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BALANCING COMPLEXITY AND PRAGMATISM TO DRIVE AGRICULTURAL ADAPTATION

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By

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Abstract

BALANCING COMPLEXITY AND PRAGMATISM TO DRIVE AGRICULTURAL ADAPTATION

Jon Eldon

Agricultural systems are highly complex, due to both inherent characteristics such as emergent processes and transient dynamics, and often high levels of ignorance and uncertainty regarding the relevant system components and interactions. Agricultural systems are also often targeted for change to increase various performance measures or decrease undesired social and environmental externalities. As a result, this complexity is not merely a theoretical issue, but also a practical one, and effective adaptation of these systems requires balancing an appreciation for complexity with the pragmatic goals and constraints of these efforts. This dissertation presents three related interdisciplinary studies that wrestle with this problem in three distinct contexts and for three often-distinct audiences. The first chapter focuses on the field of development studies, where academics, government officials, and members of non-government organizations discuss ways to bring about societal change, often relating to rural livelihoods and non-industrialized nations heavily dependent on agricultural systems. This chapter assesses the discussions among these diverse participants and provides a resolution for semantic entanglements so that the complexity of the problems does not undermine the practical efforts for change. The second chapter is directed towards land managers working in Mediterranean landscapes as they seek to influence land use changes and alternative agricultural practices to increase soil carbon storage. This chapter summarizes the relevant scientific literature and discusses related issues to both inform immediate action and direct future research. The third chapter is a multi-year study in Senegal and The Gambia that uses a network of farmer field trials to test alternative seed and soil

management practices within a socially and spatially heterogeneous system. Rather than supporting the current recommendations or identifying alternative “best practices,” these trials identified a range of adaptive options that were comparably effective but varied widely in cost, risks, and availability. This finding encourages farmers to actively explore their alternatives rather then simply adopt official recommendations, and for researchers to support this through more collaboration and less prescription in agricultural research.

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Memorandum regarding previously published material

The text of this dissertation includes reprints of the following previously published material:

> Eldon, J. (2017) What we talk about when we talk about "development", *Cogent Social Sciences*, 4: 1336855.
>
> Eldon, J., & Gershenson, A. (2015). Effects of cultivation and alternative vineyard management practices on soil carbon storage in diverse Mediterranean landscapes: a review of the literature. *Agroecology and Sustainable Food Systems*, *39*(5), 516-550.

The co-author listed in the second publication, Dr. Alex Gershenson (San Jose State University), directed and supervised the research that forms the basis of that chapter of the dissertation, but was not included in my final dissertation committee due to a subsequent shift in focus. Dr Gershenson secured funding for this research and corresponded with the publishing journal, while I conducted all of the underlying research and wrote the entirety of the final manuscript.

General Introduction

Agricultural systems are ecosystems that are managed under economic and logistic constraints to meet social needs and interests related to food and fiber production. As such, they are critical to a broad range of issues and interests, from environmental concerns related to conservation and ecosystem services to social concerns related to poverty and justice. While the interested parties vary widely, they agree that agricultural systems throughout that world are underperforming in important ways and need to be adapted to better meet a range of goals, such as increased yield and input efficiency, or decrease reliance on inputs and unwanted externalities.

Such a statement would be a suitable introduction for a dissertation that focused on anything from the use efficiency of nitrogenous inputs to the legal details of international trade policies. The implication with such transitions is that the specific focus would be particularly appropriate response to the more general problem, and this is often directly stated. There is nothing necessarily wrong with this approach and it is important to both focus on specific problems and contextualize them within larger issues. However, this habit of quickly jumping from a general concern to a specific response can distract from the fact that there are numerous equally valid but radically different specific responses, and a whole series of response at intermediate scales linking the research specifics with the general context.

This dissertation takes a different approach, and the following chapters are not linked by a specific geographic focus or a single highly focused research question, but by a larger epistemological problem facing efforts to bring about change within agricultural systems. Agricultural systems are inherently complex, which means that

that they behave in surprising or non-linear ways that are difficult or impossible to predict in the way that an engineered system might be predictable. This is a result of both inherent features, such as emergent processes and transient dynamics, as well as incomplete and uncertain knowledge of these systems. As such, they cannot be treated like engineered systems or reconstituted from reductionist or piecemeal analysis. This complexity in agricultural systems can be investigated as a purely theoretical problem, but—like it or not—the results are often applied to practical concerns, such as management strategies and alternative policies. This problem then is how to balance complexity and pragmatism to drive adaptation in agricultural systems.

This problem is not pursued directly—whatever that might look like—but through three more focused interdisciplinary studies that are practical and pertinent engagements with this philosophical issue. These studies address this epistemological problem within three different study systems and with three different target audiences in mind. The first looks at the interdisciplinary field of development studies and seeks to help academics better understand the semantics of these conversations so that they can better participate in them. The second summarizes the scientific literature on soil organic carbon storage within diverse Mediterranean landscapes to help land managers make carbon-informed decisions. The third investigates alternative management options within a complex and heterogeneous agricultural landscape in semi-arid West Africa to help farmers and rural organizations make more adaptive decisions.

Chapter 1: Processes, patterns, practices, and perspectives: What we talk about when we talk about "development"

The first chapter, which will be published in the Sociology section of *Cogent Social Sciences* in June 2017, is a study of the semantics of the term "development" within the field of development studies. This emerging field has far-reaching interests related to international relations, social and institutional change, rural poverty, poverty alleviation efforts, and many other interrelated topics. Agricultural systems and adaptive change are dominant themes in this literature, which addresses many perspectives and issues not normally appreciated in the agricultural sciences. The field of development studies explicitly appreciates the complex nature of the relevant questions, and emerged as an academic subject through the recognition that no single discipline to properly tackle the necessary issues alone. The field also has high practical engagement with these issues, and the participants are often trying to inform policy decisions, influence non-government organizations, or find some other way to effect change.

Unfortunately, these efforts to balance complexity and pragmatism are limited by some avoidable semantic confusion. The term "development" is central to this interdisciplinary conversation, but it is used in diverse and highly specific ways among the participating disciplines. Economists are likely to use it to refer to economic growth, politicians might assume it refers to specific policies and deliberate interventions, and anthropologists often relate it to externalities of colonization and globalization. These meanings are well understood within each discipline but there is little shared understanding between them. Careful semantic analysis is not necessary in the former, and perhaps as a result it is not common in the latter. Instead, influential authors in the field are willing to conclude that the term "development" cannot be defined, even though it is used to define the field itself. Most authors have been willing to leave this situation there, perhaps in their hurry to tackle the complexity of the issues and get on with more normative efforts.

This chapter applies Confucius' insight that the "rectification of names" is a necessary first step in an intellectual investigation, and directly investigates this semantic question directly. Using insights from Socrates and Wittgenstein, I survey the development studies literature to produce a descriptive typology of the variety of distinct but related ways the word is used in the field. I then demonstrate the benefit of this typology for interpreting complicated discussions of "development" by conducting a textual analysis of influential texts that propose provocative alternative understandings of "development." I then do the same for articles from the prominent journal *World Development* to examine shifts in patterns of use over the last 40 years. In doing so, I am able to document evidence of the maturation of development studies from a conglomerate of multiple distinct disciplines to an increasingly unified field that in the future may be considered a coherent discipline in its own right.

Chapter 2: Effects of Cultivation and Alternative Vineyard Management Practices on Soil Carbon Storage in Diverse Mediterranean Landscapes: A Review of the Literature

The second chapter, which was published in *Agroecology and Sustainable Food Systems* in 2015, is a literature review of how soil organic carbon levels are affected by changes in land use and land cover, and how these changes can be mitigated by alternative agricultural management practices. These related questions reflect a growing shift towards investigating and responding to climate change and other environmental issues at ecosystem or landscape scales, and to do so by balancing multiple interacting forces. Such systems approaches are in contrast to more reductionist investigations that target specific processes but do not attempt to bring them to bear on each other. For example, the possibility of carbon sequestration through alternative management practices has often been investigated at the field scale and without any historical context. Such analysis can be interesting, but it is not sufficient to understand overall landscape carbon storage patterns or opportunities, or to direct efficient management practices within diverse settings. Such interpretations requires additional analysis, such as comparing the potential effect of alternative practices against the amount of carbon that was originally lost through the conversion of the land into agriculture, or could be recovered through alternative land uses, rather than alternative agricultural management practices.

This particular study was conducted at the request of The Nature Conservancy of California to inform their activities within agricultural landscapes, so is a clear example of the need to balance the complexity of the relevant processes with the pragmatic need to inform management activities. Given the geographic context, The Nature Conservancy was particularly interested in questions of carbon management within Mediterranean landscapes and commercial vineyards. Their request was simply to summarize the relevant literature and develop carbon budget estimates to inform spatial models. Unfortunately, this was not simply a case of insufficient knowledge reaching management practitioners, but also of a research gap within the scientific literature. Despite the substantial interest in carbon storage within managed landscapes, I found a serious dearth in relevant studies on both change in land use/cover and the effects of alternative vineyard practices. There was also a tendency to rely on inappropriate methods, such as shallow sampling depths. This question was therefore not simply a case of the ecological processes being complicated and dynamic, but also dramatically incomplete knowledge of those processes.

The initial hope was to perform a meta-analysis to draw quantitative conclusions, but due to the limited availability and often low-quality of relevant published research, I had to settle for a literature review. The general pattern that I found was of dramatic declines in soil carbon with conversion of native Mediterranean land cover types into agriculture, with vineyards often containing the least soil carbon of any land use. Alternative management practices with vineyards could increase the soil organic carbon levels, but it was clear that even the best practices could recover only a fraction of the lost carbon. I concluded this literature review with a critical analysis of certain methodological practices and assumptions, recommendations for research priorities and alternative strategies, and a discussion of the risk of making strong quantitative conclusions or predictions from insufficient and highly variable information.

Chapter 3: Field trials identify multiple adaptive management options within a complex and heterogeneous agricultural landscape in West Africa

The third and final chapter focuses on the balancing of complexity and pragmatism to inform independent farmer management decisions within rainfed cropping systems in Senegal and The Gambia. These countries form the western edge of the African Sahel, which is the region south of the Sahara desert that gets just enough rainfall to support agriculture. "Sahel" is the Arabic word for "shore," a reflection of the marginal nature of this region, and it is prone to periodic droughts and famines and often considered ground zero for how climate change is affecting agricultural livelihoods. Accordingly, the Sahel and adjacent semi-arid regions are a major target of international development efforts, which often focus on improving the rainfed cropping systems that are the primary source of food and income for the rural population. The pragmatic need for agricultural adaptation in this region is clear, but the complexity of the local agricultural systems is often overlooked, and as a result these efforts have been far less effective than expected.

At first glance, Senegal and The Gambia appear to be relatively homogeneous countries. They are flat, consist largely of sandy and low organic matter soil, and contain a continuous rainfall gradient from around 200 mm/year in the north—just enough for pasture and marginal crop growth—to over 1000 mm/year in the south—enough for thick monsoonal forests. By global standards, the rainfed cropping systems are also fairly homogeneous, with little fertilization or mechanization and low productivity. They look nothing like the highly productive systems of more industrialized countries but, the thinking goes, they should. Most agricultural recommendations in the region, and even the way in which research is done and recommendations are made, are primarily derived not from the local systems but from some more industrial example. Agricultural adaptation is often assumed to be analogous to the adoption of practices from these more productive systems.

On second glance, however, there is a high level of spatial and social heterogeneity that is relevant to rural livelihoods and greatly influence the ways in which these systems can change. A great adaptive opportunity for one farmer might be impossible or even maladaptive for their neighbor due to subtle differences that might easily go unnoticed by the most careful researcher. This heterogeneity is due to factors that are known but often overlooked, such as political insecurity, factors that are known but difficult to quantify, such as household purchasing power, and factors that may simply be unknown to researchers, such as farmer preferences. Moreover, the fact that one system is not as productive as another—which is only one of many measures of performance in an agricultural system—does not mean that it can be transformed through simple imitation. Adaptation, as understood in ecology and evolution, is not “adaptation towards” some target or end goal, but “adaptation from” some starting place, and the situation is no different in agricultural systems.

This research turned the conventional approach to driving agricultural adaptation on its head by emphasizing relative change from the current practices and performance, rather than to some optimal or idealized state. Trials were conducted not on research stations under carefully controlled conditions, but in farmers’ fields and with their full participation, such that the results would best capture the full complexity and heterogeneity of the system. This research was conducted over three years through partnership with local and international non-government organizations and thousands of participating rural households. It began with 50 trials in 2014, expanded to 420 trials in 2015, and finished with nearly 600 in 2016. These trials were split among 6 major crops and 7 regions spanning the heterogeneity of Senegal and The Gambia. Half of the trials tested multiple new cultivars and the other half, which are discussed here, tested alternative practices relating to 1) certified seed stock of new cultivars, 2) inorganic fertilization, and 3) local organic materials. These pathways are all sometimes used to improve yield, but differ widely in cost and availability. Eighteen different treatments were tested on each of the 1000+ trials, one of which was the common practice of using local seed and no fertility inputs, and another was the common official recommendation of using new seed, high levels of inorganic fertilization, and no organic amendments.

These trials found that each of these three adaptive pathways—new seed, inorganic fertilizer, and organic amendments—could improve the production of rainfed crops, and the benefits were reliable across these countries, comparable to each other, and largely additive in combination. The recommended practice, which relies on imported high cost inputs, on average doubled the crop yield, but this same result could be had through three of the other treatments, which were all lower cost and less dependent on infrastructure and global markets. Other practices had a greater effect than the recommendation, and the addition of a low rate of manure to the recommended practice led to nearly a tripling of yield. However, the outcome of these trials was not to identify some new general recommendation for maximum production but to get away from that top-down prescriptive sort of approach entirely and to emphasize the role of farmer decision-making in agricultural adaptation. That there are multiple adaptive options rather than a single "best practice" is of critical importance, and presenting farmers with options and allowing them to determine what it best for their circumstances is a new and highly effective means of driving change within complex and heterogeneous agricultural systems.

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Processes, patterns, practices, and perspectives: What we talk about when we talk about "development"

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Abstract: "Development" is a central term in an interdisciplinary discussion that brings together a diverse range of more conventional disciplines, including economics, politics, anthropology, and history. While this word is often used in highly specific ways within each of these contributing fields, the use can vary widely between them, leaving explicitly interdisciplinary discussions of "development" open to unnecessary semantic confusion. This paper breaks this multifaceted term down into the individual facets and constructs a descriptive typology that can be used to interpret individual uses in a text. This typology is then applied to four classic works that attack conventional understandings of "development" and a selection of articles in the journal *World Development* from 1973, 1993, and 2013. This analysis appears to document a maturation of interdisciplinary discussions of "development," as evidenced through observation of increasing rigor, specificity, and a now nearly standard reliance of adjacent qualifying terms when "development" is used in an interdisciplinary text. However, it also finds that while these qualifiers are a semantic aid, they are not a satisfactory replacement for careful use of the term and clear presentation of the underlying ideas.

Jon Eldon

ABOUT THE AUTHOR

Jon Eldon trained in biology and philosophy (BS/BA, Stanford University), before moving into ecology and conservation biology (MS, University of Hawaii), and then the agricultural sciences with an emphasis on international settings (PhD candidate, University of California-Santa Cruz). This paper emerged from trying to understand how to use this word across these diverse disciplines and within emerging interdisciplinary fields.

PUBLIC INTEREST STATEMENT

It is common for a single word to refer to multiple ideas or concepts, but the intended meaning is usually shared among discussion participants or clear from the surrounding context. However, some discussions are intentional efforts to bring together people with diverse perspectives, who may use words in different ways and interpret the context quite differently. This interdisciplinary approach is often productive, but it can also easily result in avoidable misunderstandings if semantic issues are not addressed. This is particularly likely in the field of development studies, which relies on the word "development" to bring together diverse disciplines, each of which have a precise but unique understanding of the term. This paper surveys the literature of this field and describes the variety of ways in which the word is used within the interdisciplinary discussions. In doing so, it also documents the emergence of development studies as a coherent field of study and an increasingly careful discussion.

cogent • social sciences

Subjects: Development Studies; Research Methods in Development Studies; Development Theory; Philosophy of Language

Keywords: development; philosophy of language; development studies; interdisciplinary; semantics; literature review

1. Introduction

Bringing diverse perspectives to bear on shared problems or interests is an increasingly popular intellectual strategy that is being applied a wide range of issues, such as those relating to social and environmental concerns (O'Rourke, Crowley, & Gonnerman, 2016). This approach is explicitly central to the trans- and inter-disciplinary literature and is foundational to many recently emerged fields, such as environmental and international studies (Repko & Szostak, 2016). Even many academic fields that are now often considered to be coherent disciplines in themselves, such as ecology, were founded as intentionally integrative studies and retain high internal heterogeneity (Odum, 1977). However, these discussions among diverse participants can easily be hampered by unnecessary confusion resulting from semantic differences among the participating intellectual disciplines (O'Rourke, Crowley, Eigenbrode, & Wulfhorst, 2013). The need to develop a shared language is often identified as critical for cross-disciplinary communication, but there has been limited application of this idea to practice or discussion of what such semantic inquiry should look like (Repko & Szostak, 2016).

This study focuses on the use of the word "development" in the field of "development studies," which is a particularly tricky example of the more general semantic problem. Whereas some interdisciplinary discussions have a central word that is broadly understood in a common way, such as perhaps "international" in "international studies," this is not the case in this field. Instead "development" is used in diverse but highly specific ways that vary widely among the interacting disciplines, yet it is also relied upon to bring those disciplines together and provide coherence to the resulting discussions (Thomas, 2000). In this case it is not likely that the participants would settle for a single shared concept, nor any reason why they should. Rather than arguing that a specific understanding of "development" should be given priority, this study presents a summary of the diverse but related ways in which the word is used and how that use has changed over time.

This paper begins by introducing the semantic issues surrounding the use of "development" in development studies then discusses the philosophical foundations of semantic inquiry, with a focus on Socrates and Ludwig Wittgenstein. Prominent literature in development studies is then surveyed to produce a classification scheme, or descriptive typology, of the diverse ways in which the word is used in these interdisciplinary conversations. This typology is then used to perform textual analysis on certain influential and provocative texts and on select publications in the journal *World Development* from 1973, 1993, and 2013, an analysis that allows for the identification of general changes in use over time.

2. Development studies

The final chapter of the seminal book *Doctrines of Development* is entitled "The Jargon of Development" and is focused around the question "*what is development*?" (Cowen & Shenton, 1996, p. 407). The authors Michael Cowen and Robert Shenton conclude, "*development defies definition*," (p. 407) and support this claim with a wide-ranging critique of diverse attempts to provide a positive answer to this seemingly straightforward question. This conclusion and the method of inquiry echo the first sentence of the book, which is "*Development seems to defy definition, although not for a want of definitions to offer*" (p. 2). The authors' intent with such statements is clearly not to argue that the term is therefore meaningless, but rather to encourage a more subtle investigation, one that requires the reading of the several hundred intervening pages. This line of questioning and the resulting ambiguous conclusion are not uncommon in semantic discussions of "development" within the field of development studies. For example, James Ferguson begins his preface to *The Anti-Politics Machine* with the same question and concludes that while it is "*almost nonsensical to deny* *that there is such as thing as 'development,' or to dismiss it as a meaningless concept … it seems almost impossible to question it, or to refer it to any standard beyond its own*" (Ferguson, 1990, p. xiii). He then proceeds to focus in on a specific interpretation of "development" and critique it from a standard of his own.

Ferguson and many other modern commentators, such as Amaryta Sen in *Development as Freedom* (1999), Caroline Moser in *Gender Planning and Development* (1993), and Arturo Escobar in *Encountering Development* (1995), take issue with some conventional understanding of "development" and seek to expose unappreciated implications (Ferguson), define new goals (Sen), demand expanded dialogues (Moser), and encourage the transition to a "post-development" future (Escobar). However, while each author attacks some conventional interpretation of "development" and presents an alternative understanding, their views of "development" have little in common. Escobar is clearly not seeking to move beyond Sen's concept of expanding human freedoms, nor is Moser explaining how to conduct gender planning within what Ferguson describes as a political vacuum. While all of these authors make careful and diverse arguments attacking some understanding of "development," they also rely heavily on the word itself to support their divergent positions. For example, Escobar uses the word over 150 times prior to the first chapter of the book that has since defined him as a "post-development" thinker. The result is the ironic intellectual situation where a central term apparently cannot be defined, yet it continues to define the discussion itself.

A partial explanation for this situation lies in the semantic history of the term. The deep etymology of "development" is uncertain, but one prominent theory is that it comes from the Latin words "dis," to open or part, and "volvere," to roll (Klein, 1971). In support of this, the modern English word can be traced more immediately to the Old French term "desveloper," which appears in texts starting in the mid 1700s where it carried the literal meaning of "to unfold or unfurl" (Klein, 1971). By 2017, however, the Wikipedia entry for the word was a "disambiguation" page with over 60 links to more specific entries. Eleven of these are classified under "Social Science," eight under "International and Regional," and three under "Land Use," all of which are major overlapping themes in the interdisciplinary field of development studies. (Wikipedia, 2017). This pattern suggests a semantic radiation, where the historical root word differentiated over to time to lead to a variety of highly specialized uses. While this word may have once related to a single concept, this is no longer the case.

The diverse perspectives that contribute to development studies represent a wide range of these specialized understandings of "development." By and large, economists use it to imply economic growth, politicians recognize it as referring to policies and deliberate interventions, anthropologists imply the side effects of colonization and globalization, and historians interpret it as some specific result of interacting historical forces. Within each of these fields, the occurrence of "development" in a text or conversation is unlikely to cause significant semantic confusion. However, when these communities interact, the interpretation of even a seemingly well-qualified phrase, such as "the process of global economic development," is highly dependent on the specific background of each reader.

"Development" is therefore not an ambiguous term because it has not yet been adequately defined, but rather because it has been rigorously defined in diverse but related ways. As Cowen and Shenton point out, "development" in such discussions *"comes to be defined in a multiplicity of ways because there are a multiplicity of 'developers'"* (Cowen & Shenton, 1996, p. 3). This presents a semantic situation that is unlike terms that are ambiguous due to the lack of any specific use, and it increases the odds that discussants depending on the word "development" might be talking rigorously but entirely past each other.

This semantic investigation of the term "development" may seem to lack the moral and political overtones that are common in development studies, but no less than Confucius identified this "rectification of names" as the appropriate first step to take in pursuing normative goals. "*If names be not correct*," he writes in the Analects, "*language is not in accordance with the truth of things,*" and the resulting confusions will undermine subsequent efforts (translated by Waley, 1938). The philosopher Henry Bergson takes a similar but more general position when he says that the common "*first error*" in trying to understand a system of thought is "*to take for the constitutive element of doctrine what was only the means of expressing it.*" (Bergson, 1946, p. 91). Given the importance of the larger human issues that come to the surface in discussions of "development" and the benefits of drawing from multiple perspectives, it would be a shame if the conversations were then undermined or inhibited by avoidable semantic misunderstandings. This paper therefore leaves it to others to explore the concepts associated with "development," and instead addresses the less glamorous work of shoring up the semantic framework that supports these conversations.

