Agroecology and Sustainable Food Systems

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/wjsa21

The evolving landscape of agroecological research

Rachel E. Mason , Alissa White , Gabriela Bucini , Janica Anderzén , V. Ernesto Méndez & Scott C. Merrill

To cite this article: Rachel E. Mason , Alissa White , Gabriela Bucini , Janica Anderzén , V. Ernesto Méndez & Scott C. Merrill (2020): The evolving landscape of agroecological research, Agroecology and Sustainable Food Systems, DOI: 10.1080/21683565.2020.1845275

To link to this article: https://doi.org/10.1080/21683565.2020.1845275

Published online: 30 Nov 2020.

AGROECOLOGY AND SUSTAINABLE FOOD SYSTEMS
https://doi.org/10.1080/21683565.2020.1845275

Taylor & Francis
Taylor & Francis Group

The evolving landscape of agroecological research

Rachel E. Mason [a,b], Alissa White[a,c,d], Gabriela Bucini[a,d], Janica Anderzén[a,c,d], V. Ernesto Méndez[a,c,d], and Scott C. Merrill[a,c]

[a]Department of Plant and Soil Science, University of Vermont, Burlington, VT, USA; [b]National Socio-Environmental Synthesis Center, Annapolis, MD, USA; [c]Gund Institute for Environment, University of Vermont, Burlington, VT, USA; [d]Agroecology & Livelihoods Collaborative, University of Vermont, Burlington, VT, USA

ABSTRACT

It has been widely argued that agroecological science, which originally developed as the application of ecological principles to agricultural systems, should engage with the social and political issues that affect production agriculture, and incorporate knowledge from a variety of sources. In this paper, we use techniques from network science and bibliometrics to evaluate the degree to which this transformation has taken place. By creating networks based on over 3,000 agroecology papers and the roughly 160,000 references they cite, we distinguish the sub-fields ("research fronts") that made up agroecology in three time intervals: 1982–2004, 2005–2013, and 2014–2018. We also identify the main disciplines from which the research fronts in 2014–2018 drew their supporting knowledge. We suggest that, very broadly, themes in agroecological research include: Ecosystem services; (agro)biodiversity; approaches to agricultural intensification; tropical agroecosystems (particularly coffee); pest and weed management; organic agriculture; cropping systems; system transitions, modeling, and design; climate change adaptation; food sovereignty; education; and the nature and purpose of agroecology itself. Some research fronts mainly cite papers in natural science fields such as ecology, environmental science, agriculture, and entomology. However, others draw upon work in social science areas including development studies, environmental studies, and anthropology. The analysis presented in this paper demonstrates that agroecology has indeed evolved to possess many of the characteristics of an "ecology of [the entire] food system." We anticipate that this work will also be of use to those wishing to gain an overview of the field or identify key papers, knowledge gaps, and potential collaborations.

KEYWORDS

Agroecology; food systems; bibliometric analysis; network analysis; bibliographic coupling; metaknowledge

Introduction

Agroecology is a complex and wide-ranging field. The term "agroecology" suggests that the discipline deals with the union of ecological and agricultural sciences, and indeed agroecology has been defined as "the application of

CONTACT Rachel E. Mason rachel.e.mason1@gmail.com Department of Plant and Soil Science, University of Vermont, Burlington, VT, USA.

ecological concepts and principles to the design and management of sustainable agroecosystems" (Gliessman 2000). Prominent papers matching this definition address topics such as the ecological basis of indigenous farming systems (Altieri 2004; Gliessman, Garcia, and Amador 1981), the effects of biodiversity in agroecosystems (Altieri 1999; Ratnadass et al. 2012) and the roles and functions of soil micro-organisms (Burger and Jackson 2003; Gianinazzi et al. 2010).

At the same time, agroecology is not solely a curiosity-driven, basic science; it is also an applied field rooted in concern about, and response to, the environmental and social harms caused by the rise of industrial agriculture. Wezel et al. (2009) describe how, in contexts such as 20th century France and Germany, this concern was expressed as a scientific investigation into agricultural principles and practices that could produce food with lower environmental costs than Green Revolution techniques. Agroecological farming tends to replace costly external inputs with farmer knowledge. In developing-world contexts, such as Latin America, agroecology was identified as a means by which peasant farmers could maintain their livelihoods and self-reliance in the face of a food system that increasingly concentrates power and profits in the hands of transnational agribusiness corporations (Altieri and Toledo 2011; Rosset and Altieri 2017; Rosset and Martínez-Torres 2012). As Wezel et al. (2009) point out, agroecology has evolved to be simultaneously a science, a social movement, and a set of farming practices.

If it is to effectively support a transition to environmental, economic, and social sustainability, agroecological *science* will need to go beyond simply researching farming principles and practices that can be both productive and environmentally sound. The choices of individual farmers (and the ability of people to take part in agriculture in the first place) are constrained by the social, economic, and political systems in which they exist (Gonzalez de Molina 2016). Ecosystem services and other agricultural outcomes are also influenced by events and processes on scales much larger than a single farm (Tomich et al. 2011). This argues that agroecological research must encompass the macro-scale issues of economics, politics, social structures, etc. that shape the options available in the field.

Francis et al. (2003) advocated for this kind of holistic approach to agroecology, arguing that the discipline should be defined as "the ecology of food systems." They point out that human behavior is a critical driving force in the food system, that focusing only on production limits our understanding of the current system and the generation of possible alternatives, and that we have a moral duty to engage with issues of equity in food access, nutrition, and health. The many fields that Francis et al. consider relevant include environmental sciences, economics, sociology, anthropology, literature, and ethics (see also Tomich et al. 2011).

This call for research spanning many disciplines was reiterated by Méndez, Bacon, and Cohen (2013). They also urge that agroecology projects should focus on solving real-world problems in close collaboration with the individuals and communities affected by those problems. In other words, agroecology should be "transdisciplinary, participatory, and action-oriented," integrating knowledge from throughout and beyond the academic arena. Then, in order for agroecological solutions to scale beyond the local, Gonzalez de Molina (2013) emphasizes the need for a "political agroecology" that develops the institutions, policies, and social momentum needed to support the agroecological transition.

Guidelines for systems-based research in agriculture have been developed (Drinkwater, Friedman, and Buck 2016), and some transdisciplinary, participatory, and transformative projects have been documented around the world (Bacon et al. 2014; Mier Y Terán Giménez Cacho et al. 2018; Schattman et al. 2015; Anderzén et al. 2020). However, continued progress in this area is not guaranteed. Many factors act to favor discipline-based research that essentially conforms to the dominant, production-oriented, technology-focused regime (Levidow, Pimbert, and Vanloqueren 2014; Vanloqueren and Baret 2009) and in the U.S. at least, systems-based agriculture research projects that include social and economic elements receive a particularly small share of government funding (DeLonge, Miles, and Carlisle 2016).

Given the perceived need for a broader and more inclusive science of agroecology, and the potential barriers to achieving it, a handful of authors have examined the extent to which agroecological science integrates fields other than the strictly biophysical, and how the importance and treatment of larger spatial scales has been changing over time. Dalgaard, Hutchings, and Porter (2003) showed that papers referring to agroecology could be found in databases of natural science, social science, and economics literature. Most papers were found only in the natural science database; the greatest overlap was between natural science and economics; and no papers were contained in all three databases. This implies that most work at that point focused on biophysical issues, with few interdisciplinary projects and the field as a whole just beginning to involve the social sciences.

Around the same time as Dalgaard, Hutchings, and Porter (2003) were examining the literature, Buttel (2003) divided agroecology into five strands: (1) Ecosystems agroecology and (2) agro-population ecology were based on natural science, with different ecological perspectives as their foundation; (3) Agronomic agroecology was mainly informed by the science of agronomy; (4) Ecological political economy, on the other hand, was characterized by a political-economic critique of industrial agriculture and drew heavily from the social sciences; and finally, (5) multi-functional agroecology, then in its infancy, integrated ecological, agronomic, economic, and social perspectives, and approached farming and food in the context of their surrounding

geographical and institutional landscapes. Buttel's analysis highlights the political element within the field and the emergence of a new, interdisciplinary variety of agroecology.

Wezel and Soldat (2009, 14) determined that the field broadened and expanded in the 2000s, increasing its scope to include "(sub-)disciplines … at the intersection between agriculture and nature, biodiversity, culture, food production, sustainable development and policy." In addition, they found that agroecology's spatial scales and research approaches grew to encompass not only the plot/field but also the whole farm, and finally the entire food system. In Wezel and Soldat's estimation, the food systems approach coexists with an "agroecosystems" approach that does not explicitly consider politics, economics, and society. This is consistent with Méndez, Bacon, and Cohen (2013)'s division of the field into two distinct and broad agroecological perspectives, one largely restricted to natural science and another that engages with wider agri-food system issues. Méndez, Bacon, and Cohen (2013) also point that there exist a diversity of perspectives in between these two extremes.

Many more agroecology papers have been published since the above studies were carried out, and new data sets and analysis techniques allow an updated and extended assessment of agroecological research. In this paper, we reevaluate the evolution of agroecology by applying bibliometric techniques and network science methods to thousands of articles drawn from the Web of Science (Materials and methods). In particular, we examine (1) changes in the breadth of the field and the topics it addresses, (2) the specific sub-fields that have formed, and (3) the areas of knowledge from which agroecology is drawing. We do this in the following ways:

1) In Changes in word use over time we calculate the occurrence of certain key terms over time. We hypothesize that, if the scope and emphasis of agroecological science is changing, we will observe changes in the vocabulary used by the field. The relative frequency of words such as "weeds" or "soil" may decrease, while the use of words like "economics" or "justice" may rise. This global analysis would show that new terms were entering agroecology and their usage increasing.

2) In Agroecology's evolving research fronts, we identify and illustrate evolving sub-fields, or "research fronts" (de Solla Price 1965) in agroecology. Scientific research fields tend to be composed of fairly distinct sub-fields that deal with different subjects in different ways, and the adoption of new concepts, methods, and supporting knowledge most likely does not proceed at a uniform rate across an entire subject area. By constructing bibliographic coupling networks for the papers in the data set, we detect the sub-fields of the discipline and determine how they have changed over time.

The networks are made by counting the number of cited references that pairs of papers have in common, assuming that overlapping reference lists imply shared interests and background knowledge (Bornmann and Daniel 2008; Kessler 1963; Weinberg 1974). Communities in the networks – groups of

papers that are more tightly connected to each other than to other papers – are interpreted as the research fronts of agroecology. Words that are frequently used in the titles of the papers in the research fronts indicate the topics they address. By dividing the agroecology papers into three time periods (1982–-2004, 2005–2013, 2014–2018), we can see how research fronts form and change.

3) A further step is needed to uncover the base of knowledge that agroecology draws from and how it differs between research fronts. As Francis et al. (2003) argue, there are many disciplines that could usefully inform (and be informed by) agroecology. Knowledge from other disciplines may enter agroecology at different times, and researchers in different subfields of agroecology may be more open to contributions from some areas than from others. In addition, a few influential researchers can have a disproportionate effect on the evolution and goals of a field (Crane 1972), potentially leading to changes that reflect their areas of interest while neglecting others.

So, to visualize agroecology's supporting knowledge base (The knowledge base of agroecology), we first construct a "science overlay map" for the field (Porter and Rafols 2009; Porter and Youtie 2009). This process consists of creating a base map that lays out approximately 250 subject categories covering all of science, then superimposing the subject categories of the papers that are cited by the papers in our agroecology data set. The resulting graphic gives a high-level overview of the contributions that knowledge from different fields makes to agroecology. We then group the subject categories into a handful of broader "macro-disciplines" and produce a heatmap showing how frequently each agroecology research front refers to papers in each of those macro-disciplines.

To complement this work, we provide interactive versions of the bibliographic coupling networks that show the first author, publication year, and title of all the papers they contain. These may be useful for students wishing to find key papers, researchers who would like to fill gaps in their knowledge, or those interested in forming new collaborations.

Acknowledging the considerable work that is done to advance agroecology in non-academic settings and in different languages (with a large number of contributions in Spanish, Portuguese, and some in French), we emphasize that this study is restricted to research that is published in formal academic documents, and mostly in English.

Materials and methods

This section briefly summarizes the collection, preparation, and analysis of the data presented in Results. Further information can be found in the Supplementary Material.

Data acquisition and cleaning

The data used in this study were obtained from among the 72 million records in journals, books, and conference proceedings indexed in the Web of Science (WoS) Core Collection. The database was queried via the WoS Application Programming Interface on April 5th, 2019, using the following search term: 'Topic = "agroecolog*" OR Topic = "agro-ecolog*"'. The asterisk or 'wildcard' character stands for any character(s), so this search string captures words such as "agroecology," "agro-ecological," and "agroecologist." Searching by topic returns items from 1982[1] to the present that contain the specified search term in the title, abstract, author-assigned keywords, or "Keywords Plus" (keywords that are automatically assigned by WoS). These items can be journal articles, papers in conference proceedings, books, etc., but will be referred to here simply as "documents" or "papers."

The 5,568 documents returned with publication dates through 2018 are used for this study (Table 1). The metadata (titles, abstracts, keywords, authors, etc.) available for those papers were 'cleaned' in two ways before proceeding with the analysis. First, the keywords were edited. The data set contains 12,615 unique author-assigned keywords, including numerous (near-)synonymous terms. This includes singular and plural words (e.g. aflatoxin, aflatoxins), Latin and common names (e.g. glycine max, soybean), and words and phrases with very similar meanings (e.g. organic farming, organic agriculture, organic production). The 674 keywords that are used at least 5 times were inspected by hand and the possible variations were converted into a single, standard term. Then, a similar procedure was applied to words in the titles and abstracts of the papers (lists of terms that were modified in this process are available as described in the Supplementary Material).

An author's use of "agroecology," "agroecological," and related terms may reflect very different relationships with the field of agroecology. In particular, phrases like "agroecological zones" are often used simply to indicate that data were obtained in a specific set of environmental conditions, and does not necessarily denote any of the kinds of research discussed in Introduction. Therefore, to identify the subset of papers expected to be most relevant to the issues at hand, a second data set was created that excludes papers whose titles, abstracts, and keywords *only* use "agroecological" followed by a geographical or physical indicator (i.e., zone, region, site, area, environment, conditions,

Table 1. Basic information about the full "Agroecolog*" data set, and the "Agroecology" subset that is used for the analysis in subsequent sections (see text for definitions).

Data Set	Source Papers	Total Cited References
Full Agroecolog* data set	5,568	256,543
Agroecology subset	3,277	164,550

locations, and variations on those words). This resulted in a total of 3,277 papers (Table 1). *The full set of search results, and the more agroecology-specific subset, will be referred to as the "Agroecolog*" and "Agroecology" data sets, respectively.*

The references cited by each paper are also indexed in WoS, and a second search was carried out for each paper to retrieve the titles, authors, journals, and other information about the cited references. *In the rest of this work, the documents returned by the initial WoS search will be referred to as the "source" or "citing" documents or papers, and the documents they cite as the "cited references".* To determine how many cited references were shared by pairs or groups of source papers, "fuzzy" text matching was carried out, allowing for identification of identical references even in the presence of small errors, spelling differences, etc.

Each journal, book, and conference proceedings in WoS is assigned one or more subject categories (SCs), so, when a cited reference corresponded to a document that was indexed in WoS, its SC(s) were determined using publication:SC spreadsheets provided by WoS customer support. SCs are not available for cited references that appear in publication types (e.g. reports, theses, trade publications) not indexed by WoS, in specific books, journals, and proceedings that are not included in WoS, or that contain missing or incorrect data that prevent them being matched with items in WoS. In the 1982–2004 and 2005–2013 time intervals, SCs could be identified for ~50% or fewer of the cited references, whereas 61% of references cited by articles in 2014–2018 were associated with SCs.

