market demand. Such policies would simultaneously allow farmers to respond to climate signals. Pingali argues that governments need to create a supportive environment for diversified agriculture through credit and infrastructure.

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A specific stimulus for knowledge and information creation is needed, not only as an integrated part of the economic development process, but also to compensate for the loss of information due to climate change. There is now a growing body of scientific literature on knowledge creation, the role of networks, and diversification. As we look toward the future, we need to ask how these insights can be translated to climate action. In practice, diversification is often mentioned in climate action plans (Bedmar Villanueva et al. 2015), but scientific studies provide few actionable insights to inform such strategies. An emerging information "frame" could eventually provide an approach to evaluate diversification strategies.

Design

Recent scientific publications have characterized the challenges that agriculture faces as so-called "wicked problems." Most certainly, climate change and increasing pressure on natural resources cannot be addressed through agrotechnological solutions alone. These problems are "wicked" because their solutions require changes in human behavior as well as the values held by agricultural producers, traders, consumers, and the institutions in which these actors are embedded. Scientists have responded to this "wickedness" by supporting a more systemic perspective and by stimulating co-learning processes for stakeholders to collaborate with scientists (Kristjanson et al. 2014; Struik et al. 2014). Both approaches have been suggested in relation to the interaction between climate and agrobiodiversity.

In the context of climate change adaptation and adjacent domains, the metaphor of "pathways" is often used to refer to decision-making processes that address the "wickedness" of problems. In their review of the emerging literature on pathways, Wise et al. (2014) critique the "predict-and-provide" and impact-analytical approaches that have been followed thus far by the IPCC, both of which "close down" the problem too early in the process. The pathways metaphor is deemed to be better at acknowledging (a) the connected nature of the climate adaptation challenge across space, scale, and organizational domains; (b) the inertia in many processes that result from path dependency; (c) the difficulty of monitoring adaptive responses; and (d) the way in which institutional culture enables or constrains social processes. Wise et al. (2014) suggest a number of deliberative and participatory methods that work well, such as scenario building, future visioning, and stakeholder forums.

The term "wicked problem," however, is rooted in an incisive critique of science itself. As one of the founders of the modern design movement (see Buchanan 1992), Horst Rittel coined the term to argue that there are problems that science is unable to address. Wicked problems are badly structured problems that are open to multiple interpretations, but with a single opportunity to find a solution. Scientists normally address relatively well-defined problems,

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find solutions that are either right or wrong, and can repeat their tests for as long as time and resources allow. Rittel suggested that design is not an applied science. Designers would never find creative solutions to problems if they simply applied scientific insights and did not produce novel knowledge themselves; design thinking uses problem-solving strategies that are different from those of science.

Climate change, agrobiodiversity, and their interactions have all the characteristics of wicked problems as put forth by Rittel. Archaeological and environmental studies characterize the climate–agrobiodiversity interaction as a historically contingent process. The climate change problem is not well defined; it challenges existing, narrowly defined models, especially when the role of agrobiodiversity comes into the picture. Climate action is an urgent, real-time challenge: only time will tell what is right or wrong. The climate change problem breaks down into many other complications.

Since the design community has engaged with these types of problems for a much longer time than other disciplines, it is important to examine the approaches developed by designers. The approaches discussed by Wise et al. (2014) share a large number of characteristics with elements emphasized in design literature, but there are also differences. In a recent book on design methodology, Dorst (2015) argues that a main distinguishing element of design thinking is that it places the creation of new frames at the center of the problem-solving process. Often, a design problem cannot be solved on its own terms; thus reframing the problem becomes essential to finding a solution. The connectedness of a problem should not be reduced by applying an obvious existing model to the situation just to make it manageable. Instead, designers treat the connections as a context that can lead to fresh solutions. They distil their findings as themes that are used to suggest different metaphors or patterns of relationships. These patterns are then tested to see if they provide new and inspiring suggestions toward a solution. One example from Dorst's book is a nightlife area in Sydney, where crime rates were invariably high, despite increased police presence. Designers suggested the frame of a "music festival." This frame proposed a large number of effective solutions that although commonplace in managing music festivals were never imagined when the problem was framed as one of policing and crime. Dorst describes "frame innovation" as a disciplined process of problem solving, outlines the principles that guide the process, and illustrates the process with successful examples (and failures) of redesign of public spaces, care provision systems, and retail experiences. Over time, designers accumulate experience and develop a particular set of skills and reasoning style that can be applied to a diverse set of problems.

Agricultural scientists have started to explore design approaches, especially in agroecology. Duru et al. (2015) suggest that to support the design and implementation of biodiversity-based agriculture, it is crucial for learning tools to be created. Knowledge bases are one type of support tool "that contain structured scientific facts and empirical information compiled from cumulative experiences and demonstrated skills and that enable biodiversity management to be inferred in specific situations" (Duru et al. 2015:1272). To improve adaptive management, they also emphasize the importance of easy-to-use monitoring tools to assess *in situ* the ecological dynamics of diversified farming systems and landscapes. Another approach is to use game-based modeling methods as learning tools to explore different dynamics. The new role for science in the perspective sketched by Duru et al. (2015) is to support design processes that generate locally specific, agrobiodiversity-based solutions to complex challenges.

