Title
Conceptualizing Agricultural Sustainability: Valuing Ecosystem Services in the Assessment of Cover Crops

Author
Crézé, Cynthia Marie

Publication Date
2021

Peer reviewed|Thesis/dissertation

Conceptualizing Agricultural Sustainability:
Valuing Ecosystem Services in the Assessment of Cover Crops

By

CYNTHIA MARIE CRÉZÉ
DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Soils and Biogeochemistry

in the

OFFICE OF GRADUATE STUDIES

of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

____

Dr. William R. Horwath, Chair

____

Dr. Kate M. Scow

____

Dr. Bruce D. Lampinen

Committee in Charge

2021

ABSTRACT

The conceptualization of agricultural sustainability has become increasingly complex. Sustainable food production must account for multiple societal imperatives, including meeting the nutritional needs of a growing population, adapting to climate change and mitigating its effects as well as preserving biodiversity in support of natural ecosystems. Ecosystem services refer to the multiple benefits, which humanity obtain from ecosystems. To address challenges facing agriculture, sustainable practices have been developed through scientific research. My dissertation explores the case of cover cropping for perennial systems, as one such science-based practice developed to support agricultural sustainability. Cover crops are plant species that are seeded in addition to the main food crop in agro-ecosystems. Prior literature demonstrates that cover crops can improve nutrient cycling and other soil properties, and can also bring other services, such as refuge for beneficial insects and the suppression of weed species. Despite considerable scientific evidence, there remains low adoption of cover crops in global agriculture. I believe that major gaps between the establishment of scientific evidence and the actual uptake of sustainable practices hinders progress. In the case of cover crops, this lag may in part be due to remaining data gaps hampering the successful establishment and use of the practice. However, I suggest that lack of adoption is due less to large gaps in knowledge, and more a result of conflicting ecosystem service valuation systems among stakeholders. In Chapter 1, I present the results of a farmers' survey specific to almond production in California. The purpose of this survey was to better understand the factors that affect the decision to use cover crops for almond farmers. Results indicate that while most farmers recognize the many ecosystem services of the practice, concerns over water use and economic costs of the practice can dissuade farmers from adopting the practice. However, the perception of cover crop outcomes was not uniform among farmers. Our results reveal distinct systems of ecosystem service valuation, determined by farm size and regions of California (Sacramento Valley, North San Joaquin Valley and South San Joaquin Valley). In Chapter 2, I conducted a systematic review of cover crop literature to explore scientific rationales for cover cropping. Our analysis of researchers' knowledge pathways indicates two distinct systems in the valuation of cover crop services: a biological management approach, which considers ecological conservation as inherently valuable, irrespective of immediate profitability, and a nutrient management approach, which prioritizes resource conservation for sustainable crop production. Our results highlight different conceptualizations of agricultural sustainability within literature. Chapter 3 explores how cover crop ecosystem service frameworks vary across commodity types. Our analysis reveals different systems of ecosystem service valuation specific to commodity types and their diverse approaches to agricultural sustainability. Certain commodities (i.e., olive and vineyard systems) focused on cover crop outcomes specific to water use services whereas others prioritized biological control services. These findings emphasize the need to reflect stakeholder priorities in the design of ecosystem service frameworks, to inform their decision to cover crop. This work supports the development of data-based decision-making systems, which reflect diverse approaches to agricultural sustainability.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I dedicate this journey to my mother and my grandmother. You have shown me the true meaning of hope and resilience.

Thank you to my mentor, Dr. William Horwath. I have learned so much in your lab. I also want to thank my peers of the Department of Land, Air and Water Resources. I appreciate your help and support throughout this journey.

Thank you to my Qualifying Exam committee, Dr. Kate Scow, Dr. Anthony O'Geen, Dr. Bruce Lampinen, Dr. William Horwath and Dr. Jeffrey Mitchell. Thank you for the insightful conversations, perspectives, and expert advice. I really appreciate your guidance.

Thank you to Dr. Chandra Madramootoo, Professor at McGill University, Montreal, Canada. Thank you for your mentorship during my Master's program in bioresource engineering and thank you for encouraging me to pursue a Ph.D. degree. I greatly appreciate your continued mentorship, your guidance and invaluable advice throughout my academic journey.

I wish to extend my special thanks to Shila Ruiz. I am so glad that I had your support and managerial know-how at many important moments of my Ph.D. journey.

I am grateful to the funding sources, which have made my research projects possible: the Donald Crosby Graduate Fellowship (2020-2021), the Henry A. Jastro Graduate Award (2019-2020), the John Muir Institute of the Environment Graduate Fellowship (2019-2020), Annie's Sustainable Agriculture Scholarship (2018-2020), the UC Davis Plant Sciences Departmental Graduate Student Research Award (2017-2021), and the UC Davis Soils & Biogeochemistry Graduate Group Fellowship (2016). The material in this dissertation is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, through the Western Sustainable Agriculture Research and Education program under project number [GW18-142]. Any opinions, findings, conclusions, or recommendations expressed in this document are those of the author and do not necessarily reflect the view of the U.S. Department of Agriculture.

I thank the people of Davis, who welcomed me to California. Davis is a very special place, and holds a beautiful community of people, who are generous and kind. I especially want to thank Miguel and Marisol for the home-made juices and guided meditations. Thank you to Kyle and Arina for the backyard gatherings. Thank you for the care and support, which you have shown me. Davis will always hold many wonderful memories for me.

This journey would not have been possible without a sturdy support system. I am so grateful to my American family: Gabe, Rayna, Barbara and Cliff. You are truly wonderful people. Thank you Barbara for all of the home cooked meals and the beautiful cello music. Thank you Cliff for your countless hours of reflection. They were very helpful. Thank you Rayna for all of the words of wisdom. And Gabe, you have been there every single step of the way. You are an extraordinary partner, an advocate, and the best of allies. Thank you for your care and compassion. I love you all.

Chapter 1: Growers' regional tradeoff analysis of cover cropping and impact on its adoption in California almond systems

Abstract

The positive relationship between biodiversity and ecosystem function observed in natural ecosystems suggests that increasing plant diversity in agroecosystems through cover cropping could enhance multiple ecosystem services (ES) simultaneously. Due to their multi-strata architecture and perennial nature, orchard agroecosystems provide unique opportunities to support a wide breadth of ecosystem services. The first records of almonds (*Prunus dulcis* (Mills.) D.A. Webb) planted in California's Central Valley date back to 1853. The growth of the California almond industry is intricately linked to the state's socio-ecological history and, particularly, its development of large-scale infrastructures to sustain agricultural growth. The California almond industry now accounts for 84% of the global production. In agriculture, a stark temporal gap often exists between the establishment of scientific findings and the uptake of sustainable agricultural practices. Despite nearly a century of cover crop research in California orchard systems, cover cropping was never widely implemented in the Central Valley. In a survey of almond growers, we explore the socio-ecological drivers of this lag in adoption in California. Our results bring to light the multidisciplinary dimension of growers' decision process in the adoption and continued use of cover crops. Willingness to adopt cover cropping was determined by growers' assessment of opportunity costs and risk aversion rather than by their perception of ecosystem service gains. In particular, the evaluation of economic setbacks and associated water costs differed substantially between adopters and non-adopters. Among cover crop adopters, we observe wide variation in management practices and rationales for cover cropping. Poor germination limited growers' continuation of the practice. Our results reveal distinct systems of ES prioritization, determined by farm size and region in California (Sacramento Valley, North San Joaquin Valley and South San Joaquin Valley). We highlight a need to identify best-suited species and to develop optimized cover crop designs, in support of local seed providers. Solely top-down monetary incentives would not adequately address current barriers to cover crop adoption, which remain socio-ecological in nature. Our results highlight the important role of extensionists and practitioners in bridging social and ecological systems in favor of sustainable agriculture.

Introduction

Almond is one of California's most important crops (Sumner *et al.*, 2014), with an estimated output of $21.5 billion to California's economic activity. Despite evidence of the benefits of cover cropping on other woody perennial systems globally, cover cropping has never been widely implemented in California (CA). Recognizing California's unique agro-environmental history is central to understanding how cover crop adoption evolved in CA almond systems.

CA is the home of environmental pioneers: John Muir (1838-1914), founder of the US National Parks and renowned ecologist, Mary Hunter Austin (1868-1934), acclaimed environmental novelist and Gary Snyder (1930-present), a distinguished writer and environmental activist. Key written work foundational to American environmental history emerged from the minds and sensitivities of Californian pioneers (Guthman, 1998). As a state, CA demonstrated an early engagement in the politics of conservation and environmental protection and is now at the forefront of climate change policies and the Climate Smart Agriculture discourse in the United

States (Pathak *et al.,* 2018; Lewis & Rudnick, 2019). It was the first state to certify organic agriculture.

CA is also un-paralleled in its manipulation of the natural environment. Through the Central Valley Project, started in 1933, CA has effectively diverted water resources across the state through a complex network of federal, state, and local infrastructures, allowing for vast acreages to be claimed for agriculture. CA's agrarian history is particularly exceptional in that it was never predominantly constituted of small landholders. Instead, large-scale landholdings emerged as the legacy of Spanish and Mexican land grant systems and were subsequently reinforced by Gold-Rush generated wealth (Guthman, 1998). These immense landholdings were originally utilized for large-scale wheat production and grazing until the droughts of the late 1800s, which instigated the redistribution of land into smaller tenancies. Then between 1890-1914, facilitated by the emerging technical expertise of immigrants, development of irrigation projects, cooperative marketing and cheap labor, Californian land was gradually converted into intensive specialty crop farms and high-value perennial production systems (Siebert, 2003).

The first records of almonds (*Prunus dulcis* (Mills.) D.A. Webb) planted in CA date back to 1853 (Wickson, 1889). Even though it was recognized that irrigation could enhance almond productivity, growers did not start using irrigation until the 1930s (Wood, 1937). Major growth in almond production occurred from 1964 to 1985, supported by almond post-harvest product development and strong marketing schemes. Californian agriculture particularly benefited from the early development of unified growers' organizations, many of which were commodity-based. These unions played an important role in regulating their growing industries. One such organization was the Almond Board of California (ABC), founded in 1950 as a non-profit organization that substantially contributed to the expansion of the almond industry. Such commodity-based grower organizations participated in shaping irrigation districts, resulting in increased irrigated land, a key factor in facilitating the expansion of high-value specialty crops in the Central Valley (Johnston, 2003). With vertical integration, water rights acquisitions and immense wealth potential in almond production, farm management structures stratified making way for tenant and contract farming, thereby making it possible for key stakeholders to live remotely from the land (Arax, 2019). Today, the CA almond industry continues its relentless growth: it now encompasses 1,530,000 acres and accounts for 84% of the global production (Almond Board of California, 2011).

Central to California's agricultural growth is the state's early development of strong science-based extension through the Land Grant and Cooperative Extension systems built by the Morrill Acts of 1962-1890, the Hatch Act of 1887, and the Smith-Lever Act of 1914. These information structures spurred the early experimentation of cover cropping in almond. Early records of cover crop trials in orchard systems date back to the 1920s, conducted by the University of California Cooperative Extension (UCCE) (Figure 1.1 & 1.2). Growers' objectives in the early use of cover crops in the understories of orchards were "*soil conservation and to prolong the life of agriculture*" (Kell & McKee, 1936). However, due to concerns over potential increases in water usage and the provision of refuge for pests, combined with the advancement of synthetic fertilizers in the 1900s, cover crops were largely abandoned. In 1994, the BIOS project (Biologically Integrated Orchard Systems) led by a growers' alliance (CAFF) built upon previous efforts and developed participatory growers' networks to demonstrate the possibility for pesticide and synthetic fertilizer reduction by cover cropping. In contrast with early records of soil-focused objectives for cover cropping, BIOS explored other associated ecosystem services, particularly the biological control of insect pests as a key motive to adoption (Bugg *et al.,* 1994). However, despite early efforts to adapt this practice to Californian almond systems, there is still low adoption of cover cropping, due to remaining concerns, and the forceful pull towards industrialized models to optimize yields. A recent survey by the Almond Board of California indicates that in 2016 only about 6% of almond growers include cover crops in their farming systems (ABC Sustainability Survey, 2017).

Despite scientific evidence of the benefits of cover cropping, lags in cover crop adoption have been reported in many parts of the United States (USDA, 2017). We consider that the gap between scientific evidence and the actual uptake of sustainable practices hinders progress. Surveys have been conducted to identify farmers' concerns and the actual barriers of cover cropping (O'Connell *et al*., 2015; Moore *et al*., 2016; Dunn *et al*., 2016; Roesch-McNally *et al*., 2018). These works are important to identify the needs of farmers and to inform the development of cover crop research. However, as most farmers' surveys have been focused on annual systems, there remain important knowledge gaps specific to perennial systems and to Californian farmland. We believe that understanding farmers' concerns and needs with regards to cover cropping is key to address existing lags in adoption.