The above data are used for basic bibliometric analyses (Bibliometric and content analysis, Overview of the data and Changes in word use over time), to construct bibliographic coupling networks (Bibliographic coupling analysis and Agroecology's evolving research fronts) and to create cited reference subject category usage maps (Cited reference subject categories and The knowledge base of agroecology). Figure 1 gives a simplified overview of the workflow in this paper (see also Figure 1 in the Supplementary Materials).

Bibliometric and content analysis

The metadata associated with each paper is used to give an overview of the field, including the most common journals and keywords and the rapid, recent increase in publication rates. The frequency with which certain terms are used in the paper abstracts each year is also calculated. The choice of terms to count is based on the authors' impression of, and participation in, the ongoing conversation about the nature and purpose of agroecology, and reflects words and phrases that we expect would indicate whether relevant shifts have occurred. This is discussed further in Changes in word use over time and Reflections on this analysis.

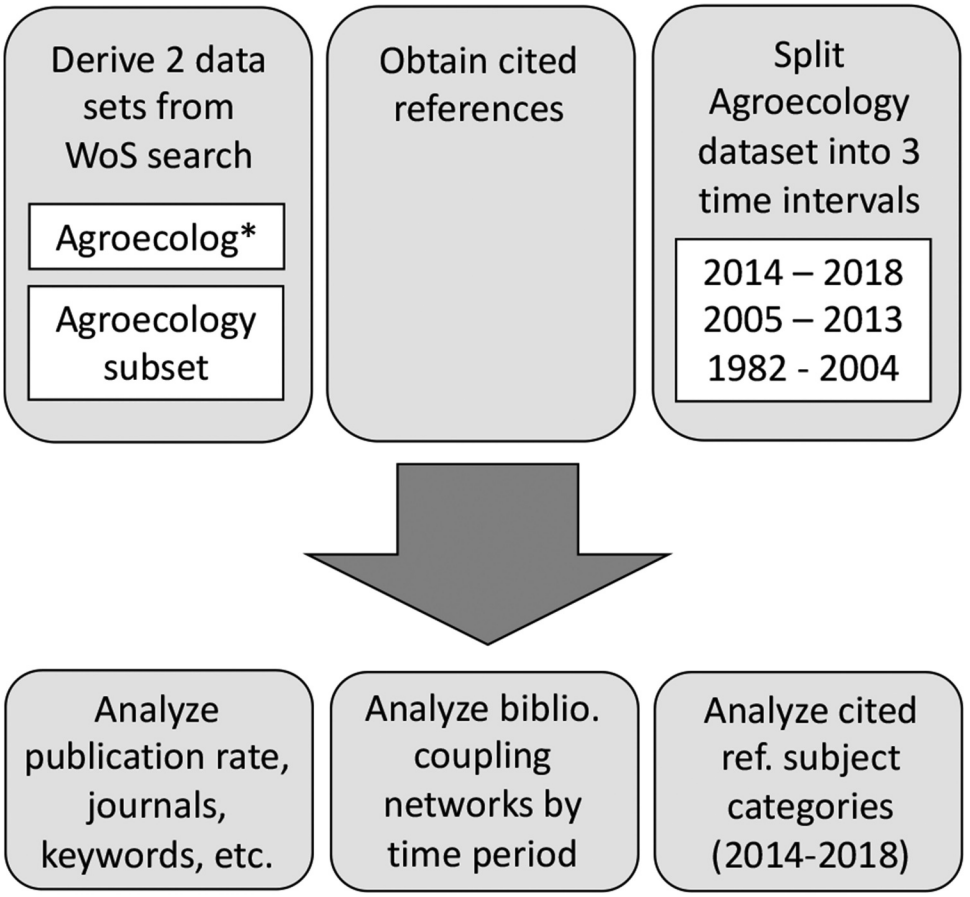

Figure 1. Simplified overview of the workflow in this paper. See the Supplementary Material for more information.

Bibliographic coupling analysis

To investigate the research topics of agroecology and how they have changed over time, we use the technique of bibliographic coupling (BC) to determine connections between papers. Bibliographic coupling can be used to identify the current topics, or research fronts, within a field (Boyack and Klavans 2010; Jarneving 2005; Zupic and Čater 2015). The technique compares the reference lists within papers and links two papers when they share cited references. The more cited references two papers have in common, the higher the weight of the link between them. A BC network can then be created in which the nodes are the citing papers and the edges are the common-reference-based links between them. A community detection algorithm (e.g. Blondel et al. 2008; Wallace, Gingras, and

Duhon 2009) can then be used to divide the network into clusters of papers that tend to draw from the same underlying knowledge base: the research fronts.

BC networks were constructed for three time periods: 1982–2004, 2005–2013, and 2014–2018. Those intervals were selected by simple visual inspection of Figure 3, and loosely correspond to changes in the rate of publication of agroecology papers. For 2005–2013 and 2014–2018, papers were required to share at least 5 cited references with at least one other paper to be included in the network. For 1982–2004, requiring 5 common papers resulted in only small groups of papers by the same authors being included in the network, so a lower threshold of 3 common references was used instead.

The research fronts in each time period were named by inspecting the list of most common title words and the actual titles of all the papers in each RF and creating a term that was felt to capture the essence of those titles. This was carried out by one author and corroborated by another with a very different academic background.

Cited reference subject categories

If agroecology is "the ecology of food systems," the field should incorporate knowledge from (i.e, cite references from) a variety of subject areas. An accurate and detailed description of the subjects covered by each of the roughly 122,000 unique references cited by the 3,277 papers in the Agroecology data set would be difficult to generate, but it is possible to obtain a crude picture using the 252 subject categories (SCs) that Web of Science assigns to each journal/book/proceedings in their database. For example, WoS places the Journal of Applied Ecology into the Biodiversity Conservation and Ecology categories; while the European Journal of Agronomy is assigned the SC of Agronomy; Science and Nature belong to Multidisciplinary Sciences; and so on. If a cited reference appeared in a publication that is indexed in WoS, then, we can derive the broad area of knowledge from which the citing paper was drawing.

To produce digestible information from the SC data, we (1) visualize the usage counts by overlaying them on network maps showing the entire set of SCs for science as a whole, and (2) group the SCs into a smaller number of broader "macro-disciplines" and use heatmaps to show how frequently each macro-discipline is cited. The procedure used to gather SCs into macro-disciplines is based on how frequently journals in different SCs cite each other and is described in the Supplementary Materials; Table 2 lists the resulting macro-disciplines and some of the SCs that belong to them. As noted in Materials and methods, SCs could be identified for relatively few cited references in 1982–2004 and 2005–2013. The analysis of subject categories in this paper is therefore restricted to the 2014–2018 period, for which SCs could be determined for 61% of cited references.

Table 2. Macro-disciplines and representative subject categories.

Macro-discipline	Representative SCs
Agriculture & Food Science[1]	Agriculture, Dairy & Animal Science; Agriculture, Multidisciplinary; Nutrition & Dietetics
Arts and Humanities[2]	Folklore; Philosophy; Religion
Bio/medical Sciences	Cell Biology; Horticulture; Multidisciplinary Sciences; Plant Sciences; Tropical Medicine
Chemistry & Materials	Energy & Fuels; Polymer Science; Spectroscopy
Earth, Ecosystems & Environment	Agronomy; Ecology; Environmental Sciences; Geology; Soil Science
Health and Society	Education & Education Research; Social Science, Biomedical; Social Work
Miscellaneous[3]	Dentistry, Oral Surgery & Medicine; Materials Science, Biomaterials
Physical Science & Engineering	Astronomy & Astrophysics; Engineering, Industrial; Mathematics
Social Sciences	Development Studies; Economics; Environmental Studies; Geography; Political Science

[1]Relatively small macro-discipline; other agriculture-related SCs are found elsewhere.
[2]Not present in the journal citation data used to construct Figure 13; manually assigned to the Social Sciences macro-discipline.
[3]Contains only 4 SCs, all irrelevant. Omitted from Figure 14.

Results

Overview of the data

Some basic properties of the full Agroecolog* data set are presented in Figure 2 and Table 1. Perhaps the most striking characteristic of the data is that the number of papers has increased dramatically since the turn of the century (Figure 2). While just a handful of agroecology papers were published each year in the 1980s, 2018 saw more than 700 papers in the field. Wezel and Soldat (2009) remarked on this phenomenon a decade ago, and this new analysis confirms that the number of papers continues to rise.

These documents are published in almost 1300 journals, books, and conference proceedings. Agroecology papers most frequently appear in Agroecology and Sustainable Food Systems (formerly known as the Journal of Sustainable Agriculture) and Agriculture, Ecosystems, and Environment. However, a range of journals related to sustainability, development, and crop and animal research is represented in the 12 most common journals shown in Figure 2.

Figure 2 also shows the top 12 most frequently used keywords in the articles. The most commonly used keyword is 'sustainable agriculture,' and climate change, biodiversity, and ecosystem services are also well represented. Food security is in the top 12 while food sovereignty is not; maize is the most common crop-related keyword; and organic farming and agroforestry are the systems/methods/practices most frequently referred to. Weeds appear to be the production-related problem attracting the most research effort.

As Figure 3 shows, the Agroecology subset (Materials and methods, Table 1) places more emphasis on agroecological practices, principles, and approaches than the full Agroecolog* data set. The most common words following "agroecological" are now "system" and "practice", and "knowledge",

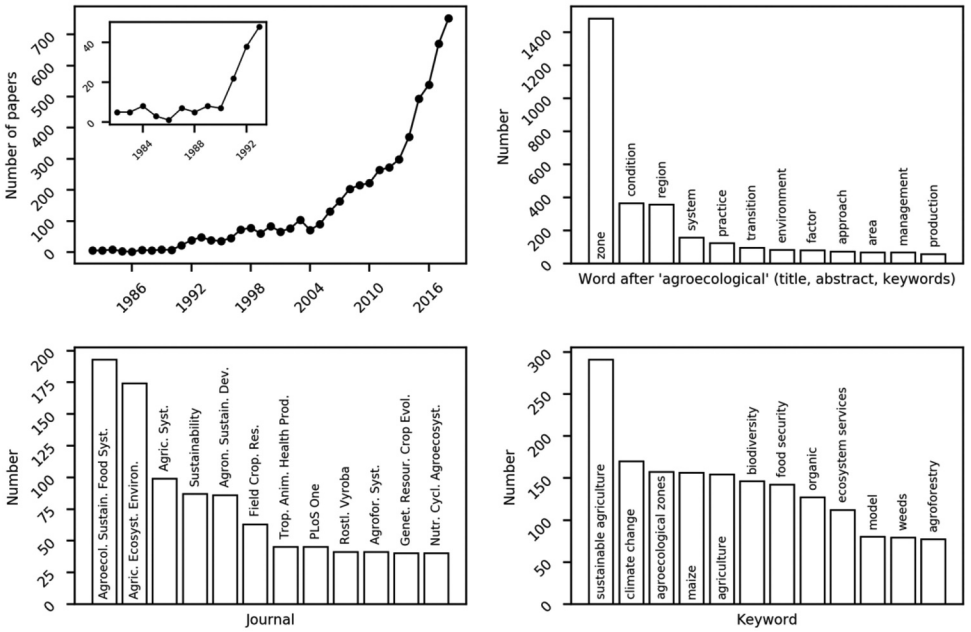

Figure 2. Overview of the full Agroecolog* data set. Upper left: Number of papers per year. Upper right: Number of occurrences of the words that most frequently follow "agroecological", when that word is used in the title, abstract, or keywords. Variations on each word are included (e.g. "zone" includes "zones", "zonation", etc.), and the word 'and' is excluded. Lower left: Number of occurrences of the journals in which these papers are most frequently published. Agroecology and Sustainable Food Systems includes papers published under the journal's previous name, Journal of Sustainable Agriculture. Lower right: Number of occurrences of the most commonly-used keywords (omitting the keyword "agroecology"; keywords have been standardized as described in Materials and methods).

"research", and "principle" have entered the top 12. The same journals appear in the top five, but Field Crop Research and Tropical Animal Health and Production have been displaced by the Journal of Applied Ecology and Eurasian Soil Science. Agriculture and Human Values, a journal focused on the social sciences and humanities, has moved into the 12 most common journals. Sustainable agriculture is still the most common keyword, but climate change has moved several places down the rankings, biodiversity has moved up, and food sovereignty now approaches food security in frequency of use.

To constrain the scope of the analysis, the remainder of this article focuses exclusively on the Agroecology subset of papers. We believe this sample better captures the multiple dimensions of the evolution of the field over time.

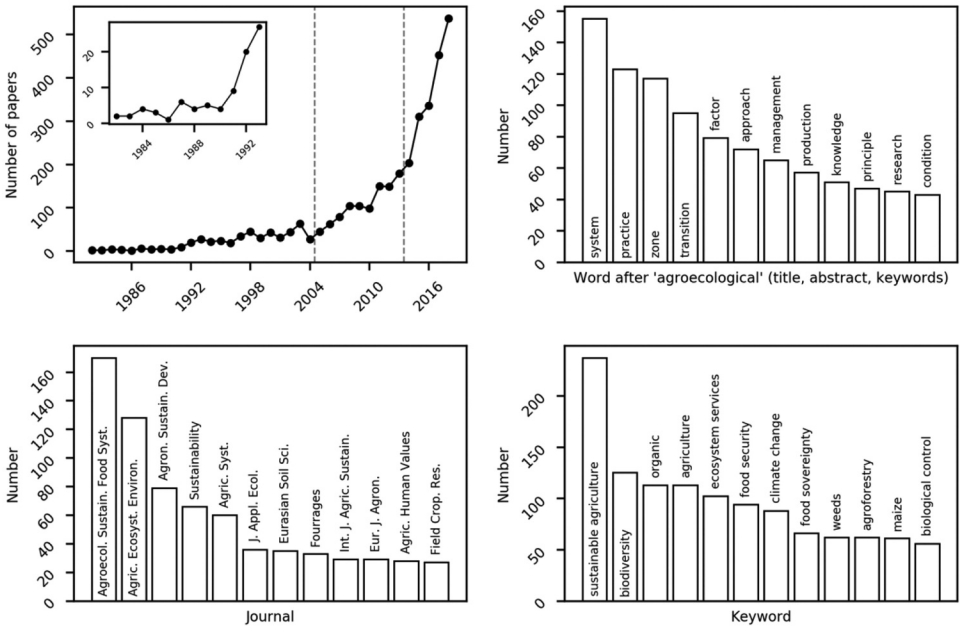

Figure 3. Overview of the Agroecology subset. Upper left: Number of papers per year. Dashed vertical lines indicate the time periods referred to in Agroecology's evolving research fronts. Upper right: Number of occurrences of the words that most frequently follow "agroecological", when that word is used in the title, abstract, or keywords. Variations on each word are included (e.g. "zone" includes "zones", "zonation", etc.), and the word 'and' is excluded. Lower left: Number of occurrences of the journals in which these papers are most frequently published. (Agroecology and Sustainable Food Systems includes papers published under the journal's previous name, Journal of Sustainable Agriculture.) Lower right: Number of occurrences of the most commonly-used keywords (omitting the keyword "agroecology"; keywords have been standardized as described in Materials and methods).