3. A philosophical foundation for semantic inquiry

The aforementioned semantic inquiries into "development" pose the question *"what is 'development?'"* and expect that it be answered in the positive with *"'development' is ________."* When it cannot be, the authors then conclude that "development" cannot be defined. However, this approach rests on a common but naïve philosophical view of semantic inquiry that equates meaning with an explicit denotative definition. As a result, the seemingly nihilistic conclusions, while useful as a rhetorical tool, should not be understood as the result of a rigorous semantic investigation.

The "*what is X?*" form of questioning was widely popularized by Socrates and other early Greek philosophers as a fundamental method of inquiry, and they considered a failure to supply a satisfactory response to this question as an indication that either the term was meaningless, the respondent was ignorant, or both. However, such a conclusion was in fact often the point of their questioning, and Socrates repeatedly states that recognizing the extent of his own ignorance (and the ignorance of others) is sufficient consolation for not answering the original question. When he would accept a positive response from an opponent, it was typically as a set-up for then undermining some larger edifice with a well-timed "*okay, but if X is Y, then what is Y?*" Socrates in fact often directly ridiculed the notion that he could answer his own questions of this form, such as when he replies to a student, "*you come to me as though I professed to know about the questions which I ask*" (*Charmides,* 165b in Hamilton, 1961). As the Greek scholar W. K. C Guthrie describes it, "*the essence of the Socratic method is to convince the interlocutor that whereas he thought he knew something, in fact he does not*" (Guthrie, 1968, p. 127). Despite the original negative application of this method, this form of direct questioning has since been widely adopted with the expectation that it should lead to a positive definition of a term.

Socrates liked to point out that seemingly satisfactory articulation does not necessarily imply knowledge, and more recent thinkers have argued that the converse is also true and some knowledge simply resists articulation. This latter insight is well captured in Henri Bergson's statement that "*philosophical systems are not cut to the measure of the reality in which we live*" and Michael Polanyi concise declaration that *"we can know more than we can tell"* (Bergson, 1946, p. 1; Polanyi, 1966, p. 4). The implication here is that while a seemingly satisfactory answer to "*what is X?*" does not guarantee knowledge, an unsatisfactory answer or even none at all does not necessarily indicate a lack of understanding or meaning. This point is implied by Cowen, Shenton, and Ferguson when they use their seemingly defeatist response to "*What is 'development?'*" as a rhetorical device to introduce their more subtle investigation of the term. That approach does not, however, offer a framework for understanding how this central term is used in interdisciplinary discussions or suggest a strategy to avoid or unravel semantic confusion when the term is used.

This potential disconnect between understanding and articulation revolutionized the thinking of Ludwig Wittgenstein, who began his career in the philosophy of language with an exceptionally linear and positivistic view, to the extant that he wrote his first major work as a numbered list of declarative propositions. In his preface to this work, *Tractatus Logico-Philosophicus*, he claimed that the "whole meaning [of the book] could be summed up somewhat as follows: What can be said at all can be said clearly; and whereof one cannot speak thereof one must be silent" (Wittgenstein, 1921, p. 27). With this view, Wittgenstein became the champion of many "analytic" philosophers, but he re-emerged decades later with a competing and radically tacit view of language that is exemplified in his statement, *"For a large class of cases … the meaning of a word is its use in the language"* (Follesdal, 1996; Wittgenstein, 1953, p. 43).

The conventional approach of asking "*what is X?*" and expecting a positive *"X is _____"* response suggests a straightforward association between the word *"X"* and some unified concept or common essence. Wittgenstein directly counters this assumption in an oft-cited passage from *Philosophical Investigations*:

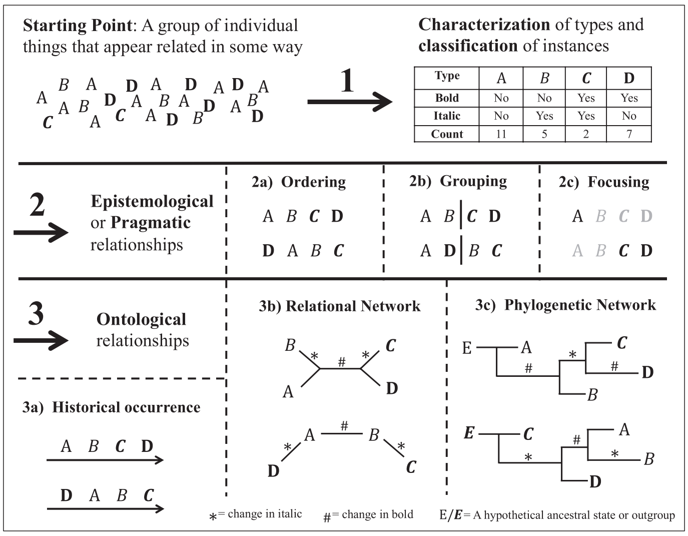
> Consider for example the proceedings that we call "games". I mean board-games, card-games, ball-games, Olympic games, and so on. What is common to them all? – Don't say: "There must be something common, or they would not be called 'games'"-but look and see whether there is anything common to all for if you look at them you will not see something that is common to all, but similarities, relationships, and a whole series of them at that. (Wittgenstein, 1953, p. 66)

This contrasting "look and see" approach demands a survey of the diverse uses of *"X"* to empirically assess whether the word can be strictly associated with a single concept or if there are multiple categories of use that would imply multiple related concepts.

This task of characterizing and categorizing individual instances is common to many intellectual fields, with this descriptive survey providing the foundation for the study of relationships among types. In the biological sciences, for example, the current interest in ecological and evolutionary relationships only became possible after centuries of observational surveys and taxonomic classifications identified relevant groupings of individuals, such as populations, species, and communities. Once established, a descriptive typology of individual instances can support a wide range of questions about relationships, such as epistemological or pragmatic associations that might be informative of disciplinary or personal interests. Identifying which specific categories that an author references can help to clarify what sorts of games they prefer, what types of organisms they study, or what they mean when they talk about "development" even if they do not state this focus directly. In some cases, such as biology, this inquiry into relationships can also focus on historical associations or other ontological relationships among types. A simplified conceptual example of categorizing individual instances and exploring relationships among general types is described in Figure 1.

Figure 1. A conceptual schematic describing the construction of a descriptive typology (1) and application of it to explore relationships among types that are based on interest, values, or purpose (2) or hypothesize an empirical relationship (3).

Note: Two alternative formulations are given for each type of relationship (a-c), which are only in competition for the latter ontological category (3).



The beginnings of a descriptive typology of "development" can be seen in the dichotomies that are sometimes made in the interdisciplinary literature. One such common distinction is between "immanent development," as the general process of societies changing over time, and "intentional development," as the deliberate practice of intervening in an attempt to influence this change (Bebbington, 2004; Cowen & Shenton, 1996). Another is between "development" as a set of social ideals or goals, and either the immanent process of change (Ingham, 1993) or the intentional practice of intervention (Sen, 1999). These dichotomies are typically used to clarify an author's interests, as in *"this meaning, not that meaning,"* and are not intended to represent a survey of the field. One exception is Alan Thomas who, in a response piece to *Doctrines of Development*, describes three general categories of use: immanent processes, intentional practices, and social ideals (Thomas, 2000). His justification for extending simple dichotomies into a descriptive typology echoes Wittgenstein's observational approach as he writes, *'the question is one of usage … rather than of trying to show which meaning is the "correct" one'* (Thomas, 2000, p. 774).

A well-developed classification scheme provides a starting point for additional semantic inquiries and can immediately reduce the confusion surrounding "development" in several ways. The first and most direct is that it provides a formal framework for interpreting individual uses of "development" in interdisciplinary literature, which is particularly helpful when the uses are surprising to a reader. Second, many authors make complex arguments that weave among alternative uses of "development," and the ability to trace the change in the meaning among individual uses can provide additional and potentially nuanced insights into their broader argument. Third, it allows for the quantitative assessment of texts, which can be used to compare and contrast among diverse authors and works in order to clarify conceptual differences. Finally, while a descriptive typology cannot offer normative prescriptions of how "development" should be used, it can provide authors with a guide of how a use might be interpreted by an interdisciplinary audience, which can help them to avoid ambiguous or misleading language. Options to do so include explicitly stating their intended meaning and contrasting it with other uses, adding adjacent qualifiers to clarify an individual use of "development," and replacing the term entirely with a more specific phrasing.

4. Methodology

This formal survey of the use of "development" in development studies combined depth, through focused analysis of critical texts, and breadth, through a broader sampling of journal articles across a 40-year period. The previously identified books by Sen, Ferguson, Moser, and Escobar were selected to meet the depth requirement, and the textual analysis focused on the prologues or introductions where the authors explicitly wrestled with semantic issues. The journal *World Development* was selected to meet the breath requirement, as it is a leading publication in the interdisciplinary field and has been semantically self-conscious from the first issue in 1973, when the editors introduced the journal by identifying the diverse concepts that they associate with "development" (*World Development Editorial Board,* 1973). Textual analysis was limited to journal articles from 1973, 1993, and 2013 that used the word "development" in the title. As all articles published in this journal are presumably about "development" in some form but it is also possible that they might not use the word itself, this filter was applied to ask the more specific question, *"when an author prominently and explicitly associates their text with 'development' in an interdisciplinary context, how do they then use the term?"* This selection was further restricted to original research articles of greater than 3 pages, and excluded all book reviews, speech transcripts, and short comment articles. The selected articles are listed in Appendix 1. The final descriptive typology used for classification emerged as the result of an iterative learning process and does not presume to be exhaustive or authoritative within the field.

This resulting typology was then reapplied to the same texts to quantify patterns of use within and across the selected works. All individual uses of the term were classified within each text, with the exception of keywords, legends, footnotes, and references. All acronyms containing "development" were interpreted as full uses of the term and classified accordingly. Proper nouns and direct quotations containing "development" were recorded but not classified within the typology, as they did not represent the author's word choice. Uses that were considered to be outside of the common interdisciplinary discussion of "development" were also recorded as "unrelated." These were primarily uses that referred to the emergence of a specific product, idea, or activity, such as the "development" of a new technology. Occurrence of related terms such as "developing" and "developed" was also recorded and classified as referring to societies, not referring to societies, or within proper names or quotes. Immediately adjacent qualifiers, such as "economic [development]" or "[development] plan" where recorded during the analysis. Where multiple qualifiers were used, such as "land development banks" and "regional development policy," only the more specific qualifier was recorded, which was usually the one following "development." The final textual analysis of all selected journal articles was performed over three days with the articles analysed in a random order.

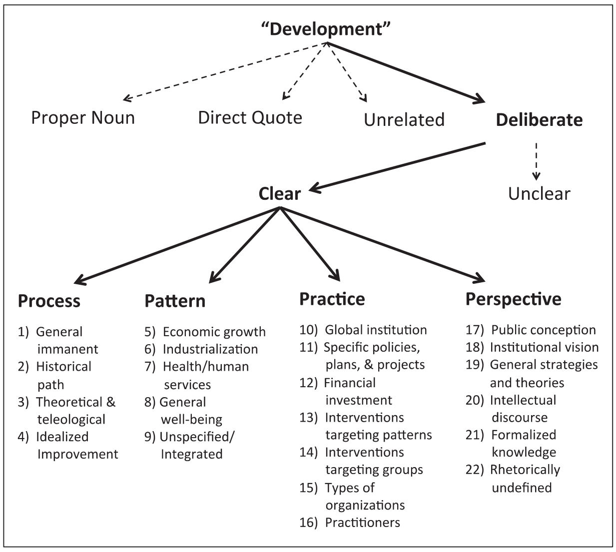
The interpretation and categorization of each individual use was based primarily on the immediately surrounding text, as this is what a reader would first turn to when faced with a surprising use of the term. However, the "principle of charity" was also used to ensure that the local contextual interpretation was consistent with or at least not contradictory to the author's larger stated interests. This approach, which was popularized by W.V.O. Quine, maintains that effort should be made to interpret a text or argument in a way that is rational, internally coherent, and as viable of an argument as is possible (Follesdal, 1982; Wilson, 1959). This general strategy helps to avoid oversimplified interpretations and straw-man arguments, and is particularly appropriate for "development" owing to the diverse and sometimes rhetorical or even sarcastic use of the term in the literature. However, some individual uses of "development" resist classification, such as when an author's broader position is not straightforward and there are no adjacent qualifiers or the individual uses are highly variable. Rather than demand classification of every use and thereby sprinkle ambiguity throughout the analysis, such rare instances were simply marked as "unclear."

5. Results and discussion

The results are presented in three sections, with focused discussion following each set of results and the more general discussion reserved for the conclusion. The first section is a summary of the four general and 22 specific categories of use identified in the final descriptive typology. The process of categorizing individual uses within this framework is described in detail in Figure 2. The second section is the application of this typology to the interpretation of the four provocative and semantically self-aware texts, which combines the textual analysis of uses of "development" with a broader interpretation of these selections and authors. The results of this textual analysis are summarized in Appendix 2. The final section is the survey of articles from *World Development* from 1973, 1993, and 2013. This analysis focuses exclusively on the use of the word "development," and does not attempt

Figure 2. A schematic of the process that was used to classify textual occurrences of "development" within the final descriptive typology.

Notes: The solid lines and bold categories indicate the route of classification of the uses that are the primary interest in this analysis. For the 2nd and 3rd levels, the classification proceeded left to right, such that "Deliberate" and "Unclear" were everything that wasn't classified in the alternatives to the left of each.



to balance this with the broader interests of each article, as the goal is instead to track patterns of use over time within this interdisciplinary field.

5.1. Categories of use

5.1.1. Processes (immanent)
A foundational assumption to interdisciplinary discussions of "development" is the idea that societies are not static entities waiting for policy decisions to have their intended effect, but rather dynamic complex systems. It was in this sense that the philosopher Georg Hegel, who greatly influenced Karl Marx and through him countless modern thinkers, claimed in 1830 that "*the history of the world … is the process of development*" (as quoted in Arndt, 1981). While Hegel, Marx, and many of their intellectual descendants have tended to view this as a successional transition through distinct states, the more general conception is that societies are in a process of continuous change. "Development" might be used in this sense to refer to (1) a general process of immanent social change, (2) the historical path that led to a specific social condition or situation, (3) a theoretical process that leads to a specific state or outcome, or (4) an idealized process of general social improvement.

5.1.2. Patterns (immanent)
Investigations into immanent social trajectories often focus not on the overall process, but on the observable patterns that emerge and can be used to characterize and compare ever-changing societies. The uses of "development" in this sense is often in reference to (5) general economic growth, (6) an increase in industrial activity, physical infrastructure, and the exploitation of natural resources, (7) an increase in access to health and human services, or (8) some other observable improvement in well-being. It may also be used as (9) an unspecified or integrative measure of society that allows for them to be assessed and compared, such as when societies are classified as being "developed," "underdeveloped," or "developing."

5.1.3. Practices (intentional)
An understanding of immanent processes and observable patterns is often used to direct intentional practices that seek to influence the larger social trajectory, and "development" in this case refers to these practices themselves. Such use might focus on (10) the general practice or global institution of such social interventions, (11) specific policies, plans, or projects, (12) financial investment to support such efforts, (13) interventions targeting specific patterns, (14) interventions targeting specific social groups, (15) types of intervening organizations, or (16) the practitioners themselves.

5.1.4. Perspectives (intentional)
Attempts to understand the interaction of the processes, patterns, and practices associated with "development" has led to a fourth general use that references the perspectives that are associated with these reflective discussions. This might include (17) public conception of processes, patterns, or practices, (18) the broad and often implicit institutional vision behind interventions, (19) general strategies or theories guiding interventions, (20) general intellectual discourse on the topic, and (21) formalized knowledge and associated commentators that emerge from this discourse. It may also be (22) rhetorically undefined, such as in asking, "what is 'development?'"

In theory, these four general categories relate to each other very neatly. Societies are always changing (Processes) and these changes can often be observed (Patterns) and influenced (Practices), and this interaction of processes, patterns, and practices can also be studied and assessed (Perspectives). However, the actual use of "development" is far more complicated. While some authors may restrict their discussion to a single general or even specific category of use, many others will deliberately build more complex arguments that use "development" in multiple ways. For example, it is common to criticize specific practices as being dissociated from the underlying processes or inspired by unrealistic patterns. Other authors may wander from one category of use to another in a single text and in ways that are not always immediately clear in context or necessarily deliberate.

These categories of use should not be considered exhaustive of the development studies literature, and necessarily reflect the limited scope of the survey and the subjectivity inherent in this single author approach. For example, while there is significant interest in studying institutional change, such as the emergence of property rights, court systems, and financial regulations, there were no instances of "development" used in this sense, or at least they were not interpreted as such by this author. In addition, this typology of uses of "development" should also not be confused with a typology of the concepts that are discussed in this literature, which would be the more ambitious project of trying to understand and categorize *"what people think about when they think about 'development.'"*

5.2. Interpretation of provocative texts

5.2.1. Development as freedom (Introduction)—Amartya Sen

In his introduction to this 1999 book, the Nobel-prize winning economist Amartya Sen introduces an alternative view of "development" as not growth in GDP (#5, Pattern) or the industrialization of an economy (#6, Pattern), but rather as *"the process of expanding the real freedoms that people enjoy"* (#4, Process, p. 3). He explicitly recognizes potential semantic ambiguity surrounding this term and describes the former understandings as "*narrower views of development"* (p. 3–4). He also explicitly avoids common economic connotations by stating that his understanding of "development" is "*relevant even for richer countries"* (p. 6). While this process of expanding freedom could be measurable, only two individual uses were classified in this way (#9, Pattern), while 27 of the 39 individual uses in the Introduction refer to an idealized process of general improvement (#4, Process). This interplay between processes and patterns is recognized throughout the introduction, such as through his repeated statement that human freedoms are both the "*constituent components*" (#4, Process, p. 4) and "*principal ends*" (#9, Pattern, p. 4) of his understanding of "development." Interestingly, while Sen's larger interests and legacy concern the global institution of interventions (#10, Practice) and the stated goals of idealized interventions (#18, Perspective), he does not in fact make any specific reference to even the general category of Practice in this introduction. Instead, the ten remaining individual uses are classified under the general category of Perspectives, with most concerning the public conception of the term (#19, Perspective). This textual analysis helps to identify Sen's Introduction to *Development as Freedom* as a deliberate attempt to place his subsequent discussion of interventions within the public understanding of the general process of societal improvement. While 24 of the 39 individual uses of "development" in this introduction lacked adjacent qualifiers, none of these uses were found to be ambiguous or falling outside of the typology that was constructed for these interdisciplinary discussions.

5.2.2. The anti-politics machine (Preface)—James Ferguson

This 1990 book by James Ferguson is an attack on the conventional design of and justification for deliberate interventions (#20, Perspectives), along with the colloquial understanding of the term (#19, Perspectives). In sharp contrast to Sen's normative discussion of how these interventions should be designed and justified, Ferguson makes it clear in his preface that he "*does not aim to rectify or to correct 'development' thinking*" that is driving these interventions (p. xv). Rather, his intention is to elucidate the difference between what these interventions say they are doing and the actual effects that they often have. In particular, Ferguson points out the tendency of such interventions to be detached from the local reality of their target regions, and while they often fail to meet their professed goals, they nonetheless have unintended and unavoidable consequences within those region. He argues that this situation undermines local political forces and creates a chaotic power vacuum that seems to necessitate further intervention. Using the country of Lesotho as a case study, Ferguson claims that the global institution of deliberate interventions acts as "*an 'anti-politics machine' … everywhere whisking political realities out of sight, all the while performing, almost unnoticed, its own pre-eminently political operation of expanding bureaucratic state power*" (p. xv). As with Sen, Ferguson recognizes that his is a specialized use of the term "development" and he clearly states, "*most of the grander and global questions about the origin and meaning of the modern figure of 'development' are bracketed and laid to one side here*" (p. xvi). This focus is clear in the textual analysis, as 30 of the 35 individual uses fall within the Perspectives category, with 13 of those relating to public conception of "development" (#17), 10 in the broad institutional visions behind interventions (#18), 6 rhetorically undefined (#22), and 1 referring to the general intellectual discourse (#20). Four of the remaining five uses were classified as the general institution of intervention (#10, Practice), and the final use described a "stage of development" as a theoretically teleological process (#3, Process). As with Sen, Ferguson did not have any ambiguous or outside uses of "development."

5.2.3. Gender planning and development: theories, practice, and training (Introduction)—Caroline Moser

In this 1993 book, Caroline Moser summarizes her experiences over years of working within deliberate interventions to incorporate gender issues into the design of specific projects. As the title suggests, her interest here is to convey what she has learned and support others who are taking this same approach with the goal of making gender planning a regular component of the design of interventions in the way that, as she notes, environmental planning had recently become standard. Both the conventional understanding of "development" that she is attacking—one that doesn't include gender planning—and the alternative that she is proposing fall within this theme of deliberate interventions, and this focus is clearly reflecting in the way in which she uses "development" in the introduction. Nearly 75% of the individual uses in this introduction fall within the specific category of the explicit strategies, theories, and policies guiding interventions (#19, Perspective), with the majority of the rest (16% of overall) falling within the specific category of an idealized processes of social improvement (#4, Processes), which is the stated intent of such interventions. Of the 61 total uses, only two were considered ambiguous, and of the remaining, only two where found that did not contain adjacent qualifiers. The sharp focus of Moser's writing and the rigor with which she uses "development" leaves little room for confusion or misinterpretation of her interests or argument.

5.2.4. Encountering development (Preface and Introduction)—Alberto Escobar

This 1995 book by Arturo Escobar is a direct attack on the related assumptions that (1) the industrialized nations of North America and Europe are appropriate models for the rest of that world, (2) that these former countries are justified to intervene in the latter to encourage this similarity, and (3) that these interventions are in the best interests of the targeted populations. This broad objection explicitly references the general categories of processes, patterns, and practices, and Escobar also recognizes the general category of perspectives in his preface by expanding his far-ranging understanding of "development" to include "*the forms of knowledge that refer to [development] and through which it comes into being and is elaborated into objects, concepts, theories, and the like; the system of power that regulates its practice; and the forms of subjectivity fostered by this discourse, those through which people come to recognize themselves as developed or underdeveloped*." (p. 10) While his analysis touches on every general category identified in the descriptive typology and he notes that "*an entire constellation of usages…is beginning to surface,*" (p. 23) he also writes, "*to sum up, I propose to speak of development as a historically singular experience*" (p. 10). In addition, while he expresses interest in "*the end of development*," (p. 29) asks "*whether we can unmake development*," (p. 20) and has popularized the term "post-development," he also defines his ideas through heavy use of the term itself, with a total of 10 individual uses in the preface and 143 in the introduction (Escobar, 2007). The ambitious scope and integrated intent of this work makes it quite unlike the other three texts, which are all explicit in the narrowness of their attacks on some conventional understanding of "development." This approach may lend itself to semantic confusion making this textual analysis particularly useful for elucidating Escobar's larger objectives.

Escobar's initial uses of "development" in the preface cover a wide spectrum of categories, beginning with the global institution of deliberate intervention (#10, Practice) and followed by a general but observable measure of progress (#9, Pattern), an unrelated use in "*the development of a framework*," (p. vii) and a return to the general global institution with the addition of the apparently original qualifier "*development apparatus*" (p. vii). His broader focus and larger goals are better reflected in the overall analysis where, of the 139 individual uses that are classified within the four general categories, 33.8% fall within Practices and 62.6% within Perspectives. Of these, the general institution of intervention (#10, Practice) constitutes 28.1% of the classified total and the institutional vision behind these interventions (#20, Perspective) constitutes 27.3%. In contrast, the immanent general categories of Processes and Patterns make up only 1.4% and 2.1% respectively. Escobar also included 14 uses of "developed" with respect to societies, 8 of which were of his own choosing, although this analysis did not further identify when he was in fact criticizing the practice of characterizing societies in this way.