The objective of our study was (1) to determine differences in users and non-users' perception of benefits and tradeoffs of cover cropping, (2) to identify how grower characteristics (geographical location and farm size) influence the perception of benefits and tradeoffs, and thereby adoption, (3) to survey currently-used cover crop management practices in almond orchards, (4) to identify the most important sources of information about cover crops for growers, and (5) to define most important knowledge gaps to inform research on cover crop adoption in almond production in the Central Valley. Respondents were asked to evaluate the importance of a suite of cover crop benefits pertaining to ecosystem regulating services (water infiltration and retention, soil structure and field access and soil health), supporting services (pollinator habitat, aboveground pest control (navel orangeworm (*Amyelois transitella* (Walker)(NOW))), belowground pest control and weed control) and provisioning services (tree nutrition) (MEA, 2005). The information drawn from this survey will provide a platform to tailor research agendas, so as to bring relevant and applicable information that addresses growers' data needs. Finally, this research will provide valuable information for the development of effective policy measures as well as guide future science extension efforts.

Materials and Methods

Survey design

A questionnaire was designed in 2017 following the Tailored Design Method (Dillman *et al.,* 2008) and using Qualtrics ©, a cloud-based survey software. Participation was anonymous and voluntary. Questions were chosen to meet four main objectives. In a first section, respondents were asked to evaluate potential opportunities provided by cover cropping in almond systems. This section identified motivators of non-users (perceived benefits) and of current users (perceived benefits and realized benefits following implementation) for cover cropping. In a second section, respondents were asked to define potential barriers respective to (1) ecosystem tradeoffs, which could offset short-term agronomic productivity, (2) the practicality of integrating cover cropping operations in almond orchard systems and (3) potential economic setbacks of cover cropping. In a third section, questions provided insight on currently-used cover crop management practices across the Central Valley and their respective popularity among users. In a final section, the survey ranked farmers' performance among a list of information sources. Growers were asked to assess current gaps in knowledge, which could be considered as information barriers to cover crop adoption. Questions included Likert-scale, ranking, binary, multiple and single choice, and open-ended questions. A copy of the survey questions is available in Appendix A - Supplementary Information 1.1.

Survey respondents

The target group of respondents are individuals involved in the decision-making process of almond farms: owners, managers and/or operators. The target group of respondents did not include external farm advisors nor extension specialists. Respondents of the survey were asked to identify themselves as either users or non-users of cover crops. Two separate questionnaires were developed to target each audience. Questions addressed to both users and non-users sought to identify perceived benefits and concerns associated with cover cropping. The questionnaire addressed specifically to users included questions relating to their experience with cover crops (types of crops grown, proportion of the land with cover crops, annual or perennial, winter or spring, single or multi-species mix) and to their management practices (seeding date and date of termination). The definition of users specified in the survey was: “growers having cover crops grown on either part or all of their acreage with a minimum of 1 acre, in at least one growing season in the past five years”. Respondents were not incentivized nor compensated for completing the survey. Considering that relative benefits and tradeoffs of cover crops may vary among CA’s ecozones, respondents were asked to identify the county in which they grow almonds.

Survey distribution

An IRB human subjects’ approval was obtained for this study for the graduate student and PI. The survey questions were communicated to the Almond Board of California and sent for distribution in December 2017. The paper-version of the survey was distributed for two years at the Almond Board of California Annual Conference. An online version was also made available through a UC Davis project website. On 06/30/2019, the survey was also communicated in an online UCCE extension post through the Almond Doctor website. Paper-versions of the survey were distributed through UCCE almond-specific growers' workshops and outreach events. The survey was also communicated through the Western Farm Press, the Almond Board of California Newsletter, the Blue Diamond Growers Newsletter, Resource Conservation Districts (RCDs), and UCCE County Newsletters. Survey distribution ended in December 2019. Overall, distribution reached over 3,500 growers in CA.

Quality check processing

Data extraction for survey analysis occurred on January 7th, 2020 at 12:56 PM. Of a total of 174 responses, 90 passed the quality check process, all of which were online surveys. As a first step, Qualtrics survey previews were removed from the dataset. Incomplete questionnaires with less than 45% completion were removed. Of the remaining surveys, 35% did not meet the survey prerequisites: (1) respondents' primary activity must be almond farming and (2) their almond acreage must be of at least 1 acre. Surveys for farming operations outside of CA (i.e., Spain, England and Qatar) were removed. Based on the redundancy of IP addresses, duplicate responses from identical farm operations were removed. If multiple IP addresses were identical, we kept the one response that contained: (1) the greatest answer completion and (2) the most recent submission. Of the remaining dataset, we removed incomplete surveys for which the response duration was below four minutes, as we estimated this could compromise the quality of the response. Finally, data conversion and extraction were verified, and errors (<1% of answers) were corrected. The final dataset had responses with complete usage group identification, geographical region and/or farm acreage, and were thereby usable for response group analyses.

Survey analyses

Both qualitative and quantitative analyses were used to interpret the response dataset. For Likert-scale questions, the average importance score was calculated as a sum of points: the answer "not important" was given 0 points, "somewhat important" corresponded to 1 point and "most important" was 2 points. The same relative scale was used for knowledge-scale and improvement-scale questions. The Mann-Whitney Wilcoxon test was then used to compare categorical groups. For multiple choice type questions, contingency tables and Chi-squared tests were built to test the association between categorical variables: usage or non-usage of cover crops, small or large farm acreage, and geographical region. When the number of observations in each cell violated the assumptions of the Chi-squared, the Fisher exact test was used as an alternative method. Statistical tests were considered significant at $P<0.05$. All statistical analyses were conducted using JMP Pro 14 Statistical Visualization Software (SAS Institute Inc.).

For each response, farm geographical position, user group and farm size were mapped based on reported zip codes, using Tableau ® Data Analytics and Visualization Software (2020.2.1). User groups were defined by whether respondents used cover crops in their orchard. Therefore, this did not differentiate floor management practices for multiple land parcels within one farm. As such, the reported cover cropped acreage for CA almond may either over or under-represent the actual acreage per management practice: cover cropped or unseeded orchard floors. Indeed, the objective was to visualize scales of operations and management structures distributed across the Central Valley. Growers who reported acreages in more than one zip code were categorized either by their largest orchard in Figure 1.3 or as separate landholdings in Figures 1.4 and 1.5. In Figures 1.6 and 1.7, statistical analyses determining the influence of geographical location on cover crop perception was based on the zip code of the largest acreage of each respondent. Small and large farm distributions were based on total acreage owned by farm. The "small farm" was defined as having less than or equal to 420 acres whereas the "large farm" category included all farms of more than 420 acres (Figures 1.8 and 1.9). This categorization followed the process used by Khalsa & Brown (2017). One respondent reported >1000 acres, which was replaced by 1001 acres for analytical purposes. Of the farm acreages reported, none were of the scale of the largest almond operation in CA.

Results

Farm background and growers' analysis of cover crop benefits

We sent the survey (total of 64 questions) to more than 50% of CA's 6,800 almond farms through our distribution efforts. The response rate was estimated at about 5% (178 responses) and usable survey responses represented about 1% (90 respondents). Of respondents, a proportion of 55% reported using cover crops in their orchards and 58% use organic matter amendments, with a significantly greater probability of growers, using cover crops, if they also used organic amendments (Fisher's exact test, P=0.01). This suggests a potential predisposition of respondents towards innovative practices.

Interestingly, regardless of categorical group (cover crop usage, geographical location, or farm size), all respondents recognize that cover cropping in almond orchards presents potential benefits (Figures 1.6, 1.8 and 1.10). Across all groups, growers' primary interest in growing cover crops was directed towards agronomic benefits, as opposed to operational or economic gains.

Furthermore, all groups placed supporting and regulating benefits at the forefront of cover crop interests. Overall, growers' greatest interest was for (1) soil structure and field access, (2) soil health, (3) pollinator habitat, (4) water infiltration and retention. Comparing users and non-users of cover crops, there were minimal differences in the perception of benefits (Figure 1.10). The only significant difference found was in the importance given to (1) soil structure and field access and (2) soil health (P=0.01 and P=0.02, respectively), with cover crop users attributing greater importance to these services.

Influence of geographical location on growers' analysis of cover crop concerns

Survey locations were distributed across the Central Valley with the majority (53%) located in the North San Joaquin Valley (NSJV) region. Total cumulative almond acreage reported was 112,754 acres with an average landholding size of 1,162 acres (Figure 1.5). Interestingly, the average farm size varied widely by region: the average farm size in the NSJV was 433 acres whereas it exceeded 1,400 acres for both the Sacramento Valley (SV) and South San Joaquin Valley (SSJV) (Figure 1.5). However, there was greater participation of growers in the NSJV, with more than twice the number of participants, than the SV and SSJV regions. Due to a larger size of the landholdings, the total farm acreage surveyed in the SV and SSJV were ~1.5 times that of NSJV. This difference in landholding scale and acreage of the respective regions suggest potential differences in farm managerial structure and stratification as well as top-down decision processes, which may affect decisions regarding cover crops. Furthermore, differences in scale of landholdings may imply variation in farms' margins-of-error and market price dependency influencing growers' level of risk aversion relative to these production systems. It is important to note that our survey results for the SV were skewed towards farms of larger acreage: in the SV, the majority of growers have farm acreages of >1,400 acres.

Despite differences in farm size by region, most economic concerns were similar among regions, except for the cost of water. Concerns about water costs associated with cover crops significantly increased with decreasing latitude in the Central Valley (P=0.01), following the precipitation gradient (Figure 1.7). The SV benefits from adequate to ample water supply compared to the San Joaquin Valley, conjunctly due to higher annual precipitation and greater provision of surface water through the more consistent Sacramento River water availability. With reduced water costs, our study recorded significantly less concerns over cover crop transition in the SV compared to the San Joaquin Valley (P=0.02) (Figure 1.7). Growers of the SV were also less concerned about potential frost control complications with cover cropping (P=0.04). In almond ecosystems, conventional frost freeze protection is water-dependent, as it uses irrigation, to facilitate heat transfer in the orchard. Therefore, in line with the state water supply, growers in SV had both the least concern over water costs and least concerns over frost control. It is important to note that, while the SV's almond acreage (151,276 acres) is a fifth that of the San Joaquin Valley (725,396 acres), it benefits from nearly 3 times its mean annual water flow (18 mMAF and 6 mMAF, respectively) (CDFA, 2019; USBR, 2016). As such, large discrepancies likely exist in farm input costs impacting risk aversion behavior, across regions of the Central Valley. Results (n=121) of our survey suggest a potential link between region-dependent water costs and cover crop adoption within the Central Valley.

The NSJV had the most participation with 64 growers, representing >50% of total participants, indicating a higher interest in the research topic compared to other regions (Figure 1.3). Respondents from the NSJV were composed mostly of cover crop adopters (70%) (Figure

1.4), with in total nearly 4x as many adopters as in other regions. Growers of the NSJV expressed significantly greater need for aboveground pest biological control as a key cover crop ecosystem service ($P<0.001$). Despite this region having the highest adoption rate, it also expressed the greatest data needs (Figure 1.3, Appendix A – Supplementary Information 1.2): compared to other regions, the NSJV indicated greater interest in nearly all knowledge gap categories of this survey, except for "frost complications" (Appendix A – Supplementary Information 1.2).

Influence of farm size on growers' analysis of cover crop concerns

In this survey, 67% of respondents were categorized as small farms (≤420 acres), whereas 33% were identified as large farms (>420 acres) (Figure 1.5). Farm acreage varied widely from 1.5 to 27,280 acres, suggesting vastly different socio-economic contexts. Farm size tended to be smaller in the NSJV where about 40% of CA almond acreage is currently located (CDFA, 2019), whereas comparatively, the average farm size tripled in SV and in SSJV regions. In our survey, the association between farm size and region was not statistically significant (Fisher's Exact test, $P=0.87$).

In line with our findings of significant differences in aversion to water costs by region (Figure 1.7), we found that large farms have significantly higher interest for improved water infiltration and retention through cover cropping (Figure 1.8) ($P=0.04$), as well as for soil structure and field access ($P=0.03$), compared to small farms. Although larger farms expressed generally higher interests in the benefits of cover cropping, they were largely in disagreement with concerns proposed in this survey. Through open-ended responses, large farms suggested twice as many additional concern categories as small farms including "water usage", "cover crop termination for frost", and "nitrogen cycling" concerns (Figure 1.9). Considering the higher vulnerability of larger farms to market price volatility and competition from an industrialized market, large farms may experience a stronger pull towards controllable and intensified production practices, which currently do not encompass cover cropping practices or management. Indeed, in this survey, although the association between farm size and cover crop adoption was not significant (Fisher's Exact test, P=0.36), approximately 60% of cover crop users were small farms, thus suggesting higher risk aversion in larger operations.