Changes in word use over time

Agroecology's scope and areas of focus have changed over time, influenced by factors such as articles that have intentionally tried to steer the direction of the field, papers that have highlighted new methods, theories, or lines of investigation, and broader trends outside of the discipline itself. Papers that specifically aim to influence the research subjects and practice of agroecology, or point out areas of contention, have used words such as:

- Food system(s): Francis et al. (2003) propose that agroecology be the "ecology of food systems."
- Justice: Several authors have urged agroecologists to pay attention to issues of equity in the food system (Bezner Kerr et al. 2019; Coolsaet 2016; Francis et al. 2003; Gliessman 2014; Timmermann and Félix 2015).
- Participatory: Méndez, Bacon, and Cohen (2013) and Méndez et al. (2017) advocate using participatory research methods.

- Livelihoods: Amekawa (2011) explains how sustainable livelihoods and agroecology could be integrated; see also Addinsall et al. (2015) and Tittonell (2014).
- Food security and food sovereignty: These concepts have been defined, dissected, and criticized by numerous authors (e.g. Agarwal 2014; Bernstein 2014; Holt-Giménez and Altieri 2013; Holt-Giménez and Shattuck 2011).

At the same time, concepts such as "sustainability," "climate change," and "organic" have become more widely used by researchers, the popular media, and the public in recent years (e.g. Boykoff and Boykoff 2007).

Figure 4 shows the prevalence of the above terms in the abstracts of the Agroecology papers over time. The fraction of abstracts containing each term in each year is relative to the total number of Agroecology abstracts *for that year*. Because very few papers were published in the early years (Figure 3), certain words can appear in a very large fraction of papers and their frequency can vary by a large amount from 1 year to the next in that time period. For example, "food security" appears in 25% of papers in 1988 and 0%

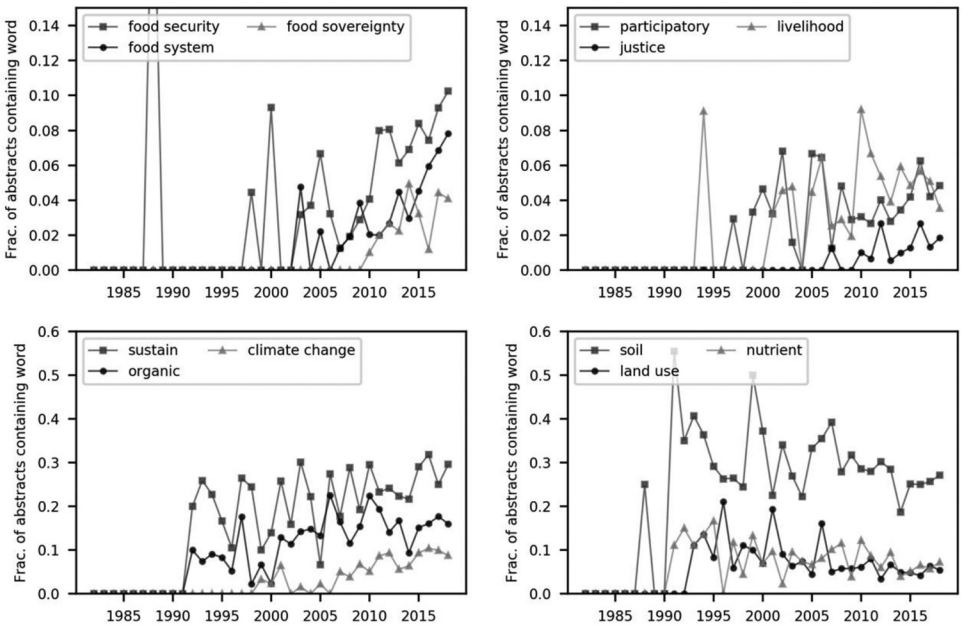

Figure 4. Number of abstracts containing certain text strings each year, divided by the total number of papers in the Agroecology data set that year. These text strings can match whole or partial words (so "sustain" finds papers whose abstracts include "sustainable", and "sustainability"; "nutrient" includes "nutrients", etc.). The number of papers in the early years is small (Figure 3), so large variations in the fraction of abstracts containing a word are common in that period. Note the different y scales of the upper and lower panels.

in 1989, but this simply means that the phrase occurred in 1 of the 4 papers that were published in 1988 and 0/5 in 1989.

In more recent years, several words show a marked increase in usage. In particular, "food security" and "food system" were used in only about 2% of abstracts in the mid-2000s but now appear in roughly 8–10%. The first use of "food sovereignty" in the Agroecology sample of papers did not occur until 2010, but that term was used in 4% of abstracts in 2018. "Participatory" and "justice" are also becoming more common, although their usage has increased at a slower rate. No clear trend is discernible in the usage of "livelihood."

"Climate change" and "sustain" (including "sustainability," "sustainable," etc.) are also used more frequently than in the past, but references to "organic" have been fairly constant. Other words that have been stable or declining in popularity include "soil," "land use," and "nutrient." Overall, terms that may reflect a concern for the agency and interests of participants in the food system, and a wider food systems perspective, have experienced a rise in usage.[2] Words like "soil" and "organic," though, which can be used to refer solely to biophysical processes and practices, are still widely used, appearing in roughly 30% and 15% of recent abstracts, respectively.

The usage counts of this small number of pre-selected terms give some indication of the topics addressed by agroecology, and of changes within the field. However, this relies on a subjective assessment of the words and phrases that are important to evaluate, and does not illustrate how these topics are distributed within the subject. In the following section, we use citation relationships between papers to extract the research communities within agroecological science, building a broader and less biased view of the discipline.

Agroecology's evolving research fronts

Basic characteristics of the BC network for each time period are given in Table 3, and further described below.

The early years: 1982 – 2004

The BC network for 1982–2004 is shown in Figure 5, in which the four largest research fronts are highlighted. The research fronts were named by visual

Table 3. Characteristics of the bibliographic coupling networks.

Time Period	Papers in Time Period[1]	Threshold[2]	Papers in Network (%)	Connected Papers[3] (%)
1982–2004	423	3	141 (33%)	33 (23%)
2005–2013	950	5	323 (34%)	173 (54%)
2014–2018	1808	5	772 (43%)	573 (74%)

[1]Excludes 96 papers that do not cite any references (cf Table 1).
[2]Number of cited references that a paper must have in common with at least one other paper in order to be included in the network.
[3]Number of papers in the network that belong to the largest connected component (the largest sub-group in which all papers can be reached by following connections from any other paper).

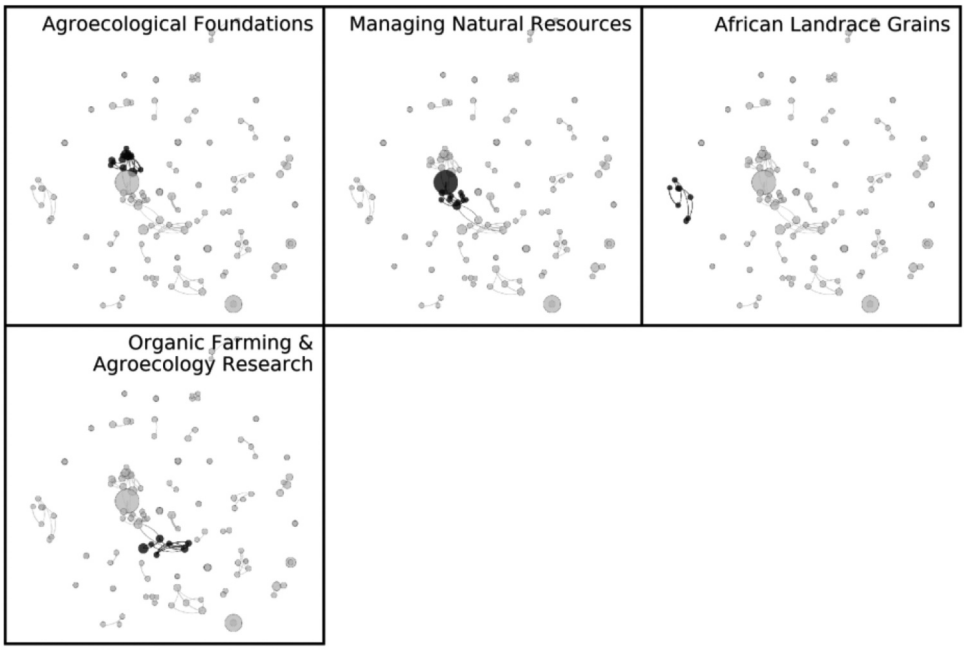

Figure 5. Agroecology bibliographic coupling network for **1982–2004**, highlighting the four largest research fronts. The size of each node (research paper) is a function of the relative number of citations to that paper. The largest node/most-cited paper in the 1982–2004 period had 982 citations in WoS at the time of data collection, compared to 610 and 143 citations to the most-cited papers in the 2005–2013 and 2014–2018 networks, respectively: because of the very different numbers of citations to papers in the three time periods, node sizes in Figure 5, 7, and 10 are not directly comparable. The thickness of each link is related to the number of cited references shared by those two papers. An interactive, color-coded version of this figure, showing the first author, year, and title of each paper, is available here http://www.uvm.edu/~rmason4/agroecology_BC_network/agroecology_1982_2004/.

inspection of the titles of the papers in each one, and Figure 6 illustrates their most common title words. Only four research fronts are highlighted in this time period because the others contain mainly or only papers by the same first author (for example, the fifth-largest front contains six papers, of which four are by S. O. Oikeh), or are very small.

The largest research front, "Agroecological Foundations$_{1982\text{-}2004}$", contains 15 papers. Much of this front deals with developing countries in South and Central America. Topics are varied, including Sri Lankan forest gardens (Nuberg, Evans, and Senanayake 1994), alternative agriculture in California (Altieri 1992), and quantifying farm performance and sustainability (Dalsgaard, Lightfoot, and Christensen 1995; Dalsgaard and Oficial 1997). Several papers mention social, cultural, and political factors (Holt-Giménez 2002; Macdonald 1998; Méndez, Lok, and Somarriba 2001; Steinberg 1998), or reflect on agroecological research and perspectives (Altieri 1989; Francis et al. 2003; Worster 1990; Zimmerer 1994). Given the range of topics covered in this

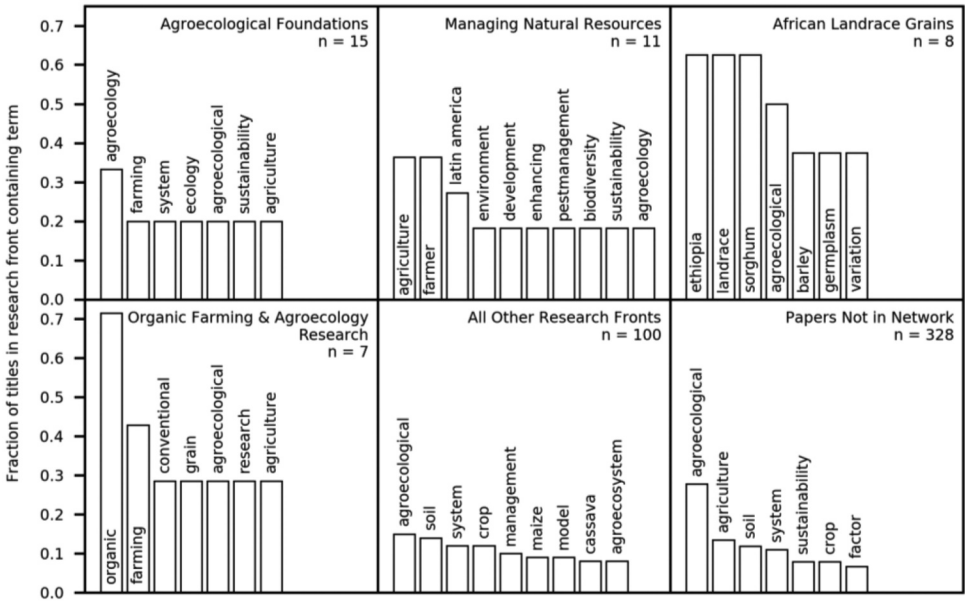

Figure 6. The most common words in the titles of the papers belonging to the largest research fronts in the **1982–2004** network. Up to ten words are included; where showing all of the next most frequent words would require >10 bars, fewer words are included. (For example, the seven words in the Agroecological Foundations subplot are used by five and three papers in that research front, while four more words are used by two papers each and are therefore not shown.) The number of papers in each research front is indicated.

research front, it is perhaps not surprising that the documents most frequently cited by its members, "Agroecology: the scientific basis of alternative agriculture" (Altieri 1987) and "Agroecosystem analysis" (Conway 1985) contain material that is fairly widely applicable.

Several of the papers in the next-largest front, "Managing Natural Resources$_{1982\text{-}2004}$", address topics related to pest management, while others deal with ecological and natural resource issues such as biodiversity (Altieri 1999) and soil health (Sherwood and Uphoff 2000). As with Agroecological Foundations$_{1982\text{-}2004}$, this research front pays attention to matters other than the strictly biophysical. These include policy agendas (Sherwood and Uphoff 2000), farmer participation and farmer-to-farmer programs (Andrews, Bentley, and Cave 1992; Hawkesworth and García Pérez 2003), indigenous knowledge (Altieri 1993), and contradictions within alternative agriculture (Rosset and Altieri 1997).

"Managing Natural Resources$_{1982\text{-}2004}$" includes the most highly cited paper from this time period: "The ecological role of biodiversity in agroecosystems" (Altieri 1999). This paper had 982 citations recorded in the Web of Science at the time the search was performed, and is the most-cited paper in the Agroecology data set. It is followed by "Ecological intensification of cereal production systems" (Cassman 1999; 634 citations) and "Global food security:

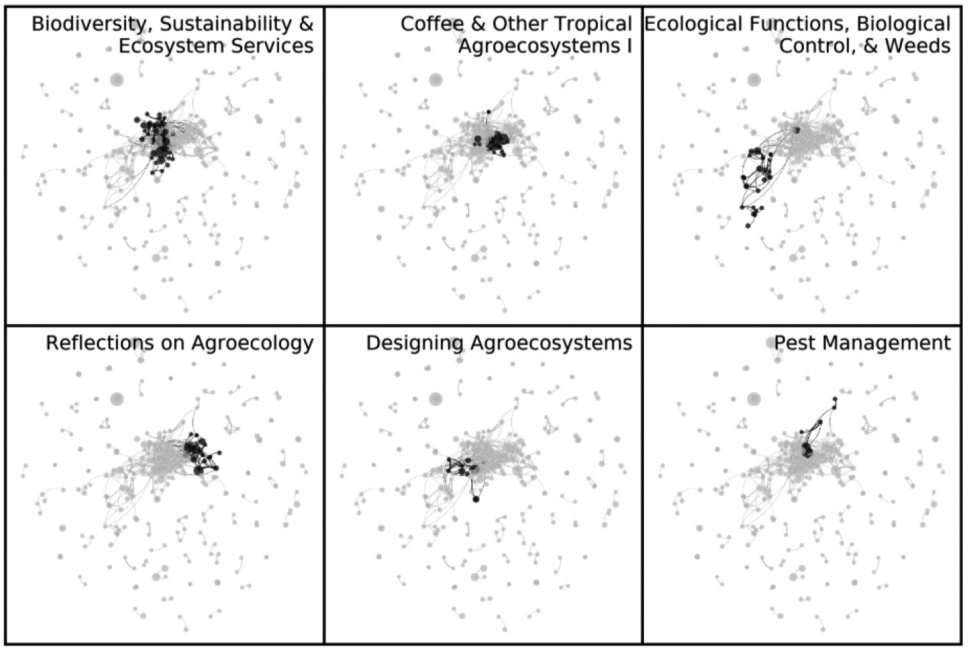

Figure 7. Agroecology bibliographic coupling network for **2005–2013**, highlighting the six largest research fronts. The size of each node (research paper) is a function of the relative number of citations to that paper. The largest node/most-cited paper in the 2005–2013 period had 610 citations in WoS at the time of data collection, compared to 982 and 143 citations to the most-cited papers in the 1982–2004 and 2014–2018 networks, respectively: because of the very different numbers of citations to papers in the three time periods, node sizes in Figure 5, 7, and 10 are not directly comparable. The thickness of each link is related to the number of cited references shared by those two papers. An interactive, color-coded version of this figure, showing the first author, year, and title of each paper, is available here http://www.uvm.edu/~rmason4/agroecology_BC_network/agroecology_2005_2013/.