5.3. Deliberate uses within World Development

When the journal *World Development* began publishing in 1973, the editors explicitly described their use of "development" as referring to the global institution of deliberate intervention (#10, Practice) with a hope that these activities can generate observable increases in social well-being (#9, Pattern). They wrote, "*much has been written about aid and trade, but few writers have treated development as part of a total relationship between rich and poor countries, encompassing much more than tariff policy and development assistance…Development must be redefined as an attack on the chief evils in the world today: malnutrition, disease, illiteracy, slums, reemployment and inequality.*" (World Development Editorial Board, 1973) After 40 years of publication, the editors' explicit understanding of "development" had expanded to also include Processes and the Perspectives that had grown around the term during the intervening decades. The description of the journal in 2017 reads, "World Development *recognizes 'development' as a process of change involving nations, economies, political alliances, institutions, groups, and individuals*" (#1, Process: WD editorial board, 2017). The editors continue by recognizing the increasingly broad and interdisciplinary discussion surrounding "development" when they write, "*Our goal is to learn from one another, regardless of nation, culture, income, academic discipline, profession or ideology*" (#22, Perspective: WD editorial board, 2017). This careful handling of "development" by the editors of *World Development* and their explicit recognition of the diverse and expanding uses of the term suggests that they are trying to capture the breadth of use within the field of "development studies." However, these editorial directives are of course no guarantee of how the term is actually used in the articles contained within this journal, or how that use might have changed over this time-period as the interdisciplinary discussions surrounding "development" increased and gathered momentum as an emerging theme in itself (Cowen & Shenton, 1996).

Table 1. Summary of the general temporal trends of use of "development" observed in selected articles from *World Development*, with evidence from multiple lines of textual analysis

Observed trend	Textual analysis				
	# of articles (Table 2A)	Total uses (Table 2B)	Median uses/ article (Table 2C)	Use of qualifiers (Table 3)	Categories represented (Table 4)
1. Decreasing reliance on "development"	Decrease in % articles meeting selection criteria				
2. Increasingly rigorous use	Decrease in % articles with unclear and unrelated uses	Decrease in % unrelated and unclear uses	Decrease in % unrelated and unclear, increase in % clear	Increase in all measures of qualified use	
3. Increasingly specialized use	Decrease in % with unrelated/ unclear	Decrease in % unrelated and unclear uses	Decrease in % use for all general categories	Increase in % qualified	Decrease in # categories represented
4. Formalization of interdisciplinary discussion	Increase in % of articles using proper nouns		Increase in % use of proper nouns	Increase in use of qualifiers within all general categories	
5. Shift away from discussing Processes		Decrease in % referencing Processes	Decrease in % referencing Processes		Decrease in weighted score for Processes

Table 2. Summary of the textual analysis of selected journal articles from *World Development* in 1973, 1993, and 2013, shown here as (A) the number of articles with representation (1+ uses), (B) the total uses across all articles, and the (C) median and (D) maximum use within each article

	A. # of articles			B. total uses			C. median uses/article			D. max uses/article		
	1973	1993	2013	1973	1993	2013	1973	1993	2013	1973	1993	2013
Published articles	43	141	181									
Selected articles	11	24	20									
	25.6%	*17.0%*	*11.0%*									
Selected uses				363	1,284	1,064	27	41.5	41	82	191	278
Proper nouns	6	19	16	40	111	236	1	3	3.5	22	25	143
	54.5%	*79.2%*	*80.0%*	*11.0%*	*8.6%*	*22.2%*	*4.8%*	*6.0%*	*9.5%*	*27.3%*	*47.1%*	*51.4%*
Direct quotes	4	13	5	12	73	13	0	1	0	5	26	4
	36.4%	*54.2%*	*25.0%*	*3.3%*	*5.7%*	*1.2%*	*0%*	*2.2%*	*0%*	*11.6%*	*22.0%*	*7.1%*
Unrelated	7	13	6	17	36	9	1	1	0	4	9	3
	63.6%	*54.2%*	*30.0%*	*4.7%*	*2.8%*	*0.8%*	*2.7%*	*0.9%*	*0%*	*20.0%*	*23.5%*	*8.4%*
Deliberate	11	24	20	294	1,064	806	25	37.5	33.5	58	180	135
	100%	*100%*	*100%*	*81.0%*	*82.9%*	*75.8%*	*87.7%*	*86.9%*	*88.6%*	*97.3%*	*100%*	*100%*
Unclear	7	15	8	19	71	18	2	1	0	6	20	7
	63.6%	*62.5%*	*40.0%*	*6.5%*	*6.7%*	*2.2%*	*5.6%*	*3.0%*	*0%*	*25.0%*	*30.0%*	*18.4%*
Clear	11	24	20	275	993	788	23	35.5	32	57	165	133
	100%	*100%*	*100%*	*93.5%*	*93.3%*	*97.8%*	*94.4%*	*97%*	*100%*	*100%*	*100%*	*100%*
Processes	11	22	15	82	138	128	6	2.5	2	18	56	58
	100%	*91.7%*	*75.0%*	*29.8%*	*13.9%*	*16.2%*	*33.3%*	*13.2%*	*6.6%*	*78.3%*	*75.0%*	*82.9%*
Patterns	11	20	16	82	192	263	7	4.5	8	14	34	68
	100%	*83.3%*	*80.0%*	*29.8%*	*19.3%*	*33.4%*	*24.6%*	*15.5%*	*17.2%*	*55.6%*	*85.7%*	*100%*
Practices	10	17	16	78	282	271	3	6.5	1.5	38	45	123
	90.9%	*70.8%*	*80.0%*	*28.4%*	*28.4%*	*34.4%*	*16.7%*	*20.4%*	*8.3%*	*66.7%*	*76.1%*	*100%*
Perspectives	9	21	14	33	381	118	2	5	1	9	94	41
	81.8%	*87.5%*	*70.0%*	*12.0%*	*38.4%*	*15.0%*	*16.7%*	*25.0%*	*3.5%*	*30.8%*	*72.0%*	*74.5%*

Notes: Each measure is broken down into hierarchical categories following the schematic in Figure 2, and presented as count and percentage (bold/italic). For A and B, the percentage is calculated from the adjacent count, while for C and D the percentage is calculated within each article and presented as the Median/Maximum percent use per article.

The temporal context for this analysis is a dramatic increase in the publication rate of original research articles within the journal *World Development*, against which several other trends stand out (summarized in Table 1). First, there has been a decrease in the reliance on the term "development" to discuss the associated issues, with the per cent of articles that meet the selection criteria dropping from over 25% of the total published in 1973 to 17.0% in 1993 and 11.0% in 2013 (Table 2). Second, the term has come to be used more rigorously over this period, such as is evidenced by a decrease in the occurrence of unclear and unrelated uses and an increase in the use of adjacent qualifiers (Tables 2 and 3). Third, this increasingly rigorous use is also increasingly specialized, with a decrease in the number of general categories referenced within each article (Table 4). Fourth, a dramatic increase in the use of "development" within proper nouns and an increase in the use of qualifiers may indicate an increase in the official use of the term in related agencies and activities, and an increased formalization in the discussion of these official efforts (Tables 2 and 3). Finally, there has been a decrease in the use of "development" to refer to imminent processes and an increased focus on the perspectives found in the interdisciplinary discussions (Table 4). This is also reflected in a decrease in the use of "developed" and "developing" to refer to societies, which may have also been influenced by the criticism of Escobar and others (Table 5).

Together, these trends appear to show a maturation of interdisciplinary discussions of "development" and perhaps the emergence of development studies as an integrative discipline in its own right, rather than simply a conversation among other existing disciplines. This transition from an interdisciplinary discussion to being considered a coherent discipline is not without precedent, and a recent striking example is the emergence of ecology in the twentieth century out of the confluence botany, zoology, soil science, and other natural science disciplines (Moore, 1920; Odum, 1977). This process likely requires increasing interest, coherence, and self-identity among the intellectual participants, along with some more formal recognition in the academic setting. The trends observed in this survey of *World Development* provide some evidence of the first requirement, and the increasing number of degrees offered in Development Studies, International Development, and related topics is

Table 3. Occurrence of adjacent qualifiers with textual use of "development" in the selected articles of *World Development*

Use of qualifiers	1973	1993	2013
% Articles with 100% qualified and no unclear uses	0%	12.5%	20.0%
Median % qualified uses within each article	72.7%	88.4%	96.8%
% Qualified of total clear uses	73.4%	84.1%	95.3%
% Qualified of total uses classified as *Processes*	61.0%	51.1%	82.8%
% Qualified of total uses classified as *Patterns*	64.6%	76.6%	96.7%
% Qualified of total uses classified as *Practices*	87.2%	94.0%	98.5%
% Qualified of total uses classified as *Perspectives*	93.9%	92.4%	98.3%

Table 4. Representation of general categories within *World Development* in the selected years, measured as the mean number of categories found in each article (out of 4) and the mean of a weighted score for each category

	1973	1993	2013
Mean # of categories represented	3.73	3.33	3.05
Mean weighted score			
Processes	2.91	2.23	1.90
Patterns	3.05	2.31	2.55
Practices	2.09	2.02	2.03
Perspectives	1.68	2.48	3.05

Notes: The weighted score was calculated as follows: within each article, the highest use general category received a 4, the next highest a 3, etc., with a tie recorded as a split (3.5, 2.5, etc.) and a category that wasn't used given a 0.

Table 5. Summary of use of "developed" and "developing" to refer to societies within the selected articles from *World Development*

"Developed" and "Developing"	1973	1993	2013
# Articles with both	8	12	9
% Articles with both	72.7%	50.0%	45.0%
# Articles with neither	1	3	6
% Articles with neither	9.1%	12.5%	30.0%
Developed			
# Articles with 1+ use	8	14	10
% Articles with 1+ use	72.7%	58.3%	50.0%
Total # uses	125	69	45
Median	6	1	0.5
Mean when > 0	15.6	4.9	4.5
Maximum	85	17	16
Developing			
# Articles with 1+ use	10	18	13
% Articles with 1+ use	90.9%	75.0%	65.0%
Total # uses	126	157	89
Median	5	2	1.5
Mean when > 0	12.6	8.7	6.8
Maximum	47	57	25

some evidence of the second (Woolcock, 2007). While it is impossible at this time to predict whether development studies will remain explicitly interdisciplinary and whether the word "development" will remain diversely multifaceted, it is clear that this field itself is in the process of changing over time.

This strategy of using a descriptive typology to analyse specific texts allows for such change to be monitored through the recognition of measurable patterns, an approach that compliments the more individual impressions of the participants. Recognition of these patterns might also help to intentionally direct this change, such as by offering new insights into the diverse ways in which "development" is used in practice and guidelines for how it might be most clearly used. For example, the use of adjacent qualifiers may not be as effective of a strategy in this interdisciplinary discussion as it is within the represented disciplines. This textual analysis found that each individual author was highly specific in their use of adjacent qualifiers, but that there was much less agreement among them. No author used the same qualifier of "development" in multiple specific categories, but as a group, 15 of the top 25 most common qualifiers were used in more than one of the four general categories, while nine of these were used in both immanent (Process/Pattern) and intentional (Practice/Perspective) categories (Appendix 3). This suggests that while qualifiers of "development" can be useful for reducing some of the ambiguity surrounding a textual use of the term, they should be used with care in development studies, as they may also be disciplinary relics that demand their own semantic investigations. This self-reflective perspective on this emerging intellectual field may therefore be both an indication of and an influence on the development of development studies.

6. Conclusion

This descriptive typology and the associated textual analysis can add rigor to the use and interpretation of "development" in interdisciplinary discussions and texts by identifying patterns of use that might be overlooked in more qualitative assessments or statements of disciplinary norms. The most critical conclusion from this survey is that there is no replacement for clear thought and careful writing when presenting complex ideas to a diverse audience. The authors of the books and articles analysed here have found a variety of ways to limit ambiguity while still making prominent use of "development." These include explicitly addressing the question of what they mean when they use "development," restricting their use of the term to selected categories of meaning, and making rigorous and extensive use of reliable qualifiers. These practices appear to be becoming more common in the interdisciplinary discussions surrounding "development," while at the same time other authors on the same topics appear to be increasingly avoiding the term entirely in favour of directly addressing the concepts that "development" was once trusted to convey. These strategies and the trends found in this survey offer strong evidence that authors participating in interdisciplinary discussions of "development" do not think that the term cannot be defined, but rather are wrestling with this semantic problem on a regular basis whenever they use, or choose not to use, the term "development." The observational and quantifiable approach applied in this project supports these efforts by providing tools for participants to hone their messages and avoid common semantic confusions.

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Appendix 1. Articles from *World Development* selected for textual analysis

Year	Authors	Title
1973	Bass L	The role of technologic institutes in industrial development
	Bruton H	Economic development and labor use: a review
	Economides C	Earned international reserve units: the catalyst of two complementary world problems – the monetary and development
	Gaitskell A	Alternative choices in development strategy and tactics: the Mekong river project as a case study
	Griffin K	An assessment of development in Taiwan
	Helleiner GK	Manufacturing for export, multinational firms and economic development
	Hirschman AO	The changing tolerance for income inequality in the course of economic development
	Sinha RP	Competing ideology and agricultural strategy: current agricultural development in India and China
	Stever G	Impact of space on *World Development*
	Streeten P	Trade strategies for development: some themes for the seventies
	Streeten P	The multinational enterprise and the theory of development policy
1993	Adams WM	Development's deaf ear: downstream users and water releases from the Bakolori Dam, Nigeria
	Bardham P	Analytics of the institutions of informal cooperation in rural development
	Clements P	An approach to poverty alleviation for large international development agencies
	Cole R	Economic development in the South Pacific promoting the private sector
	Dieke P	Tourism in The Gambia: some issues in development policy
	Doner RF, Ramsay A	Postimperialism and development in Thailand
	Farzin, YH	Importance of foreign investment for the long-run economic development of the United Arab Emirates
	Geisler G	Silences speak louder than claims: gender, household, and agricultural development in Southern Africa
	Haque, CE	Human responses to riverine hazards in Bangladesh: a proposal for sustainable floodplain development
	Hewison K	Nongovernmental organizations and the cultural development perspective in Thailand: a comment on Rigg (1991)
	Ingham B	The meaning of development: interactions between "new" and "old" ideas
	Jackson C	Doing what comes naturally? Women and environment in development
	De Janvry A, Sadoulet E	Market, state, and civil organizations in Latin America beyond the debt crisis: the context for rural development
	Kaminarides J, Nissan E	The effects of international debt on the economic development of small countries
	Kardam N	Development approaches and the role of policy advocacy: the case of the World Bank
	Morgan EA, Power GD, Weigel VB	Thinking strategically about development: a typology of action programs for global change
	Pack H	Productivity and industrial development in sub-Saharan Africa
	Quiggin J	Common property, equality, and development
	Rock MT	"Twenty-five years of economic development" revisited
	Roe EM	Public service, rural development and careers in public management: a case study of expatriate advising and African land reform
	Sofer M	Uneven regional development and internal labor migration in Fiji
	Taylor L	The World Bank and the environment: The *World Development* Report 1992
	Uphoff N	Grassroots organizations and NGOs in rural development: opportunities with diminishing states and expanding markets
	Zimmerer KS	Soil erosion and labor shortages in the Andes with special reference to Bolivia, 1953–91: Implications for "conservation-with-development"

(*Continued*)

Appendix 1. (*Continued*)

Year	Authors	Title
2013	Branisa B, Klasen S, Ziegler M	Gender inequality in social institutions and gendered development outcomes
	Carr-Hill R	Missing millions and measuring development progress
	Cramb RA	Palmed off: incentive problems with joint-venture schemes for oil palm development on customary land
	Headey DD	Development drivers of nutritional change: a cross-country analysis
	Herzer D, Nunnenkamp P	Private donations, government grants, commercial activities, and fundraising: cointegration and causality for NGOs in international development cooperation
	Hickey S	Beyond the poverty agenda? Insights from the new politics of development in Uganda
	Hudson J, Minea A	Innovation, intellectual property rights, and economic development: a unified empirical investigation
	Humphrey C, Michaelowa K	Shopping for development: multilateral lending, shareholder composition and borrower preferences
	Leonard DK, Bloom G, Hanson K, O'Farrell J, Spicer N	Institutional solutions to the asymmetric information problem in health and development services for the poor
	Mersland R, D'espallier B, Supphellen M	The effects of religion on development efforts: evidence from the microfinance industry and a research agenda
	Nunnenkamp P, Ohler H, Schworer T	US based NGOS in international development: financial and economic determinants of survival
	Orihuela JC	How do "mineral-states" learn? Path-dependence, networks, and policy change in the development of economic institutions
	Pepinsky TB	Development, social change, and Islamic finance in contemporary Indonesia
	Permanyer I	Using census data to explore the spatial distribution of human development
	Rijkers B, Soderbom M	The effects of risk and shocks on non-farm enterprise development in rural Ethiopia
	Rousseau PL, d'Onofrio A	Monetization, financial development, and growth: time series evidence from 22 countries in sub-Saharan Africa
	Sesan T, Raman S, Clifford M, Forbes I	Corporate-led sustainable development and energy poverty alleviation at the bottom of the pyramid: the case of CleanCook in Nigeria
	Smith LC, Khan F, Frankenberger TR, Abdul Wadud AKM	Admissible evidence in the court of development evaluation? The impact of CARE's SHOUHARDO project on child stunting in Bangladesh
	Verrest H	Rethinking microentrepreneurship and business development programs: vulnerability and ambition in low-income urban Caribbean households
	Wyndow P, Li J, Mattes E	Female empowerment as a core driver of democratic development: a dynamic panel model from 1980 to 2005

Appendix 2. A summary of textual use of “development,” “developed,” and “developing” by Sen, Ferguson, Moser, and Escobar in the Prefaces and/or Introductions of the selected texts. The uses are reported following the hierarchical categories identified in Figure 2, with the total count at each level indicated in bold. “Q” indicates a qualified use of “development” that contains an adjacent clarifying term and “U” indicates an unqualified use of “development” that does not

	Sen			Ferguson			Moser			Escobar		
	Total	***Q***	***U***	**Total**	***Q***	***U***	**Total**	***Q***	***U***	**Total**	***Q***	***U***
Total	39			35			73			153		
Proper nouns	0			0			6			2		
Direct quotes	0			0			1			2		
Unrelated	0			0			5			3		
Deliberate	39			35			61			146		
Unclear	0			0			2			7		
Clear	39	*15*	*24*	35	*20*	*15*	59	*57*	*2*	139	*83*	*56*
Percent of clear		*38.5*	*61.5*		*57.1*	*42.9*		*96.6*	*0.4*		*59.7*	*40.3*
Processes	**27**	*5*	*22*	**1**	*1*		**11**	*9*	*2*	**2**		*2*
1. General immanent process												
2. Historical path							1		*1*			
3. Theoretical and teleological				1	*1*					2		*2*
4. Idealized improvement	27	*5*	*22*				10	*9*	*1*			
Patterns	**2**	*2*								**3**	*3*	
5. Economic growth												
6. Industrialization												
7. Health and human services												
8. General well-being	2	*2*								3	*3*	
9. Unspecified/integrated												
Practices				**4**	*3*	*1*	**2**	*2*		**47**	*21*	*26*
10. General/global institution				3	*2*	*1*				39	*13*	*26*
11. Specific policies, plans, projects							2	*2*				
12. Financial investment										3	*3*	
13. Interventions targeting patterns												
14. Interventions targeting groups										2	*2*	
15. Types of organizations				1	*1*					2	*2*	
16. Practitioners										1	*1*	
Perspectives	**10**	*8*	*2*	**30**	*16*	*14*	**46**	*46*		**87**	*59*	*28*
17. Public conception	6	*4*	*2*	13	*6*	*7*				15	*5*	*10*
18. Broad institutional vision				10	*10*					38	*26*	*12*
19. General strategies and theories							44	*44*		14	*14*	
20. Intellectual discourse	2	*2*		1		*1*	2	*2*		8	*5*	*3*
21. Formalized knowledge	1	*1*								8	*8*	
22. Rhetorically undefined	1	*1*		6		*6*				4	*1*	*3*
Developed							**1**			**14**		
With reference to societies										7		
Other							1			1		
Quotes and proper nouns										6		
Developing	**1**						**4**			**1**		
With reference to societies	1						2			1		
Other							2					
Quotes and proper nouns												

Appendix 3. The top 25 most commonly used qualifiers for deliberate and clear uses of "development," in the selected articles from *World Development*, shown here as combined across 1973, 1993, and 2013 and classified to general categories only

Qualifying term	Use in selected articles (*n* = 55)		Use with Reference to:			
			Immanent		Intentional	
	Count	Percent	Processes	Patterns	Practices	Perspectives
Policy (-ies)	26	47.3			14	12
Economic	25	45.4		24	1	
Strategy (-ies)	18	32.7				18
Process (-es)	17	30.9	12		1	4
Rural	17	30.9	2	1	14	
Women	15	27.3			5	10
Agency (-ies)	12	21.8			12	
Project (s)	12	21.8		1	11	
Agriculture (-al)	11	20.0		8	3	
Program (s)	10	18.2			8	2
Community	10	18.2			8	2
Literature	9	16.4				9
Activity (-ies)	8	14.5			8	
Effort (s)	8	14.5			8	
Planning	8	14.5				8
Sustainable	8	14.5	5	2		1
Approach (-es)	7	12.7				7
Assistance	7	12.7			7	
Capitalist (-ism)	7	12.7	3	4		
Goal (s)	7	12.7		1		6
Industry (-ial)	7	12.7		7		
Infrastructure (-al)	7	12.7		5	2	
Problems	7	12.7	1	3		3
Outcomes	6	10.9		6		
Plans	6	10.9			5	1

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Effects of Cultivation and Alternative Vineyard Management Practices on Soil Carbon Storage in Diverse Mediterranean Landscapes: A Review of the Literature

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Managing carbon storage at the landscape level through emission reduction and carbon sequestration is emerging as a viable local response to atmospheric carbon loading from anthropogenic activities. The conversion of uncultivated land uses and land covers (LULCs) to arable or perennial cropping systems is widely recognized as resulting in significant decomposition of soil organic carbon (SOC). Minimizing conversion and advocating alternative management of these cultivated land uses have been identified as having the potential to minimize this loss and potentially sequester atmospheric carbon. However, effective landscape management requires a more rigorous understanding to inform local decision-making. This review of published studies within diverse Mediterranean landscapes found that cultivated areas contained roughly half of the SOC of uncultivated LULCs, with vineyards often containing the lowest observed SOC levels in a landscape. Mitigation through alternative management can result in higher SOC levels than conventional management, but the latter is likely to be a fraction of the C loss from initial cultivation. However, the majority of relevant studies relied on shallow standardized sampling depths and other protocols that have been demonstrated to lead to miscalculations of existing SOC stocks. Novel sampling techniques and emerging research opportunities have the potential

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to revolutionize our understanding of this question and support scientifically sound carbon-based landscape management.