Growers' tradeoff analysis of cover crop concerns by user group

Although there were few differences among growers' perception of cover crop benefits, large differences were found in growers' evaluation of concerns: non-users of cover crops ranked economic concerns as 10x more important than adopters, but also ranked the lack of available information on cover crops as twice as important as for adopters (P=0.001) (Figure 1.10 & 1.11). A few agronomic and operational concerns were also ranked higher by non-users including: (1) impediments to orchard sanitation, (2) complicated transition towards cover crop implementation, (3) difficult termination, and (4) difficult almond harvest (P=0.03, P=0.004, P=0.008 and P=0.003, respectively) (Figure 1.11). These results suggest a need for both clear cost-benefit assessments of cover cropping under different farm scale scenarios, but also a need to address agronomic and operational concerns through the development of best management practices, which would account for different water cost contexts relevant to regions of CA. Overall, reluctance to adoption was driven by risk-aversion to cover crop concerns and opportunity costs, rather than lack of potential gains.

Current cover crop management practices of early adopters

Baseline cover crop management practices in CA are reported in Appendix A – Supplementary Information 1.2. Most early adopters in this survey reported that they used complex cover crop mixes of four species or more, suggesting growers used diverse cover crop mixtures to enhance multiple ecosystem services, simultaneously. Brassica and legume plant species were the most used followed by grass species. Of early adopters, 40% rotated plant species within the mix and 30% of growers alternated cover crop mixes within alleyways of their orchard. 96% of users established covers of 6 feet width or more in their orchard alleyways. This indicates that current adopters implement cover crop cultivation practices, which optimize spatio-temporal biodiversity within their orchards.

Although 84% of growers indicated that cover cropping met their expectations, 16% reported having discontinued cover cropping, partially in certain fields or completely, due to substantial barriers listed above. Most growers who discontinued the practice reported germination difficulties. Interestingly, none of the growers who discontinued cover cropping indicated economic factors as a constraint to adoption, even though water availability was mentioned as a related cause to poor germination. Furthermore, only 39% of growers irrigated the cover crop, suggesting most growers do not incur supplemental water costs with cover cropping. None of the respondents reported cover crop incompatibility with other orchard operations (i.e., sanitation, frost control) as a cause for discontinuing the practice. In fact, 64% of growers reported conducting pruning of their orchard after cover crop seeding and 62% crush or flail-mow mummies in their cover crop during the winter. Additionally, 32% of growers reported that they do not terminate the cover and that this does not create complications at harvest: the cover is left to reseed and dies naturally during the summer due to lack of water. Therefore, experiences from current users indicate a minimal footprint of cover cropping on conventional orchard operations. This is in line with previous findings of this survey, indicating significantly lower agronomic and operational concerns of users compared to non-users: users were less concerned with (1) potential impediments to orchard sanitation, (2) difficult termination and (3) difficult almond harvest due to potential cover crop debris ($P=0.03$, $P=0.008$ and $P=0.003$, respectively). In line with previous results, this suggests that adoption is influenced by risk aversion, rather than by growers' valuation of potential gains.

Knowledge diffusion structures

Growers' ranking of most important information sources reveal the fundamental role of in-person communication and of regional expertise within the existing knowledge structure (Appendix A - Supplementary Information 1.3). At the top of the rankings were farm advisors, Cooperative Extension specialists, pest control advisers (PCA), certified crop advisers (CCA) and other growers. Similarly, in the "Other category", growers added other contributing individuals: seed industry experts, private advisors/consultants, the United States Department of Agriculture's Natural Resources Conservation Service (NRCS) and Project Apis m. (PAm) representatives. This shows that the existing agricultural knowledge system exists across a broad diversity of sectors. Although Cooperative Extension holds a central node in the information network, multiple other actors contribute to supporting science communication. The network includes farms, private consultants, industry, and non-governmental organizations (NGOs). Furthermore, research collaboration was given a relatively high ranking, which may be skewed by the survey population which decided to participate in this survey's research and thus, found importance in participatory research efforts. We notice that high degrees of education and technical knowledge were wellappreciated by growers who took the survey. Expertise was also attributed to region-specific experiential knowledge: growers mentioned that their experience and several generations of farming were at the core of their knowledge system. Thus, knowledge systems not only involved a diverse network of actors but also engaged multiple learning pathways including self-learning as well as social learning from other growers. More generic communication and outreach material (websites, CA-wide newsletters, and books) were viewed as less important, as sources of information than in-person scientific extension. Surprisingly, there was no mention of high-tech solutions (i.e., smartphone applications, cover crop selection software) to provide support for cover cropping decisions.

Knowledge gaps and considerations for future research

Growers were asked to identify what they viewed as the most important knowledge gaps regarding cover crops. It is important to note that for most data gap categories proposed in the survey, there were at least two respondents, who considered it important (Appendix A - Supplementary Information 1.3). There was one exception with no respondents indicating concerns over N immobilization data gaps in the South San Joaquin Valley (Appendix A - Supplementary Information 1.3). Of the regions represented in this survey, the NSJV had the most participants to the survey, most of whom were cover crop users: 53% of the survey population was in the NSJV of which 70% were cover crop users. Growers in the NSJV indicated a greater need for data in all categories except for “frost complications”, however there were no statistically significant differences.

Discussion

Three distinct regions across the Central Valley

Although cover crop adoption has been widely studied in other parts of the continental United States (Arbuckle & Roesch-McNally, 2015; Myers & Watts, 2015; O'Connell *et al*., 2015; Moore *et al*., 2016; Silva & Moore, 2017), the sustainable use of cover crops in California crops is unique due to the State's complexity of crops and intensive management practices. Arguably more than any state, CA possesses the greatest climate gradient, which requires large differences in irrigation management, agricultural input costs and regulation by crop and by region, resulting in broad variation in agricultural profitability across the state (Siebert, 2003). With the impacts of climate change and the undeniable burden of drought on the state, water costs play a central role in impacting agricultural crop profitability (Pathak *et al*., 2018). This was evident in our survey which suggested the presence of three distinct categorical groups of respondents: (1) Respondents of the SV characterized by larger landholdings (average farm size= 1,636 acres) and having the least water cost concerns (P=0.01), (2) respondents of the NSJV characterized by smaller landholdings (average farm size = 433 acres) and having increased water cost concerns, and (3) respondents of the SSJV characterized by larger landholdings (average farm size = 1,417 acres) and having the highest water cost concerns.

Our results indicating large variations in farm scale between the north and south of the San Joaquin Valley are in line with findings reported in the 2012 United States Department of Agriculture (USDA) Census: of the two largest almond-producing counties in CA, the average farm size in Kern county (SSJV) is nearly 6x that of Stanislaus county (NSJV) (1116 acres and

192 acres, respectively) (NASS-USDA, 2012). Within the San Joaquin Valley, the considerably larger landholdings in the south are likely linked to increased water costs and the resulting stronger pull towards high-value crop commodities. The prevalence of larger tenancies in the south are also attributed to the region's early agricultural history, whereby large farm tenancies were most impactful in shaping regional irrigation schemes and acquiring water rights and resources for agriculture (Abel, 1950).

In almond production systems, water is used for multiple purposes beyond crop irrigation, including fertigation and frost freeze protection. In the Central Valley, the incremental benefits per acre of practices and inputs are heavily dependent on output and therefore tied to irrigation water costs and supply, which are minutely regulated across the Central Valley. Large discrepancies in input profits among regions have been previously demonstrated, particularly during the ban of methyl bromide (MeBr) in 2005 (Siebert, 2003). Prior to its statewide ban, the fumigant was used in tree nuts as a soil microbiocidal fumigant. Profits in these agro-ecosystems differed among regions: in peach production, farms using MeBr brought in 4.7$/acre in the SV, whereas profit was 7.1$/acre in the San Joaquin Valley (Siebert, 2003). In almond production systems, soil fumigants are still used conventionally at pre-planting to control for parasitic nematodes and diseases (Browne *et al*., 2006). Considering differences of farm scale and water concerns among the three regions defined in our survey, large discrepancies like these are likely to exist in the incremental benefits of cover crops as well as its sustainable use, by region.

Different objectives and needs for ecosystem service augmentation by region

Our results suggest that both marketable and non-marketable ecosystem services are of interest to growers across groups: both users and non-users recognize the value of supporting and regulating services associated with cover cropping, beyond their interests for provisioning services (tree nutrition). This suggests that lack of perceived benefits is not a barrier to cover crop adoption. However, there were noticeable differences within the three Central Valley regions in growers' relative preference of ecosystem services and concerns over disservices of cover crops. In the Northmost region where there are heavier annual winter rains, growers had greater interest for improved soil structure and field access through cover cropping, whereas in San Joaquin regions, growers placed higher importance towards pollinator habitat, as opposed to better soil structure and field access (Figure 1.6).

Our results demonstrate that growers' decision to adopt a practice is not a unilateral one, but rather involves complex analyses of numerous tradeoffs and cost benefits, which are regionally dependent. The positive relationship between biodiversity and ecosystem function has been previously demonstrated (Tilman *et al*., 1996; Cadotte *et al*., 2008; Cardinale *et al*., 2012). It has been suggested that intentionally increasing plant diversity through cover cropping could substantially augment multiple ecosystem services (Davis *et al*., 2012; Schipanski *et al*., 2014; Finney & Kaye, 2016). However, knowledge on how greater planned biodiversity in agroecosystems impacts associated biodiversity and the provision of multiple ecosystem services remain scarce, especially in the context of CA. Studies from the Midwest have suggested that cover crops can reach diverse objectives through the selection of plant functional traits in cover crop mix designs (Blesh, 2017). Our results bring valuable insight on cover crop objectives, which can be used to tailor cover crop optimization trials and inform research agendas to meet regional needs and define most sustainable cover crops by region.

It has been previously suggested that crop-specific incentives that reflect climate, water availability and environmental regulation changes would best support adoption of cover cropping

(DeVincentis *et al.,* 2020). However, our survey results suggest that solely top-down monetary incentives would not adequately address current barriers, which remain socio-ecological in nature. We observe a wide variation of management and rationales in current cover crop practices: there is a need for precise and region-specific recommendations beyond accounting for potential regional water costs. Most growers who discontinued the practice reported germination difficulties. This group of growers who discontinued cover cropping bring valuable insight on actual barriers and provide key experiential knowledge, based on trial-and-error pathways (Lubell *et al.*, 2014). Their feedback highlights agronomic constraints challenging the transition towards cover cropping. Early adopters' decision to intensify biodiversity in cover crop mixes may be a successful strategy to partially amend for poor germination and weak establishment of the cover crop, in void of region-specific BMPs.

Our results highlight the need for research to develop region-specific BMPs for almond cover cropping in CA, and particularly to address germination difficulties and identify best-suited species in support of the work of local seed providers. Successful extension efforts would need to capitalize on the existing synergy among these diverse actor groups and learning structures. In particular, applying knowledge to diverse region-specific contexts through in-person consulting will likely provide the best results for cover crop adoption and improved agro-ecological sustainability. Our results suggest that there is a potential to reach growers and farm managers through relatively inexpensive communication systems but also denotes that there are no existing centralized knowledge platforms nor information tools. These results highlight the crucial role of in-person extension networks and the importance of local knowledge supported by extension and consultation for cover crop adoption.

The North San Joaquin Valley, central to knowledge diffusion

Literature suggests that the level of awareness of conservation practices (Perry-Hill & Prokopy, 2014) and willingness to learn (Dunn *et al*., 2016) are overarching factors influencing innovation adoption. The higher adoption rates observed in the NSJV are especially remarkable, as water costs are considerably higher in this region compared to the SV. This suggests that despite the considerable influence of water costs on cover crop decisions in CA, growers' valuation of cover crop benefits can override associated water constraints, which might be minimized through optimized cover crop management practices. Theoretical models suggest that early adopters cope with uncertainty in innovation, through experimentation and learning-from-others mechanisms facilitated by their centrality within their networks and thus, their extensive contact with information sources (Padel, 2001; Rogers, 2003; Dunn *et al.*, 2016; Lubell *et al*., 2014). As such, the identification of early adopters to introduce an innovation (i.e., "injection point" or IP) has an important impact on innovation diffusion rates, and it can positively affect the mobilization of information through social network pathways (Tey & Brindal, 2012; Santeramo, 2018). Due to its larger population of early adopters and growers' high willingness to gain new knowledge and to innovate, the NSJV may represent a network center, with a stronger capacity to support learning-from-others mechanisms, as described by Lubell *et al.* (2014), which could enhance the diffusion of innovation across the Central Valley. Based on this survey's participation results, the NSJV region would likely be most receptive to governmental incentives and science extension. For effective innovation diffusion, this survey's results indicate a need to address data gaps and develop region-specific BMPs, in parallel to potential policy incentives.

Limitations & Future Research

Our survey's response rate of about 5% suggests limited overall interest of farmers for cover cropping in almond systems of CA. The large proportion of growers who already use cover crops and/or work on small-scale farms may create a bias in our survey results. Actual adoption rates of cover crops in CA almond production systems are estimated to be approximately 6% (ABC, 2017). Future research would need to broaden the survey to a larger community of almond growers in California. In particular, developing means that do not require electronic distribution of the survey may be necessary to reach different groups of respondents. All responses used in our study were electronically submitted because few written responses met the quality check criterion.