Challenges and policies" (Rosegrant and Cline 2003; 343 citations). The former paper is in a small research front in the periphery of the network, while the latter is not included in the network. In fact, only six of the top ten most-cited papers from 1982–2004 appear in this time interval's BC network.

"Organic Farming & Agroecology Research$_{1982\text{-}2004}$", is connected to Managing Natural Resources$_{1982\text{-}2004}$ because Lotter (2003) and Dalgaard, Hutchings, and Porter (2003) in Organic Farming & Agroecology Research$_{1982\text{-}2004}$ cite some of the same references as Altieri (2002) in Managing Natural Resources$_{1982\text{-}2004}$. However, the topics of the papers in Organic Farming & Agroecology Research$_{1982\text{-}2004}$ are less diverse than those of Agroecological Foundations$_{1982\text{-}2004}$ and Managing Natural Resources$_{1982\text{-}2004}$ (even considering the larger size of the latter fronts). Five of the seven papers mention organic farming in their titles, while the remaining two reflect on the scope of agroecological research (Dalgaard, Hutchings,

and Porter 2003) and the application of agroecology in farming systems research (Delate 2002). Papers in this research front are all from 2001 or later.

"African Landrace Grains$_{1982\text{-}2004}$," is also a coherent research front, consisting entirely of research about sorghum and barley in Africa and the Middle East. Judging by the paper titles, the work in this research front is essentially biophysical in nature. African Landrace Grains$_{1982\text{-}2004}$ is entirely disconnected from all other fronts, meaning that none of its papers shares three or more references with any paper outside the research front. This is typical of research fronts in this network: the largest connected component (LCC; the largest sub-group in which all papers can be reached by following connections from any other paper) includes only 33/141 (23%) of the papers in the network as a whole (Table 3), while the remaining 108/141 (77%) of papers share cited references with very few other papers.

In fact, the network in Figure 5 contains just 141 papers (Table 3), which is only 33% of the 423 papers that were published during this time period. The remaining papers were excluded from the network because they shared fewer than three cited references with any other paper. Those papers must either deal with similar topics but draw from different source material (i.e., cite different references), or cover different topics without forming coherent communities. Overall, the fragmented nature of the network in the 1982–2004 time period, and the relatively small fraction of papers included in the network suggest a field in the early stages of assembling its knowledge base and topics of enquiry.

The middle period: 2005 – 2013

By 2005–2013 the bibliographic coupling network consists of a relatively large, interconnected core, a handful of more peripheral but still connected research fronts, and a scattering of smaller, distinct fronts (Figure 7). A similar fraction of the papers from this time interval are included in the network compared to 1982–2004 (323/950 vs 141/423; 34% vs 33%), even though more common cited references were required for a paper to be included in the network (5 vs 3; Table 3). The percentage of papers belonging to the largest connected component has also increased, from 33/141 (23%) to 173/323 (54%). These numbers suggest that during this period the field continued to coalesce into groups that draw from common pools of background knowledge.

The most common title words for the six largest research fronts are shown in Figure 8. The largest front, "Biodiversity, Sustainability & Ecosystem Services$_{2005\text{-}2013}$", has a strong emphasis on biodiversity (e.g. Gabriel et al. 2013; Tscharntke et al. 2012) and associated ecosystem services (e.g. Carvalheiro et al. 2010; Kremen and Miles 2012). It also contains studies exploring sustainability and sustainable intensification (Gomiero, Pimentel, and Paoletti 2011; Pretty 2008; Pretty, Toulmin, and Williams 2011), as well as a handful of papers proposing research and policy agendas or examining the factors that shape them (Lee 2013; Thompson and Scoones 2009; Vanloqueren

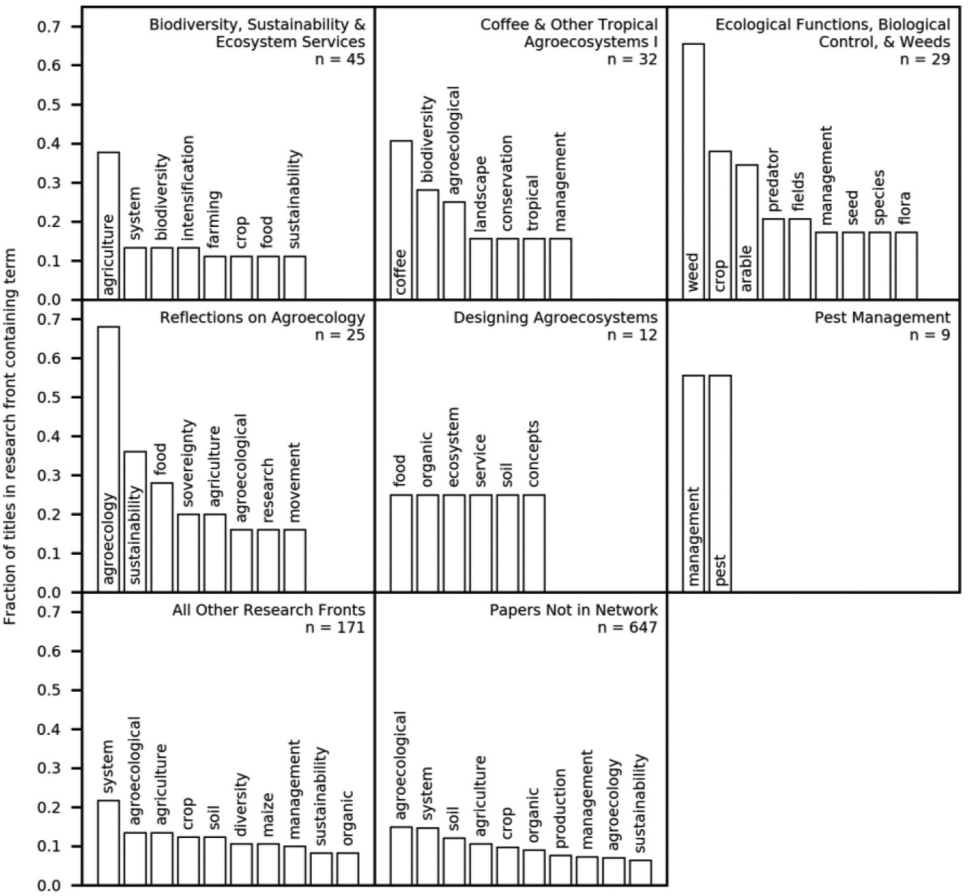

Figure 8. The most common words in the titles of the papers belonging to the largest research fronts in the **2005–2013** network (Figure 7). See Figure 6 for information about the number of bars shown in the panels.

and Baret 2009). While some of the work in this research front pertains to developing countries, it also includes studies of temperate agroecosystems (Lovell et al. 2010; Morelli 2013; Stanley, Gunning, and Stout 2013).

The next largest research front, "Coffee & Other Tropical Agroecosystems $I_{2005\text{-}2013}$", deals mainly with agriculture-related issues in the tropics, with a focus on coffee production and biodiversity. A number of its members are firmly biophysical in nature, relating to topics such as evaluating bird communities using remote sensing (Ranganathan, Chan, and Daily 2007). However, this front also includes social science-related themes such as coffee farmer livelihoods (Méndez et al. 2010) factors governing reforestation in Vietnam (Meyfroidt and Lambin 2008), and climate change adaptation strategies among subsistence farmers (Mercer, Perales, and Wainwright 2012).

Following these two fronts, "Ecological Functions, Biological Control, and $Weeds_{2005\text{-}2013}$" is another large but comparatively diffuse and peripheral

research front. Aside from two papers that include participatory approaches and management science (Duru 2013; Duru et al. 2011), this front is largely restricted to biophysical topics. This is quite different from the fourth research front, "Reflections on Agroecology$_{2005\text{-}2013}$". Most of the papers in this group describe and question the purpose and direction of agroecology (e.g. Fernandez et al. 2013; Holt-Giménez and Altieri 2013), and examine some of its theoretical underpinnings (e.g. Rosset and Martínez-Torres 2012).

The final two research fronts highlighted in Figure 7 are "Designing Agroecosystems$_{2005\text{-}2013}$" and "Pest Management$_{2005\text{-}2013}$". The former touches on ecological intensification and agroecosystem modeling, while the latter mainly deals with management of insect pests. The remaining fronts in this network contain eight or fewer papers. Their most common title words, as well as those of the papers that are not in the network, tend to be biophysical or production-related terms like "soil," "crop", "organic", and "management" (Figure 8). This may imply that work that considers the social, political, etc. aspects of agroecology is more likely to be found in the connected core of the network.

All of the top 10 most-cited source papers from this time period are included in the network, and all but one are in one of the named research fronts. The top three are "Global food security, biodiversity conservation, and the future of agricultural intensification" (Tscharntke et al. 2012; 610 citations), "Agricultural sustainability: concepts, principles, and evidence" (Pretty 2008; 467 citations), and "Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia" (Deressa et al. 2009; 366 citations). In general, Figure 7 shows that Biodiversity, Sustainability & Ecosystem Services$_{2005\text{-}2013}$ and Coffee & Other Tropical Agroecosystems I$_{2005\text{-}2013}$ have been rich sources of highly cited papers.

The vast majority of the references cited by the papers in this time period are to documents that are not in the Agroecology data set. However, patterns in citations to papers that are within the Agroecology data set, and specifically to papers in the 1982–2004 time period, give some insight into the influence of the earlier research fronts on more recent work in the field. To visualize these patterns, Figure 9 presents a heatmap of citations from research fronts in 2005–2013 to research fronts in the 1982–2004 network (and to papers that are in the Agroecology data set but were below the threshold for inclusion in the network).

The clearest link between research fronts is from Reflections on Agroecology$_{2005\text{-}2013}$ to Agroecological Foundations$_{1982\text{-}2004}$. This is mostly due to papers citing the influential article by Francis et al. (2003); over two-thirds of the citations from Reflections on Agroecology$_{2005\text{-}2013}$ to Agroecological Foundations$_{1982\text{-}2004}$ are to that paper. Reflections on Agroecology also draws on Managing Natural Resources$_{1982\text{-}2004}$ and on Agroecology papers outside the network. Citations to these groups are also

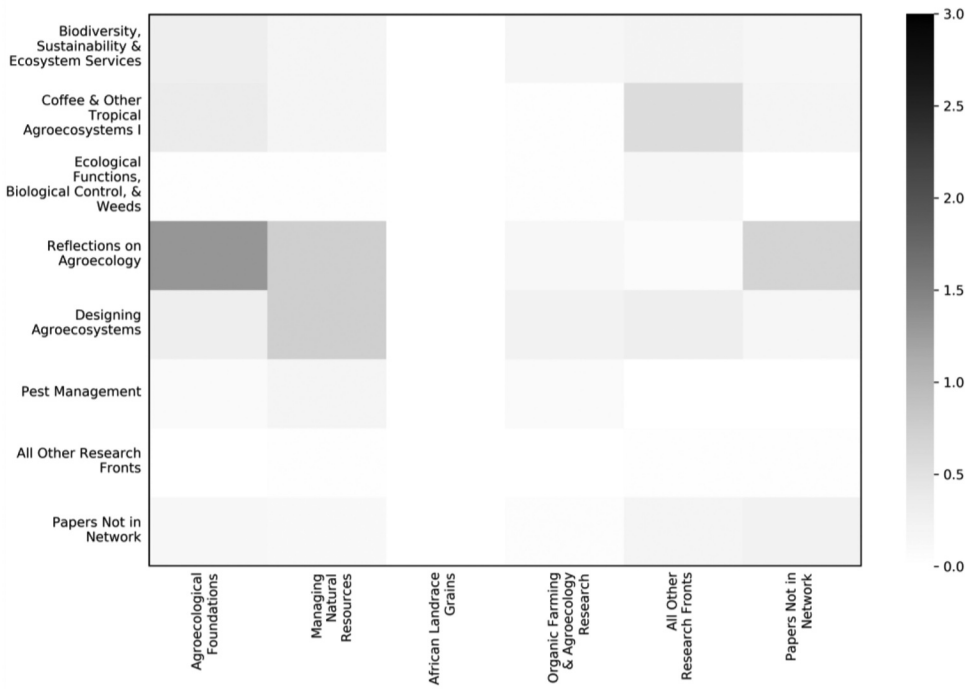

Figure 9. Heatmap of citations from each research front in 2005–2013 to each research front in 1982–2004. The color bar indicates the mean number of citations per paper in the citing research front to papers in the cited research front (so, on average, each of the 25 papers in Reflections on Agroecology$_{2005\text{-}2013}$ cites 1.3 papers in Agroecological Foundations$_{1982\text{-}2004}$).

dominated by just a few papers; in Managing Natural Resources$_{1982\text{-}2004}$ these are Altieri (2002) and Rosset and Altieri (1997).

Coffee and Other Tropical Agroecosystems I$_{2005\text{-}2013}$ most commonly cites papers outside the main research fronts in 1982–2004, mainly Perfecto and Vandermeer (2002) and Mas and Dietsch (2003). Coffee agroecology was certainly studied prior to 2005, but evidently not in a sub-field detectable through its shared cited references. Designing Agroecosystems$_{2005\text{-}2013}$ draws on Managing Natural Resources$_{1982\text{-}2004}$, but only through citations to Altieri (2002) and Altieri (1999). Ecological Functions, Biological Control, and Weeds$_{2005\text{-}2013}$, Pest Management$_{2005\text{-}2013}$, and Others cite very few Agroecology papers from the previous time period. African Landrace Grains$_{1982\text{-}2004}$ appears not to have prompted much subsequent work within agroecology (at least, not among papers in the 2005–2013 network).