KEYWORDS soil carbon, vineyard management, grassland conversion, climate change

INTRODUCTION

Understanding carbon dynamics within anthropogenic landscapes is critical for identifying practical local means of sequestering carbon and/or reducing emissions to mitigate atmospheric loading. Within managed terrestrial systems, rapid human-induced changes in local landscape carbon storage come primarily as a result of a) the conversion of one type of land use/land cover (LULC) to another, and through b) alternative management practices within a single LULC (Guo and Gifford 2002; Stockmann et al. 2013). While changes also result from global processes such as climatic changes associated with atmospheric carbon levels, these local issues in land management are an opportunity for land managers to take the initiative and use an understanding of the carbon cycle to inform their management decisions. Landscape-level management of carbon might address both of these approaches, such as through the reforestation of degraded agricultural fields or the increased amendment with organic materials within cultivated fields. However, identifying appropriate carbon management at the landscape level requires reliably estimating the implications of LULC change and alternative management practices on landscape carbon storage. Given recent paradigm shifts and revelations in our understanding of the carbon cycle, particularly with regards to soil organic carbon (SOC), it is not clear that such information is sufficiently available to meet this increasing demand (Schmidt et al. 2011; Stockmann et al. 2013).

This literature review investigates the effects of LULC conversions and alternative management practices on soil carbon storage within diverse Mediterranean agricultural landscapes, with a special focus on the establishment and management of vineyards. Vineyards and viticulture constitute a culturally and economically important sector of agricultural production in Mediterranean climates around the world. The growth of the global wine trade in recent decades has encouraged the planting of uncultivated areas, such as grasslands, forest, pasture, and the shrubby and sparsely forested vegetation that dominates unmanaged areas under Mediterranean climates. Unlike with most annual crops, vineyards can be established on hillsides and in marginal soils, and this extensification is identified as a threat to watersheds and native ecosystems and has raised fears of increased carbon emission through the disturbance of uncultivated soils (Carlisle et al. 2010). As of 2013, California alone had 570,000 acres of wine grape production, a 4.5% increase from 2012, with much of this coming through conversion of grasslands (Climate Action Reserve 2012; California Department of Food and Agriculture 2014). In addition, vineyards and orchards can be managed through a broad range of practices and recent evidence appears to show a strong influence of certain management practices on soil carbon levels in vineyards (Carlisle et al. 2010).

The impact of LULC conversions and management practices on soil carbon storage has recently been identified as a specific topic of interest by land managers and agricultural scientists working in diverse Mediterranean landscapes (Aguilera et al. 2013; Seddaiu et al. 2013). However, these studies point out the need for more research to better inform carbon-based management. One recent white paper, which was independently published by both the Verified Carbon Standard (2012) and the American Carbon Registry (2013), suggests that land managers conduct carbon balance equations that involve detailed local quantification of attributes that are simply not known, such as the "carbon stock of belowground crop biomass for Participant Field *p* in the baseline scenario in year *y*." The more pragmatic authors of a 2010 summary on greenhouse gas emissions for the California Sustainable Winegrowing Alliance suggest estimates based on the combination of global carbon models and sequestration rates and a California-specific model that focused almost exclusively on aboveground carbon dynamics (Carlisle et al. 2010). Given some of the unique characteristics of Mediterranean landscapes, which typically contain low fertility soils adapted to low rainfall and low nutrient input, and the growing recognition of the importance of soil organic carbon in the global carbon cycles, this more practical recommendation may also be inappropriate.

This review takes a different approach, which is to search the literature for information that might be immediately available to land managers looking to understand how their management decisions might influence landscape carbon storage within their region of focus. The results are summarized and interpreted in light of recent insights and paradigm shifts within the scientific understanding of soil organic carbon. The goal is to identify general trends of the direction, magnitude, and variability of the effects of LULC conversions on soil carbon storage across Mediterranean landscapes and as a result of alternative management within vineyards. Specific quantifications of these trends will be offered if they are found to be generally reliable, and this review will conclude with recommendations for both specific further research and immediate pragmatic interpretation of what is currently known.

Soil Carbon and Response to Management

Analysis of terrestrial carbon dynamics historically often focused on aboveground carbon, and sequestration models were proposed as recently as 2006 that were based on yield and crop residue management rather than soil management and belowground carbon dynamics (Kroodsma and Field 2006). However, belowground carbon storage is often several times that of the adjacent aboveground carbon pool and, while more stable can also be very sensitive to changes in the local environment and surface management (Lal 2004). In agricultural soils this carbon is found primarily but not exclusively within organic compounds, with inorganic carbonates typically occurring at high levels only in alkaline soils, which are less frequently cultivated. The SOC pool, which globally is estimated to be four larger than the terrestrial aboveground carbon pool, has therefore become the focus of carbon-based assessment and management of diverse agricultural landscapes (Stockmann et al. 2013).

Carbon enters the soil organic pool primarily through the microbial decomposition of aboveground or belowground biomass, and is primarily lost through continued decomposition leading to volatilization or through physical removal from the area of interest through surface erosion (Table 1). These processes co-occur and vary in magnitude, often seasonally, so any measurement of SOC is a static snapshot of a dynamic equilibrium reaction. Large pulsed inputs to the soil carbon pool, such as organic soil amendment in agricultural fields, are likely to have non-linear and potentially long-term effects on SOC levels (Lal 2004). While the surface horizon is an important site of carbon addition and is often immediately responsive to land use or management changes, high levels of soil organic carbon can be stored below the surface (Rumpel and Kögel-Knabner 2011). This vertical partitioning is particularly relevant in Mediterranean climates, where natural land cover types are often dominated by grasses, shrubs, and deep rooted trees, which all have the potential to move large amounts of carbon deep into the soil profile through root turnover and bulk flow of dissolved or particulate carbon within old root channels. For example, a 2000 meta-analysis found that the top 20 cm of shrubland soils worldwide contain on average only 33% of the carbon in the top meter and less than 20% of the total carbon found in the top three meters (Jobbágy and Jackson 2000). More recent studies have reinforced the importance of this "deep carbon" to the soil carbon pool and the responsiveness of subsurface carbon to surface changes, while also admitting how little is known about carbon dynamics at depth (Fontaine et al. 2007; Rumpel and Kögel-Knabner 2011). Additional recent studies have found that microbial decomposition, which drives both soil carbon dynamics, is less dependent on the intrinsic chemical complexity of organic compounds than was long thought, and more dependent on extrinsic factors that influence microbial activity and the biophysical protection of carbonaceous compounds (Schmidt et al. 2011). Important factors include soil temperature, moisture, aeration, and texture, and these site-specific characteristics interact with the chemical nature of carbon inputs to determine local SOC equilibrium levels and rates of change (Gershenson et al. 2009; Schmidt et al. 2011).

TABLE 1 Potential pathways, mechanisms, and relevant factors driving the addition to and loss of organic carbon from the soil carbon pool. "Management practices" refers to the combination of cultivation, fertilization, and irrigation practices

Pathway	Primary mechanism	Primary controlling factors
Addition of organic carbon to the soil carbon pool		
Below-ground decomposition	Microbial decomposition of roots, root exudates, and incorporated biomass	Soil and environmental characteristics; management practices; plant community and phenology
Above-ground decomposition	Microbial decomposition of surface biomass	Soil and environmental characteristics; management practices; plant community and phenology; quantity and chemical characteristics of carbonaceous amendments
Loss of organic carbon from the soil carbon pool		
SOC Decomposition	Microbial decomposition of SOC into volatile gaseous compounds (i.e. CO_2)	Soil and environmental characteristics; management practices
Erosion	Physical removal of carbon-rich topsoil from the area of interest	Soil and environmental characteristics; management practices; slope of field; surface cover

Conversion between different land use/land cover types has been found to have a strong influence on soil carbon levels, with the cultivation of previously uncultivated soils often resulting in dramatic loses of SOC (Post and Kwon 2000; Houghton and Goodale 2004). This is often considered to be primarily a result of the disturbance associated with tillage, but irrigation and nitrogen fertilization are also predicted to encourage microbial decomposition that would further reduce SOC levels (Austin et al. 2004; Lal 2004). This is recognized as an important research question in Mediterranean vineyards, where the naturally drought adapted and low fertility soils may be especially sensitive to changes in soil water and nitrogen levels (Carlisle et al. 2010). The type of cultivation is also expected to have important implications for soil carbon storage, with some researchers predicting less lose of SOC with conversion to perennial cropping systems such as vineyards, which are often minimally irrigated, fertilized, and tilled, as opposed to annual cropping systems, where such inputs and management practices are often much more intensive (Kroodsma and Field 2006; Carlisle et al. 2010). However, the increased tillage intensity in annual cropping systems also buries more surface carbon, such as crop residue, which is expected to lead to more efficient incorporation into the SOC pool than when it is left on the surface (Sanderman and Baldock 2010). In contrast, pruning residue in vineyards and orchards, for example, is typically removed from the field. In addition, annual row crops are often restricted to flatter areas, while perennial crops can be established on erosion-prone hillsides. The effect of the conversion to perennial versus annual cropping systems may therefore be highly crop, site, and management specific.

Alternative management practices within cultivated fields can have significant positive or negative effects on SOC, although even under the best circumstances the cultivated equilibrium levels are expected to be less than the pre-cultivation levels (Lal 2004; Aguilera et al. 2013). These SOC management practices can be divided into two general approaches. This first approach is to manage carbon locally within a field, and common strategies include reducing tillage intensity, seeding and incorporating cover crops as a green manure, mulching with crop residue or incorporating it into the soil, and intercropping within perennials to provide groundcover. The second approach is to amend the soil with off-site carbon, which might include fresh or composted plant or animal based products. These amendments immediately raise the carbon levels in the soil, particularly with physical incorporation, but it is often not clear to what extent this off-site carbon results in a long term increase in SOC, as much of the added biomass may be quickly volatilized. Recent studies have shown that the effect of both approaches on SOC levels can be strongly site-specific and these alternative practices have the potential to interfere with crop production, such as through increased competition for nutrients and water (Govaerts et al. 2009). This competition may be particularly relevant within vineyards, which are often water and nutrient stressed due to common Mediterranean soil and climatic conditions.

Soil organic carbon levels are often reported either as a concentration of carbon within bulk soil, typically as g C/kg soil or %C, or converted through the bulk density and sampling depth to a quantity of carbon per unit area, typically Mg C/ha. The latter unit is necessary to measure landscape carbon storage, but has some inherent shortcomings in agricultural landscapes as tillage results in a dramatic and immediate change in bulk density. This change effectively results in a new and relatively higher soil surface, such that subsequent sampling to a standardized depth does not in fact capture the same depth of soil as it would prior to tillage. There are analytic techniques that can minimize this potential error, but it remains a serious concern when comparing among cultivated and uncultivated LULCs, particularly when there isn't detailed knowledge of recent tillage events (Lee et al. 2009). Measurement of SOC levels as concentration in bulk soil avoids this problem, but it is also not immediately applicable to questions of landscape carbon storage and might be easily misinterpreted. For example, a significant increase in the surface soil does not imply a significant or even detectable overall change in the total SOC storage, and recent studies have shown that it does not even imply the direction of change (Rumpel and Kögel-Knabner 2011). This latter insight is again particularly relevant with regards to changes in tillage, which can influence both the concentration of SOC and the depth of the surface horizon. The long-held belief that no-till reliably increases SOC storage is now recognized as a result of shallow standardized depth

TABLE 2 Estimate of the percentage of SOC within the top 3 m of soil that is missed when sampling is limited to more shallow depths

Depth	Grassland	Shrubland	Forest
20	70.6	81.4	67.9
40	54.5	68.4	54.5
60	44.1	58.2	46.2
80	35.7	50.3	40.4
100	30.1	43.5	35.9
200	9.1	22.0	17.3

Adapted from Jobbágy and Jackson (2000).

sampling, and the effect of the practice appears instead to be complex and largely site-specific (Baker et al. 2007; Luo et al. 2010). Sampling of surface soil only and sampling by standardized depths are therefore both major concerns when drawing conclusions about SOC pools, and both are common in the literature through the common tendency to sample only the top 10 or 20 cm. This widespread practice, while sufficient for many agronomic concerns, is not well suited for questions of soil carbon storage (Table 2).

METHODS

This review is limited to studies since 2000, as early methods of assessing soil carbon levels are now considered less reliable, such as calculating SOC from measurements of total soil organic matter. Studies since 2000 that measure soil organic matter but not soil organic carbon were excluded, as were those that focus exclusively on SOC levels within a single LULC due to the variety of relevant factors that would make it impossible to, for example, directly compare SOC levels in a grassland in Spain against a vineyard in California. "Mediterranean" was used as a search filter for these comparative studies to ensure that all studies were in relatively similar climatic conditions. These selection criteria were relaxed for the review of vineyard management studies, as these do not necessarily include a local uncultivated LULC as reference or explicitly identify the climate zone as Mediterranean, but additional filtering was done by location to remove more temperate wine-growing regions. In this article, the analysis of alternative management practices is restricted to vineyard management, as a recent meta-analysis has addressed the broader question of conventional versus alternative management of cultivated fields but did not consider vineyard management as a unique issue (Aguilera et al. 2013). The important takeaways and shortcomings of this meta-analysis are discussed, but no attempt is made to re-analyze their data.

All meta-analyses and literature reviews face the problem of trying to summarize results among diverse studies that may use widely disparate methods, which can undermine any quantitative conclusions such as average effect size. This is a particularly critical issue here given the relatively small number of studies, the broad range of sampling depths that were used, and the diversity of landscape demarcations, which may or may not include subgroupings for topography or other relevant characteristics. Results that were reported only in more complex subgroupings, such as by LULC plus soil type or topography, were collapsed through a simple averaging within LULCs of interest. This is suboptimal, but more rigorous interpretation is not possible from the published data. Due to the limited number of relevant studies, we did not filter them based on sampling methods or attempt to correct for sampling depth through the calculations in Table 2. Results that were reported only through figures were visually quantified to the best of our ability. All results were converted to %C or Mg C/ha. While some studies included years since conversion or adoption of alternative practices, we did not attempt to calculate rates of change from this information as we considered the number of studies insufficient given the diversity of relevant factors.

EFFECT OF CONVERSION TO CULTIVATED LAND USES/LAND COVERS

This literature review did not find relevant long-term experimental LULC conversion studies or reliable observational studies that sampled before and after conversion with a sufficient timespan in between. Instead, the effect of conversion must be inferred from sampling within existing patterns of LULC. This was found to primarily be done through one of three different approaches (Figure 1). The most rigorous but least generalizable are paired-site studies, where contrasting LULCs are sampled from immediately adjacent sites that share other importance characteristics such as soil type and topography. Similar to these are mosaic landscapes, where multiple LULCs occur within close proximity to each other and land characteristics and histories are well known. At the broader scale are meta-analyses of soil samples, which often re-examine hundreds or thousands of soil cores that were collected for large-scale soil surveys and were geocoded to known LULCs, soil types, and climatic zones. For the purposes of this review, these comparisons among LULCs are also reported as the implied carbon loss with conversion, which

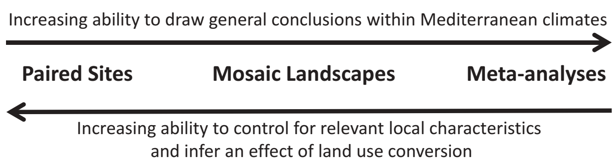

FIGURE 1 Summary of three different strategies of using existing diverse landscapes for inferring the effects of land use/land cover conversions when time-lapse studies are not available.

was calculated as percent difference relative to the uncultivated LULCs. When there are multiple potentially relevant uncultivated land cover types, this implied loss is represented as a range. All relevant studies and comparisons are summarized in Table 3.

Paired Sites

This article found five published papers that applied the paired-site approach for comparing cultivated and uncultivated fields in Mediterranean climates, all in Italy or California (USA). All of these studies, which totaled 16 unique cultivated-uncultivated paired sites, found dramatically less SOC in the cultivated fields. The average implied loss in soil carbon storage with the cultivation was 44.7% with conversion to annual cropping (n = 5 paired sites) and 46.7% with conversion to perennial cropping (n = 12). The implied loss with conversion to vineyards was 52.1% (n = 9) versus 30.6% with conversion to olive groves or citrus orchards (n = 3). One study used detailed knowledge of historical land use changes to study the conversion between perennial and annual cropping and found that the establishment of a vineyard within part of an annually cropped field resulted in a 105% increase in SOC levels after more than 30 years, while the establishment of an annual field within an old vineyard resulted in a loss of 9% of the vineyard SOC levels over the same time period (Novara et al. 2012).

One study in California's Mendocino County illustrates the variability of SOC levels within Mediterranean LULCs and the complexity of trying to correlate how the former responds with change to the latter (Williams et al. 2011). This study applied a paired-site approach within a mosaic landscape of five vineyards that were in close proximity but highly variable in terms of soil type, topography, and internal heterogeneity. Six paired sites were selected within these five vineyards where representative vineyard plots were immediately adjacent to representative uncultivated areas of "wildland." Paired soil pits were dug to a minimum of one meter at each of the six sites and the SOC concentration and bulk density was measured at 0–15, 15–45, 45–75, 75–100 intervals. The total carbon storage within each pit was found to be highly variable within wildlands, ranging from 110 to 200 and averaging 146.7 Mg C/ha and within vineyards, ranging from 30 to 100 and averaging 70.8 Mg C/ha. The difference between adjacent wildland-vineyard paired sites, interpreted here as the implied SOC loss with conversion to vineyard, ranged from 10 to 110 Mg C/ha (9.1–76.9%) with an average of 75.8 Mg C/ha (50.1%).

Mosaic Landscapes

This second approach is applied in complex landscapes where paired sites are not available, but other characteristics, such as regional climatic

TABLE 3 Summary of published articles that report SOC levels under multiple land use/land cover classes within diverse Mediterranean landscapes (average implied change in SOC is shown in bold at the bottom of the table)

			Uncultivated LULC			Cultivated LULC			Implied carbon loss with conversion		
Source	Location	Sampling depth (cm)	Description	%C	Mg C/ha	Description	%C	Mg C/ha	Difference in %C	Difference in Mg C/ha	% loss of uncultivated C
Paired sites											
Riffaldi et al. (2002)	Sicily, Italy	0–15	Grassland	2.8		Orange groves	2.6		0.2		7.1
						Winter wheat	2.1		0.7		25.0
						Vegetables	1.7		1.1		39.3
Caravaca et al. (2002)	Central Italy	0–20	Grassland (1)	2.13		Vineyard	0.32		1.81		85.0
			Grassland (2)	1.17		Olive orchard	0.85		0.32		27.4
			Grassland (3)	1.44		Sunflower	0.55		0.89		61.8
			Grassland (4)	0.87		Wheat/ sunflower	0.39		0.48		55.2
Carlisle et al. (2006)	California, USA	0–20	Oak woodland	4.63		Vineyard	2.48		2.15		46.4
Williams et al. (2011)	California, USA	0–100	Wildlands (1)		180	Vineyard (1)		70		110	61.1
			Wildlands (2)		120	Vineyard (2)		50		70	58.3
			Wildlands (3)		140	Vineyard (3)		80		60	42.9
			Wildlands (4)		200	Vineyard (4)		95		105	52.5
			Wildlands (5)		110	Vineyard (5)		100		10	9.1
			Wildlands (6)		130	Vineyard (6)		30		100	76.9
Novara et al. (2012)	Sicily, Italy	0–40	"Garrigue"		112	Vineyard		71		41	36.6
						Olive grove		53		59	52.7
						Arable land		65		47	42.0
								Cultivated	**0.96**	**66.9**	**45.8**
								Perennial	**1.12**	**69.4**	**46.3**
								Vineyards	**1.98**	**70.9**	**52.1**

(*Continued*)

TABLE 3 (Continued)

			Uncultivated LULC			Cultivated LULC			Implied carbon loss with conversion		
Source	Location	Sampling depth (cm)	Description	%C	Mg C/ha	Description	%C	Mg C/ha	Difference in %C	Difference in Mg C/ha	% loss of uncultivated C
								Orchards	0.26	59.0	29.1
								Annual	0.79	47.0	44.6
Mosaic landscapes											
Steenwerth et al. (2002)	California, USA	0–6	Grassland (perennial)		14.8	Agriculture (irrigated)		9.4		5.5–5.4	37.2–36.5
			Grassland (annual)		14.9	Agriculture (rainfed)		8.6		6.3–6.2	42.3–41.6
Evrendilek et al. (2004)	Southern Turkey	0–20	Forest		56.5	Cropland		32.6		23.9	42.3
Le Bissonnais et al. (2007)	Southern France	0–5	Garrigue	5.2		Vineyard	0.9		4.3		82.7
Moscatelli et al. (2007)	Central Italy	0–20	Forest	1.45		Agriculture (conven-tional)	0.8		0.65–0.55		44.8–40.7
			Grassland	1.35		Agriculture (organic)	0.9		0.55–0.45		37.9–33.3
Martinez-Mena et al. (2008)	Southeast Spain	0–5	Forest	2.1		Olive Grove	1.3		0.8		38.1
Blavet et al. (2009)	Southern France	0–5	Scrubland	3.9		Vineyard (mulched)	0.8		3.1		79.5
						Vineyard (unm-ulched)	0.5		3.4		87.2
Almagro et al. (2010)	Southeast Spain	0–15	Forest		51.9	Olive grove		26.6		25.3	48.7

Marzaioli et al. (2010)	Southern Italy	0–10	Forest	8.4		Vineyard	1.3		7.1–3.3		84.5–71.7
			Shrubland	4.6		Orchard	2.6		6.0–2.0		71.4–43.5
			Pasture	8.1							
Lagomarsino et al. (2011)	Sardinia, Italy	0–20	Oak forest	2.51		Vineyard (tilled)	1.42		1.09–0.74		43.3–34.3
			Pasture	2.16		Vineyard (no–till)	1.28		1.23–0.88		49.0–40.7
Emran et al. (2012)	Northeast Spain	0–15	Oak forest	2.90		Vineyard	0.26		3.45–1.60		93.0–86.0
			Pine forest	1.86		Olive grove	1.5		2.21–0.36		59.6–19.4
			Scrubland (w/ fire)	3.06							
			Scrubland (w/o fire)	3.71							
			Pasture	3.70							
Francaviglia et al. (2012)	Sardinia, Italy	0–100, by horizon	Oak forest		50.5	Vineyard (tilled)		36.4		17.3–14.1	32.2–27.9
			Pasture		53.7	Vineyard (no–till)		37.4		16.3–13.1	30.4–25.9
Martinez-Mena et al. (2012)	Southeast Spain	0–5	Forest	2.64		Olive Grove	1		1.64		62.1
Seddaiu et al. (2013)	Sardinia, Italy	0–100, by horizon	Oak forest		50	Vineyard (tilled)		33		49–17	59.8–34.0
			Pasture (open)		82	Vineyard (no–till)		32		50–18	61.0–36.0
			Pasture (near trees)		74						
							Cultivated		**2.73–1.77**	**24.2–15.4**	**56.5–48.2**
							Perennial		**3.12–2.01**	**31.6–17.5**	**61.4–51.1**
							Vineyards		**3.38–2.47**	**33.2–16.2**	**63.9–55.1**
							Orchards		**2.66–1.2**	**25.3**	**56.0–42.4**
							Annual		**0.6–0.5**	**11.9–11.8**	**40.9–38.9**

(*Continued*)

*Munoz–Rojas et al. (2012)	Andalusia, Spain	0–75	Scrub	49.1	Perennial	52.2	(+6.3 – +12.8)		(+12.8 – +19.5)
			Forest	47.8	Arable	58.3	(+9.2 – +10.5)		(+18.7 – +22.0)
					Cultivated		**0.63**	**68.6–25.1**	**54.5–36.0**
					Perennial		**0.7**	**72.7–64.7**	**58.7–45.3**
					Vineyards		**0.8**	**66.1–27.3**	**58.4–44.1**
					Fruit/Nut		**0.6**	**58.4–24.6**	**51.6–37.7**
					Annual		**0.5**	**63.5–53.0**	**48.6–22.8**

The original descriptions are retained when possible, but in some cases subgroups within the original literature were collapsed into more common general groupings for the table. LULCs with only periodic cultivation, such as rotational hay crops, were excluded, as were cultivated areas under long–term fallow. When appropriate, cultivated LULCs are compared against the uncultivated LULCs with the highest and the lowest SOC in the landscape to produce a range of values for the implied SOC change with conversion. The average implied changes in SOC is shown at the bottom of the table. The study with an asterisk (*) was treated as an outlier and not included in calculating these averages.

conditions, are thought to be shared among the sampled LULCs. Comparison of SOC values among LULCs in mosaic landscapes is therefore more likely than paired site studies to be influenced by factors that may in fact vary among the sampled locations, such as topography, soil type, and land use history. A common response to this potential heterogeneity is to sample broadly and make additional LULC divisions, such as between forest, shrubland, and grassland, or to make topographical categories within each LULC. While necessary, this sub-categorization makes comparison of cultivated and uncultivated areas difficult as it is not clear what, if anything, is an appropriate local reference for the cultivated areas. In general this approach might also be expected to underestimate SOC loss with conversion as the comparisons are often cultivated flat areas against uncultivated hillsides, which, all else being equal, are expected to be naturally lower in SOC than flat areas due to erosion.