Our work provides insight regarding the valuation of ecosystem services, data which could be integrated in cost-benefit models that account for discrepancies in water costs across the state. In these models, one could particularly explore existing tradeoffs among cover crop services and disservices: e.g., potential use of water as opposed to soil health benefits. Finally, our survey results highlight the need for region-specific field research, as multiple data gaps were identified. These gaps included data on actual C sequestration potential of cover crops, best-suited species for different climatic regions of CA and tradeoffs between increased water usage versus improvements in water infiltration and storage associated with cover crops.

Conclusion

California uniquely benefits from a robust extension network, that has proven to be fundamental to the growth of Californian agriculture. Our results provide important insights into the regionally-specific drivers of growers' adoption as well as impactful barriers to cover cropping in almonds. We found that, although most growers had similar appreciation of potential benefits of cover cropping, there were important discrepancies in the perception of concerns, particularly regarding economic setbacks and associated water costs. Therefore, our results suggest that the impact of risk aversion and opportunity costs may be more important than perception of potential benefits in adoption decisions. Valuation of ecosystem services and disservices (soil structure & field access, pollinator habitat and frost concerns) varied by regions suggesting the need for region-specific research and optimization trials to address specific regional objectives. It is apparent that beyond economic concerns, lack of Best Management Practices (BMPs) is currently an important barrier to cover crop adoption in CA almond. As such, implementation of policies and incentives *ceteris paribus* would be insufficient. For effective innovation diffusion, this survey's results indicate a need to address data gaps and develop region-specific BMPs, in addition to potential policy incentives. Climate change impacts on food security and livelihoods are challenging communities throughout the world. In agriculture, a stark temporal gap often exists between the establishment of scientific findings and the uptake of sustainable agricultural practices. Agricultural extension efforts largely contribute to bridging this divide by providing the necessary support to adapt these solutions to diverse socio-economic settings. Our findings highlight the need for multi-disciplinary collaboration and the integration of multiple stakeholders to ensure the adaptation of cover crop management, as pillar of sustainable agriculture, within diverse environmental and socio-economic contexts.

References

Abel, E. 1950. The Central Valley Project and the Farmers. California Law Revision 38: 653-665.

Almond Board of California (ABC). 2017. ABC Sustainability Survey. Almond Board of California Personal Communication: Modesto, CA.

Arax, M. 2019. The Dreamt Land: Chasing Water and Dust across California. Knopf Publication: New York, USA.

Arbuckle Jr, J. and Roesch-Mcnally, G. 2015. Cover crop adoption in Iowa: The role of perceived practice characteristics. Journal of Soil and Water Conservation 70:418-429.

Blesh, J. 2017. Functional traits in cover crop mixtures: biological nitrogen fixation and multifunctionality. Journal of applied ecology 55:38-48.

Browne, G., Connell, J. and Schneider, S. 2006. Almond replant disease and its management with alternative pre-plant soil fumigation treatments and rootstocks. Plant Disease 90:869-876.

Bugg, R. L., Anderson, G., Eck, R., Hendricks, L. and Lashbrook, C. 1994. Biologically Integrated Orchard Systems (BIOS) for almonds in Merced County. Community Alliance with Family Farmers Foundation Publication. Davis, CA.

Cadotte, M. W., Cardinale, B. J. and Oakley, T. H. 2008. Evolutionary history and the effect of biodiversity on plant productivity. Proceedings of the National Academy of Sciences of the United States of America 105:17012-17017.

Cardinale, B. J., *et al*. 2012. Biodiversity loss and its impact on humanity. Nature 486:59-67.

CDFA. 2019. 2018 California Almond Acreage Report. Available from: https://www.nass.usda.gov/Statistics_by_State/California/Publications/Specialty_and_Other_Releases/Almond/Acreage/201904almac.pdf

Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M. and Liebman, M. 2012. Increasing cropping system diversity balances productivity, profitability and environmental health. PLoS ONE 7:e47149.

DeVincentis, A., Solis, S., Bruno, E., Leavitt, A., Gomes, A., Rice, S. and Zaccaria, D. 2020. Using cost-benefit analysis to understand adoption of winter cover cropping in California’s specialty crop systems. Journal of Environmental Management 261:110205.

Dillman, D. A., Smith, J. D. and Christian, L. M. 2008. Internet, mail and mixed-mode surveys: Tailored design method. 3rd ed. John Wiley and Sons, New York.

Dunn, M., Ulrich-Schad, J. D., Prokopy, L. S., Myers, R. L., Watts, C. R., and Scanlon, K. 2016. Perceptions and use of cover crops among early adopters: Findings from a national survey. Journal of soil and water conservation 71:29-40.

Finney, D. M. and Kaye, J. P. 2016. Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system. Journal of Applied Ecology 54:509-517.

Guthman, J. 1998. Regulating meaning, appropriating nature: the codification of California organic agriculture. Antipode 30:135-154.

Johnston, W. E. 2003. Cross sections of a diverse agriculture: profiles of California's agricultural production regions and principal commodities. In: Siebert, J. (Ed.) California Agriculture: Dimensions and Issues. pp. 29-55.

Kell, W. V. and McKee, R. 1936. Cover crops for soil conservation. Farmers' Bulletin No. 1758. U.S. Department of Agriculture Publication.

Khalsa, S. D. and Brown, P. H. 2017. Grower analysis of organic matter amendments in California orchards. Journal of Environmental Quality 46:649-658.

Lewis, J. and Rudnick, J. 2019. The Policy Enabling Environment for Climate Smart Agriculture: A Case Study of California. Front. Sustain. Food Sys. 3:31.

Lubell, M., Niles, M. and Hoffman, M. 2014. Extension 3.0: Managing agricultural knowledge systems in the network age. Society and natural resources 27:1089-1103.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and Human Well-Being: Synthesis. Island Press. Washington D.C., USA.

Moore, V. M., Mitchell, P., Silva, E. M. and Barham, B. L. 2016. Cover crop adoption and intensity on Wisconsin's organic vegetable farms. Agroecology and Sustainable Food Systems 40:693-713.

Myers, R. and Watts, C. 2015. Progress and perspectives with cover crops: Interpreting three years of farmer surveys on cover crops. Journal of Soil and Water Conservation 70 (6):125-129.

NASS-USDA. 2012. 2012 Census of Agriculture. Available at: https://www.nass.usda.gov/Publications/AgCensus/2012/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf

O'Connell, S., Grossman, J., Hoyt, G., Shi, W., Bowen, S., Marticorena, D., Fager, K. and Creamer, N. 2015. A survey of cover crop practices and perceptions of sustainable farmers in North Carolina and the surrounding region. Renewable Agriculture and Food Systems 30(6):550-562.

Padel, S. 2001. Conservation to organic farming: A typical example of the diffusion of an innovation? Sociologia ruralis 41(1):40-61.

Pathak, T. B., Maskey, M. L., Dahlberg, J., Kearns, F., Bali, D. and Zaccaria, D. 2018. Climate Change Trends and Impacts on California Agriculture: A Detailed Review. Agronomy 8 (3): 25.

Perry-Hill, R. and Prokopy, L. S. 2014. Comparing different types of rural landowners: Implications for conservation practice adoption. Journal of Soil and Water Conservation 69(3):266-278.

Roesch-McNally, G.E., Basche, A.D., Arbuckle, J.G., Tyndall, J.C., Miguez, F.E., Bowman, T. and Clay, R. 2017. The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. Renewable Agriculture and Food Systems:1-12.

Rogers, E. M. 2003. Diffusion of Innovations, 5th ed. New York, NY:The Free Press a Division of Macmillan, Inc.

Santeramo, F. G. 2018. I learn, you learn, we gain. Experience in crop insurance markets. Applied Economic Perspectives and Policy 41: 284-304.

Schipanski, M. E., *et al*. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agricultural Systems 125:12-22.

Siebert, J. 2003. California Agriculture: Dimensions and Issues. UC Berkeley: Giannini Foundation of Agricultural Economics. Available at: https://escholarship.org/uc/item/9145n8m1

Silva, E. and Moore, V. 2017. Cover Crops as an Agroecological Practice on Organic Vegetable Farms in Wisconsin, USA. Sustainability 9:55.

Sumner, D. A., Matthews, W. A., Medellin-Azuara, J. and Bradley, A. 2014. The economic impacts of the California almond industry. University of California Agricultural Issues Center Report.

Tey, Y. S. and Brindal, M. 2012. Factors influencing the adoption of precision agricultural technologies: a review for policy implications. Prec. Agriculture 13:713-730.

Tilman, D., Wedin, D. and Knops, J. M. H. 1996. Productivity and sustainability influenced by biodiversity in grassland ecology. Nature 379:718-720.

University of California, Cooperative Extension (UCCE). Cover crop variety test. 1921. Merced county, UC Cooperative Extension Records, Box 175. UC Cooperative Extension Archives, UC Merced Library, Merced, CA. https://calisphere.org/collections/27012.

USBR. 2016. Sacramento and San Joaquin River Basins. In: Report to Congress. Available at: https://www.usbr.gov/climate/secure/docs/2016secure/2016SECUREReport-chapter8.pdf

US Department of Agriculture (USDA) National Agricultural Statistics Service. 2017. Census of Agriculture. Chapter 2, Table 41–Land Use Practice.

Wickson, M. N. 1889. The California fruits and how to grow them. 1st edition. Dewey and Co. Pacific Rural Press, San Francisco, CA.

Wood, M. N. 1937. Almond culture in California. California Agricultural Extension Service, circular 103.

Figure 1.1. Tuttle, CA: UCCE research trial from 1922, testing field peas in a tree plot (UCCE, 1921).

Figure 1.2. UCCE research trial testing the effect of different cover crop seeding dates in orchards. This research found that a difference of two weeks in the Fall seeding resulted in large differences in cover crop development. Left: seeded October 14th; right: seeded October 1st, 1921 (UCCE, 1921).

Figure 1.3. Landholdings (n=121) distribution across the Central Valley for a total of 90 grower respondents. Counties with the most landholdings were Stanislaus county (n=26) and Merced county (n=19).

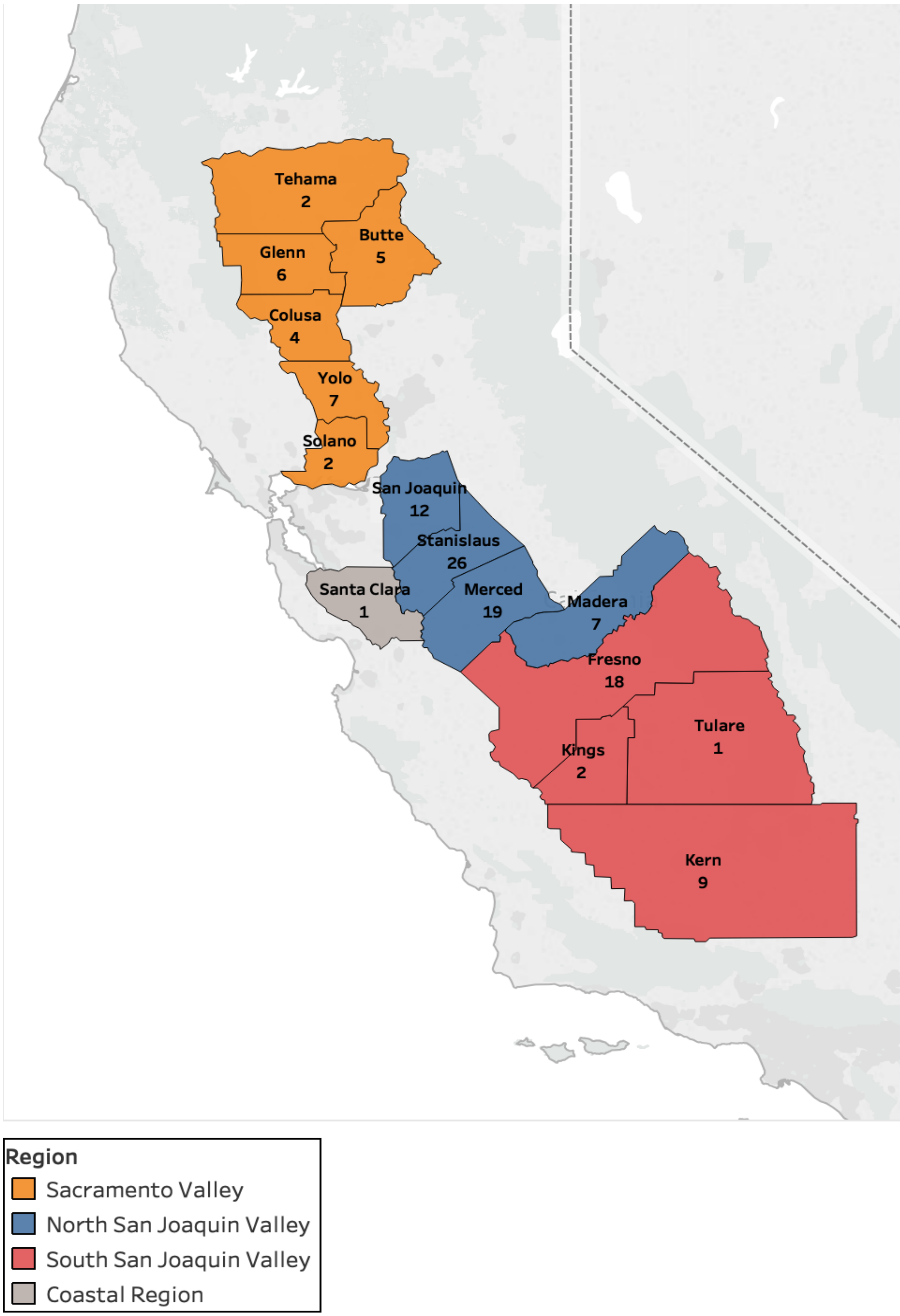


Figure 1.4. Distribution of users and non-users of cover crops (CC) across the Central Valley. Farm acreages of multiple managers were cumulated per zipcode (n=120). Farms with landholdings across the Central Valley were represented by multiple zipcodes (n=132). 55% of respondents used cover crops in this study.