Exponential growth: 2014 – 2018

By 2014–2018, the network includes 772/1808 (43%) of the papers published in this time period and contains a very large, connected core (Figure 10). 573/772 (74%) of the papers in the network now belong to the largest connected

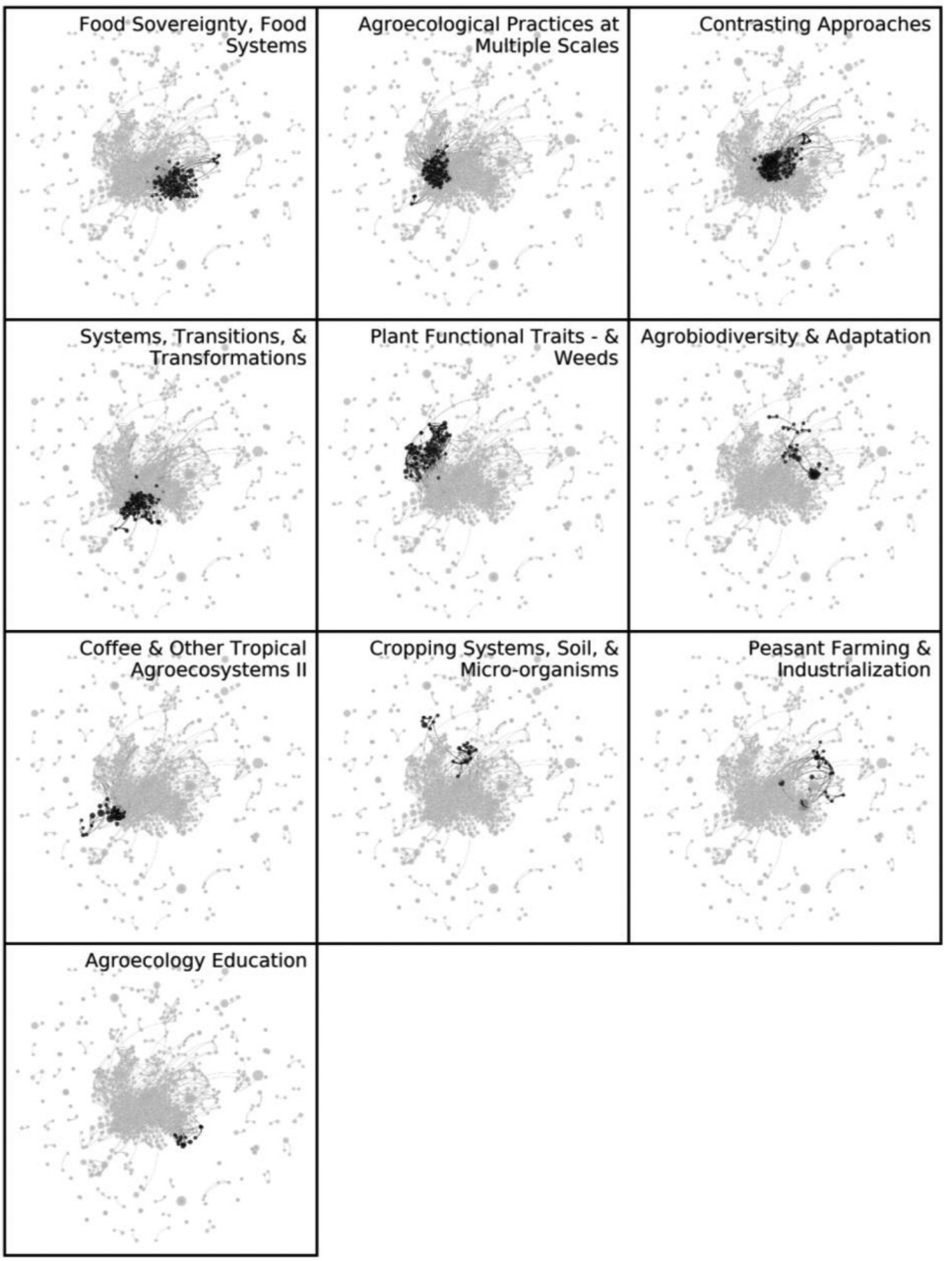

Figure 10. Agroecology bibliographic coupling network for **2014–2018**, highlighting the ten largest research fronts. The size of each node (research paper) is a function of the relative number of citations to that paper within this time period. The largest node/most-cited paper in the 2014–2018 period had 143 citations in WoS at the time of data collection, compared to 982 and 610 citations to the most-cited papers in the 1982–2004 and 2005–2013 networks, respectively: because of the very different numbers of citations to papers in the three time periods, node sizes in Figure 5, 7, and 10 are not directly comparable. The thickness of each link is related to the number of cited references shared by those two papers. An interactive, color-coded version of this figure, showing the first author, year, and title of each paper, is available here http://www.uvm.edu/~rmason4/agroecology_BC_network/agroecology_2014_2018/.

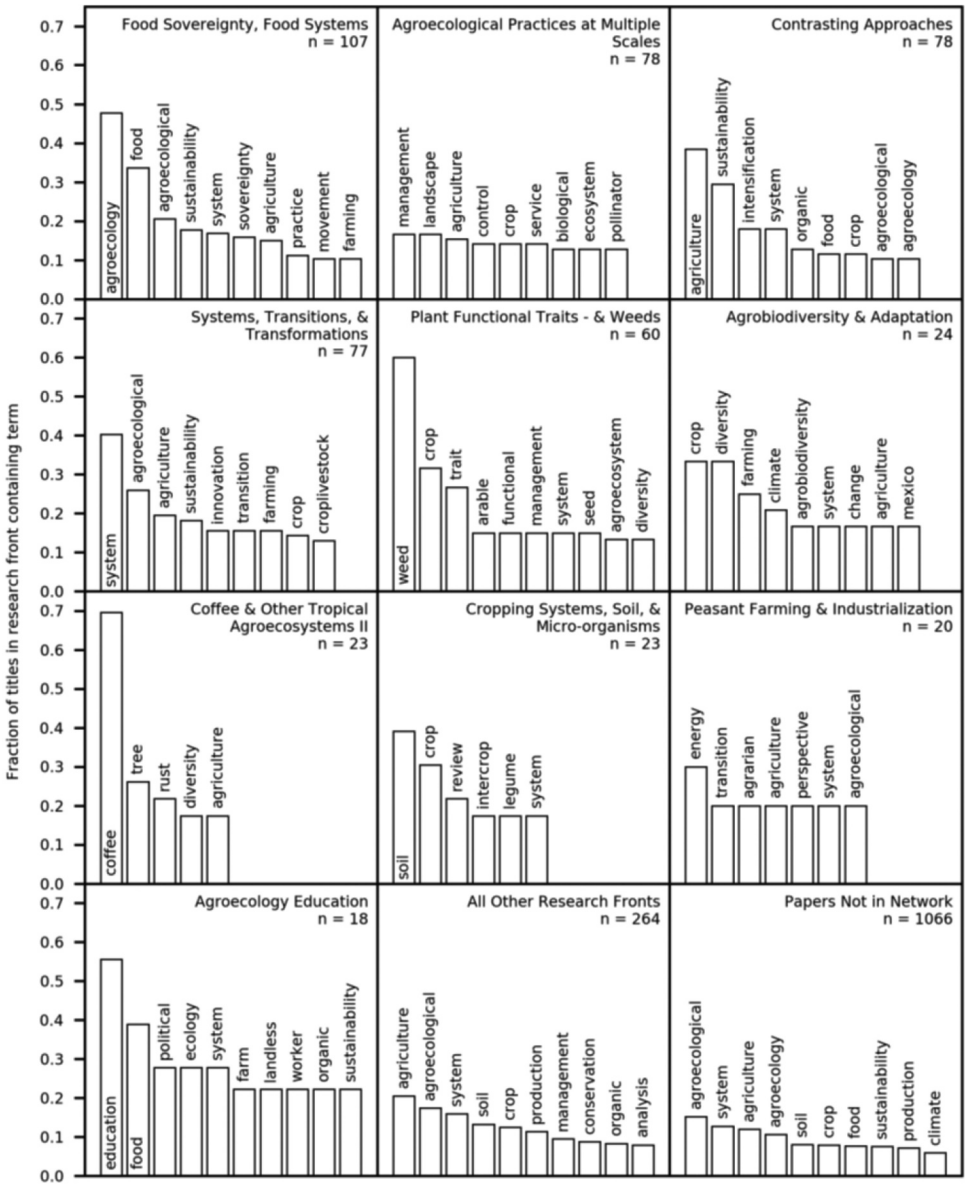

Figure 11. The most common words in the titles of the papers belonging to the largest research fronts in the **2014–2018** network (Figure 10). See Figure 6 for information about the number of bars included in each panel.

component. The number of papers and disconnected groups of papers that do not share references with other work continues to decline.

The title words of the 10 largest research fronts are shown in Figure 11. Inspecting the fronts in this time period suggests that some of the themes from 2005–2013 have evolved into related but different forms, some make up

a much smaller or larger fraction of the network than they used to, and some new research fronts have arisen. For example, some of the most common title words in Reflections on Agroecology$_{2005\text{-}2013}$, such as sovereignty and movement, now appear in the large Food Sovereignty, Food Systems$_{2014\text{-}2018}$ front. Coffee & Other Tropical Agroecosystems I$_{2005\text{-}2013}$ contained 32 papers in 2005–2013, but a rather similar front in 2014–2018 includes only 23. Either less coffee research is using agroecology as a lens, or coffee-related articles are drawing from a more scattered underlying set of papers.

Agroecology Education$_{2014\text{-}2018}$ forms a distinct research front in 2014–2018, whereas this topic must have been non-existent, too small to highlight, or subsumed into another research front in the previous period. Agroecology Education was also noted as a distinct category by Gallardo-López et al. (2019) in their review of research topics and approaches in agroecology in Latin American and the Caribbean.

Figure 12 gives a more quantitative view of the relationships between the research fronts in 2005–2013 and those in 2014–2018, tracing the citation patterns in the same way as Figure 9.[3] This supports some of the relationships suggested above.

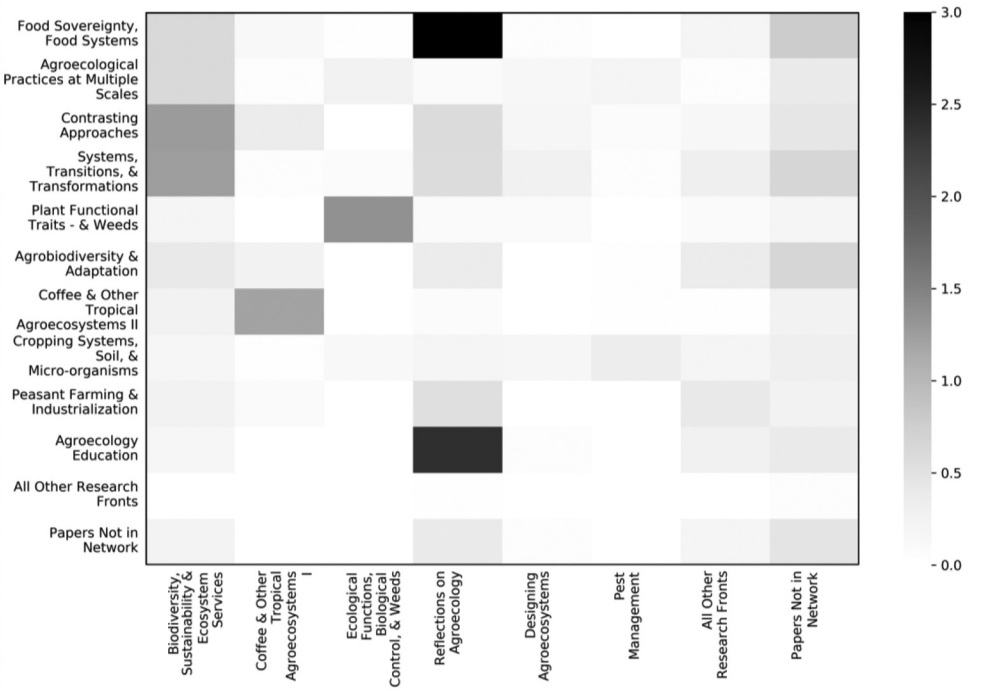

Figure 12. Heatmap of citations from each research front in 2014–2018 to each research front in 2005–2013. The color bar indicates the mean number of citations per paper in the citing research front to papers in the cited research front.

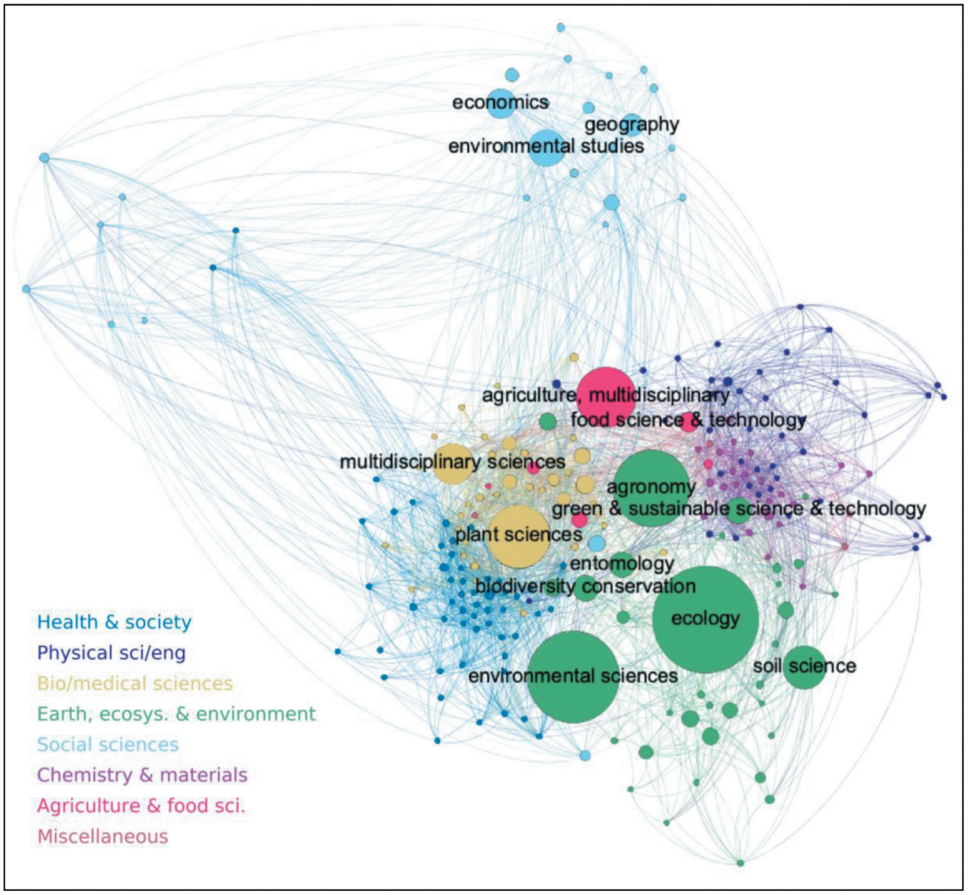

Figure 13. Global map of subject categories for all of science, with each node sized to reflect the number of times Agroecology papers cited references in journals assigned to that category (summed over all research fronts in 2014–2018). Narrow subject categories are grouped into broader macro-disciplines. Subject categories that are cited >1500 times are labeled; labels are centered over the nodes to which they refer. An interactive version of this figure can be found here http://www.uvm.edu/~rmason4/subject_categories/subject_categories/.