The overall picture that emerges from 14 studies within mosaic landscapes again shows dramatically lower SOC levels in cultivated fields compared to the surrounding uncultivated areas, presumably as a result of the conversion to cultivated LULC classes. Perennially cropped fields were found to have on average 64.1% less carbon than the uncultivated LULC with the highest SOC in the landscape, and 52.1% less than the uncultivated LULC with the lowest SOC levels in the landscape (12 comparisons in 10 studies). This implied loss in SOC with cultivation was again found to be greater for conversion to vineyards (maximum 70.7%, minimum 59.1%, 7 comparisons) than to other orchard crops (maximum 55.5%, minimum 42.3%, 5 comparisons). The comparison of annually cropped fields against uncultivated LULCs was only found in five comparisons within three studies, with the implied loss of SOC with cultivation averaging a maximum of 43.4% and a minimum of 37.3%.

These studies of mosaic landscapes illustrate many of the complications that can arise from alternative methods, particularly with sampling depth and LULC classification. A single mosaic landscape in Sardinia that contained oak forest, fields under pasture/hay rotation (5:1 years), and vineyards was the focus of three apparently independent studies. The first of these to be published used a standard sampling depth of 20 cm and the results imply that the conversion from oak forest to pasture resulted in 13.9% loss of SOC that spiked to 43.8% loss during the one year of cultivation to grow hay (Lagomarsino et al. 2011). This suggests both a very rapid loss of SOC with cultivation and a rapid recovery during the subsequent five years as pasture. However, the second study sampled the soil profile in each LULC and found that when total SOC storage estimates were corrected for the depth, SOC concentration, and bulk density of the top soil horizon, the hay fields contained the highest SOC in the landscape at 57.5 Mg C/ha (Francaviglia et al. 2012). The explanation given for this was that periodic cultivation of pasture/hay fields resulted in thicker carbon-rich surface horizons that were

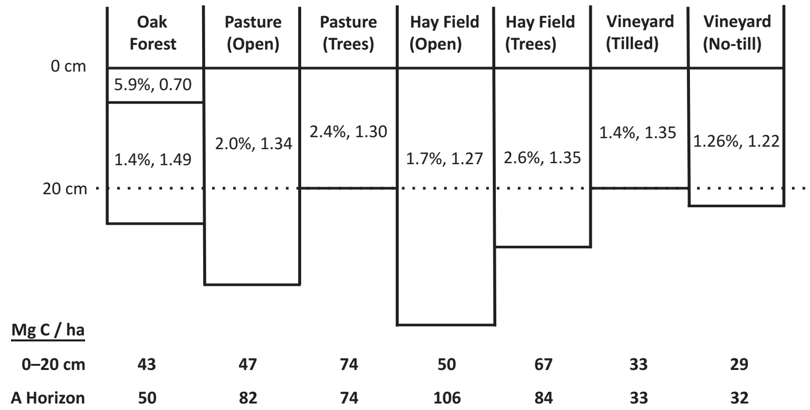

FIGURE 2 Conceptual diagram of SOC concentration, horizon depth, and bulk density (kg/dm^3) for surface soil under seven land use/land cover categories in Sardinia, Italy, as measured in Seddaiu et al. (2013). "Pasture" is in a 5:1 year rotation with "hay fields," which were presumably recently tilled but only in the "open" areas. The areas marked as "trees" were presumed by the authors to have never been tilled. The common "0 cm" level may be deceptive here, as difference in bulk density and thickness with tillage treatments may come as a relative increase in the level of the soil surface. The dotted line indicates the portion of the soil that would be sampled with a standardized sampling depth of 20 cm as opposed to by horizon depth. The associated estimates of carbon storage from each method are given at the bottom of the figure, where the "0–20" estimate is calculated as the fraction of the total storage that falls in the top 20 cm assuming homogeneous SOC concentrations within each horizon.

not adequately measured with the 0–20 cm sampling method. The most recent study found similar results within this mosaic landscape, and also observed thicker surface horizons in the open areas within pastures and hay fields that received periodic tillage as opposed to the portions of these same fields where solitary oak trees prevented cultivation of the immediately surrounding soil (Figure 2; Seddaiu et al. 2013). All three of these studies found that conversion of oak forest to vineyards resulted in an implied SOC loss of more than 30%, making it by far the LULC with the least carbon storage within this landscape.

Meta-Analyses of Soil Surveys

The third approach to estimating the effects of LULC conversions on SOC storage is to conduct meta-analyses of hundreds or thousands of soil samples that were part of large-scale soil surveys, and to correlate the SOC results with maps of land use, soil types, climate, and other relevant spatial information. This approach lacks the resolution of the earlier methods and shares many of the concerns found of the analysis of mosaic landscapes, but the spatial scale of these meta-analyses supports general inference of the effect of conversion.

Only five meta-analyses of SOC were found in the literature and they were focused only on France (2) and Spain (2), with an addition meta-analysis restricted to Southern Spain. The four country-wide studies all found dramatically lower SOC values under cultivated areas than uncultivated areas, and in all direct comparisons vineyards were found to have greater implied SOC loses than orchards and both were greater than annual cropland (Table 3). These conclusions are in agreement with the general trends found in the paired-site and mosaic landscape studies, but surprisingly, the meta-analysis restricted to Southern Spain shows a radically different trend, with SOC levels being higher in both perennial and annual cropland than in uncultivated forest or scrubland. The reasons for this are unclear, but may be attributed to LULCs in this region being strongly correlated with patterns of topography or parent material that might be naturally low in SOC.

The two meta-analyses from France represent alternative ways to conduct large-scale estimates of SOC stocks. The 2001 study combined data from multiple pre-existing forest, agricultural, and rangeland soil surveys, which used different sampling protocols and analytic methods, including fixed depth versus horizon-based sampling and carbon stock estimates through associated bulk density measurement versus those that were not. The analysis was restricted to the top 30 cm to try to correct for some of these difference, although it is not clear how the authors interpreted the surveys that sampled as 0–20 cm and 20–40 cm. These georeferenced soil samples were then classified within seven LULC classes, which included "arable land," "vineyards, fruit trees, and olives," and what the authors called "complex cultivation practices" and 17 soil types. This LULC + Soil Type classification makes it difficult to infer the general effect of cultivation, but vineyards and perennial crops had the lowest carbon stocks in all soil types except for one, in which it was virtually identical to SOC stocks under annual crops (Arrouays et al. 2001).

The 2011 meta-analysis within France interpreted SOC stocks from a 1974 soil survey that used a spatial sampling design and standardized sampling method. In this survey, a 16-×-16 km grid was drawn over France and at the center of each cell 25 soil samples where taken by auger to 30 cm and bulked, with a single representative pit dug to measure local bulk density at fixed depth intervals. The SOC stock was then calculated for the 0-30 cm soil layer within each cell using a single laboratory protocol. Land use and land cover was classified hierarchically into 7 primary, 22 secondary, and 41 tertiary classes, which allowed for multiple interpretations of the correlation of SOC stocks with LULC. The median SOC storage under vineyards (32 Mg C/ha) was higher only than uncultivated coastal areas (24.2), and dramatically less than other LULC types such as orchards (~40), annual crops (~45), forest (70), and grasslands (75.7). The highest observed SOC storage under vineyards was also lower than the highest observations under orchards and annual crops, with the latter showing both broader variability and a large number of outliers with high SOC stocks (Martin et al. 2011).

EFFECT OF ALTERNATIVE MANAGEMENT WITHIN CULTIVATED FIELDS

A 2013 meta-analysis of soil carbon management studies within Mediterranean cropping systems found that alternative practices had the potential to increase SOC levels compared to conventional management. This trend was observed to be highest within horticultural production, where the alternative practices on average increased the SOC levels by as much as 48% over the conventional comparisons. Cereal and perennial crops showed an average response of 15% and 25%, respectively. However, when broken down to specific practices, the primary finding of this meta-analysis was that practices that added large amounts of off-site carbon to the soil resulted in higher amounts of soil carbon. In contrast, the manipulation of local carbon had mixed results, with cover cropping resulting in an average of only 10% increase over conventional management and no-till increasing SOC in horticultural crops by 18.2% but reducing it in woody perennials by 22.5%. The combination of off-site carbon amendment and local carbon management produced the best results within the agronomically viable options, with an average increase of 49.2% over conventional management (Aguilera et al. 2013). This increase through combined management amounted to 1.11 Mg C/ha per year, but there was no mention that this rate must surely plateau over time as the soil carbon pool reaches a new equilibrium point (Stewart et al. 2007). Without this context, it is unclear how this rate might compare to the estimates of carbon lost through the initial cultivation of previously uncultivated LULCs, which in a single mosaic landscape ranged from 10 to 110 Mg C/ha with conversion to vineyards (Williams et al. 2011). Most strikingly, this meta-analysis found that alternative management practices increased SOC levels by, on average, 51.6% over conventional management in controlled experimental studies, but only by 11.4% in on-farm observational trials, which corresponds to sequestration rates of 1.28 and 0.31 Mg C/ha per year. This meta-analysis shows that while it is possible to increase SOC levels in cropped fields through alternative management, this increase may be relatively minor in the larger landscape context. As most of these studies use a shallow sampling depth (average of 25.7cm) and measure SOC levels as a concentration, these results cannot be directly compared to carbon storage of uncultivated LULC. In addition, with only five studies of management within woody perennial species and no further distinction made among perennial crop types, additional analysis is necessary to draw conclusions and management recommendations for vineyards.

Seven papers were found that sampled among commercial vineyards that were applying alternative management strategies under real-world agronomic constraints (Table 4). Seven of the 14 comparisons within these papers compared management of local carbon through no-till intercropping (5) or mulching with pruning (2), two compared known amendments with

TABLE 4 Summary of published articles that measured SOC levels within existing vineyards under conventional and alternative management practices (average implied change in SOC is shown in bold at the bottom of the table)

				Conventional		Alternative		Implied C gain with alternative	
Source	Location	Sampling depth	Carbon source	Description	%C (Mg C/ha)	Description	%C (Mg C/ha)	Difference in %C (Mg C/ha)	% gain of conventional C
Besnard et al. (2001)	Champagne, France	0–10	Local	Pruning residue is removed and no carbonaceous soil amendment is used	1.5	Mulched with pruning residue	2.6	1.1	73.3
			Off-site		1.5	Mulched with oak bark	5.2	3.7	246.7
			Off-site		1.5	Mulched with urban compost	2.9	1.4	93.3
Probst et al. (2007)	Eastern France	0–10	Local + off-site	Not Biodynamic certified	3.1	Biodynamic	3	−0.1	−3.0
Blavet et al. (2009)	Southern France	0–5	Local	Pruning residue is removed	0.5	Pruning residue is incorporated	0.8	0.3	60.0
Okur et al. (2009)	Western Turkey	0–20	Local + off-site	Not organically certified	0.75	Organic	0.78	0.03	4.0
Coll et al. (2011)	Southern France	0–15	Local + off-site	Not organically certified	1.02	Organic (7 years)	1.08	0.06	5.9
						Organic (11 years)	1.24	0.22	21.6

						Organic (17 years)	1.35	0.33	32.4
Lagomarsino et al. (2011)	Sardinia, Italy	0–20	Local	Tilled	1.42	No-till	1.28	−0.14	−9.9
Francaviglia et al. (2012)	Sardinia, Italy	Surface horizon	Local	Tilled	(36.4)	No-till	(37.4)	(1.0)	−2.8
Virto et al. (2012)	Northeast Spain	0–5	Local	Tilled	0.92	Intercropped w/ grass (1 year)	1.57	0.65	70.7
						Intercropped w/ grass (5 year)	1.25	0.33	35.9
		5–15			0.89	Intercropped w/ grass (1 year)	1.11	0.22	24.7
						Intercropped w/ grass (5 year)	1.00	0.11	12.4
		15–30			0.88	Intercropped w/ grass (1 year)	0.93	0.05	5.7
						Intercropped w/ grass (5 year)	0.94	0.06	6.8
Seddaiu et al. (2013)	Sardinia, Italy	Surface horizon	Local	Tilled	(33)	No-till	(32)	(–1)	−3.2
						Observational studies		**0.52**	**37.8**

off-site carbon, and five did not describe specific management practices but compared conventional vineyards against those that were managed as organic or biodynamic. Of these, the first group of studies found only minor and mixed results from no-till intercropping but more dramatic increases with the mulching or incorporation of pruning residue; the second group found large increases in SOC among the vineyards that had received heavy carbon-rich amendments; and the third found SOC levels to be generally higher within active organic or biodynamic vineyards than analogous conventional vineyards, but the difference was variable even within the same study and region. The average response to alternative management among the observational studies was an increase of +0.52% C with highly variable sampling depths, which was on average an increase of 37.8% over the conventional management (Table 4).

Eleven experimental studies were found that studied management of local carbon through intercropping with groundcover species (19 comparisons), cover cropping that is seeded then incorporated as green manure (4), and mulching with crop residue from pruning (1) (Table 5). All of these studies found SOC levels to increase with the alternative management, for an average change of +0.36% C and an average of 61% increase over the conventionally managed comparison. This was found to be significant in many of the comparisons, but often only at the soil surface. As these practices are expected to reduce erosion as compared to conventional tillage or soil kept bare through herbicide application, the observed increases in SOC could come through sequestration of atmospheric carbon or by reduced losses of existing SOC through erosion (Table 5).

Six experimental studies were found that totaled 19 comparisons of vineyard plots amended with off-site carbonaceous materials against those that were not. All of these comparisons found an increase in SOC levels following amendment by an average of +0.67% C, a 68% increase over unamended soil. However the type and quantity of material used varied tremendously and the difference was again often only significant in the top 5 or 10 cm of the soil. While the increase in carbon in amended soils might include some that is sequestered from the atmosphere or maintained through reduced erosion, it is likely that much of the observed increase in vineyard SOC levels is simply residual off-site organic carbon that had been transplanted into the vineyard soil pool (Table 5).

CONCLUSIONS, IMPLICATIONS, AND DIRECTIONS FOR FUTURE RESEARCH

The clear trend throughout the literature on soil organic carbon storage in Mediterranean landscapes is that conversion to cultivated LULCs leads to dramatic losses of SOC. Conversion to perennial cropping was found to

TABLE 5 Summary of published articles that measured SOC levels through experimental manipulation of vineyard management practices. Statistically significant differences are indicated with an asterisk and the average implied changes in SOC is shown at the bottom of the table

				Conventional		Alternative		Implied C gain with alternative	
Source	Location	Sampling depth	Carbon source	Description	%C	Description	%C	Difference in %C	% gain of conventional C
Blavet et al. (2006)	Southern France	0–5	Local – intercropping	Tilled	1.6	No-till, seeded w/ rye/fescue	1.5	−0.1	−6.25
Lejon et al. (2007)	Burgundy France	0–20	Local – intercropping	Tilled (Site 1)	0.98	No till, seeded w grass	1.18	0.2*	20.4
						No till, seeded w/ clover	1.71	0.73*	74.7
						No till, seeded w/ fescue	1.26	0.28*	28.6
			Local – pruning residue	Tilled, residue is removed (Site 2)	0.55	Tilled, residue is incorporated	0.77	0.22*	40.9
Smith et al. (2008), Steenwerth and Belina (2008)	California, USA	0–30	Local – intercropping	Tilled	1.10	No till, seeded w/ rye	1.55	0.45*	40.9
						No till, seeded w/ fescue	1.40	0.30*	27.2
Celette et al. (2009)	Southern France	0–100	Local – intercropping	No till, soil is kept bare with herbicide	0.61	No till, seeded w/ barley	0.58	−0.03	−4.9
						No till, seeded w/ fescue	0.56	−0.05	−8.2
		0–30			0.86	No till, seeded w/ barley	0.84	−0.02	−2.3
						No till, seeded w/ fescue	0.84	−0.02	−2.3

(*Continued*)

TABLE 5 (Continued)

				Conventional		Alternative		Implied C gain with alternative	
Source	Location	Sampling depth	Carbon source	Description	%C	Description	%C	Difference in %C	% gain of conventional C
Okur et al. (2009)	Western Turkey	0–20	Local – cover cropping	Tilled, natural regeneration	0.8	Tilled, oat/vetch cover crop	0.9	0.1	12.5
Marquez et al. (2010)	Central Spain	Not given	Local – intercropping	Tilled, natural regeneration	0.98	No till, seeded w/ brachypodium	1.05	0.07	7.1
						No till, seeded w/ rye	1.04	0.06	6.1
Adams (2011)	California, USA	0–10	Local – cover cropping	Tilled, natural regeneration	0.6	Tilled, grass/clover cover crop	0.61	0.01	1.7
Bartoli and Dousset (2011)	Eastern France	0–5	Local – cover cropping	Tilled, natural regeneration	1.39	Tilled, clover cover crop	2.56	1.17*	84.2
						Tilled, fescue cover crop	3.24	1.85*	133.0
Peregrina et al. (2012)	Northern Spain	0–45	Local – intercropping	Tilled	0.60	No till w/ natural vegetation	0.73	0.13*	20.0
López-Piñeiro et al. (2013)	Southwest Spain	0–10	Local – intercropping	Tilled	0.17	No till w/ natural vegetation	1.37	1.20*	705.9
Ruiz-Colmer et al. (2013)	Central Spain	0–10	Local – intercropping	Tilled	0.59	No till, seeded w/ rye	0.91	0.32*	54.2
						No till, seeded w/ grass	0.91	0.32*	54.2
Blavet et al. (2006)	Southern France	0–5	Off-site	Unamended	1.7	Mulched with straw	1.6	−0.1	−6.25

Lejon et al. (2007)	Burgundy, France	0–20	Off-site	Unamended (1)	0.98	Straw	1.22	0.24*	24.5
						Conifer bark	1.63	0.65*	66.3
						Conifer compost	1.71	0.73*	74.5
				Unamended (2)	0.55	Farmyard manure (high)	0.98	0.43*	78.2
						Farmyard manure (low)	1.07	0.52*	94.5
						Mushroom compost (high)	0.94	0.39*	70.9
						Mushroom compost (low)	1.36	0.81*	147.3
Okur et al. (200)9	Western Turkey	0–20	Off–site	Unamended	0.8	Manure (high) + oat/vetch cover crop	0.98	0.18*	22.5
						Manure (low) + oat/vetch cover crop	0.96	0.16*	20
Bartoli et al. (2011)	Eastern France	0–5	Off–site	Unamended	1.39	Conifer bark	2.65	1.26*	90.6
						Conifer compost	2.29	0.9	64.7
						Straw	1.71	0.32	23
Mugnai et al. (2012)	Central Italy	0–30	Off–site	Unamended	2.18	Compost (w/o NPK)	5.26	3.08	141.3
						Compost (w/ NPK)	2.75	0.57	26.1
Peregrina et al. (2012)	Northern Spain	0–25	Off–site	Unamended	0.65	Fresh spent mushroom substrate (high)	1.22	0.57*	87.7
						Fresh spent mushroom substrate (low)	0.94	0.29*	44.6

(*Continued*)

TABLE 5 (Continued)

				Conventional		Alternative		Implied C gain with alternative	
Source	Location	Sampling depth	Carbon source	Description	%C	Description	%C	Difference in %C	% gain of conventional C
						Composted spent mushroom substrate (high)	1.6	0.95*	146.1
						Composted spent mushroom substrate (low)	0.92	0.27*	41.5
						Experimental studies		**0.49**	**65.0**
						Local carbon management		**0.33**	**63.4**
						Cover cropping + pruning residue		**0.67**	**54.5**
						Intercropping		**0.24**	**66.2**
						Off-site carbon amendment		**0.65**	**66.9**

have on average a greater implied carbon loss than conversion to annual cropping, with vineyards often having the lowest observed SOC levels within diverse agricultural landscapes. These conclusions may in fact underestimate the carbon lost with conversion, as the current uncultivated sites used for comparison are more likely to be on marginal soils that are naturally low in soil organic carbon. Due to this and the nearly ubiquitous shallow sampling depth used by these studies, the quantification of these trends as presented in Table 3 should not be considered a reliable predictor of potential carbon loss with future conversion. Instead, while the broader trends appear to be nearly universal to Mediterranean landscapes, quantification should be done locally in an attempt to capture site-specific characteristics and local carbon dynamics.

While a return to uncultivated LULCs might be an appropriate land management practice to sequester carbon in some circumstances, there is increasing interest in how to improve soil carbon stocks in actively cultivated fields through alternative management practices. Observational and experimental studies show that there is potential to have higher SOC levels in vineyards under alternative management, at least in the surface soil, but it is unclear to what extent this increase would be sequestration of atmospheric carbon as opposed to improved local retention of existing SOC or the addition of carbon from off-site sources. While potentially effective, these alternative practices should not be expected to compensate for the carbon lost with initial establishment of vineyards in previously uncultivated soils. Due to the relatively small number of studies and the wide variety of sampling depths, topography, and other factors that are known to be relevant to SOC dynamics, the summary statistics presented in Tables 4 and 5 should be applied with caution to specific landscapes to quantitatively estimate changes in SOC levels with alternative management. In general, the observed trends should guide management decisions only until more locally adapted estimates can be made.

Improved Soil Sampling

Perhaps the most striking shortcoming in our current understanding of SOC dynamics is a result of the tendency to use shallow standardized sampling depths. This practice is largely a result of the difficulty of sampling to greater depths and may also be in part a holdover from agronomic soil testing of nutrient levels for shallow rooted crops. An improvement can be seen in some recent papers that incorporate the depth of the surface horizon in the calculation of SOC stocks (Francaviglia et al. 2012; Seddaiu et al. 2013). However, this approach still has the potential to miss deeper carbon and can become more arbitrary when horizons are not clear. The traditional alternative to shallow surface sampling is to dig soil pits, but less intensive alternatives have recently been developed and are now available to soil scientists and other interested researchers. These techniques commonly involved soil augers or corers that are powered by small engines or hydraulic systems, and these alternatives give an operator the necessary power to remove compact soil at depth while still retaining the precision to remove soil between desired depths intervals (Rau et al. 2011). These improved sampling techniques can inform three-dimensional soil maps that allow for more accurate calculation of soil carbon stocks and support representative rather than randomized soil sampling.