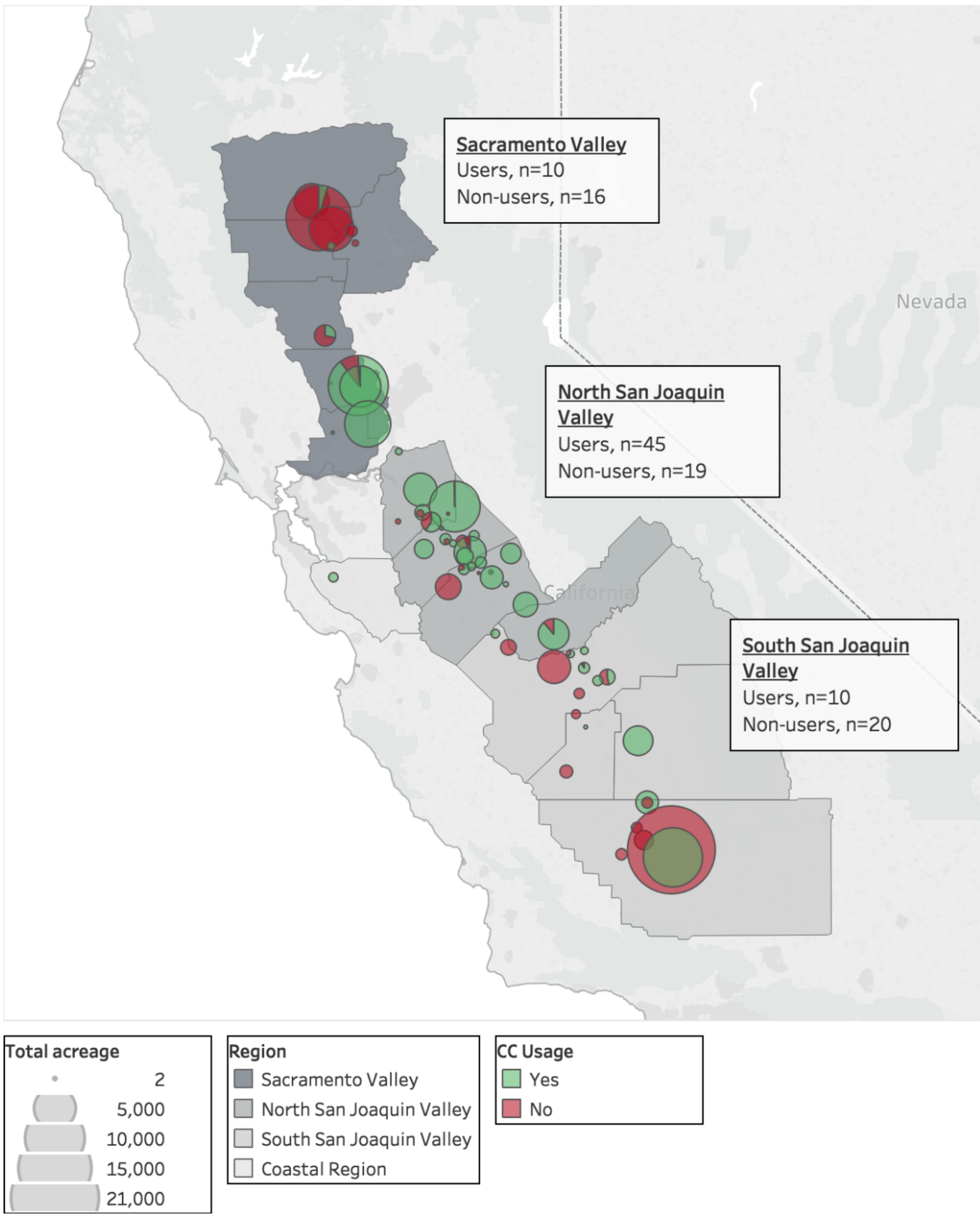


Figure 1.5. Survey of farm size distribution (n=120) across the Central Valley. When acreage per zip code was not reported, the full acreage of the farm was divided evenly by reported zip codes. The color and point size gradients both report the acreage of landholdings.

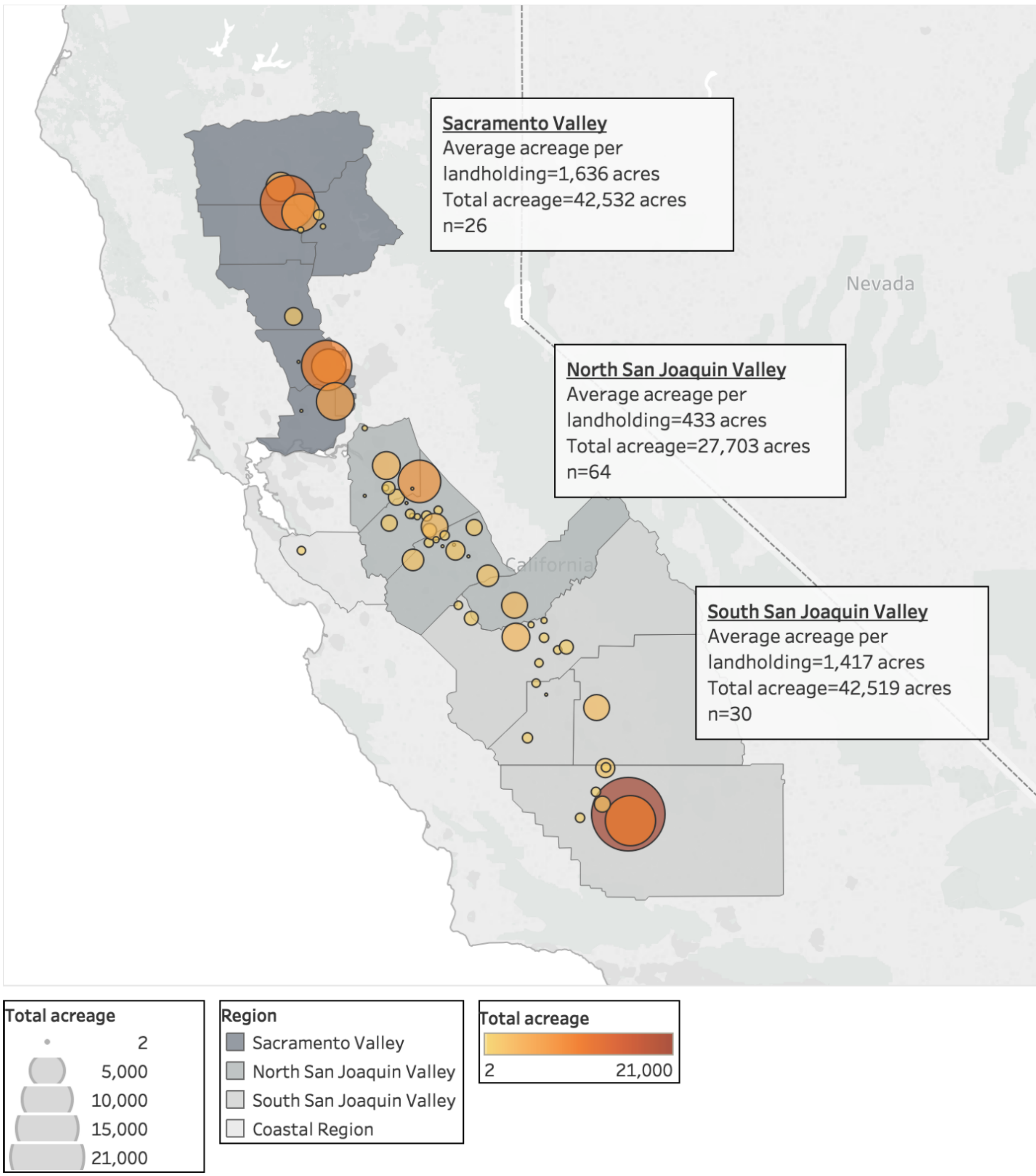


Figure 1.6. Perceived cover crop benefits as influenced by geographic region (Sacramento Valley, North San Joaquin Valley, and South San Joaquin Valley) and average importance score of benefits. Significant differences in the ranking distribution were determined using the Mann-Whitney test and are indicated by ** (p<0.05), *** (p<0.001) or NSS for not statistically significant.

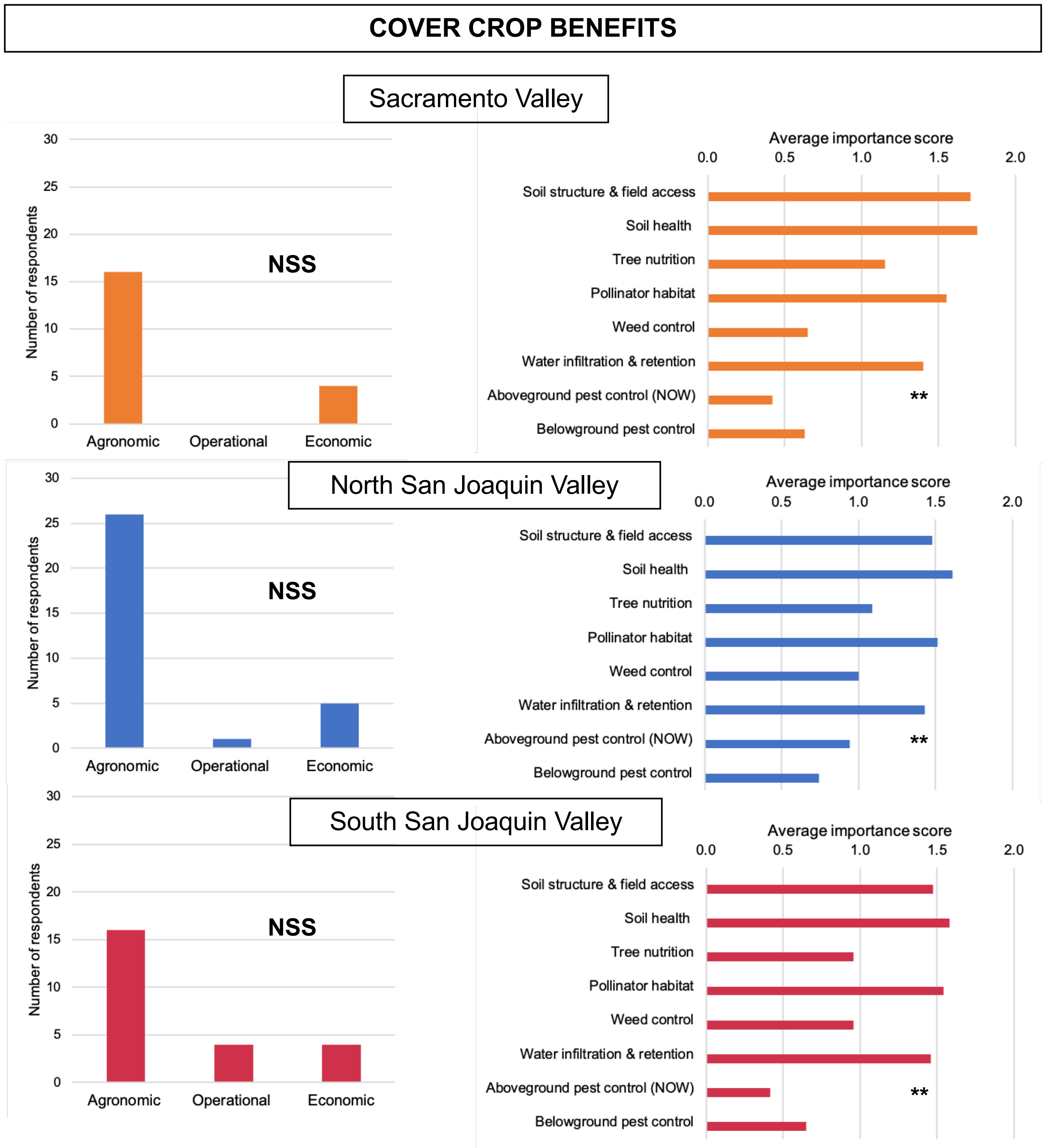


Figure 1.7. Perceived cover crop concerns as influenced by geographic region (Sacramento Valley, North San Joaquin Valley, and South San Joaquin Valley) and average importance score of concerns within agronomic, operational, and economic categorical groups. Significant differences in the ranking distribution were determined using the Mann-Whitney test and are indicated by ** (p<0.05), ***(p<0.001) or NSS for not statistically significant.