Reflections on Agroecology$_{2005\text{-}2013}$ has exerted the most influence on the most recent period in agroecological research. Food Sovereignty, Food Systems$_{2014\text{-}2018}$ and Agroecology Education$_{2014\text{-}2018}$ are most likely to cite this front. In contrast to citations from Reflections on Agroecology$_{2005\text{-}2013}$ to its own precursor, Agroecological Foundations$_{1982\text{-}2004}$, which were mostly to a single paper in that front, citations from Food Sovereignty, Food Systems$_{2014\text{-}2018}$ to Reflections on Agroecology$_{2005\text{-}2013}$ are fairly evenly distributed. The three most-cited papers are "Agroecology as a science, a movement and a practice" (Wezel et al. 2009), "The agroecological revolution in Latin America: rescuing nature, ensuring food sovereignty, and empowering peasants" (Altieri and Toledo 2011), and "Agroecology as a transdisciplinary, participatory, and action-oriented approach" (Méndez,

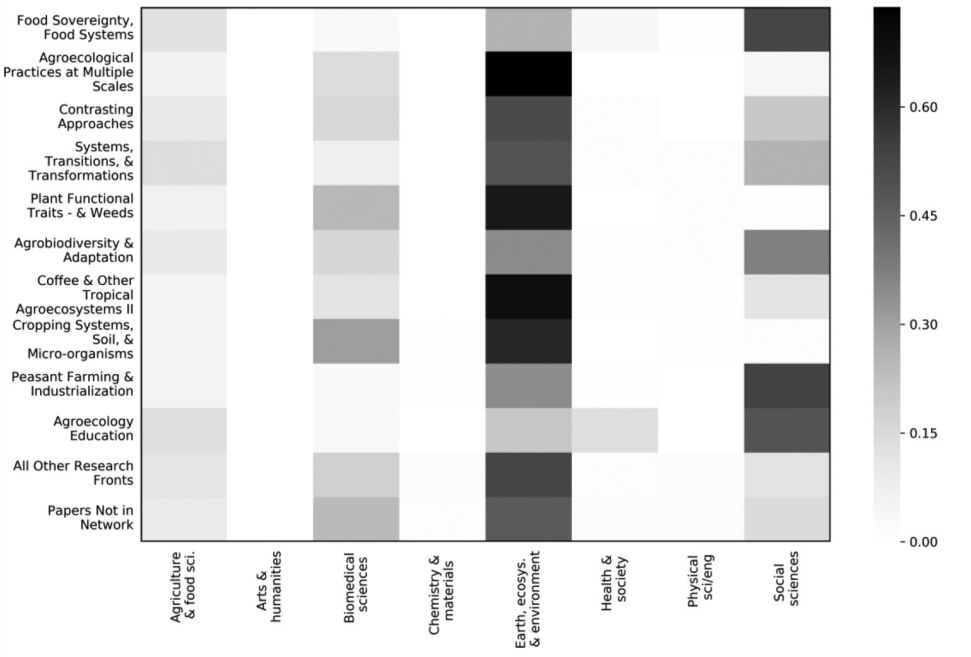

Figure 14. Heatmap of citations from research fronts in the 2014–2018 network to references in 8 different macro-disciplines. The color bar shows the fraction of cited references from each research front that are to documents in each macro-discipline (for the 61% of references for which this information could be established).

Bacon, and Cohen 2013). Food Sovereignty, Food Systems$_{2014\text{-}2018}$ also cites some papers that were not included in the previous period's network; "Agroecology: foundations in agrarian thought and sociological theory" (Sevilla Guzmán and Woodgate 2013) is the most-referenced of these.

Agroecology Education$_{2014\text{-}2018}$ also draws mainly from Reflections on Agroecology$_{2005\text{-}2013}$. Although the most-cited paper is again Wezel et al. (2009), this research front also cites education-related papers including "Innovative Education in Agroecology: Experiential Learning for a Sustainable Agriculture" (Francis et al. 2011), "Phenomenon-Based Learning in Agroecology: A Prerequisite for Transdisciplinarity and Responsible Action" (Francis et al. 2013), and "Individualized student-centred education: prototype for an agroecology BSc programme" (Waldenström et al. 2008). This suggests that, while education in agroecology has been a topic of research for some years, it is now amassing a coherent enough knowledge base to become identifiable as a (small) sub-field in its own right.

Not surprisingly, Coffee & Other Tropical Agroecosystems II$_{2014\text{-}2018}$ mainly cites Coffee & Other Tropical Agroecosystems I$_{2005\text{-}2013}$, although at

a rate of only 1.2 citations to Coffee & Other Tropical Agroecosystems $I_{2005\text{-}2013}$ per paper in Coffee & Other Tropical Agroecosystems $II_{2014\text{-}2018}$. The most commonly cited papers are Perfecto and Vandermeer (2008), Méndez et al. (2010), and Méndez, Gliessman, and Gilbert (2007). These articles all address (agro)biodiversity in relation to the needs and strategies of smallholder farmers.

Contrasting $Approaches_{2014\text{-}2018}$ and Systems, Transitions, & $Transformations_{2014\text{-}2018}$ cite Biodiversity, Sustainability, & Ecosystem $Services_{2005\text{-}2013}$ at a similar rate. Although it is a fairly varied research front, Contrasting $Approaches_{2014\text{-}2018}$ is named for the preponderance of papers regarding organic/conventional agriculture, the land sharing/sparing debate, and approaches to intensification. This is reflected in the fact that 22 of its 78 members (28%) cite "Global Food Security, Biodiversity Conservation, and the Future of Agricultural Intensification" (Tscharntke et al. 2012) from Biodiversity, Sustainability & Ecosystem $Services_{2005\text{-}2013}$.

Figure 12 also suggests that Plant Functional Traits – & $Weeds_{2014\text{-}2018}$ is the successor to Ecological Functions, Biological Control, & $Weeds_{2005\text{-}2013}$. The research focus and methods have shifted, though: the newer research front seeks to apply functional trait ecology to agricultural systems, with a focus on crop breeding, crop yields, nutrient cycling, and primary productivity (Martin and Isaac 2018). The remaining research fronts (Agroecological Practices at Multiple $Scales_{2014\text{-}2018}$, Agrobiodiversity & $Adaptation_{2014\text{-}2018}$, Cropping Systems, Soil, & $Microorganisms_{2014\text{-}2018}$, Peasant Agriculture & $Industrialization_{2014\text{-}2018}$) rely relatively little on papers in the 2005–2013 network. In the opposite direction, research fronts Designing $Agroecosystems_{2005\text{-}2013}$ and Pest $Management_{2005\text{-}2013}$ do not appear to have greatly influenced the larger research fronts in the most recent time period, although this may be partly due to their relatively small size.

Citations *to* the papers in the 2014–2018 network are only starting to accumulate for the most recent articles. At this time, nine of the top ten most-cited papers are included in the network, of which the top three are "Land sparing vs land sharing: moving forward" (Fischer et al. 2014), "Diversification practices reduce organic to conventional yield gap" (Ponisio et al. 2015) and "Agroecological practices for sustainable agriculture. A review" (Alexander Wezel et al. 2014). The only member of the top ten most-cited articles that is not in the network is "A global spectral library to characterize the world's soil" (Viscarra Rossel et al. 2016).

The above analysis illustrates the research fronts of agroecology at three points in time and uses patterns of citations between these time periods to trace the lineage and development of the fronts. However, the overwhelming majority of the references cited by the papers in the research fronts are papers that are not contained in the Agroecology data set. Those papers contribute knowledge to agroecology, but that knowledge base is not revealed by the data

presented in this section. In the next section, then, we investigate the subject categories of the cited references, visualizing the fields from which agroecology research fronts draw their supporting knowledge.

The knowledge base of agroecology

The overall SC usage map for agroecology (for all research fronts in 2014–2018) is shown in Figure 13, in which the size of each node reflects the number of times a document in a publication belonging to that SC was cited. The top seven subject categories are Ecology, Environmental Sciences, Agronomy, Plant Sciences, Agriculture Multidisciplinary, Soil Science, and Multidisciplinary Sciences. The first subject categories in the Social Science macro-discipline, Environmental Studies and Economics, are the 8th and 9th most-cited categories, respectively. If the WoS-assigned subject categories are reasonably accurate, this suggests that agroecology draws a substantial fraction of its supporting knowledge from the biophysical realm.

The journals cited by agroecology papers support this interpretation: In most of the top seven categories, the journals that are most frequently cited by agroecology papers are associated with biophysical subjects (see Table 1 in the Supplementary Material). There are three possible exceptions: Ecological Economics, Global Environmental Change – Human & Policy Dimensions, and Agriculture and Human Values. The first two are highly cited within the Environmental Sciences category, while the third is highly cited in Agriculture Multidisciplinary. Citations to papers in these interdisciplinary journals may refer to work from a variety of subject areas including natural science but also the social sciences and humanities. Broadly speaking, then, we can conclude that agroecology as a whole mainly draws from natural science but that social sciences are also integrated.

In Figure 14 the macro-discipline citation counts are split up by research front. This shows that most research fronts draw most heavily upon Earth, Ecosystems, & Environment, while a handful take their largest fraction of references from Social Sciences. The most heavily social science-citing fronts are Food Sovereignty, Food Systems$_{2014\text{-}2018}$, Peasant Agriculture & Industrialization$_{2014\text{-}2018}$, and Agroecology Education$_{2014\text{-}2018}$. Food Sovereignty, Food Systems$_{2014\text{-}2018}$ cites work in a wide range of Social Science categories; its top 10 most-cited SCs include Development Studies, Environmental Studies, Anthropology, Geography, Sociology, and Economics. For Peasant Agriculture & Industrialization$_{2014\text{-}2018}$, History also enters the top 10. The "hotspot" for Agroecology Education$_{2014\text{-}2018}$ in Health & Society is due to citations to the Education & Educational Research SC, but this research front also cites widely in Geography, Sociology, History & Philosophy of Science, etc.

Bio/medical Sciences contributes a substantial fraction of cited references for some research fronts, most noticeably to Plant Functional Traits – & $Weeds_{2014\text{-}2018}$ and Cropping Systems, Soil, and $Microorganisms_{2014\text{-}2018}$. Citations to this macro-discipline are usually to journals in the Plant Sciences category, although Entomology, Microbiology, and Biotechnology & Applied Microbiology also appear in the top 10 cited SCs for some research fronts. The Agriculture & Food Science macro-discipline is not frequently cited, but this is probably due to the small number of subject categories that are assigned to this group.

Discussion

Main findings

The number of agroecology papers published each year has risen dramatically in the last three decades. In time periods from 1982 through 2018, 33–43% of these publications form a network in which papers are linked when they have at least 3–5 cited references in common (Agroecology's evolving research fronts). The remaining papers must either address topics that are similar to those in the network but base their research on a more scattered set of cited articles, or deal with different issues without having established common pools of underlying knowledge. As time progresses, the fraction of agroecology papers that are included in the network rises, and the fraction of the network that consists of small, disconnected research fronts falls (Table 1). These are signs of a maturing field that increasingly recognizes a common and transdisciplinary base of knowledge (Bettencourt, Kaiser, and Kaur 2009).

Based on the titles of the papers in each research front in the network, we suggest that the topics that concern agroecology include: Ecosystem services; (agro)biodiversity; approaches to agricultural intensification; tropical agroecosystems (particularly coffee); pest and weed management; organic agriculture; cropping systems; system modeling, design, and transitions; climate change adaptation; food sovereignty; education; and the nature and purpose of agroecology itself. These topics ebb and flow over time. There can be periods of focus and common interest in understanding a particular phenomenon, as demonstrated by the existence of a large coffee-related research front between 2004–2013 that subsequently dissipated. In the following period, 2014–2018, three of the top 10 most-cited papers came instead from a large research front concerned with land sparing/sharing, organic/conventional agriculture, and approaches to intensification.

A few research fronts in the field of agroecology have been more persistent. This includes an influential line of introspective scholarship in 2005–2013, which examined the development and future direction of agroecology and set the foundation for later research on food systems and food sovereignty in 2014–2018. Pest

management has also been an active field of research from the earliest period examined here, but its topics and methods have evolved. Weeds consistently remain a subject of considerable interest. Agroecology education has also been an area of research for some years, but papers on this topic now cite enough overlapping references to be recognized as a research front in their own right.

Integrated over all agroecology papers, patterns of word use over time also suggest that the research topics and areas of emphasis of the field are evolving. These patterns imply that the field as a whole continues to be grounded in the biophysical science of sustainable agriculture, but increasingly includes social, political, and systems perspectives. The use of words related to physical systems and processes, such as "soil," "nutrient," and "organic," is widespread and has stayed stable or slightly declined. However, terms that may reflect a concern for the agency and interests of a diversity of actors in the food system, a broad food systems perspective, and questioning of the dominant regime (e.g. "participatory," "food system," "justice"), are becoming more frequently used (Changes in word use over time).

Although confined to a single time period, the analysis of cited reference subject categories in The knowledge base of agroecology confirms that in 2014 – 2018, agroecology research drew on knowledge from many different fields. While the discipline as a whole has a strong foundation in sciences such as ecology, agronomy, environmental sciences, and plant science, it also uses information from fields that include development studies, environmental studies, anthropology, geography, sociology, economics, and others. The word counts discussed above suggest that the focus on social issues has strengthened over time. However, it should also be acknowledged that these concerns have been present to some extent since the earliest period in this analysis, with articles from the 1980s and 1990s discussing subjects like indigenous knowledge, cultural changes, and various other socioeconomic aspects of agriculture (The early years: 1982 – 2004).

The extent to which references outside the natural sciences are cited, though, varies from research front to research front. Papers in research front Agroecological Practices at Multiple Scales$_{2014\text{-}2018}$ tend to cite works in largely biophysical fields: ecology, environmental science, entomology, etc. On the other hand, roughly half of the references cited by articles in Food Sovereignty, Food Systems$_{2014\text{-}2018}$ come from the Social Science area – in particular, development studies, environmental studies, and anthropology.

The nature and evolution of agroecological scholarship

The rising publication rate of agroecology papers is consistent with models of scientific development that predict a phase of rapid growth as a field starts to experience social and intellectual cohesion (Mulkay, Gilbert, and Woolgar 1975). In addition, the growing recognition of agroecology by policy-

oriented actors such as the Food and Agriculture Organization of the United Nations (Bruil et al. 2019) may suggest that credibility is increasingly being accorded to agroecology as a scientific field, helping to attract researchers who see it as a promising area of study – while others react to the possibility of agroecology being co-opted by powerful actors (Giraldo and Rosset 2018). At the same time, the growing interest from, and work done by, the scientific community may itself help to increase the legitimacy that agroecology is perceived to possess (Montenegro de Wit and Iles 2016).

As well as illustrating the growth of the field, this work also illuminates the scope of agroecological research, showing that it draws on the diverse sources of knowledge that are required to respond to complex social-ecological challenges that move beyond the farm level and cross disciplinary boundaries. In this sense, agroecological research is bridging some of the historical gaps between agricultural sciences and ecology, and agricultural and social sciences, described by Tomich et al. (2011). The use of terms like "justice" and "sovereignty" also highlights a vein of politically engaged scholarship that appears to be growing in prominence. However, certain sub-fields are more likely than others to refer to work outside the biophysical sciences, consistent with previous suggestions that different agroecological perspectives continue to coexist (Méndez, Bacon, and Cohen 2013), and that some agroecologists consider politics and practice to lie outside the realm of their research (Montenegro de Wit and Iles 2016).

In their bibliographic analysis of agroecological research, Wezel and Soldat (2009) identified broad applications and multiple meanings that they proposed would facilitate the field's ability to respond to important real-world questions about agriculture, land use, climate change, and food security. Changes in the research fronts within agroecology suggest that the field does indeed co-evolve, at least to some degree, with the complex and shifting problems faced by agriculture and society. The boom in coffee-related agroecology research in 2005–2013 likely reflects, in part, the response of agroecology to one of the pressing social-ecological challenges of that time: the coffee price crises of the early 2000s, and the poverty and livelihood issues that resulted. Similarly, the recent focus on land sparing/sharing, organic/conventional agriculture, and approaches to intensification may indicate agroecology's engagement with current debates around land use among NGOs, academics, policy actors, and others (e.g. Phalan et al. 2011; Wilson 2016).

In 2003, leaders in agroecology education and research in the US made the case for incorporating wider social and economic aspects of sustainable food systems into agroecological scholarship, stating that "we find it impossible to deal effectively with the complexity of resource use and design of future systems if we only focus on the production aspects, short-term economics, and environmental impacts in the immediate vicinity of farm fields" (Francis et al. 2003). In 2020, the analysis in this paper indicates that the call is at least

partially being answered. Moreover, we find that agroecological scholarship has remained self-reflective – questioning and defining what agroecology is, and what it is becoming.

Reflections on this analysis

We wish to acknowledge and draw attention to some limitations and subjective elements of the analysis presented in this paper. While quantitative analyses may be transparent, systematic, and reproducible, they all rely on the authors' judgment at some point(s) in the process, and are subject to limitations in the quality and quantity of data, methodology, tools, etc. that are used. Here we specify the main ways in which this work is affected by those phenomena.