Landscape Carbon Models

The common current approach to correlating SOC stocks with land use/land cover conversions and alternative management practices is to measure SOC storage under different conditions or treatments. However, this sampling strategy may not capture the full heterogeneity in the landscape and the corresponding variation and distribution of values within each LULC or management practice. In addition, the goal from a land manager's perspective is to build predictive models that allow for reasonable inference of carbon stocks and response dynamics across diverse landscapes. This requires estimating both how SOC levels respond to the interaction of LULC type, topography, climate, and other landscape characteristics, and how these levels might change over time, particularly in the context of global climatic changes. Much more research is clearly needed, but some authors are already working on this next step and have begun to build such models of carbon stocks in diverse landscapes. Three recent efforts in particular deserve special mention within Mediterranean landscapes as they demonstrate early efforts to model SOC dynamics over space and time.

The previously discussed study in Mendocino County combined the SOC measurements from the 12 paired soil pits and an additional 32 soils pits at representative vineyard and wildland sites with high resolution spatial mapping to calculate total belowground carbon stocks within each managed ranch (Williams et al. 2011). This approach modeled the interaction of soil type, LULC, topography, and other potentially relevant factors, and found that within each ranch the wildland areas contained on average only 16% more SOC than vineyards rather than the 100% that was found through the paired site approach. This difference may be due to the likely preference for establishing vineyards in fertile—and relatively carbon rich—areas, such that the remaining wildlands are now found in naturally lower carbon soils. The integrated model-based approach used in this study, which also measured aboveground carbon stocks, offers a relatively rare example of quantifying total carbon storage within a spatially bounded area, which could soon be used to estimate carbon stocks and associated carbon credit for property owners.

The 1974 soil survey of France that was the basis of Martin et al. (2011) was repeated between 2000 and 2009 using a similar sampling protocol, and the spatially explicit results were the foundation of a model of SOC storage that incorporated climate, soil type, land use, and management practices (Meersman, Martin, De Ritter, et al. 2012; Meersman, Martin, Lacarce, et al. 2012). This modeling approach allowed for estimates to be made at a 250 m resolution across France and for an average SOC stock to be calculated for each LULC type that takes into account variation in other relevant factors, rather than simply as a direct mean of all observations within a predefined category. This approach calculated that throughout France, vineyards and orchards had SOC levels on average one third that of forests and grasslands and dramatically less than annual croplands (Table 6). The reinterpretation of the soil data as a model allows for site-specific estimates to be made that take into account local soil and climatic characteristics and to estimate the local effect of LULC conversion under different landscapes characteristics through the modeling equivalent of a paired-site approach.

One of the three published studies of the mosaic landscape in Sardania, Italy used the observed SOC measurements and known land use histories to apply the Rothamsted Carbon Model for this mosaic landscape to generate 90 year projections given alternative global emission and local climatic scenarios (Francaviglia et al. 2012). These simulations estimated increases in SOC in all LULCs with little or no active cultivation (oak forest, pasture/hay, semi-natural fallow areas) but dramatic continued declines within both tilled and untilled vineyards (Table 7). This study found that in 2007 the tilled vineyards, the LULC with the lowest soil carbon stocks, contained 66.5% of the carbon found in pasture, the LULC with the highest observed stocks, but on average the model predicted that this difference will increase and in 90 years the same vineyards will contain only 42.1% of the SOC stored in pastures.

TABLE 6 Average SOC stocks within multiple LULCs in France as estimated by a landscape carbon model the integrates climate, soil type, land use, and management practices on soil carbon storage, based on 2,000+ soil samples

		Implied carbon loss with conversion	
LULC type	Average SOC stock (Mg C/ha)	Mg C/ha	% loss of uncultivated C
Forest	94.1	N/A	N/A
Grassland	85.8	N/A	N/A
Cropland	55.7	38.4–30.1	40.8–35.1
Vineyard/orchard	32.7	61.4–53.1	65.2–61.9

Adapted from Meersman, Martin, De Ridder, et al. (2012).

TABLE 7 Estimates SOC stocks in 2097 within multiple LULCs in a region Sardinia, Italy, under two scenarios of atmospheric carbon levels and two scenarios of local weather implications, as modeled through the Rothamsted Carbon Model and based on sampling in 2007 (the "former vineyards" had gone out of production in 1977)

		High global CO_2 emissions		Low global CO_2 emissions		
	2007 Baseline	Climate Model A	Climate Model B	Climate Model A	Climate Model B	Average predicted 2097 SOC storage
Tilled vineyards	36.3	−13.6	−13.6	−13.6	−13.3	22.8
No–till vineyards	37.5	−8.5	−8.3	−8.5	−9.5	28.8
Hay fields	54.6	4.7	3.3	2.8	3.7	58.2
Pasture	52.5	2.3	2.4	2.6	2.9	55.1
Former vineyards	44.5	3.9	4.2	3.8	4.3	48.6
Oak forest	50.5	1.6	1.6	1.7	2.1	52.3

Adapted from Francaviglia et al. (2012).

Targeted Surveys of Diverse Landscapes and Vineyards

The most rapid and cost-effective means of furthering our understanding of how SOC stocks respond to changes in land use/land cover and specific management practices is likely to be conducting targeted soil surveys within diverse landscapes and existing managed areas. Past studies of mosaic landscapes have attempted to control for potential heterogeneity by sampling strictly within simple predefined categories, such as LULC or LULC + Topography. Future surveys, however, could support a more model-based interpretation if the sampling design were to explicitly capture the range of all potentially relevant characteristics and measure them locally whenever possible. Such characteristics would include soil type and horizon depths, land use history and time since conversion, management practices, and climatic conditions. A similar modeling approach was applied to interpret the most recent soil survey of France, but these studies use a gridded sampling scheme that may not be appropriate to capture the full range of potentially relevant variables when applied for finer spatial resolution studies (Meersman, Martin, De Ritter, et al. 2012; Meersman, Martin, Lacarce, et al. 2012). Such a targeted soil survey could be particularly useful for understanding the effects of alternative management within vineyards, which can vary widely in the scale and intensity of both initial cultivation and subsequent management.

Life-Cycle Analysis of Specific Alternative Practices

As more land comes under cultivation every year, leaving less uncultivated soil behind to convert in the future, there will continue to be increasing interest in studying the effect of alternative practices. However, before alternative management practices can be strongly recommended and rewarded as mitigating atmospheric loading of the carbon cycle, the broader implications of these production practices need to be understood. Some recent studies of alternative vineyard management do document differences in wine quality or grape yield, with one study observing an average decline of 40% with alternative management (Celette et al. 2009; Ripoche et al. 2011; Ruiz-Colmenero et al. 2011). However, an integrated life-cycle analysis is often entirely lacking, which would place these gains in the context of agronomic concerns and potential changes in greenhouse gas emissions with alternative practices. The California Sustainable Winegrowers Alliance recently summarized the literature on these emissions and put forth a strategic research plan, so more integrated analyses may be forthcoming (Carlisle et al. 2010).

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Field trials identify multiple adaptive management options within a complex and heterogeneous agricultural landscape in West Africa

Abstract

Rainfed crop production in Senegal and The Gambia is the primary means of food security and income generation for rural livelihoods in this region. These agricultural systems are complex, understudied, and contain a high level of social and spatial heterogeneity, such as relating to rainfall patterns, soil characteristics, and socio-economic conditions. The use of purchased certified seeds and high levels of inorganic fertilizer are widely prescribed as general "best practices" to guide farmer adaptation. However, these recommendations are based primarily on highly controlled research trials that do not capture the heterogeneity of the region or the complexity of on-farm interactions. This study fills this research gap by testing integrated alternative practices related to seeds and cultivars, inorganic fertilizers, and organic amendments through nearly 600 farmer field trials spanning the heterogeneity of the region. These three pathways were all found to reliably and comparably increase yield for rainfed crops across the region, and had a largely additive effect in combination but were poor predictors of resulting yield due to high underlying variability. The current recommendation was found to be of only intermediary effect, and was not highly valued by participating farmers, who showed a wide range in preferences that likely reflects diverse constraints and opportunities. These findings suggest that farmers in this region should be encouraged to select among multiple adaptive options based on their individual circumstances, rather than prescribed general "best practices." This study also encourages the use of on-farm field trials as a supplement or alternative to

highly controlled trials when testing alternative management practices and seeking to inform farmer adaptation.

Introduction

Agricultural systems throughout the world are under increasing stress from a broad range of factors, such as population growth, competing land uses, and climate change (Foley et al 2011). The management decisions of independent farmers are a critical fulcrum for adapting to these stressors, and improved practices have the potential to provide an immediate economic benefit to producers while also meeting broader social and environmental goals (Thompson and Scoones 2009, Chen et al 2011). Accordingly, a key function of agricultural research is to test alternative practices and identify relevant adaptive options to inform independent management decisions.

However, farmer adaptation is often considered to be analogous to the adoption of official recommendations regarding “best” practices, “improved” varieties, “proven” technologies, and “right” fertilization strategies (Le Gal et al 2011). Such recommendations are derived primarily from highly controlled small plot experiments that test artificially simplified conditions, and do not represent the heterogeneity and complexity found in the targeted production system (Kravchenko 2017). The results of such experiments are then used to generate prescriptive management recommendation, which are then extended beyond the tested locations and conditions with the assumption that the adoption of the recommendations will be widely and reliably adaptive (Hounkonnou et al 2012). This assumption may often be true in relatively homogeneous and well-understood agricultural systems, but it is less likely to be in those that are not, and it is often the highly heterogeneous and poorly understood systems that have the most urgent need and potential for adaptation (Scoones et al 2007).

This study uses a large network of on-farm field trials across Senegal and The Gambia to compare current farmer practices against seventeen alternative integrated management practices related to seeds and varieties, imported inorganic fertilizers, and local organic soil amendments. This approach allows for analysis of broad patterns of effect and to inductively address multiple applied research questions: 1) Do the alternative management practices offer reliable benefits given the complexity and heterogeneity of the landscape? If not, and they are outweighed by rainfall or other factors, then general recommendations are not appropriate at this scale. 2) Are the current official recommendations of adopting new cultivars and applying high levels of inorganic fertilizers widely effective, appreciated by farmers, and better than other options? If not, this recommendation requires more specificity and should not be considered the "best" practices. 3) Does the direct comparison of multiple alternative practices identify a singular "best practice"? If not, recommendations should present multiple adaptive options and support individualized farmer management, rather than claim prescriptive solutions. 4) Can farmer field trials effectively function as both experimentation and demonstration, thereby supporting collaborative learning by researchers and farmers? If not, the common division between research and extension and top-down emphasis on researcher-led interpretations of trials results may be appropriate.

A new model of farmer adaptation

Agriculture is the management of complex ecological systems to meet social needs and interests, a goal-driven effort that is highly constrained by economic and agronomic circumstances (Shennan 2008). These systems contain the inherent complexity of both natural ecosystems and socio-economic systems, and include multivariate and dynamic causal interactions, and often radically incomplete or uncertain knowledge of the system (Walters and Holling 1990, Dore et al 2011). In addition, the relevant factors and interactions driving these complex emergent processes can vary dramatically over small spatial, temporal, and social scales, and such subtle differences have the potential to radically alter relevant outcomes (Scoones et al 2007, Tittonnell et al 2014). This complexity and heterogeneity makes agricultural systems notoriously difficult to predict, and successful agricultural operations are not the smooth workings of an engineered process, but the effective management of ignorance, uncertainty, causal complexity, and dynamic processes (Thompson and Scoones 2009).

It is common for farmers to respond to these circumstances by actively adjusting their management practices to match changes in constraints, opportunities, and knowledge of their specific production systems. This deliberate effort at adaptation is a stepwise selection among alternative management practices, with the selective pressures and adaptive options strongly defined by local and individual system characteristics (Giller et al 2011). This change should be conceived not as a steady linear progression towards some maximum or optimal state, but as a wandering pathway within a dynamic fitness landscape, an interpretation of adaptation that is now common in ecology and evolution (Poelwijk et al 2007, Tittonell 2014). In highly complex or heterogeneous agricultural systems, the fitness landscape is likely to be sufficiently rugged and the starting points sufficiently diverse that many adaptive pathways are circuitous, prohibitively maladaptive barriers are possible, multiple peaks are likely, and tipping points can occur in both directions (Thompson and Scoones 2009, Tittonell 2014).

This continuous adjustment is an iterative process, and mistakes are likely to be made both in failing to adopt an adaptive practice (Type 1) and adopting a maladaptive practice (Type 2). The odds of correctly adopting or abstaining are increased with a farmer's improved knowledge of their production system, which includes both general factors, such as environmental and market conditions at regional or global scales, and more individual factors, such as personally or locally unique conditions, constraints, and opportunities (Dore et al 2011). This knowledge comes primarily from a farmer's own experiences, the experiences of other farmers in similar circumstances, and the advice of off-farm specialists, such as agricultural scientists. While such specialists are often in the better position to understand the relevant general factors, they are likely to have limited insights into the more individual factors or how the two interact to determine the overall adaptive value of an alternative practice (Thompson and Scoones 2009).

Farmer adaptation and alternative experimental methods

Conventional agronomic research relies primarily on highly controlled small-scale plot studies on research stations that are intentionally removed from the circumstances found in production fields (Vanluewe et al 2016, Kravchenko et al 2017). Rather than representing the complexity and heterogeneity of the target system, these experiments manipulate a small number of variables while maintaining the rest under constant and often optimal conditions (Johnson et al 1994, Yan et al

2002). This approach reflects the limitations of historical statistical methods, which were not well suited for assessing multivariate interactions or dissecting complex relationships among categorical treatment and continuous non-treatment variables (Krupnik et al 2015). Accordingly, these experiments are intentionally designed to isolate specific causal relationships of interest from other known and unknown factors that might influence the response, which allows for a straightforward treated/untreated comparison (Rubel 1935). The interpretation of such experiments contains the implicit premise of *ceteris paribus*, or "all else being equal," which acknowledges that the observed relationship may be contingent on the controlled conditions.

Generating recommendations for complex production systems from these simplified experimental systems requires the further assumption that the relationships studied in the latter will reliably hold true in the former. This is often explicitly stated in studies of nutrient constraints on crop growth as Liebig's "law of the minimum," which assumes that the studied interaction is a rate-limiting step that will outweigh the surrounding untested complexity of the target system (Rubel 1935). This assumption often goes unstated in other topics, but it is necessarily relied upon whenever the findings from highly controlled studies are extrapolated to untested conditions. While this assumption may be a reliable proxy for some questions of crop physiology, simple and stable stoichiometric relationships cannot be expected in complex and dynamic agricultural systems (Yeater et al 2015). This is particularly true when the predicted outcome is not crop growth, but profitability, food security, or some other measure of an agricultural system that integrates social, ecological, and economic factors (Giller et al 2011). In addition, this assumption relates only to multivariate interactions under stable conditions, and does not apply to situations where the complexity in the target system is due to transient dynamics, ignorance, or uncertainty (Thompson and Scoones 2009). This causal assumption is therefore most tenuous in understudied or highly dynamic agricultural systems.

This issue is recognized in agronomic theory, and the common suggestion is to use ground-truthing field trials as a follow-up to the highly controlled experiments and prior to the production of management recommendations (Williams et al 2012). Such trials are embedded within the complexity of the system and manipulate key variables in a production system without attempting to control the rest, thereby testing the assumption that the relationships observed under the highly controlled conditions will hold in practice. While this intermediary step is often recommended, it is also widely considered to be a demonstration or proof-of-concept, rather than an integral part of research to inform farmer adaptation (Knapp 1909, Johnson et al 1994). As a result, when resources for research are limited, such as in understudied and highly heterogeneous systems that require more rigorous investigation to make strong causal claims, there is a strong bias towards the highly controlled trials that are considered to be the foundation of agricultural research. In such cases, the ground-truthing step is often missing or incomplete.

An alternative approach is to use these embedded field trials as a primary rather than a secondary research method, and rely on highly controlled experiments to explore relevant causal mechanisms but not to estimate emergent system behavior or directly generate management recommendations (Johnson et al 1994, Vanlauwe et al 2016). This approach is common in ecology, where the large number of interactive components, highly dynamic processes, and high levels of ignorance and uncertainty discourage more reductionist assumptions (Hurlbert 1987). With appropriate placement and sufficient replication at the field level, these trials can also capture the relevant complexity and diversity of the target system to estimate the reliability of alternative practices under variable conditions (Kravchenko 2017). The analysis of such trials has advanced considerably with the development of statistical techniques that can address complex multivariate interactions and the relative influence of non-treatment variables, but these remain underused in agronomy (Krupnik et al 2015, Yeater 2015).

Using embedded trials as a primary research method radically changes the relationship between researchers and farmers and the ways in which research can inform farmer adaptation (Vanlauwe et al 2016). Highly controlled trials are physically removed from production fields and require a secondary extension effort to reach farmers. As the experiments are managed and interpreted by researchers alone, the result is a top-down two-step process of technology transfer that contains limited feedback mechanisms. The reliance on highly controlled designs and conventional statistical methods also encourages dualistic "good or bad" conclusions, rather than the relative "better or worse" interpretations that reflect the decision-making process underlying of farmer adaptation (Hounkonnou et al 2012, Zhang et al 2016). The effectiveness of this model is therefore strongly dependent on the subjective ability of individual researchers to understand, incorporate, and respond to the complexity and diversity of the target system, and can do little to influence farmer adaptation when the recommendations are not adopted or prove not to be adaptive (Giller et al 2011). In contrast, embedded research trials also serve to demonstrate multiple alternative options, which can empower farmers to adapt in diverse ways that may be unforeseen by researchers. This approach is therefore less dependent on prior researcher knowledge to drive farmer adaptation. Networks of embedded trials and rigorous assessment of relevant heterogeneity can inductively identify multiple adaptive pathways and produce context-specific "recommendation domains" that would likely be missed by the conventional approach (Hildebrand 1984, Baudron et al 2012).

Rainfed agriculture in Senegal and The Gambia

The semi-arid Sahel and Savannah zones of West Africa mark the transition zone between the fully arid Sahara desert to the north and the increasingly wet forests to the south (Raynaut 2001). The countries of Senegal and The Gambia span this gradient along the Atlantic coast, which moderates the continental temperatures along the coastal areas and brings additional rainfall in the wetter south (Xie and Arkan 1996, Himans et al 2005). Soils in these regions generally reflect the north-south precipitation gradient, with higher sand content, higher pH, and lower soil organic matter in the more arid north, but are also influenced by the east-to-west history of soil erosion and deposition (Hengl et al 2015). Most of the population centers are in the west, which has implications for market access, income-earning opportunities, and land and local resource demand (Linard et al 2015). While most of Senegal has been politically stable for decades, southern Senegal is the site of a long-running civil war and The Gambia has been plagued with political repression and associated insecurity (Evans 2004). These countries also contain numerous overlapping ethnic groups and high socio-economic variation at the community level (Raynaut 2001). As a result of this complexity and heterogeneity, a simple stressor, such as low rainfall, can have highly variable implications in a single location, and a widespread outcome, such as low crop productivity, can be the result of multiple causal pathways (Tittonnel 2014, Farrow et al 2016).

Rainfed crops have been cultivated in these semi-arid countries for thousands of years and are the primary means of both subsistence and income generation for the majority of rural households (Nyong et al 2007). However, short rainy seasons with low annual rainfall and high spatial and temporal variability make these production systems notoriously temperamental, a problem that is exacerbated by naturally sandy and low organic matter soils, limited market access and income-generating activities, and changes in land tenure that restrict seasonal migration (Raynaut 2001, Baro and Deubel 2006). As a result of major drought-induced famines in the twentieth century, this region has seen decades of national and international investment in agricultural development, primarily in the form of top-down technological prescriptions (Mortimore and Adams 2001, Hounkonnou et al 2011).

There are a limited number of management opportunities within these rainfed systems, and some adaptive pathways with high potential to increase production, such as dramatic increases in capital inputs, are also highly constrained by agro-ecological and socio-economic conditions. As a result, recommendations that are optimized to maximize production are not necessarily applicable to most farmers, and widespread adoption may be generally maladaptive (Vanlauwe et al 2016). Two critical and widely relevant entry-points for alternative management of these systems are 1) seed quality and crop varieties, and 2) soil fertility management practices (Evenson and Gollin 2003, Vanlauwe et al 2014). In both cases, producers can chose from a range of low or no-cost options, such as improved seed saving practices and in-field management of crop residue, to high cost but potentially high reward options, such as the purchase of certified seed of newly developed varieties along with inorganic fertilizers.

West Africa is the site of the domestication and historical diversification of a number of pulse and grain crops specifically adapted to semi-arid climates, including millet, cowpea, sorghum, and rice (Meyer et al 2012). More recent breeding programs targeting these and other crops, particularly maize and groundnut, have produced a large number of shorter duration and more drought tolerant varieties (Ba et al 2005, Ndiaye et al 2005). Historical management of seeds and varieties depended on farmers saving and exchanging seeds, with local markets becoming increasingly important sites of exchange as agriculture became more commercialization during the colonial period (Patick 2009). High quality seeds of specific new varieties are now also for sale in many parts of Senegal and recent national certification programs are seeking to verify and standardize the quality of this seed (Stads and Sene 2011).

Current official recommendations and nation-wide extension efforts regarding seeds and varieties focus primarily on the purchase of certified seed of specific new varieties, which include both recently developed and more established "improved" varieties (Toenniessen et al 2011). Many of these varieties were developed or locally tested in the central Thies region of Senegal, and there have been limited trials in other parts of the country and few in The Gambia (Ndiaye et al 2005). Despite decades of promotion, increasingly by private industry, the availability and utilization of certified high quality seeds and new varieties varies widely among and within regions, and many farmers continue to rely on seed saved from the previous year or purchased from local uncertified sources (Niangado 2010).

Historical fertility management in this region relied primarily on long-term crop/fallow rotational practices with livestock integration during annual fallow periods or seasonally after harvest (Khouma et al 2005). Increasing population density, commercialization of agriculture, and alternative land uses have increased pressure on soil fertility resources, such as through expansion into less suitable areas, decreased fallow periods, and reduced availability of herd livestock for rotations (Giller et al 2011). Alternatives include the collection and application of household manure and the purchase and application of inorganic fertilizers, but many farmers do not use any soil fertility amendments. Burning of crop residue is common in some regions, particularly the wetter ones, to prepare the field for planting, and “cut and carry” application of crop residue is rare (Khouma et al 2005).

Current official recommendations and nation-wide extension efforts regarding soil fertility management focus primarily on the use of purchased inorganic fertilizers in the form NPK mixtures with the addition of urea for cereals (Posner & Crawford 1992, Khouma et al 2005). Recommended rates vary by crop, region, and the recommending organization, but are generally around 150-200 kg/ha for composite NPK and the same for urea for cereals. Specialized NPK mixtures, such as 6-20-10 or 8-18-27 are sometimes recommended but widely unavailable, and often in practice replaced by the more ubiquitous 15-15-15. As of 2014, the average application rate of inorganic fertilizers on arable land was 6.7 kg/ha in Senegal and 5.6 kg/ha in The Gambia (FAO 2014). As cost is widely recognized as a limited factor in inorganic fertilizer use, these recommended rates are likely cost prohibitive to all but the wealthiest farmers, who are likely applying the majority of the fertilizer (Baudron et al 2012). As is often the case in sub-Saharan Africa and perhaps worldwide, the recommendations that reach farmers do not necessarily reflect the current state of research, but instead often come with insufficient information on timing or application method and may not be well adapted to specific crops, local agro-ecological conditions, interacting management practices, and diverse farmer constraints (Peters and Schulte 1994, Rware et al 2014).