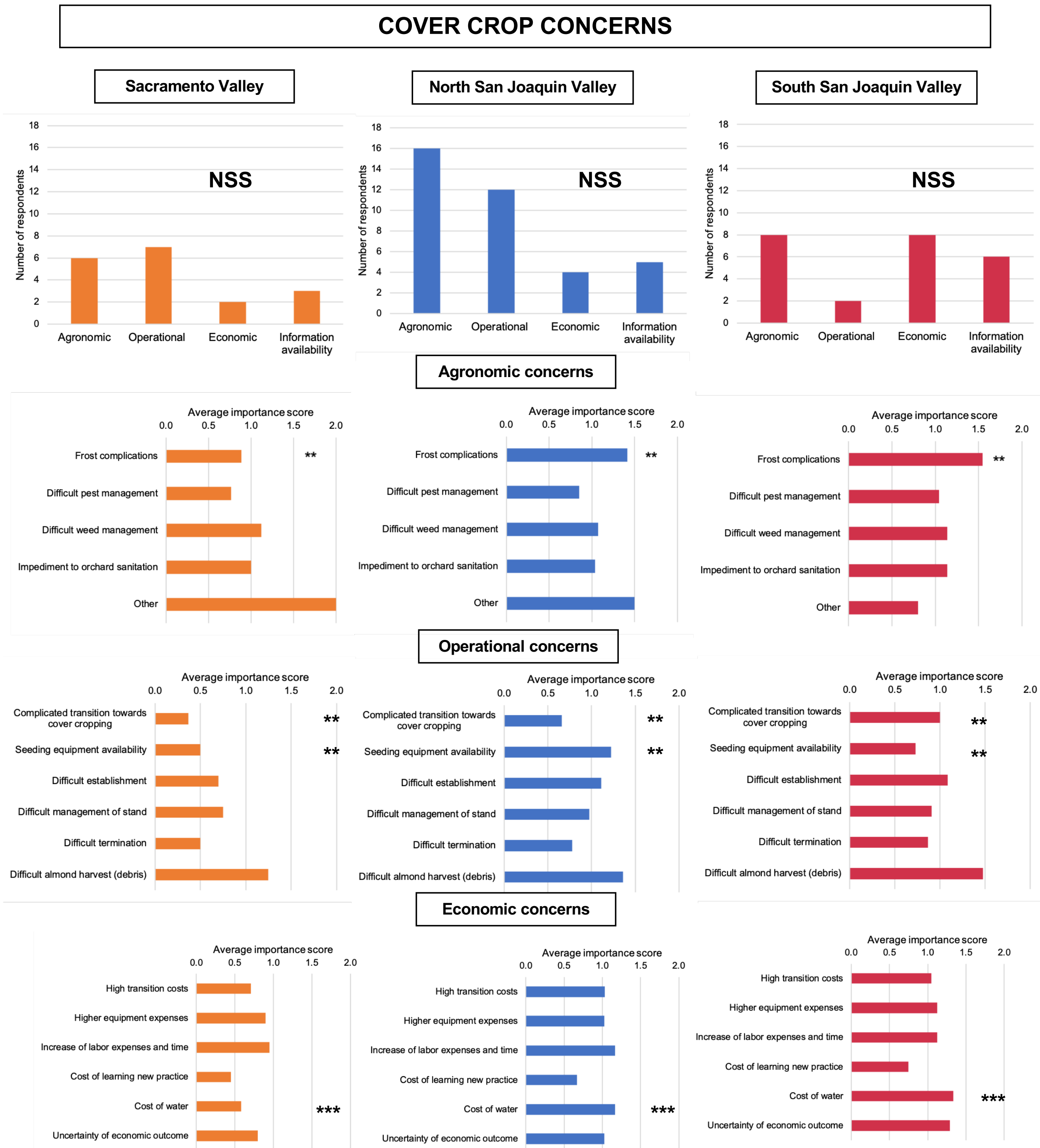


Figure 1.8. Perceived cover crop benefits as influenced by farm acreage (small farms corresponded to acreage of ≤420 acres and large farms were of >420 acres) and average importance score of benefits. Significant differences in the ranking distribution were determined using the Mann-Whitney test and are indicated by **(p<0.05), ***(p<0.001) or NSS for not statistically significant.

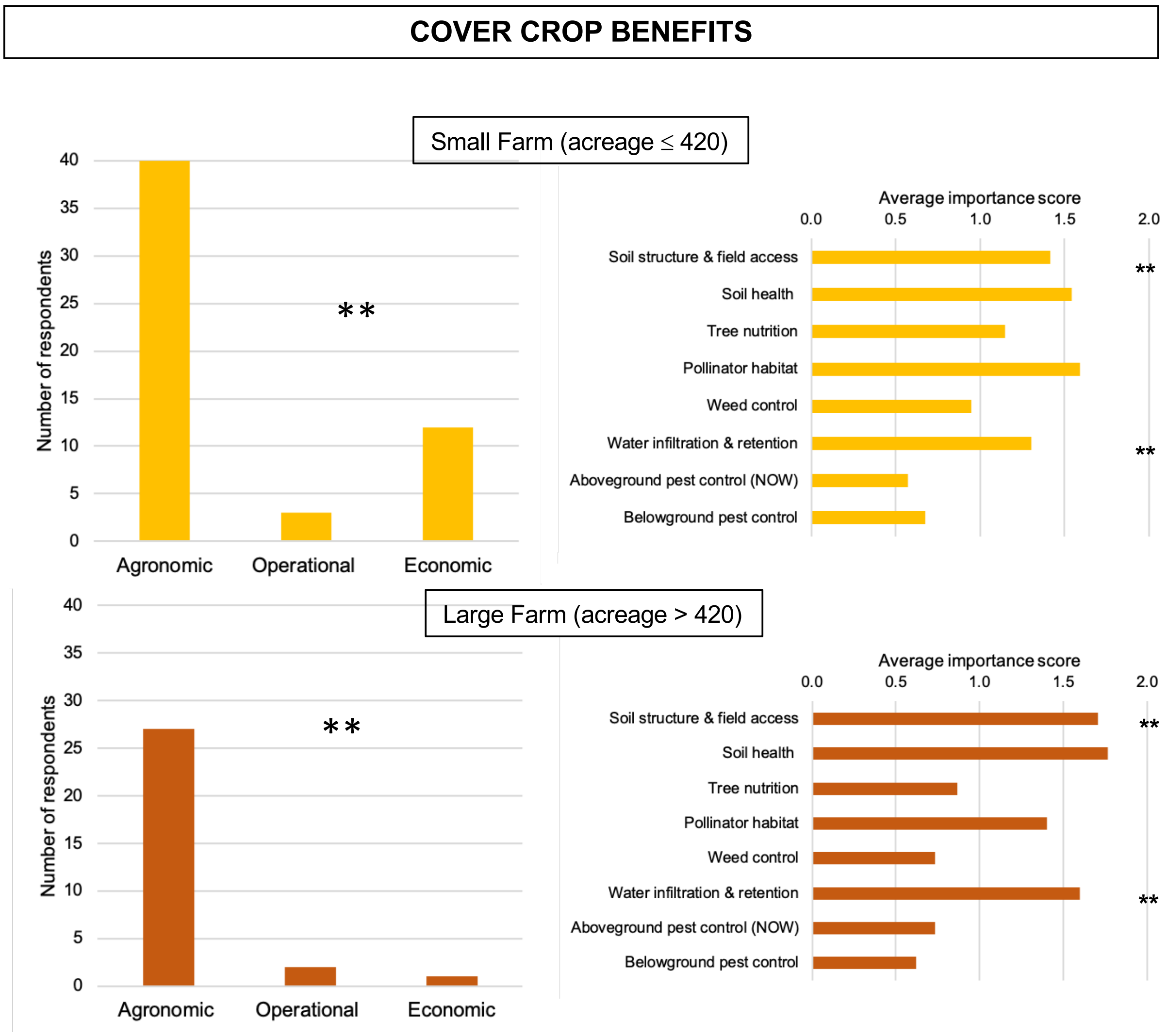


Figure 1.9. Perceived cover crop concerns as influenced by farm size and average importance score of concerns within agronomic, operational, and economic categorical groups. Significant differences in the ranking distribution were determined using the Mann-Whitney test and are indicated by **(p<0.05), ***(p<0.001) or NSS for not statistically significant.

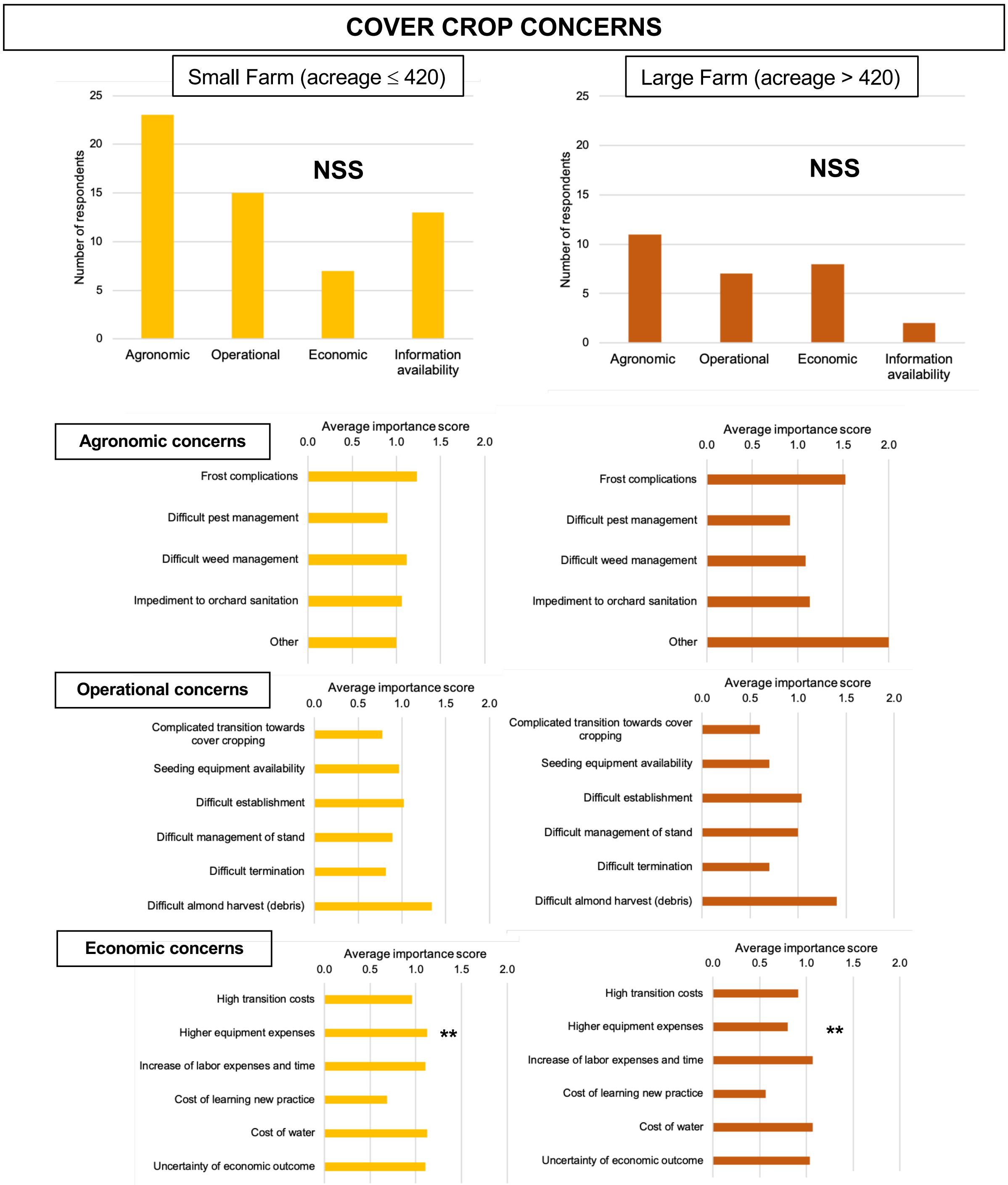


Figure 1.10. Perceived cover crop benefits as influenced by usage group (user and non-user) and average importance score of benefits: soil structure and field access, soil health, tree nutrition, pollinator habitat, weed control, water infiltration and retention, aboveground pest control and belowground pest control. Significant differences in the ranking distribution were determined using the Mann-Whitney test and are indicated by **(p<0.05), ***(p<0.001) or NSS for not statistically significant.