First, coverage of the social sciences and (especially) the humanities in WoS, while growing, is less complete than that of the natural sciences (see the Supplementary Material). If agroecology is widely discussed in journals, conference proceedings, and books that are not indexed by WoS, this analysis is blind to that discussion. The fact that only 61% of the references cited by papers in 2014–2018 were associated with WoS-assigned subject categories (Cited reference subject categories) is likely also a consequence of this issue. Little is known about potential biases in the 39% of cited references without subject category information – whether a given RF heavily cites a humanities field with poor WoS coverage, say, or "gray literature" that is not indexed in WoS – and this may limit the accuracy of the analysis in The knowledge base of agroecology.

Second, the terms included in Changes in word use over time were chosen based on our own knowledge of the debate around the direction of agroecological research, and consist of words and phrases that we believed would effectively test the direction of the field. (In addition, the dominance of English-language articles in our data set may have led to the omission of important trends occurring outside the English-speaking world.) Similarly, the naming of the research fronts (Bibliographic coupling analysis) may well reflect some of our own biases and preconceptions. The interpretations advanced in Bibliographic coupling analysis rely heavily on our judgment as researchers in agroecology.

Finally, some subjective decisions had to be made while employing the methods in Agroecology's evolving research fronts. To reduce noise, a lower limit was imposed on the number of common references required for inclusion in the network, a process which Zupic and Čater (2015) describe as "definitely more art than science". The network community detection method requires the user to set a parameter related to the size of the clusters in the data. Because of this type of user intervention, Skupin (2004) suggests that the purpose of this kind of algorithm "is not to discover optimal feature space

partitions," but rather to serve "as a stepping stone in the support of visual exploration toward domain comprehension." Choosing a network visualization algorithm and setting its parameters also involves user judgment.

In the spirit of Skupin (2004), then, we have presented what we judge to be a useful and informative discussion of the evolution of agroecological research. At the same time, the approach used here complements existing research by offering detailed insights into the structure of the field and how it has changed over time. These methods build on previous work based largely on expert opinion (Buttel 2003; Méndez, Bacon, and Cohen 2013) by offering transparent and, in principle, reproducible results. This work also extends the data used in earlier, quantitative studies (Dalgaard, Hutchings, and Porter 2003; Wezel and Soldat 2009) to a much larger number of papers. The science mapping techniques used in this paper give a visual overview of the field, along the lines of "macroscopes" that allow us to "observe what is at once too great, too slow, and too complex for our eyes" (Börner 2010; De Rosnay 1979).

Conclusions

To map the changing structure and research areas of agroecological research, we have applied network science and bibliometric methods to more than 3000 agroecology papers and the ~160,000 references they cite. We find that a formerly fragmented field is maturing into a more coherent discipline that increasingly draws from a shared body of knowledge. Some research topics within the field (e.g. weed and pest management) have persisted over time, others (such as coffee agroecosystems) may be dissipating after having generated considerable research interest around a decade ago, and new areas (such as agroecology education) are in the process of coalescing. Inspecting the subject categories of the references cited by recent agroecology papers shows that some of these sub-fields draw mainly on biophysical knowledge, while others refer also to work in the social sciences. The frequency of certain terms related to social concerns is also rising in agroecology papers as a whole.

In broad terms, our analysis of these documents indicates that agroecological science as a whole has many of the characteristics that would be expected from a field focused on the "ecology of food systems": a broad scope with an increasing eye toward social and political issues that influence agriculture, a knowledge base that includes work from many different disciplines, and current streams of research that address matters from biodiversity to food sovereignty. Reviews from the past two decades make the case for increasingly incorporating human, political, and economic aspects of research into agroecology to address the complex social-ecological reality of problems in the food system. Our paper documents that this trend is occurring.

The next question, then, is the extent to which these research areas are integrated into a discipline-spanning whole in which a range of natural

science fields interact with each other and with a "reflexive perspective that … [is] clear about the normative values, politics, and possibilities for transformative change that are at play in today's agro-food systems" (Méndez, Bacon, and Cohen 2013, p7; see also Anderson et al. 2019; González de Molina et al. 2019). Such a field would include collaborations in which members bring knowledge from their specialties yet operate and engage with others outside them, gaining a holistic view of problems that encompasses levels from the molecular to the societal (Gehlert et al. 2010). Future network analyses that link connections based on co-authorship with research topics and supporting knowledge could help to further illuminate how far along this path agroecology has progressed.

Acknowledgments

REM would like to acknowledge J. Görres for thought-provoking comments on an early version of this manuscript, and also appreciates support from the UVM College of Agriculture and Life Sciences. The authors are grateful to the anonymous reviewer for constructive comments that significantly improved the presentation of the results in this paper.

Declaration of interests

The authors have no competing interests.

Notes

1. The University of Vermont's WoS subscription supplies records dating to 1982; other institutions may have different arrangements.
2. See the Supplementary Material for corroboration of this result in a wider and less academic-focused data set.
3. As in 2005–2013, most citations from research fronts in 2014–2018 are to papers outside the Agroecology data set.

ORCID

Rachel E. Mason http://orcid.org/0000-0003-4805-0990

References

Addinsall, C., Glencross, K. Scherrer, P. Weiler. B. and Nichols, D. 2015. Agroecology and sustainable rural livelihoods: A conceptual framework to guide development projects in the Pacific Islands. *Agroecology and Sustainable Food Systems* 39:691–723. doi:10.1080/21683565.2015.1017785.

Agarwal, B. 2014. Food sovereignty food security and democratic choice: Critical contradictions, difficult conciliations. *The Journal of Peasant Studies* 41:1247–68. doi:10.1080/03066150.2013.876996.

Altieri, M. 1989. Agroecology: A new research and development paradigm for world agriculture. *Agriculture, Ecosystems & Environment* 27:37–46. doi:10.1016/0167-8809(89)90070-4.

Altieri, M. 1992. Agroecological foundations of alternative agriculture in California. *Agriculture, Ecosystems & Environment* 39:23–53. doi:10.1016/0167-8809(92)90203-N.

Altieri, M. A. 1987. *Agroecology: The scientific basis of alternative agriculture*. Boulder, Colorado: Westview Press.

Altieri, M. A. 1993. Ethnoscience and biodiversity: Key elements in the design of sustainable pest management systems for small farmers in developing countries. *Agriculture, Ecosystems & Environment* 46:257–72. doi:10.1016/0167-8809(93)90029-O.

Altieri, M. A. 1999. The ecological role of biodiversity in agroecosystems. *Agriculture, Ecosystems & Environment* 74 (1–3):19–31. doi:10.1016/S0167-8809(99)00028-6.

Altieri, M. A. 2002. Agroecology: The science of natural resource management for poor farmers in marginal environments. *Agriculture, Ecosystems & Environment* 93:1–24. doi:10.1016/S0167-8809(02)00085-3.

Altieri, M. A. 2004. Linking ecologists and traditional farmers in the search for sustainable agriculture. *Frontiers in Ecology and the Environment* 2 (1):35–42.

Altieri, M. A., and Toledo, V. M. 2011. The agroecological revolution in Latin America: Rescuing nature, ensuring food sovereignty and empowering peasants. *Journal of Peasant Studies* 38 (3):587–612. doi:10.1080/03066150.2011.582947.

Amekawa, Y. 2011. Agroecology and sustainable livelihoods: Towards an integrated approach to rural development. *Journal of Sustainable Agriculture* 35:118–62.

Anderson, C. R., Bruil, J. Chappell, M. J. Kiss, C. and Pimbert, M. P. 2019. Moving from transition to domains of transformation: Getting to sustainable and just food systems through agroecology. *Sustainability* 11:5272. doi:10.3390/su11195272.

Anderzén, J., Luna, A. G., Luna-González, D. V., Merrill, S. C., Caswell, M., Méndez, V. E., & Jonapá, R. H. 2020. Effects of on-farm diversification strategies on smallholder coffee farmer food security and income sufficiency in Chiapas, Mexico. *Journal of Rural Studies*, 77: 33–46.

Andrews, K. L., Bentley, J. W. and Cave, R. D. 1992. Enhancing biological controls contributions to integrated pest management through appropriate levels of farmer participation. *The Florida Entomologist* 75:429. doi:10.2307/3496124.

Bacon, C. M., Sundstrom, W. A. Flores Gómez, M. E. Ernesto Méndez, V. Santos, R. Goldoftas, B. and Dougherty, I. 2014. Explaining the "hungry farmer paradox": Smallholders and fair trade cooperatives navigate seasonality and change in Nicaragua's corn and coffee markets. *Global Environmental Change* 25 (1):133–49. doi:10.1016/j.gloenvcha.2014.02.005.

Bernstein, H. 2014. Food sovereignty via the 'peasant way': A sceptical view. *Journal of Peasant Studies* 41 (6):1031–63. doi:10.1080/03066150.2013.852082.

Bettencourt, L. M. A., Kaiser, D. I. and Kaur, J. 2009. Scientific discovery and topological transitions in collaboration networks. *Journal of Informetrics* 3 (3):210–21. doi:10.1016/j.joi.2009.03.001.

Bezner Kerr, R., Hickey, C. Lupafya, E. and Dakishoni, L. 2019. Repairing rifts or reproducing inequalities? Agroecology food sovereignty, and gender justice in Malawi. *The Journal of Peasant Studies* 46:1499–518. doi:10.1080/03066150.2018.1547897.

Blondel, V. D., Guillaume, J. L. Lambiotte, R. and Lefebvre, E. 2008. Fast unfolding of communities in large networks. *Journal of Statistical Mechanics: Theory and Experiment* 10:10008. doi:10.1088/1742-5468/2008/10/P10008.

Börner, K. 2010. *Atlas of science: Visualizing what we know*. Cambridge, MA: The MIT Press.

Bornmann, L., and Daniel, H. D. 2008. What do citation counts measure? A review of studies on citing behavior. *Journal of Documentation* 64:45–80. doi:10.1108/00220410810844150.

Boyack, K. W., and Klavans, R. 2010. Co-citation analysis, bibliographic coupling, and direct citation:Which citation approach represents the research front most accurately? *Journal of the American Society for Information Science and Technology* 61 (12):2389–404. doi:10.1002/asi.

Boykoff, M. T., and Boykoff, J. M. 2007. Climate change and journalistic norms: A case-study of US mass-media coverage. *Geoforum* 38:1190–204. doi:10.1016/j.geoforum.2007.01.008.

Bruil, J., Anderson, B. Bernhart, A. and Pimbert, M. 2019. Strengthening FAO's commitment to agroecology. http://www.agroecologynow.com/wp-content/uploads/2019/02/coventry-fao-agroecology-Feb7.pdf.

Burger, M., and Jackson,L. E. 2003. Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. *Soil Biology & Biochemistry* 35 (1):29–36. doi:10.1016/S0038-0717(02)00233-X.

Buttel, F. H. 2003. Envisioning the future development of farming in the USA: Agroecology between extinction and multifunctionality? In *New directions in agroecology research and education*, 1–14.

Carvalheiro, L. G., Seymour, C. Veldtman, R. and Nicolson, S. W. 2010. Pollination services decline with distance from natural habitat even in biodiversity-rich areas. *Journal of Applied Ecology* 47:810–20. doi:10.1111/j.1365-2664.2010.01829.x.

Cassman, K. G. 1999. Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences* 96:5952–59. doi:10.1073/pnas.96.11.5952.

Conway, G. R. 1985. Agroecosystem analysis. *Agricultural Administration* 20:31–55. doi:10.1016/0309-586X(85)90064-0.

Coolsaet, B. 2016. Towards an agroecology of knowledges: Recognition, cognitive justice and farmers' autonomy in France. *Journal of Rural Studies* 47 (165–171):165–71. doi:10.1016/j.jrurstud.2016.07.012.

Crane, D. 1972. Invisible colleges; diffusion of knowledge in scientific communities. Chicago, IL: University of Chicago Press.

Dalgaard, T., Hutchings, N. J. and Porter, J. R. 2003. Agroecology, scaling and interdisciplinarity. *Agriculture, Ecosystems & Environment* 100 (1–3):39–51. doi:10.1016/S0167-8809(03)00152-X.

Dalsgaard, J. P. T., Lightfoot, C. and Christensen,V. 1995. Towards quantification of ecological sustainability in farming systems analysis. *Ecological Engineering* 4:181–89. doi:10.1016/0925-8574(94)00057-C.

Dalsgaard, J. P. T., and Oficial, R. T. 1997. A quantitative approach for assessing the productive performance and ecological contributions of smallholder farms. *Agricultural Systems* 55:503–33. doi:10.1016/S0308-521X(97)00022-X.

De Rosnay, J. 1979. *The macroscope: A new world scientific system*. New York, NY: Harper Row.

de Solla Price, D. J. 1965. Networks of scientific papers. *Science* 149 (3683):510–15. doi:10.1126/science.149.3683.510.

Delate, K. 2002. Using an agroecological approach to farming systems research. *HortTechnology* 12 (3):345–54. doi:10.21273/HORTTECH.12.3.345.

DeLonge, M. S., Miles, A. and Carlisle, L. 2016. Investing in the transition to sustainable agriculture. *Environmental Science & Policy* 55:266–73. doi:10.1016/j.envsci.2015.09.013.

Deressa, T. T., Hassan, R. M. Ringler, C. Alemu, T. and Yesuf, M. 2009. Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. *Global Environmental Change* 19:284–255. doi:10.1016/j.gloenvcha.2009.01.002.

Drinkwater, L., Friedman, D. and Buck, L. 2016. Systems research for agriculture. Sustainable agriculture research and education program.

Duru, M. 2013. Combining agroecology and management science to design field tools under high agrosystem structural or process uncertainty: Lessons from two case studies of grassland management. *Agricultural Systems* 114:84–94. doi:10.1016/j.agsy.2012.09.002.

Duru, M., Cruz, P. Jouany, C. and Theau, J. P. 2011. Combining agroecological research and participatory approach to build tools for evaluating permanent grasslands. *Cahiers Agricultures* 20 (3):223–34. doi:10.1684/agr.2011.0486

Ernesto, M. V., Gliessman, S. and Gilbert, G. S. 2007. Tree biodiversity in farmer cooperatives of a shade coffee landscape in western El Salvador. *Agriculture, Ecosystems & Environment* 119:145–59.

Fernandez, M., Goodall, K. Olson, M. and Méndez, V. E. 2013. Agroecology and alternative agri-food movements in the United States: Toward a sustainable agri-food system. *Agroecology and Sustainable Food Systems* 37 (1):115–26. doi:10.1080/10440046.2012.735633.

Fischer, J., Abson, D. J. Butsic, V. Chappell, M. J. Ekroos, J. Hanspach, J. . . . von Wehrden, H. 2014. Land sparing versus land sharing: Moving forward. *Conservation Letters* 7 (3):149–57. doi:10.1111/conl.12084.

Francis, C., Breland, T. A. Østergaard, E. Lieblein, G. and Morse, S. 2013. Phenomenon-based learning in agroecology: A prerequisite for transdisciplinarity and responsible action. *Journal of Sustainable Agriculture* 37 (1):60–75.

Francis, C. A., Lieblein, G. Gliessman, S. R. Breland, T. A. Creamer, N. Harwood, R. R. . . . Poincelot, R. 2003. Agroecology: The ecology of food systems. *Journal of Sustainable Agriculture* 22 (3):99–118. doi:10.1300/J064v22n03.