Methods

Nearly 600 field trials were in established over 2015 and 2016 through partnership with regional cooperatives and locally identified influential lead farmers. These trials targeted six common rainfed crops and seven regions selected to best represent the environmental heterogeneity of rainfed cropping in Senegal and The Gambia (Figure 1). The same crops were trialed in all regions in 2015, resulting in the same number of trials established, but this was modified in 2016 as a result of regional crop failures (Table 1). Trials within each region were split among 4-6 community clusters. The experimental design combined alternative management options relating to seeds/varieties, inorganic fertilizer, and organic amendments, using an overlapping "strip-plot" design that resulted in 18 non-replicated 5m X 10m treatment plots per trial.

The new varieties used in the trials were selected from among the nationally certified varieties commercially available each year, and all seed and inorganic fertilizer was purchased through licensed dealers in Senegal and distributed to participating farmers for use in the trials. 15-15-15 NPK was used as the inorganic fertilizer along with urea (46-0-0) for cereals, and cattle manure and millet husks, the residue from threshing the grain, were used as the organic amendments (Table 2). The manure and husks were collected locally and hand pulverized by each participating household, then applied to the soil surface immediately prior to planting. Regional field officers supervised the field selection, establishment, amendment/fertilization, and harvest of the trials, and the lead farmers provided the necessary labor and made all other management decisions, including the time and means of planting, weeding, and harvesting. Harvest analysis consisted of the number of mature plants and dry threshed or cleaned seed weight within each plot. Total yield and relative treatment effect (% change from adjacent Local/Zero/None control plot) were calculated for each plot as kg/area, plants/area, and kg/plant.

Participating households in 2016 were surveyed prior to planting for socio-economic conditions and after harvest for perspectives on the alternative management treatments. Surveys were also conducted with an equal number of neighboring households that were conducting additional cultivar-only trials, most of whom had conducted the described trials in 2015 and attended all training and discussion meetings associated with this project. Accordingly, the surveys results do not dissociate between the two trial types. In all cases, the survey was conducted between the regional field officer and the male or female head of household that was most involved with management decisions for the specific crop.

Rainfall characteristics were estimated for 2016 from the daily 10km resolution 15-year RFE2 dataset using a single pixel centered within the regional community clusters or individually within each cluster when they were more widely dispersed (Xie and Arkin, 1996). Annual rainfall and season length were estimated between the first and last days of at least 10 mm/day. Regional cropland soil characteristics were estimated from an overlay of the European Space Agency Climate Change Initiative (ESACCI) land use map and the Africa Soil Information System (AFSIS) spatial model (Bontempts et al 2013, Hengl et al 2015). This approach that cannot take into account potential changes in soil characteristics with cultivation, so may overestimate organic matter and pH, which often decrease with cultivation in this region (Peters 2000). Political insecurity was calculated within each region since 1997 using the Armed Conflict Location and Event Data (ACLED) database (Raleigh et al 2010).

Soil pH, percent soil organic matter, and percent sand were analyzed for 2016 trials at a soil lab established at a large regional cooperative in central Senegal. Soil was sampled at 0-20cm and bulked from four representative locations within or adjacent to the trials towards the end of the rainy season. Soil pH was measured with 15g of air-dried soil in 1:1 ratio with distilled water using a handheld multi-meter. Percent soil organic matter was calculated from weight loss on ignition of 5g of oven-dried soil after four hours at 500C in a muffle furnace. Percent sand was calculated from the weight loss of 100g of oven-dried soil following a 12 hour soak in distilled water, wet sieving by hand through a 0.53mm sieve, and re-drying at 100C.

Trial results were analyzed within a Bayesian generalized linear model (GLM) framework using two model types and yield (harvest weight / area) and maturation success (# harvested plants / area) as outcome variables. Plant vigor (harvest weight / plant) was not modeled, as it was not measured directly but calculated within each plot as harvest/maturation success, so would not contain new information. In the primary models, which were used to model both absolute yield and relative treatment effect, harvest and maturation success were estimated directly as outcomes of a multivariate normal additive model, i.e.

$$[yield\_i, matsucc\_i] \sim MVN\ ([u\_yield\_i, u\_matsuc\_i], \Sigma),$$

where u_yield_i and u_matsuc_i are the respective yield and maturation success means of plot i and are log-linked additive functions of predictor variables, and Σ is the standard variance-covariance matrix of the multivariate normal distribution. In the secondary models, yield and survival were transformed into new treatment difference variables by subtracting the local/no-input control plot from the observed outcomes in all treatment plots, i.e. for each observation i in each site j, resulting in the new outcome variables yield_diff and matsuc_diff, i.e.

$$yield\_diff\_i = yield\_i - yield\_control\_j$$

$$matsuc\_diff\_i = matsuc\_i - matsuc\_control\_j$$

These new outcomes were again modeled as multivariate normal, i.e.

$$[yield\_diff\_i, matsucc\_diff\_i] \sim MVN\ ([u\_yield\_diff\_i, u\_\ matsucc\_diff\_i], \Sigma)$$

where u_ yield _diff_i and u_ matsucc_diff_i are the respective harvest and maturation success means of plot i and are identity-linked additive functions of predictor variables, and Σ is the standard variance-covariance matrix of the multivariate normal distribution. These secondary models were used to assess the relationship between treatments and underlying trial productivity, as estimated from the control plot measures.

Model selection between competing variations of additive predictors in both model types was performed using the Watanabe-Akaike information criterion (WAIC), which balances the explanatory value of each additional variable against a penalty for over-inclusion. Direct effects of all treatment variables (organic, inorganic, cultivar) and biologically critical variables (crop type, cultivar-crop nested effect) were fixed in all compared models. Environmental variables (rainfall, season length, SOM, soil pH, soil sand %), socioeconomic variables (indices of mechanization, draft labor availability, human labor availability), selected interaction effects, and multilevel structures by study region and individual trial were iteratively assessed using WAIC. In the secondary models, control plot yield was included as estimator of underlying pre-treatment productivity, both as a solitary additive effect and as an interaction effect with treatment variables. The model outputs were 1) variable coefficients, which were assessed for relative magnitude and variability, 2) treatment effect as percent change from the local no-input control, and 3) absolute yield (harvest weight/area) and maturation success (plants/area) estimates of each treatment. These models were not used to estimate expected yield for specific crops, treatments, and regions, due to the sample size and imbalance.

Results:

Regional heterogeneity:

Spatial patterns of select variables are shown in Figure 2 and summarized in table 3. Population density, percentage of land under cultivation, and relative population density per cultivated land were highest in the central target regions of Thies and Kaolack. The level of political insecurity was highest in the Ziguinchor region, where nearly 1000 fatalities have been reported since 1997 as the result of over 300 distinct political insecurity events. While the Gambian regions show low insecurity measures, they small regions may have been more impacted by the overall insecurity of the country, which has reported 129 fatalities from 126 events.

Average estimated annual rainy season characteristics over the last 15 years varied dramatically among the target regions, ranging from 313 mm over 78 days in Louga to 855 mm over 100 days in Ziguinchor, with a corresponding gradient in the regularity and intensity of rainfall events (Table 3). Estimated rainfall at the trial locations during the study seasons of 2015 and 2016 varied from a low of 254 mm over 71 days at a target community with the Matam region to 748 mm over 102 days at the Ziguinchor sites (Table 4).

Estimated soil characteristics identified strong north to south gradients with sand content and pH higher in the north and soil organic matter higher in the south (Table 5). Only Ziguinchor and Matam, which both contain large rivers, were estimated to have less than 60% sand in the top 15cm of intensively cultivated soils, and only Ziguinchor was estimated to have greater than 1% SOC. Analysis of soil sampled from the trial fields found the same general trends but lower values for most measures and less differentiation of Ziguinchor and Matam from the other regions. The high sand content regions of Kaolack (Senegal) and North Bank (Gambia) were found to have pH values far lower than estimated.

Baseline surveys and prior practices

Surveys of participating farmers found high variability within all regions for relevant socio-economic measures. Variability among regions was less pronounced, although over 50% of the participating households in Matam had only 1-2 individuals working in the rainfed fields, and this region also had the highest percentage in the lowest categories for animal traction and associated equipment. Ziguinchor skewed towards more laborers and mechanical equipment per household, while the other regions showed mostly similar overall patterns of distribution with high internal variability. Results are summarized in Table 6.

The perceived value of alternative practices prior to participation in the field trials also varied considerably both among and within regions (Table X). The median perceived value of collecting manure was highest in the drier north (Louga = 2.7, Matam = 1.8) and negligible in the wetter south (Ziguinchor = 0.0, Tambacounda = 0.1). Burning crop residue prior to planting was a highly valued practice in all regions except for Matam, while collecting and applying additional residue had little value in most regions. Inorganic fertilizer was only moderately valued across the regions and was particularly low in Ziguinchor. Saving seeds for replanting was the most highly valued seed management practice in all regions, with little differentiation among the other options. Results are summarized in Table 7.

Farmer Field Trials

The harvest was assessed for only 44% of the trials due to issues that are common to production fields and on-farm trials, including drought, erosion, pest damage, and insufficient labor or supervision leading to weed competition or damage from stray animals. In some cases only a portion of a trial was harvested as a result of a localized disturbance. Physiological crop failure could not be adequately distinguished from insufficient labor or supervision at harvest, or disturbance adequately identified at each trial, so the subsequent analysis cannot be applied to cases of complete or treatment-related crop failure.

Descriptive statistics from 2016 found that all of the treatments had a positive effect on yield on the majority of trials, ranging from 69% positive with the adoption of a new variety alone (N-0-No) to 93% with the additional application of high inorganic and manure (N-Hi-M). The former treatment led to an average increase in yield of 28% over the no-input control (L-0-No) and the latter to an average increase of 180%. The common management recommendation of adopting a new variety and applying high levels of inorganic fertilizer (N-Hi-No) led to an intermediate increase of 100%, which was nearly identical to three other integrated treatments (L-Hi-CR, N-Lo-CR, L-Lo-M). The observed pattern of treatment effect on yield appears to be a combination of increase in both maturation success and plant vigor. Results are summarized in Table 8.

Analysis of the coefficients of the harvest GLMM found all five treatments to have a strong positive effect across all conditions (Figure 3). The four soil fertility treatments had low variability in treatment effect, while the cultivar coefficient, which averaged across the six crops and the wide range of local seed quality and cultivar, was highly variable but generally positive. The coefficients of the treatment interactions were zero or slightly negative, indicating that the practices were additive or slightly less than additive in combination. The effects of total annual rainfall and season length were found to be neutral overall but highly variable, indicating major anomalies from any linear relationship with yield. No strong interactive effect with cultivar was observed for either measure, or between cultivar and any of the fertility treatments. A positive interactive effect was, however, observed between cultivar and political insecurity, indicating a greater effect of adopting new cultivars in politically insecure areas.

Patterns of coefficients for maturation success were generally similar but less distinct than yield, with millet husks having no effect and cultivar outweighing the other soil fertility treatments (Figure 4). Millet husk showed a positive interaction effect in combination with cultivar, which high levels of inorganic had a more negative interaction with cultivar than for yield. The differences between these yield and maturation success indicate a variable difference in the effect of the treatments on plant vigor.

Probability density functions of treatment effect found more nuanced differences among the soil fertility treatments, all of which led to positive increases over the control no-input plot when assessed for the local cultivar (Figure 5a). High inorganic had the greatest effect of any practice in isolation, with a mean increase of approximately +105%, but this was almost identical to the effect of low inorganic with millet husk. High inorganic with millet husk increased the mean effect to approximately +155% and high inorganic with manure was approximately +200% over the control. Probability density functions of absolute yield showed the same rank order as the relative treatment effect, but much greater overlap among the treatments and with the control no-input management (Figure 5b). The effect of adoption a new cultivar is not shown as the high variability overwhelms the differences among the soil fertility treatments.

The secondary models assessing potential interaction of the treatments with underlying productivity found an increase in the treatment effect of manure and high inorganic with increasing field productivity, as measured by the adjacent control plot yield (Figure 6). However, these were weak relationships, and the data contained limited representation and high variability among the higher yielding fields. No interactions were observed for the other treatments as relating to yield.

Follow-up surveys

Post-harvest surveys of participating farmers documented an increase in perceived value for all management practices related to the treatments, and a decrease in the perceived value of field burning as a way of managing crop residue. The perceived value of the organic amendments changed the most in Ziguinchor, with an average increase from 0 to 2.5 for collecting manure and 0 to 2.4 for collecting crop residue, out of a maximum value of 3. The perceived value of inorganic fertilizer following participation was lowest in this region (0.6) and highest in the more arid north (Louga = 2.6, Matam = 2.4). Saving seed for replanting was the most highly valued means of seed management both before and after the trials, but the perceived value of purchasing new certified seed stock increased dramatically in all regions. Results are summarized in Tables 9-10.

Discussion

This network of farmer field trials found that the tested alternative management practices reliably increased yield despite the high complexity and heterogeneity found in Senegal and The Gambia, and did so in both low and high productivity fields. The benefits of adopting certified seed stock of new cultivars, applying inorganic fertilizers, and amending with local organic materials each outweighed the relative influence of both measured factors, such as local climate and soil characteristics, and unmeasured factors, such as variability in crop management practices and field history. The relative increase in yield was comparable among these alternatives when practiced in isolation, with the effect varying by a factor of approximately 2.5, and they were found to have largely additive effects when practiced in combination. Despite the reliability of the relative increase, these alternative management practices were not good predictors of resulting yield due to the high underlying variability in productivity within this region. This disconnect between relative and absolute yield measures is an indication of the complexity of the relevant interactions within this system, which must be taken into account in planning agricultural research and generating management recommendations.

These trials also found that the common recommendation of adopting new cultivars and applying high levels of inorganic fertilizers was of only intermediate value among the tested practices. This combination did result in an average yield increase of 100%, but this effect was equivalent to less costly alternatives, such as applying low rates of manure with 1/3 of the recommended inorganic fertilization and not purchasing new seed. The additional amendment of 3000 kg/ha of manure with this recommended practice nearly doubled the effectiveness, making it neither the most cost effective nor highest yielding practices. Therefore, while the combination of new seeds and high inorganic fertilizations may be a suitable for some farmers, such as those who have access to cash but not to organic amendments, there is not sufficient justification for its continued use as the primary "best practice" recommendation in this region.

There is a temptation to declare the most effective treatment, the combination of new seed with manure and high inorganic fertilization, to be the new best practice. There is an apparent precedent for this in industrial agricultural systems, where fertilizer recommendations are often a composite of source, rate, time, and place. However, the latter recommendations are made for farmers with highly similar economic circumstances and agronomic practices, and often more homogeneous environmental conditions. To make a similar claim given the spatial and social heterogeneity of Senegal and The Gambia is to confuse optimal management practices with generally adaptive recommendations. This highly effective integrated practice is also the most cost, labor, and material intensive option, and requires that all inputs be readily available and affordable. It is therefore both the most effective and presumably the least generalizable of the tested alternatives, making it a poor candidate for "best."

Instead of confirming the current best practice recommendation or identifying a new one, these farmer field trials have identified a variety of comparable better practices. This was not a foregone conclusion, and this research method could have resulted in the identification of highly specific best management recommendations, such as are often identified through agricultural research. For example, the benefit of increased drought tolerance or seed quality with the purchase of new certified seed might have dramatically outweighed the benefits of the soil fertility amendments. Similarly, the direct nutrient contribution of inorganic fertilizers might have outweighed the more general soil benefits of the organic amendments. Alternatively, the majority of the tested practices could have simply been widely ineffective, such that there would be few candidates for "best practice."

As farmer field trials could have identified a single best practice or multiple adaptive options, the finding of the latter in this case can be trusted as a reflection of the target system. In contrast, the use of highly controlled experiments at a small number of locations might have failed to recognize this possibility and mistakenly resulted in a specific recommendation as a result of methodological bias. This approach deliberately excludes much of the relevant heterogeneity and complexity to focus on specific causal interactions under specific trial conditions, and these resulting experimental conditions might be biased towards certain practices. For example, if these same treatments were assessed within a research field with high underlying soil fertility, the effect of the soil amendments would like be reduced and the cultivar look exceptionally effective in comparison. Unless these experimental conditions are explicitly designed to represent the conditions and variability found within the target system, the conclusion of a single best practice could be an artifact of the testing environment.

While a specific best practice recommendation is not appropriate for rainfed agriculture in this region, there are likely best options for specific households given their individual constraints and opportunities. This calculation requires that the benefits, which were comparable among the different options, be balanced against the associated costs and ricks, which are expectedly to vary widely across the regions and among individual households. The use of new certified seeds and inorganic fertilizers, for example, requires that these inputs be available and affordable at critical periods of the growing season. This is dependent on and can be undermined by both local factors, such as household economics and transport infrastructure, and international factors, such as global trade policies and market fluctuations. Locally-sourced organic amendments are less susceptible to those particular concerns, but they have other limitations and liabilities. The availability of crop residue or animal manure and feasibility of amendment may be particularly troublesome to many farmers given the semi-arid climate, high population densities, and low levels of mechanization. Future research might be able to effectively capture the relevant individual factors and include them in models that could narrow down the adaptive options or even identify single best practices for specific socio-economic or agro-ecological circumstances. In the meantime, however, these adaptive options should all be suggested generally but not prescribed specifically.

This conclusion of multiple adaptive options and suggestions rather than prescriptions might be problematic if it were not evident from the surveys that participating farmers were actively interpreting the field trials and drawing their own conclusions. Perceived value of alternative management practices changed dramatically with participation, including for related practices that were not directly tested, such as refraining from burning crop residue and tethering livestock. The resulting perceived values revealed both regional patterns and high variability among neighboring individuals, which indicate that farmers are making personalized calculations without any analysis or direction from researchers. These results can instead direct future research by identifying regional priorities and opportunities. In the conflict zone of Ziguinchor, for example, the perceived value of the organic amendments was negligible before the trials but high after participation, which suggest that is might be a particularly suitable adaptive pathway in this region and worth further investigation. These results, such as the prioritization of new seeds and organic amendments over inorganic fertilizer in all regions, can also inform more general efforts at encouraging farmer adaptation, such as traditional extension activities.

These results of these field trials present a model of farmer adaptation in Senegal and The Gambia that is in sharp contrast to several common assumptions made about sub-Saharan agriculture. For example, these smallholder systems are often discussed as if alternative management practices can have little effect on productivity, which is instead driven by climatic conditions, market forces, and other factors that are beyond the control of farmers (Knox et al 2012). Alternatively, it is also sometimes assumed that this productivity is invariably low without capital-intensive practices, such as reliance on inorganic fertilizers or mechanization

(Evenson and Gollin 2003). Finally, it is sometimes argued that high-yielding fields are nearing a yield ceiling and require new technologies, such as genetically modified cultivars, or that low-yielding fields are unresponsive to alternative management and not worth the investment (Paarlberg 2012). While these competing general scenarios (summarized in Figure 7) may adequately describe certain production systems in sub-Saharan Africa, or at least specific socio-economic or agro-ecological conditions within such systems, none of them accurately describe rainfed production in Senegal and The Gambia. Instead, the results of these trials suggest that farmers in these semi-arid countries have a variety of widely effective adaptive options for rapidly increasing yield through alternative management practices. This is both encouraging for this specific region, and suggestive that the alternative scenarios that assume a limited potential for farmer adaptation may deserve critical reassessment in other regions.

While the goal of using farmer field trials as a research method is to identifying general emergent patterns rather than investigate underlying mechanisms, these results suggest that there are some relevant underexplored processes. For example, millet husks have largely been overlooked as a potential soil amendment, both by farmers in Senegal and The Gambia, who often burn the piles, and by researchers, who have focused instead on the potential value for biochar (Raveendran 1995). Although carbonaceaous and slow to decompose in comparison to other common crop residues, it has been found to be particularly effective for reducing bulk density and increasing water holding capacity and crop water use efficiency (Tarafdar 2003, Anguria et al 2017). This effect could be highly beneficial in sandy soil and semi-arid climates, such as in Senegal and The Gambia, and might account for why only 3000 kg/ha of millet husk had roughly the same effect on crop yield as low rates of inorganic fertilizer (50 kg/ha 15-15-15 plus 50 kg/ha urea for cereals). This equivalence is an indication of the complexity of soil processes relating to crop growth and the variety of ways in which soil ecosystems can be manipulated to increase crop production. It also discourages relying strictly on estimated nutrient availability and mineralization rates to value crop residues or suggest rates of amendment (Palm et al 2001). While there are certainly threshold rates below which soil fertility amendments will not noticeable influence yield, these results suggest that those thresholds may be much lower, and therefore more easily attainable, than is commonly assumed.

Conclusion:

To conclude with multiple adaptive options rather than prescriptive best practices is not to admit investigative defeat in the face of complexity and heterogeneity, but to provide immediately practical results until more explicit conclusions are possible. Increased trial numbers and higher resolution measurement of relevant social and environmental factors might allow for future recommendations to be fine tuned to specific production conditions, such as for farmers in dry regions with little available labor or those in wet regions with high access to organic amendments but little purchasing power. In the meantime this approach encourages farmers to make individualized decisions based on their own understanding of their circumstances. This temporary conclusion does not diminish the role of agricultural research in driving farmer adaptation, but rather embraces a complimentary role for farmer knowledge as a replacement for problematic simplifying assumptions and the methodological removal of relevant complexity and heterogeneity from the research design. This approach, which relies on farmer field trials as a primary research method, has the potential open new avenues of agricultural research and empower farmer adaptation in new ways, and can do so in particularly complex and heterogeneous systems.

Tables:

Table 1) Total number of community clusters, trials established, and trials harvested per year and region, and crops targeted within each region in 2016.

Region	# Clusters 2015/2016	# Trials Established 2015/2016	# Trials Harvested 2015/2016	2016 Crops					
				Groundnut	Cowpea	Millet	Maize	Rice	Sorghum
Louga	4/4	30/48	16/33	X	X	X			X
Matam	4/6	30/48	3/11	X	X	X			X
Thies	4/4	30/48	8/22	X	X	X			X
Kaolack	4/4	30/60	7/15	X	X	X	X		X
The Gambia	4/4	30/48	23/31	X	X	X	X		
Tambacounda	4/4	30/60	12/25	X	X		X	X	X
Casamance	4/6	30/72	15/41	X	X	X	X	X	X
Total	**28/32**	**210/384**	**84/178**						

Table 2) Descriptions of the individual treatments for seeds/cultivars, inorganic fertilization, and organic amendments. All 18 treatment combinations were tested in each farmer field trial using an overlapping "strip-plot" design.