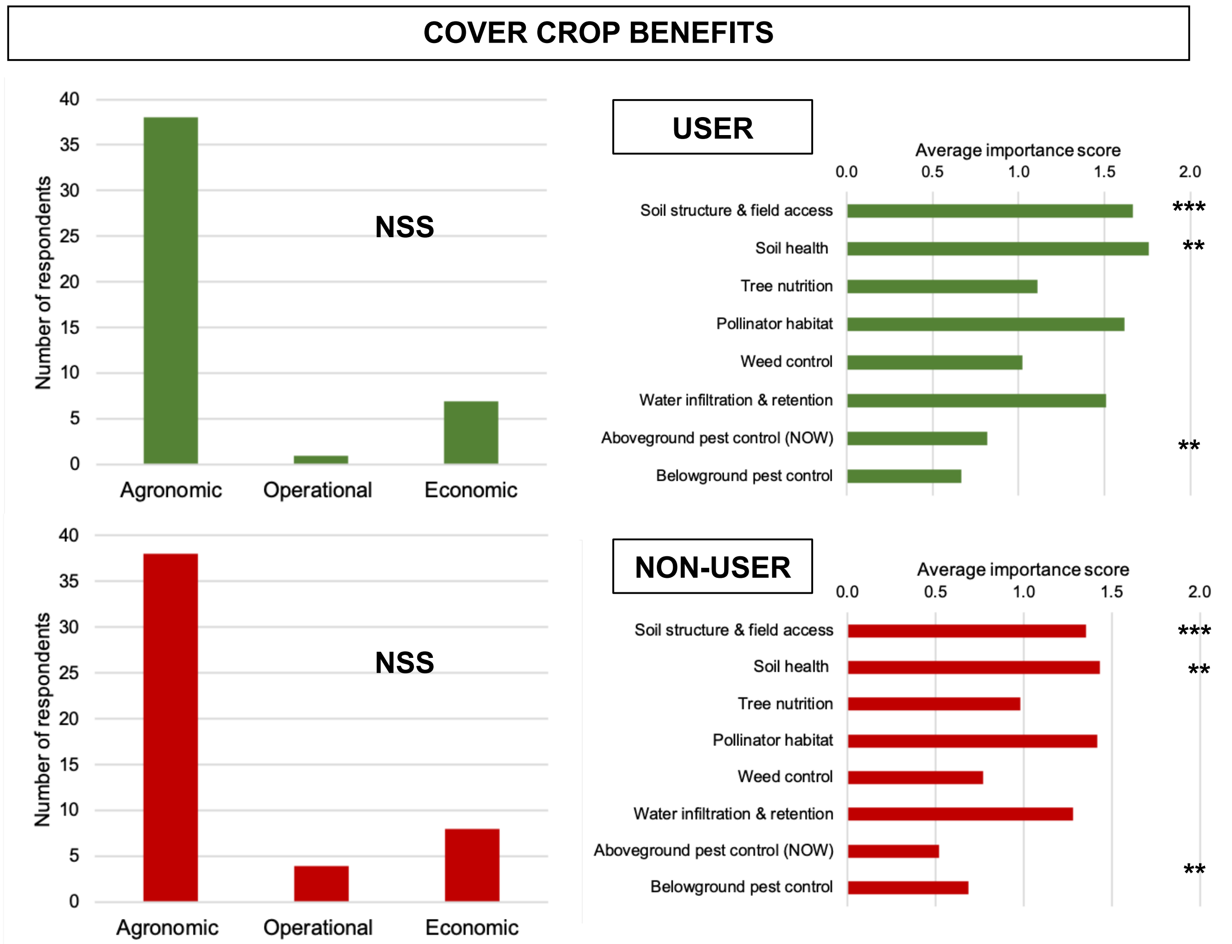
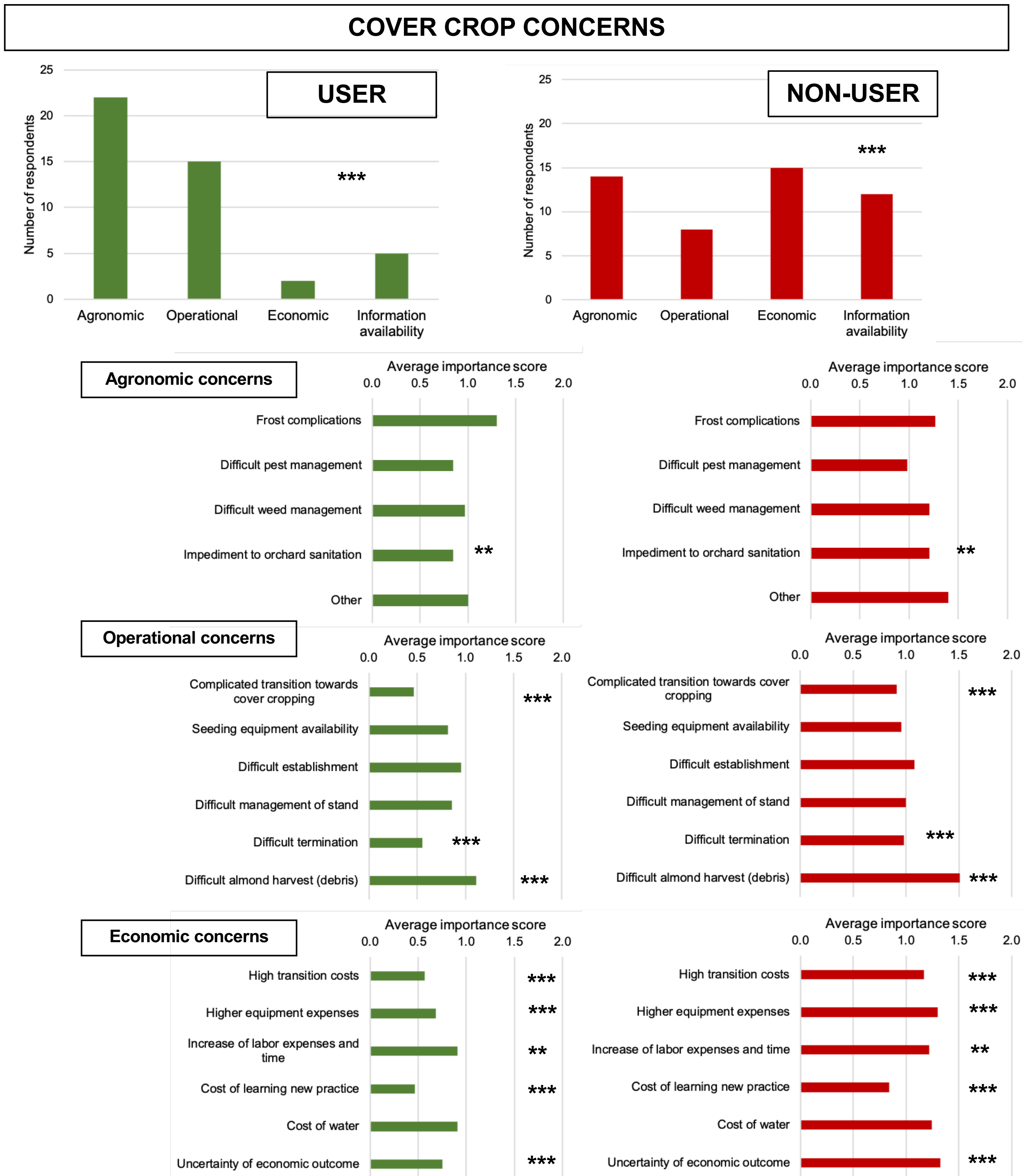


Figure 1.11. Perceived cover crop concerns as influenced by usage group (user and non-user) and average importance score of concerns within agronomic, operational, and economic categorical groups. Significant differences in the ranking distribution were determined using the Mann-Whitney test and are indicated by **(p<0.05), ***(p<0.001) or NSS for not statistically significant.



Chapter 2: Cover crop ecosystem service frameworks reveal distinct sustainability perspectives for agriculture

Abstract

Agricultural sustainability first referenced in the 17th century referred specifically to the longevity of commercial yields. As societal goals for agriculture transcend food production, the sustainability of agroecosystems has taken a multifunctional dimension. Cover cropping, a sustainable agriculture practice, has been demonstrated to support multiple ecosystem services, yet, low adoption of cover cropping suggests a mismatch between concepts of multifunctionality and farmers' perception of sustainability. In this study, we consider the constructs of multifunctionality, as evidenced in scientific literature. We take a constructivist approach to explore the socio-cultural constructs, through which cover crop knowledge has been developed, and how this social quality shapes our appreciation of this practice. We propose that the low adoption of cover cropping is not due to knowledge gaps or lack of integration, but due to a mismatch in value systems, apparent not only between researchers and practitioners, but within science. To address the divergence in value systems, we analyze the contours of researchers' knowledge pathways. Our systematic assessment reveals two distinct systems in the valuation of cover crop services: a biological management approach, which considers ecological conservation, as inherently valuable, irrespective of immediate profitability, and a nutrient management approach, which prioritizes resource conservation for sustainable crop production. Although services are heavily contextualized, the cover crop designs are not. This leaves the risks and challenges of interpretation to practitioners and extensionists. Our findings define the contours of distinct sustainability frameworks within cover crop literature that hold immediate implications for the future development and implementation of the practice. We suggest that the upscale of

cover cropping is held by a valuation-optimization bind whereby confounding ecosystem service value systems and considerable lags in seed design optimization delays cover crop adoption. Unlocking this bind will require the engagement of the seed industry to develop optimized seed varieties and to ensure their widespread distribution. This can only occur with a two-way conversation of value systems between researchers and practitioners, over the rationale of cover cropping as a pillar of sustainable agriculture.

Introduction

Global food systems are challenged with sustainably increasing agricultural productivity, while maximizing ecosystem services and social equity (Tilman *et al*., 2011; Garnet *et al*., 2013). Agricultural productivity is now recognized as a non-linear process, which holds a moral imperative to embrace the wide diversity of cultures and value systems of the populations, which it is meant to sustain (Swinton *et al*., 2006; Reuter, 2018; Zafra-Calvo *et al*., 2020; IFPRI, 2020). As societal goals for today's agriculture transcend food production, agricultural analyses increasingly integrate social and environmental ecosystem services (ES) within complex multi-service assessments (OECD, 2001). Ecosystem service multifunctionality has been defined as the simultaneous provisioning of multiple ecosystem functions and services (Hector & Bagchi, 2007). Due to the immense spatio-temporal complexity of ES and their interactions, system-level research often attempts to reduce this complexity using a reductionist approach to delimit frameworks by which ES can be characterized and bundled (Schipanski *et al*., 2014). However, the selection of ES within a multifunctional whole presents intricate challenges for scientific objectivity. In the social sciences, it has long been recognized that individual observations inherently occur within unique sets of socio-cultural frameworks and thereby entail biases (Middendorf & Busch, 1997).

Random selection as a sampling strategy is designed to support the scientific objectivity of observations (Suppe, 1988). As is often the case in applied science however, some agriculturalists contend that random selection rarely occurs in agricultural research (Suppe, 1988). Instead, the representativeness of agricultural experiments relies on verification through experimental re-testing of hypotheses by researchers and through farmers' empirical evidence. Yet, verification in itself is a non-randomized process. Frequentist perspectives of verification recycle observer biases under the guise of objectivity. The constructionist approach, as used in Bayesian statistics, tests biases with evidence so as to challenge existing knowledge and build objectivity. Verification inherently implies accounting for cognitive (*what is*) and normative (*what should be*) complexities and uncertainties (Dendoncker *et al*., 2018). Therefore, the building of knowledge occurs within distinct socio-cultural valuation systems, apparent in the choice of observation and amplified by the verification process.

Scientists commonly cross socio-cultural boundaries when advancing management recommendations to farmers, and these inherent value structures have intricate implications for agricultural research outcomes. In particular, scientists' application of the ecological concept of multifunctionality to agricultural research has been deeply contested (Manning *et al*., 2018). Indeed, the use of multifunctionality assessments to determine agricultural best management practices (BMPs) implies a transfer of values. In science, multifunctionality is often calculated as an average of standardized values (Byrnes *et al*., 2014; Finney & Kaye, 2017). Yet, any weighing of information within an assessment, even an equal weighing, is a statement on the value of information and therefore implies bias. To address this shortcoming, methods have been developed to value individual indicators in assessments according to stakeholder perceptions (Reed *et al*., 2006; Ravier *et al*., 2015). Literature has demonstrated considerable variation in the mental models, through which different agricultural stakeholder groups process and value information (Jabbour *et al*., 2013; Halbrendt *et al*., 2014). Although knowledge diffusion efforts have elucidated the logic of farmers, as recipients of scientific information, very little work has been done on the upstream production of knowledge, wherein information can be similarly systematized and influenced by scientists' specific interests.