Francis, C. A., Jordan, N. Porter, P. Breland, T. A. Lieblein, G. Salomonsson, L. . . . Langer, V. 2011. Innovative education in agroecology: Experiential learning for a sustainable agriculture. *Critical Reviews in Plant Sciences* 30:226–37.

Gabriel, D., Sait, S. M. Kunin, W. E. and Benton, T. G. 2013. Food production vs. biodiversity: Comparing organic and conventional agriculture. *Journal of Applied Ecology* 50:355–64.

Gallardo-López, F., Alejandro Hernández-Chontal, M. Linares-Gabriel, A. and Cisneros-Saguilán, P. 2019. Scientific contributions of agroecology in Latin America and the Caribbean: A review. *Revista de La Facultad de Ciencias Agrarias* 51 (1):1853–8665.

Gehlert, S., Murray, A. Sohmer, D. McClintock, M. Conzen, S. and Olopade, O. 2010. The importance of transdisciplinary collaborations for understanding and resolving health disparities. *Social Work in Public Health* 25 (3):408–22. doi:10.1080/19371910903241124.

Gianinazzi, S., GollotteA. Binet, M. N. van Tuinen, D. Redecker, D. and Wipf, D. 2010. Agroecology: The key role of arbuscular mycorrhizas in ecosystem services. *Mycorrhiza* 20 (8):519–30. doi:10.1007/s00572-010-0333-3.

Giraldo, O. F., and Rosset, P. M. 2018. Agroecology as a territory in dispute: Between institutionality and social movements. *Journal of Peasant Studies* 45 (3):545–64. doi:10.1080/03066150.2017.1353496.

Gliessman, S. 2014. *Agroecology: The ecology of sustainable food systems*. Boca Raton, FL: CRC Press/Taylor and Francis Group.

Gliessman, S. R. 2000. *Agroecology: Ecological processes in sustainable agriculture*. E. Engles, Ed. Boca Raton, FL: CRC Press LLC.

Gliessman, S. R., Garcia, R. E. and Amador, M. A. 1981. The ecological basis for the application of traditional agricultural technology in the management of tropical agro-ecosystems. *Agro-Ecosystems* 7 (3):173–85. doi:10.1016/0304-3746(81)90001-9.

Gomiero, T., Pimentel, D. and Paoletti, M. G. 2011. Is there a need for a more sustainable agriculture? *Critical Reviews in Plant Sciences* 30 (1–2):7–19. doi:10.1080/07352689.2011.553147.

Gonzalez de Molina, M. 2013. Agroecology and politics. How to get sustainability? About the necessity for a political agroecology. *Agroecology and Sustainable Food Systems* 37 (1):45–59. doi:10.1080/10440046.2012.705810.

Gonzalez de Molina, M. 2016. Political Agroecology: An essential tool to promote agrarian sustainability. In *Agroecology: A transdisciplinary, participatory and action-oriented approach*, ed. V. E. Mendez, 55–72. Boca Raton, FL: CRC Press/Taylor and Francis.

González de Molina, M., Petersen, P. F. Garrido Peña, F. and Caporal, F. R. 2019. *Political agroecology: Advancing the transition to sustainable food systems*. Boca Raton, FL: CRC Press/Taylor and Francis Group.

Hawkesworth, S., and García Pérez, J. D. 2003. Potentials and constraints of the farmer-to-farmer programme for environmental protection in Nicaragua. *Land Degradation & Development* 14:175–88.

Holt-Giménez, E. 2002. Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: A case study in participatory sustainable land management impact monitoring. *Agriculture, Ecosystems & Environment* 93:87–105.

Holt-Giménez, E., and Altieri, M. A. 2013. Agroecology, food sovereignty, and the new green revolution. *Agroecology and Sustainable Food Systems* 37 (1):90–102. doi:10.1080/10440046.2012.716388.

Holt-Giménez, E. H., and Shattuck A. 2011. Food crises, food regimes and food movements: Rumblings of reform or tides of transformation? *Journal of Peasant Studies* 38 (1):109–44. doi:10.1080/03066150.2010.538578.

Jarneving, B. 2005. A comparison of two bibliometric methods for mapping of the research front. *Scientometrics* 65 (2):245–63. doi:10.1007/s11192-005-0270-7.

Kessler, M. M. 1963. Bibliographic coupling between scientific papers. *American Documentation* 14 (1):10–25.

Kremen, C., and Miles, A. 2012. Ecosystem services in biologically diversified versus conventional farming systems: Benefits, externalitites, and trade-offs. *Ecology and Society* 17 (4):1–23. doi:10.5751/ES-05035-170440.

Lee, R. P. 2013. The politics of international agri-food policy: Discourses of trade-oriented food security and food sovereignty. *Environmental Politics* 22:216–34.

Levidow, L., M. Pimbert, and G. Vanloqueren. 2014. Agroecological research: Conforming—or transforming the dominant agro-food regime? *Agroecology and Sustainable Food Systems* 38 (10):1127–55. doi:10.1080/21683565.2014.951459.

Lotter, D. W. 2003. Organic agriculture. *Journal of Sustainable Agriculture* 21:59–128.

Lovell, S. T., DeSantis, S. Nathan, C. A. Olson, M. B. Ernesto Méndez, V. Kominami, H. C. … Morris, W. B. 2010. Integrating agroecology and landscape multifunctionality in Vermont: An evolving framework to evaluate the design of agroecosystems. *Agricultural Systems* 103 (5):327–41. doi:10.1016/j.agsy.2010.03.003.

Macdonald, K. I. 1998. Rationality, representation, and the risk mediating characteristics of a Karakoram mountain farming system. *Human Ecology* 26:287–321.

Martin, A. R., and Isaac, M. E. 2018. Functional traits in agroecology: Advancing description and prediction in agroecosystems. *Journal of Applied Ecology* 55:5–11.

Mas, A. H., and Dietsch, T. V. 2003. An index of management intensity for coffee agroecosystems to evaluate butterfly species richness. *Ecological Applications* 13:1491–501.

Méndez, V. E., Bacon, C. M. Olson, M. Morris, K. and Shattuck, A. 2010. Agrobiodiversity and shade coffee smallholder livelihoods: A review and synthesis of ten years of research in Central America. The Professional Geographer 62:357–76

Méndez, V. E., Bacon, C. M. and Cohen, R. 2013. Agroecology as a transdisciplinary, participatory, and action-oriented approach. *Agroecology and Sustainable Food Systems* 37 (1):3–18. doi:10.1080/10440046.2012.736926

Méndez, V. M., Caswell, M. Gliessman, S. and Cohen. R. 2017. Integrating agroecology and Participatory Action Research (PAR): Lessons from Central America. Sustainability 9:705

Méndez, V. E., R. Lok, and Somarriba, E. 2001. Interdisciplinary analysis of homegardens in Nicaragua: Micro-zonation, plant use and socioeconomic importance. *Agroforestry Systems* 51:85–96.

Mercer, K. L., Perales, H. R. and Wainwright,J. D. 2012. Climate change and the transgenic adaptation strategy: Smallholder livelihoods climate justice, and maize landraces in Mexico. *Global Environmental Change* 22:495–504.

Meyfroidt, P., and Lambin, E. F. 2008. The causes of the reforestation in Vietnam. *Land Use Policy* 25:182–97.

Mier Y Terán Giménez Cacho, M., Giraldo, O. F. Aldasoro, M. Morales,H. Ferguson, B. G. Rosset,P. … Campos, C. 2018. Bringing agroecology to scale: Key drivers and emblematic cases. *Agroecology and Sustainable Food Systems* 42 (6):637–65. doi:10.1080/21683565.2018.1443313.

Montenegro de Wit, M., and Iles, A. 2016. Toward thick legitimacy: Creating a web of legitimacy for agroecology. *Elementa: Science of the Anthropocene* 4 (1):000115. doi:10.12952/journal.elementa.000115.

Morelli, F. 2013. Relative importance of marginal vegetation (shrubs hedgerows, isolated trees) surrogate of HNV farmland for bird species distribution in Central Italy. *Ecological Engineering* 57:261–66.

Mulkay, M. J., Gilbert, G. N. and Woolgar, S. 1975. Problem areas and research networks in science. *Sociology* 9 (2):187–203.

Nuberg, I. K., Evans, D. G. and Senanayake, R. 1994. Future of forest gardens in the Uvan uplands of Sri Lanka. *Environmental Management* 18:797–814.

Perfecto, I., and Vandermeer, J. 2002. Quality of agroecological matrix in a tropical Montane landscape: Ants in coffee plantations in Southern Mexico. *Conservation Biology* 16 (1):174–82.

Perfecto, I., and Vandermeer, J. 2008. Biodiversity conservation in tropical agroecosystems. *Annals of the New York Academy of Sciences* 1134:173–200.

Phalan, B., Onial, M. A. Balmford, and Green, R. E. 2011. Reconciling food production and biodiversity conservation: Land sharing and land sparing compared. *Science* 333 (6047):1289–91. doi:10.1126/science.1208742.

Ponisio, L. C., Gonigle, L. K. M. Mace, K. C. Palomino,J. P. De Valpine, and Kremen, C. 2015. Diversification practices reduce organic to conventional yield gap.

Porter, A. L., and Rafols, I. 2009. Is science becoming more interdisciplinary? Measuring and mapping six research fields over time. *Scientometrics* 81 (3):719–45. doi:10.1007/s11192-008-2197-2.

Porter, A. L., and Youtie, J. 2009. How interdisciplinary is nanotechnology? *Journal of Nanoparticle Research* 11 (5):1023–41. doi:10.1007/s11051-009-9607-0.

Pretty, J. 2008. Agricultural sustainability: Concepts, principles and evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences* 363 (1491):447–65. doi:10.1098/rstb.2007.2163.

Pretty, J., Toulmin, C. and Williams, S. 2011. Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability* 9:5–24.

Ranganathan, J., Chan, K. M. A. and Daily, G. C. 2007. Satellite detection of bird communities in tropical countryside. *Ecological Applications* 17:1499–510.

Ratnadass, A., Fernandes, P. Avelino, J. and Habib, R. 2012. Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: A review. *Agronomy for Sustainable Development* 32. doi:10.1007/s13593-011-0022-4.

Rosegrant, M. W., and Cline, S. A. 2003. Global food security: Challenges and policies. *Science* 302 (5652):1917=1919.

Rosset, P. M., and Altieri, M. A. 1997. Agroecology versus input substitution: A fundamental contradiction of sustainable agriculture. *Society & Natural Resources* 10 (3):283–95. doi:10.1080/08941929709381027.

Rosset, P. M., and Altieri, M. A. 2017. *Agroecology: Science and politics*. Rugby, UK: Practical Action Publishing.

Rosset, P. M., and Martínez-Torres, M. E. 2012. Rural social movements and agroecology: Context, theory, and process. *Ecology and Society* 17:3.

Schattman, R., Mendez, E. Westdijk, K. Caswell, M. Conner, D. Koliba, C. … Darby, H. 2015. Vermont agricultural resilience in a changing climate: A transdisciplinary and Participatory Action Research (PAR) process. In *Agroecology, ecosystems, and sustainability*, ed. N. Benkeblia, 325–46. Boca Raton, FL: CRC Press/Taylor & Francis.

Sevilla Guzmán, E., and Woodgate, G. 2013. Agroecology: Foundations in agrarian social thought and sociological theory. *Agroecology and Sustainable Food Systems* 37 (1):32–44. doi:10.1080/10440046.2012.695763.

Sherwood, S., and Uphoff, N. 2000. Soil health: Research practice and policy for a more regenerative agriculture. *Applied Soil Ecology* 15:85–97.

Skupin, A. 2004. The world of geography: Visualizing a knowledge domain with cartographic means. *Proceedings of the National Academy of Sciences* 101 (Supplement 1):5274–78. doi:10.1073/pnas.0307654100.

Stanley, D. A., Gunning, D. and Stout, J. C. 2013. Pollinators and pollination of oilseed rape crops (Brassica napus L.) in Ireland: Ecological and economic incentives for pollinator conservation. *Journal of Insect Conservation* 17:1181–89.

Steinberg, M. K. 1998. Political ecology and cultural change: Impacts on swidden-fallow agroforestry practices among the Mopan Maya in Southern Belize. *The Professional Geographer* 50:407–17.

Thompson, J., and Scoones, I. 2009. Addressing the dynamics of agri-food systems: An emerging agenda for social science research. *Environmental Science & Policy* 12:386–97.

Timmermann, C., and Félix, G. F. 2015. Agroecology as a vehicle for contributive justice. *Agriculture and Human Values* 32 (3):523–38. doi:10.1007/s10460-014-9581-8.

Tittonell, P. 2014. Livelihood strategies, resilience and transformability in African agroecosystems. *Agricultural SYstems* 126:3–14. doi:10.1016/j.agsy.2013.10.010.

Tomich, T. P., Brodt, S. Ferris, H. Galt, R. Horwath, W. R. Kebreab, E. … Yan, L. 2011. Agroecology: A review from a global-change perspective. *Ssrn*. doi:10.1146/annurev-environ-012110-121302.

Tscharntke, T., Clough, Y. Wanger, T. C. Jackson, L. Motzke, I. Perfecto, I. … Whitbread, A. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation* 151 (1):53–59. doi:10.1016/j.biocon.2012.01.068.

Vanloqueren, G., and Baret, P. V. 2009. How agricultural research systems shape a technological regime that develops genetic engineering but locks out agroecological innovations. *Research Policy* 38 (6):971–83. doi:10.1016/j.respol.2009.02.008.

Viscarra Rossel, R. A., Behrens, T. Ben-Dor, E. Brown, D. J. Demattê, J. A. M. Shepherd, K. D. … Ji, W. 2016. A global spectral library to characterize the world's soil. *Earth-Science Reviews* 155 (February):198–230. doi:10.1016/j.earscirev.2016.01.012.

Waldenström, C., Salomonsson, L. Francis, C. Moulton, M. and Leiblein, G. 2008. Individualized student-centred education: Prototype for an agroecology BSc programme. *International Journal of Agricultural Sustainability* 6:236–47.

Wallace, M. L., Gingras, Y. and Duhon, R. 2009. A new approach for detecting scientific specialties from raw cocitation networks. *Journal of the American Society for Information Science and Technology* 60 (2):240–46. doi:10.1002/asi.

Weinberg, B. H. 1974. Bibliographic coupling: A review. *Information Storage and Retrieval* 10:198–196.

Wezel, A., Casagrande, M. Celette, F. Vian, J. F. Ferrer, A. and Peigné, J. 2014. Agroecological practices for sustainable agriculture. A review. *Agronomy for Sustainable Development* 34 (1):1–20. doi:10.1007/s13593-013-0180-7.

Wezel, A., Bellon, S. Doré, T. Francis, C. Vallod, D. and David, C. 2009. Agroecology as a science, a movement and a practice. *Sustainable Agriculture* 2:27–43. doi:10.1007/978-94-007-0394-0_3.

Wezel, A., and Soldat, V. 2009. A quantitative and qualitative historical analysis of the scientific discipline of agroecology. *International Journal of Agricultural Sustainability* 7 (1):3–18. doi:10.3763/ijas.2009.0400.

Wilson, E. O. 2016. *Half Earth: Our planet's fight for life*. London, UK: WW Norton & Company.

Worster, D. 1990. Transformations of the Earth: Toward an agroecological perspective in history. *The Journal of American History* 76:1087.

Zimmerer, K. S. 1994. Human geography and the new ecology: The prospect and promise of integration. *Annals of the Association of American Geographers* 84:108–25.

Zupic, I., and Čater, T. 2015. Bibliometric methods in management and organization. *Organizational Research Methods* 18 (3):429–72. doi:10.1177/1094428114562629.