Pathway	Treatment	Description
Seeds / cultivars	Local (L)	Farmer standard (highly variable among farmers and regions)
	New (N)	Groundnut – 55-437 Cowpea – Yacine Millet – Souna 3 Maize – Early Thai Sorghum – Faourou (621B) Rice – Nerica 4
Inorganic fertilizer	High (Hi)	150 kg/ha of 15-15-15 NPK preplant for all crops 150 kg/ha of 46-0-0 NPK (urea) topdressing for cereals
	Low (Lo)	50 kg/ha of 15-15-15 NPK preplant for all crops 50 kg/ha of 46-0-0 NPK (urea) topdressing for cereals
	Zero (0)	No inorganic fertilization
Organic amendment	Manure (M)	Locally collected dry cattle manure @ 3000 kg/ha
	Crop Residue (CR)	Locally collected dry millet husk @ 3000 kg/ha
	None (No)	No organic amendment

Table 3) Social and climatic characteristics of the study regions, as estimated from census and remote sensing data. "Pop" is the number of inhabitants, "Ag" is a combination of intensive, mosaic, and irrigated land use categories (ESACCI), and "P.I." is reported instances of political insecurity since 1997 (ACLED). The regions are ranked from lowest to highest total rainfall and noted as part of Senegal (S) or The Gambia (G).

Region	Social					Rainfall (2001-2016)			
	Pop / total km2	% Land in Ag	Pop / Ag km2	P.I. Events	P.I. Fatalities	Total Annual (mm)	Season Length (days)	Regularity (% days with >0)	Intensity (mm/day when >0)
Louga (S)	35	47	75	11	4	313	78	50%	7.93
Matam (S)	20	15	134	7	0	361	87	53%	7.79
Thies (S)	280	94	297	28	1	384	82	52%	9.01
Central River (G)	79	79	100	5	14	490	95	63%	8.21
Kaolack (S)	188	93	202	13	3	498	94	62%	8.64
Tambacounda (S)	17	16	103	17	11	517	98	63%	8.26
North Bank (G)	104	66	156	6	0	568	95	65%	9.17
Ziguinchor (S)	78	61	128	305	976	855	100	71%	11.92

Table 4) Estimated rainfall (mm) and season length (days) in 2015 and 2016 at the study sites, based on the 10km resolution RFE2 spatial model and 10 mm/day cutoffs for the beginning and end of the rainy season.

Region	Community	2015		2016	
		mm	Days	mm	Days
Louga (S)	Bandegne	290	77	261	70
	Ndanda	309	78	303	70
	Kelle Gueye	291	77	262	70
	Mbendiene	300	77	261	69
Matam (S)	Matam	299	79	401	77
	Dabia	269	76	394	91
	Agnam Thiodaye	254	71	355	91
	Seno Palel	336	88	404	75
	Sintithiou Bambe	N/A	N/A	411	75
	Orkadiere	N/A	N/A	430	75
Thies (S)	Kuer Balla Lo	395	83	360	66
	Takhoum	408	81	303	70
	Notto	389	82	374	66
	Pambal	353	81	349	61
Central River (G)	Kaur	469	91	326	67
	Fass	450	94	367	102
Kaolack (S)	Sibissor	487	92	455	67
	Dya	487	93	464	67
	Ndiebel	458	93	463	70
	Thiomby	480	94	484	70
Tambacounda (S)	All communities	618	103	683	102
North Bank (G)	Njawara	525	95	404	78
	Kerr Omar Sene	518	93	407	78
Ziguinchor (S)	All communities	748	102	655	91

Table 5) Average soil characteristics from 0-15cm as A) estimated by spatial models and summarized as the regional mean for the "intensive cultivation" land use category (ESACCI), and B) sampled within fields adjacent to trials and summarized as median (bold/black) and standard deviation (gray)

	A) Spatial Estimates			B) Field Sampling		
Region	**pH**	**% Sand**	**% SOC**	**pH**	**% Sand**	**% SOM**
Louga (S) n=88-89	6.9	81.2	0.32	**6.40** 0.81	**90.4** 9.2	**0.54** 0.30
Matam (S) n=82-88	6.7	57.9	0.62	**5.91** 0.92	**82.0** 16.8	**0.88** 0.83
Thies (S) n=63-72	6.4	76.2	0.50	**6.17** 0.74	**77.9** 12.2	**1.13** 0.79
Central River (G) n=33-43	5.9	63.3	0.95	**5.94** 0.76	**77.2** 11.5	**1.03** 0.60
Kaolack (S) n=71-87	5.7	78.0	0.54	**5.16** 0.68	**82.3** 6.4	**0.83** 0.37
North Bank (G) n=46-47	6.1	60.7	0.84	**5.45** 0.48	**85.8** 4.0	**0.93** 0.40
Tambacounda (S) n=92-93	5.6	66.8	0.85	**5.79** 0.84	**71.5** 11.7	**1.56** 0.85
Casamance (S) n=77-123	5.5	47.7	1.59	**5.72** 0.62	**83.9** 13.5	**1.16** 0.59

Table 6) Distribution of socio-economic resources among households within each region, as the percentage of the regional total within each resource category.

Human resources	Very Low (1-2)	Low (3-4)	Medium (5-6)	High (7-8)	Very High (9+)
Louga (n=85)	6	36	33	12	13
Matam (n=57)	54	25	5	2	14
Thies (n=64)	3	30	39	9	19
Kaolack (n=86)	19	36	27	9	9
Gambia (n=82)	1	24	57	7	10
Tambacounda (n=89)	8	42	39	7	4
Ziguinchor (n=125)	4	12	36	22	26
Draft Animals	**None (0)**	**Minimal (1)**	**Low (2)**	**Medium (3)**	**High (4+)**
Louga (n=87)	3	2	24	17	53
Matam (n=58)	40	28	10	10	12
Thies (n=65)	12	18	29	20	20
Kaolack (n=93)	28	18	22	11	22
Gambia (n=86)	1	15	24	21	38
Tambacounda (n=91)	19	42	29	11	0
Ziguinchor (n=130)	34	14	13	9	30
Mechanical Equipment	**Very Low (1-2)**	**Low (3-4)**	**Medium (5-6)**	**High (7-8)**	**Very High (9+)**
Louga (n=85)	6	36	33	12	13
Matam (n=57)	54	25	5	2	14
Thies (n=64)	3	30	39	9	19
Kaolack (n=86)	19	36	27	9	9
Gambia (n=82)	1	24	57	7	10
Tambacounda (n=89)	8	42	39	7	4
Ziguinchor (n=125)	4	12	36	22	26

Table 7) Average perceived value of alternative management practices relating to soil fertility and seeds/varieties prior to participation in the trials, where 0 = no value and 3 = high value. The mean of each region is shown in bold/black and the standard deviation is shown in gray.

	Soil Fertility					Seeds			
Region	**Tether Animals**	**Collect Manure**	**Burn fields**	**Collect Residue**	**Purchase Inorganic**	**Save Seed**	**Get from neighbors**	**Local Market**	**Purchase Certified**
Louga	**0.8**	**2.7**	**1.8**	**1.3**	**1.2**	**2.5**	**1.3**	**1.5**	**1.4**
n=91-92	1.0	0.8	1.1	1.3	1.0	0.9	1.0	1.3	1.2
Matam	**0.5**	**1.8**	**0.5**	**0.1**	**0.6**	**2.4**	**0.6**	**1.0**	**0.5**
n=59-61	1.0	1.2	0.8	0.5	1.0	0.9	0.9	1.1	1.0
Thies	**0.5**	**0.9**	**2.5**	**0.4**	**1.1**	**2.8**	**0.9**	**1.0**	**0.3**
n=66	0.8	1.0	0.7	0.9	1.0	0.5	1.0	1.1	0.8
The Gambia	**0.4**	**1.8**	**2.1**	**1.8**	**1.4**	**2.4**	**0.7**	**0.6**	**0.7**
n=50-53	0.7	0.7	0.6	0.7	0.6	0.7	0.8	0.8	0.6
Tambacounda	**0.1**	**0.1**	**2.8**	**0.2**	**1.3**	**2.6**	**0.2**	**1.6**	**0.2**
n=93-101	0.5	0.4	0.4	0.4	0.6	0.5	0.4	0.5	0.4
Ziguinchor	**0.6**	**0.0**	**2.5**	**0.0**	**0.2**	**2.3**	**0.8**	**0.3**	**0.2**
n=139-144	0.2	0.1	1.1	0.1	0.5	0.7	0.5	0.5	0.5

Table 8) Descriptive statistics of 2016 trials as A) percentage of trials with a positive treatment effect on yield and B) median observed treatment effect for yield (harvest weight/area), maturation success (harvested plants/area), and plant vigor (harvest weight/plant). Results are displayed in the 18-plot orientation of the field trials and relative to the Local Cultivar / Zero Inorganic / No Organic control treatment (dark gray).

Treatment Effect		Organic Amendments						Inorganic Fertilizer
		No Organic		Crop Residue		Manure		
A) % Positive	Yield	86	89	90	92	91	93	**High**
		79	85	87	87	87	90	**Low**
			69	71	80	77	89	**Zero**
B) Median	Yield	67	100	99	134	128	180	**High**
		31	67	57	100	98	138	**Low**
			28	29	60	53	81	**Zero**
	Mat. Success	22	30	40	53	52	68	**High**
		8	28	24	35	44	50	**Low**
			10	9	27	23	39	**Zero**
	Plant Vigor	34	51	40	62	52	82	**High**
		23	36	29	45	38	51	**Low**
			12	19	19	18	44	**Zero**
		Local	**New**	**Local**	**New**	**Local**	**New**	
		Cultivar						

Table 9) Average perceived value of alternative management practices after participation in the trials (A) and the average difference in valuation with participation (D) as value after – value before, where 0 = no value and 3 = high value. The mean of each region is shown in bold/black and the standard deviation is shown in gray.

Region	Soil Fertility										Seeds							
	Tether Animals		Collect Manure		Burn Fields		Collect Residue		Purchase Inorganic		Save Seed		Neighbors		Local Market		Purchase Certified	
	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D
Louga	**1.0**	**0.3**	**2.8**	**0.2**	**1.2**	**-0.6**	**2.2**	**0.8**	**2.6**	**1.3**	**2.4**	**-0.1**	**1.0**	**-0.2**	**0.9**	**-0.7**	**2.9**	**1.5**
n=91-92	1.2	0.7	0.6	0.6	1.0	0.9	1.3	1.1	0.9	1.7	1.0	0.8	1.0	0.7	0.9	1.0	0.5	1.2
Matam	**0.7**	**0.2**	**2.6**	**0.8**	**0.5**	**0.0**	**2.0**	**1.8**	**2.4**	**1.8**	**2.8**	**0.4**	**0.4**	**-0.2**	**0.3**	**-0.7**	**2.5**	**2.0**
n=59-61	1.1	0.8	0.7	1.0	0.9	0.8	1.1	1.1	0.8	1.1	0.5	0.8	0.7	0.8	0.8	1.1	0.8	1.1
Thies	**1.8**	**1.3**	**2.5**	**1.7**	**0.4**	**-2.1**	**1.6**	**1.2**	**1.7**	**0.6**	**1.9**	**-0.9**	**0.2**	**-0.8**	**0.1**	**-0.9**	**1.8**	**1.5**
n=66	0.9	0.9	0.5	0.9	0.8	1.0	1.3	1.3	0.6	1.5	1.3	1.4	0.5	0.9	0.3	1.1	1.4	1.7
The Gambia	**1.1**	**0.7**	**2.5**	**0.6**	**1.5**	**-0.6**	**2.5**	**0.6**	**1.2**	**-0.2**	**2.7**	**0.3**	**0.7**	**0.1**	**0.7**	**0.1**	**1.3**	**0.5**
n=50-53	1.1	0.8	0.6	1.0	0.9	1.0	0.6	0.9	0.8	0.8	0.5	0.7	0.8	0.9	0.7	0.9	0.8	1.1
Tambacounda	**0.2**	**0.0**	**1.2**	**1.1**	**0.0**	**-2.8**	**1.7**	**1.5**	**1.3**	**0.1**	**1.9**	**-0.6**	**0.2**	**0.0**	**1.0**	**-0.5**	**0.3**	**0.1**
n=93-101	0.6	0.3	0.5	0.5	0.1	0.4	0.5	0.5	0.5	0.4	0.6	0.6	0.4	0.2	0.3	0.6	0.6	0.6
Casamance	**2.5**	**2.5**	**2.7**	**2.6**	**1.0**	**-1.4**	**2.4**	**2.4**	**0.6**	**0.4**	**2.3**	**0.0**	**1.1**	**0.2**	**0.2**	**-0.1**	**2.0**	**1.7**
n=139-144	0.5	0.6	0.5	0.5	0.3	1.2	0.6	0.6	0.8	0.7	0.5	0.9	0.5	0.6	0.5	0.5	0.6	0.1
Total	**1.4**	**1.0**	**2.4**	**1.4**	**0.8**	**-1.4**	**2.1**	**1.6**	**1.5**	**0.7**	**2.3**	**-0.2**	**0.7**	**-0.1**	**0.5**	**-0.4**	**1.8**	**1.3**
n=514-500	1.2	1.2	0.8	1.1	0.9	1.3	1.0	1.1	1.0	1.1	0.8	1.0	0.7	0.7	0.7	0.9	1.1	1.3

Table 10) Survey results of participating households' prioritization of the three adaptive pathways tested in the farmer field trials (organic, inorganic, cultivar). Each household representative ranked the pathways as 1st (1), 2nd (2), and 3rd (3) priority, which are summarized as regional means.

Region	Organic	Inorganic	Seeds
Louga (n=92)	2.1	2.6	1.3
Matam (n=59)	1.3	2.7	2.0
Thies (n=66)	2.1	2.8	1.2
The Gambia (n=49)	1.0	2.9	2.1
Tambacounda (n=93)	1.5	2.5	1.9
Casamance (n=139)	1.9	2.9	1.3

Figures:

Figure 1) Approximate locations of regional clusters of farmer field trials over a map of average annual rainfall from 2001-2016 for Senegal, The Gambia, and Guinea Bissau. The rainfall legend is included in Figure 2.

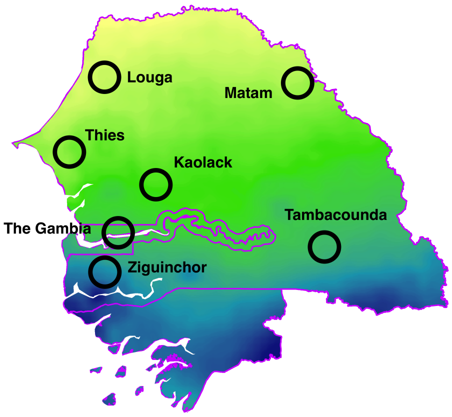


Figure 2) Spatial patterns of select variables across Senegal, The Gambia, and Guinea-Bissau that may influence rural livelihoods, agricultural constraints and opportunities, and the effectiveness of alternative practices. Maps are from Eldon and Rapaport (2017) and original data sources are identified in the Methods.

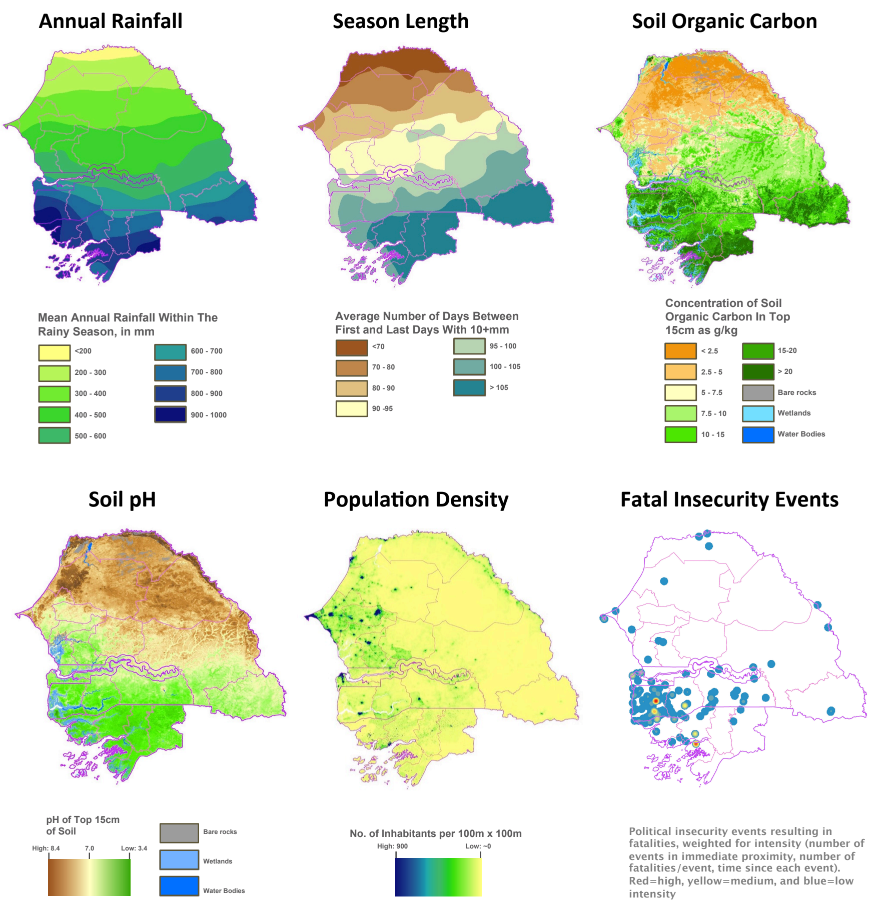


Figure 3) Magnitude and variability of coefficients of select factors in the final GLM for yield (harvested weight / area).

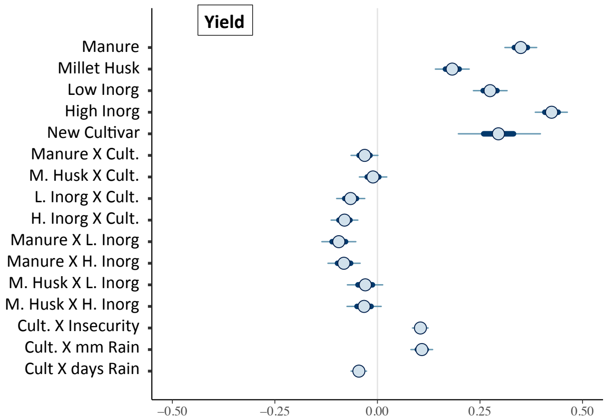


Figure 4) Magnitude and variability of coefficients of select factors in the final GLM for maturation success (harvested plants / area).

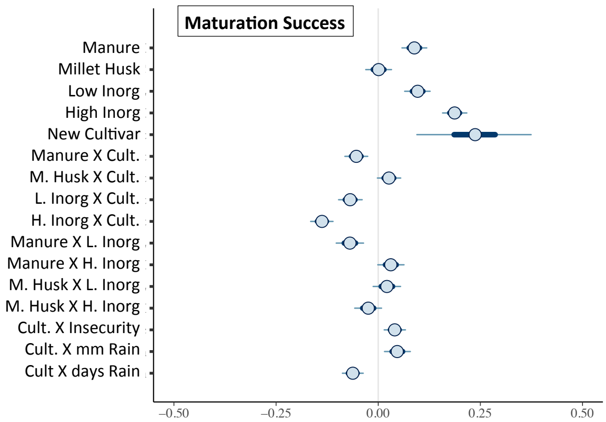


Figure 5) Probability density functions of a) treatment effect as relative increase in yield over the control (L-0-No) plot and b) resulting absolute yield, for combinations of organic and inorganic fertility treatments using local cultivars and generalized for all crops, regions, and years. The Y-axis in both figures is the probability density, which is the continuous equivalent of count frequencies in categorical histograms and is not intuitive or necessary for visual interpretation. The X-axis for (b) is a crop-generic yield measurement.

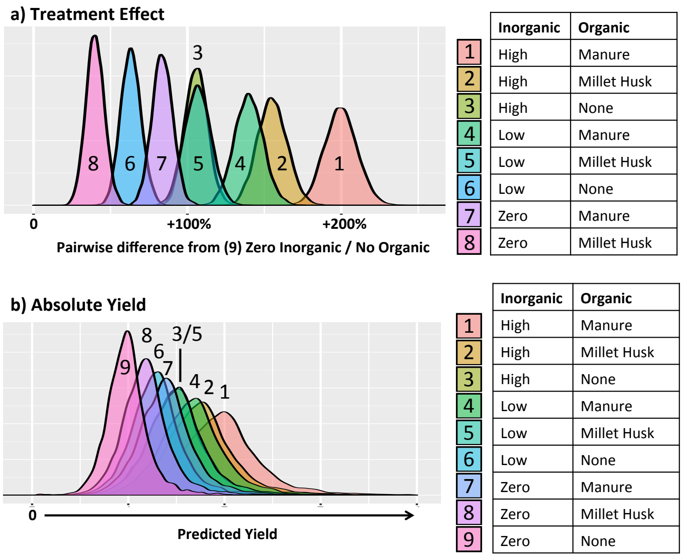


Figure 6) Modeled linear regressions comparing treatment effect and underlying field productivity, as control plot yield, for a) organic soil amendments and b) inorganic fertilization rates. Shaded regions represent the 95% confidence interval and the dashed line indicates the zero-slope line that would indicate no change in effect with underlying yield. The axis units are a crop-generic yield measure from the nested model and cannot be applied directly to any crops.

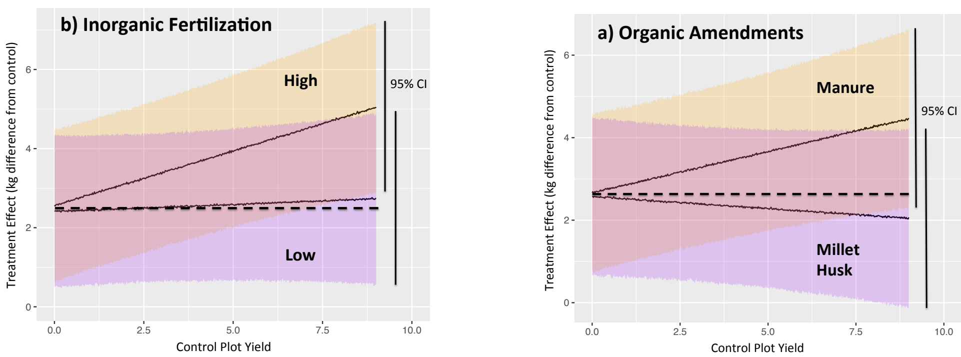
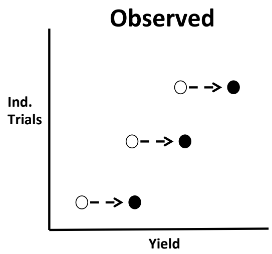
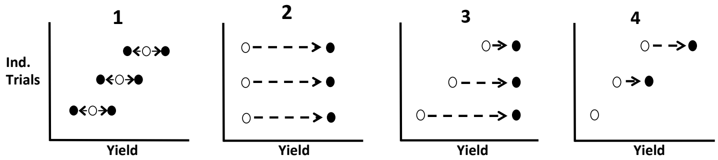


Figure 7) Conceptual schematics comparing observed patterns of yield variability and treatment effect against four alternative scenarios discussed in the literature.

Alternative Scenarios		Untreated Yield	Treatment Effect	Treatment X Yield
1	*Ineffective Treatment*	Variable	Unreliable	N/A
2	*Input Dependency*	Low	Reliable	Stable
3	*Yield Ceilings*	Variable	Little or no treatment effect in **HIGH** yielding fields	
4	*Unresponsive Thresholds*	Variable	Little or no treatment effect in **LOW** yielding fields	
Observed		Variable	Reliable	Mostly Stable





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