Berthet et al. (2016) compare three different design methods used in agriculture: one is based on a modeling approach, another on a game, while the third is based on a collective design process after a methodology used in other economic sectors. The modeling and game approaches involve artifacts which focus the attention of participants on the design process and provide a useful learning experience in itself, but also constrain solutions in some way. The particular modeling approach chosen is especially appropriate to explore stakeholder conflicts. Of these three approaches, the collective design approach comes the closest to the frame innovation process described by Dorst (2015). Different experts were invited to talk about aspects of alfalfa meadows, the focus of the design process. The collective design approach, moving between existing knowledge and new concepts, was shown to be instrumental in drawing out the different potential functions of alfalfa meadows, and the process suggested new solutions that were subsequently implemented. Berthet et al. argue that the collective design approach could be especially useful in the first stages of an innovation initiative, while the game-based exercises may be more appropriate when solution directions are clearer.

Frame creation itself is not made explicit in the description of the collective design process (Berthet et al. 2016). Reference to a concrete, named frame may further help to bring about a common focus and motivate a collective vision from which more detailed solutions flow in a natural way to address the complexity of the problem at hand. Clearly, more design experience needs to be gained in the context of agricultural climate action and related to complex problems. It seems clear, however, that much can be learned from design experiences in other sectors.

Summary and Conclusion: Clumsy Solutions

From a historical perspective, climate–agrobiodiversity interactions have undergone a radical reframing. Crop diversity emerged out of landscape-use practices after foragers and hunters intensified their use of the land and became more sedentary and reliant on local resources as a result. Diversity was the "by-product" of processes that did not have diversity creation as their conscious purpose: prehistoric migration of agriculturalists and cultural diffusion.

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Conscious selection contributed to diversity creation as well, but it was not a specialized process (see also Chapter 6). Climate adaptation was a result of trial and error while agriculture contributed to modifying the global climate. Modern breeding threatened crop diversity but at the same time needed plant genetic resources as a "standing reserve." This new framing of agrobiodiversity led to plant genetic resources conservation for breeding purposes, mainly in gene banks. Climate adaptation did not initially factor into this frame as breeding was premised on the radical transformation of growing environments through irrigation and fertilization that sought to diminish the influence of climate on production. Over the last two decades, framing has shifted. Agrobiodiversity is now viewed as a defining characteristic of ecologically and economically healthy networks of knowledge creation as well as both unintentionally and consciously designed agroecosystems or components. This corresponds to climate action as a broad response to a combined biophysical and social challenge.

This account is an oversimplification because these frames are not subsequent phases in the history of agriculture; they coexist with each other. Agriculture still holds much agrobiodiversity through *de facto* conservation, without an overall conscious strategy. Gene banks continue to play a clear role in conservation and breeding, but the ecosystems services value of *in situ* management has gained increased recognition. New attempts to create agrobiodiversity-based agriculture are still incipient and partial. Frames persist because social forces uphold them and a relatively coherent set of values underpin them. These frames will also be implied in the ongoing societal debate about climate action and agrobiodiversity. Both climate change and agrobiodiversity are highly contested areas with debates over multiple interlocking issues.

Verweij et al. (2006) note that opposing frames resurface continually in climate policy debates. Worldviews and social interactions tend to sustain each other, resulting in a limited number of stable institutional cultures. These cultures are organized around mutually exclusive principles but need each other, as neither will solve social problems alone. For example, markets typically need governments to function, yet problems surface when one of these cultures dominates. Verweij et al. argue that the Kyoto Protocol failed because it relied too much on a hierarchical culture that framed the prevention of climate change as a public good. The Protocol did not represent a balanced mix of institutional cultures. Specifically, "carbon trading" had little to do with real markets. Opponents of the Protocol emphasized values important in individualistic institutional cultures. Other opportunities exist for climate action and may more likely be able to garner support from different institutional cultures. Verweij et al. argue that renewable energy could be supported by public investment, at the same time providing opportunities for companies and constructive civic and local action. They call the arrangements that accommodate opposed institutional cultures "clumsy" solutions (Verweij et al. 2006:839):

> Clumsy institutions are those institutional arrangements in which none of the voices—the hierarchical call for "wise guidance and careful stewardship," the individualistic emphasis on "entrepreneurship and technological progress," the egalitarian insistence that we need "a whole new relationship with nature," and the fatalists's asking "why bother?"—is excluded, and in which the contestation is harnessed to constructive, if noisy, argumentation. Clumsiness emerges as preferable to elegance optimizing around just one of the definitions of the problem and, in the process, silencing the other voices.

Climate action around agrobiodiversity would benefit from this type of "clumsiness." Through frame innovation, new frames could be identified that hold opposing institutional cultures in creative tension. As an example, a number of national gene banks, including those of India and Ethiopia, have started to transfer crop seed samples directly to local and farmer organizations as part of the "Seed for Needs" initiative to restore or introduce agrobiodiversity, often with a specific focus on climate-induced stresses. This reframes gene banks: they are no longer only a "standing reserve" of plant genetic resources to breeding. A new configuration emerges similar to how renewable energies are being managed. Renewable energy is difficult to store and requires careful, information-rich management of demand and supply in a so-called "smart grid." In the same way, gene banks cease to be the equivalent of long-term stocks of fossil resources and become the "batteries" or "supercapacitators" in a "smart grid" for agrobiodiversity that would also connect with community seed banks. In such a new configuration the management of flows of seeds and information is what would drive diversity, rather than the dispensation of resources from a central deposit.

Climate change poses one of humanity's main problems today. Diversity—agrobiodiversity as well as economic and institutional diversity—will play a key role in climate action. Ultimately, climate action will depend on our human capacity to innovate technologically, economically, and politically. An important challenge in all of this will be to channel human creativity to expand and support diversity.

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