In scientific literature, cover crops are often presented as a panacea, capable of augmenting a plethora of ecosystem services. Yet, for practitioners, it is rather perceived as Pandora's box and has low adoption rates. Despite more than a century of cover crop research and advocacy, studies report low adoption of the practice in many parts of the world, i.e., 1.7% adoption in U.S. farmlands (Neill & Lee, 2001; Eilittä *et al*., 2004; DEFRA, 2017; USDA, 2017; Kinyua *et al*., 2019). We propose that cover cropping's credibility, as a sustainable agricultural practice, cannot be determined solely by scientific knowledge. Rather it is negotiated in cross-cultural interpretations between scientists and farmers. To arrive at a shared meaning of cover cropping for sustainable agriculture, we must not only consult farmers' value systems, but also reflect upon the inherent socio-cultural structures of scientific research. Indeed, transparency and inclusivity in the valuation of ES is especially important, as these services reflect inherently value-laden human-to-nature relationships. We propose that the loss of credibility of cover cropping is not due to knowledge gaps or lack of integration, but rather due to a mismatch in value systems, apparent not only between researchers and practitioners, but within different disciplines in science.

Following a constructivist approach, we consider that ES frameworks are social projections of the inherently subjective human-nature relationship (Dendoncker *et al*., 2018). Thereby, the influence of values and culture in the scientific process is manifest through the distribution of research coverage. Perennial agro-ecosystems (woody and vine) present unique opportunities to explore the impact of cover cropping on a wide breadth of ES interactions. Indeed, the architecture and perennial nature of these systems allow for the exploration of multi-strata, cross-seasonal cover crop effects not commonly observed in annual systems. Perennial agro-ecosystems account for more than 10% of the world's agricultural production (FAO, 2021) and cover approximately 86.3 Mha of agricultural land, globally (Castellano-Hinojosa & Strauss, 2020). We analyzed cover crop field studies (1963-2020) on a global scale, conducted in perennial systems (Figure 2.1; Appendix B – Supplementary Information 2.1). Through an evidence-based systematic assessment, we quantified the comprehensive research coverage of 285 individual ES frameworks, reporting 19 ES for 638 cover crops. By quantifying scientific research pathways, we unearth the leading knowledge frameworks of cover cropping in perennial systems, and their confounding rationales.

Materials and Methods

Evidence-based methods, such as systematic reviews, have been developed to support decision makers by synthesizing existing scientific information (Pullin & Stewart, 2006). Systematic mapping provides a robust method in which disparate research evidence is synthesized to fill the gaps in comprehensive knowledge. Specifically, synthesized datasets may reveal valuation systems and socio-cultural norms through which knowledge is constructed. Qualitative data can bring to light cultural implications of assessment structures and cognitive processes within evaluation systems. Such qualitative data is an especially important component of effective science messaging for non-academic stakeholders and the general public.

Improved transparency in ES valuation is particularly important in sustainable agriculture research, as the boundary between what we *want* versus what we *need* to be sustainable is often confounded. Indeed, sustainability in working landscapes is an inherently social construct. In contrast to conventional meta-analyses, our analysis steps away from statistical processing in the form of combined significance tests or p-values to understand our societal goals towards sustainability. We use descriptive statistics to quantitatively characterize a whole population, which differs from inferential or inductive statistics whereby sample data is collected and processed to understand a wider population. We use summary statistics to gain better understanding of the structures of system-based valuations used in research, shifting focus away from the volume of service outcomes. Systematic mapping enables us to integrate the narrative and visual significance of research distribution across the service linkages explored, to draw a more comprehensive picture of cover crop-mediated services, *in lieu* of fully exhaustive ecosystem assessments.

Data sources and selection of studies

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) process, adapted from Moher *et al.* (2009) was used to populate our database, using the following four steps: identification, screening, eligibility and inclusion. We use the term "perennial agro-ecosystem" or "perennial system" to refer to land-use systems, wherein woody and vine perennials are managed as agricultural crops. Our definition of "perennial systems" overlaps with certain definitions of "agroforestry systems" (FAO, ICRAF), but does not include linear agroforestry systems (i.e., riparian forest buffers, windbreaks…) (USDA). Studies testing the effect of cover cropping in perennial agro-ecosystems under field conditions were identified by searching Web of

Science (Clarivate Analytics ®), BioOne, PLOS, JSTOR, ScienceDirect, Oxford Journals, Springer Link, Taylor and Francis Journals, Wiley Online and WorldCat databases. Records were extracted on 05/05/2020. Keywords included “cover crop” x “orchard”, “cover crop” x “woody”, “orchard” x “floor management”, “woody” x “floor management”, “perennial” x “floor management” and “perennial” x “cover crop”. A total of 859 peer-reviewed studies were extracted from databases. Extracted studies included journals, extension articles and conference materials. Cover cropping was defined as a vegetative cover within orchard alleyways, as well as seeded tree berms. Screening criterion also included research reporting on catch crops, green manure, living mulch and sod. Research in which covers were not integrated within the field such as hedge rows were excluded. Native vegetation was included when grown species were identified. Field research was exclusively selected within either orchard, grove or plantation agroecosystems. Nursery studies, pre-plant studies and pre-mature orchard research were excluded. Greenhouse, glasshouse and pot studies were also excluded. Screening criterion also excluded review-based and model-based research. Because randomized block designs within single orchard plots are often not appropriate for entomology studies, different designs were accepted to compare cover crops to controls. A total of 285 studies remained following the removal of studies that did not meet our criteria.

Valuation of individual ecosystem services and linkages

Our study focuses on the scientific observation process. Studies were deconstructed into individual observations. Each observation corresponded to the monitoring of individual services or the reporting of pairwise services. Therefore, multiple observations were recorded per article. Beyond the valuation of individual ecosystem services, we surveyed co-occurring pairwise services, reported in scientific literature. Service linkages do not reflect effect size, effect exactness nor effect type (synergetic, antagonistic or neutral). Instead, we describe service linkages qualitatively and weigh linkages by their research coverage. This provides a view into the distribution of research among different pathways of scientific inquiry, thereby providing insight into the ways by which cover crop knowledge has been developed. In our study, the term "research coverage" refers to the proportion of studies within the whole body of literature, which replicate the study of a given service or linkage of services. We use the term "knowledge frameworks" or "assessment structures" or "logic", interchangeably to refer to shared pathways of scientific inquiry, in cover crop research. We use the term "specialized frameworks" or "research focus" to refer to mutually exclusive knowledge pathways with high levels of research coverage. Our study takes a constructivist approach whereby ES frameworks reflect the inherently subjective quality of human-nature relationships. We consider that the constructs of specialization and focus are intrinsically tied to scientific interests. We propose that the non-randomization of research coverage reveals socio-cultural constructs, shared situational awareness, and common scientific interests. These often-overlooked social processes define the contours of the mental frameworks and knowledge production pathways of research.

Country of study site and commodity type

We recorded the countries in which the field sites were located (Figure 2.1 and 2.2). For studies where there was more than one field site located in different countries, we recorded each country once. We recorded the type of commodity, in which the field studies were conducted (Figure 2.3). For studies in which there were more than one perennial cash crop in one ecosystem (~1% of studies), we recorded each commodity once. For studies in which there were multiple field sites and different perennial cash crops, we also recorded each commodity once.

Cover crop mix designs

We explored how species selection and assemblages were used to reach varying cover crop objectives. In our study, we recorded the species composition and number of species for each cover crop tested within each article. If individual articles reported more than one cover crop per ES assessment, then multiple cover crops were mapped from one article. We refer to "cover crop optimization" as the process of calibrating the practice and assembling mix species to enhance cover crop response to system-based needs. Plant families, genera of the Fabaceae group and species of the *Trifolium* and *Medicago* plant genera are detailed in Figure 2.8. We define 'trial' as an individual study of a cover crop species within diverse specie assemblages, published in research literature.

Meta-data analysis and visualization

Network mapping and ES assessment framework analysis

We aggregated pairwise service observations to provide a system-wide visualization of cover crop assessments and common ES frameworks. In contrast to Bayesian network analyses, our network map is based on descriptive statistics. Ecosystem service bundles were mapped to observe common knowledge frameworks used in cover crop research, and consistent pathways of investigation (Figure 2.4). The Tableau ® Data Analytics and Visualization Software (2020.2.1) was used to develop network maps. Figures 2.5, 2.6 & 2.7 provide visualization of (1) scientific observations of monitored ES, expressed in the form of nodes, (2) scientific observations of co-occurring pairwise services, in the form of links, and (3) research replications in the form of size and coloration of nodes and links. Nodes represent individual ecosystem services and are labeled accordingly. Nodes were mapped around a circle shape. The width of links followed a continuous scale, reflecting research coverage. The coloration of links was stepped in 3 increments on a 35 scale: increment 1 in yellow illustrates research coverages of 1-12%, increment 2 in orange illustrates coverage of 13-24% and increment 3 in red corresponds to 25-35% coverage. Figures 2.6 & 2.7 uses the same coloration increments as Figure 2.5, with shades of blue. Linkages are not to be read as correlations, rather they represent the pairwise co-occurrence of services within a given study.

We define "common knowledge frameworks", as bundles of services which commonly co-occur within a same study and which have received substantial research attention (increments 2 and 3). The structures of these bundles describe sets of ecosystem services, which are commonly connected within scientific rationales. Thereby, we can visualize the construction of researchers' mental models and experts' shared conceptualization of cover crop functioning. Visually, specialized frameworks appear as clusters within the network of ecosystem services, and are defined as densely connected ecosystem services, represented by nodes, which are sparsely connected to other clusters of the network. These specialized clusters define mutually exclusive networks of ES linkages of high research coverage (increment 2 and 3 links, 13-35% of all studies).

Heatmaps and hot spot analyses

Quantitative information retrieved from studies was used to generate heatmaps, to visualize research 'hot spots' as well as data gaps in our understanding of system-wide cover crop services. The Tableau ® Data Analytics and Visualization Software (2020.2.1) was used to develop the heatmaps. Figure 2.4 mapped research distribution across pairwise co-occurring ecosystem services. Cells of darker coloration indicate common ES knowledge pathways in literature. Figure

2.2 mapped the effect of country and commodity type on research distribution. Hot spots annotated in red indicate contexts of high research coverage, whereas cold spots in yellow and white highlight data gaps and unexplored themes.

Results

Contextualization of knowledge in cover crop research

Our data reveal that much of cover crop knowledge for perennial crops was developed within the distinct regulatory and socio-economic contours of a limited number of countries, whose history is marked by rapid agricultural industrialization (Figure 2.1). Nearly a third of studies were conducted in the United States (31%). The following ten countries accounted for 80% of all studies: (1) United States, (2) Spain, (3) China, (4) Brazil, (5) Canada, (6) Italy, (7) France and (7) Turkey, which held the same number of studies, and (8) India and (8) Portugal, which also held the same number of studies. Our analysis suggests different industry priorities among countries and bio-zones: Brazil distributed cover crop research among 12 perennial systems whereas Spain focused on 4 commodity groups (Figure 2.2). Thereby, much of cover crop research developed within a socio-economic context, characterized by agricultural monocultures, commodity marketization and specialized agri-solutions. Comprehensively, research efforts were most concentrated on apple systems (24% of studies, n=69/285) and vineyard systems (20% of studies, n=58/285) (Figure 2.3). Overall, the five-most researched cropping systems (apple, vineyard, olive, citrus and peach) comprised 67% of all studies. In contrast, only one study each could be found for nearly a third of perennial crops researched (n=13/44). This has important implications for our understanding of the compatibility of cover crops within a diverse range of agronomic contexts (i.e., different planting designs, harvest systems, climatic zones). In a context of heightened momentum to gauge the benefits of crop diversification, research distribution among diverse food crops is of crucial importance.

Non-randomized observation of ecosystem services

We recorded 19 ecosystem services associated with cover cropping, in perennial agroecosystem literature. Our definition of ecosystem services was based on the Millennium Ecosystem Assessment (2005), whose framework is based on works of Costanza *et al*. (1997) and Daily (1997) and based on the framework described by Schipanski *et al*. (2014) for reporting ecosystem services, provided by cover cropping, in agroecosystems. The ecosystem service approach allows for improved representation of dynamic cross-service interactions, as well as the integration of social and environmental perspectives within agroecosystem assessments (Tomich *et al*., 2011). Although much of cover crop research predates the introduction of 'ecosystem services' as a concept, most studies have reported co-occurring ecosystem functions bundled in sets, thereby describing multifunctional processes (i.e., net primary production, N mineralization and yields). We surveyed cover crops ecosystem services to understand the broader benefits of cover cropping, beyond productivity and biodiversity. We recorded research replication and the distribution of studies in the reporting of individual services. Pest suppression services included aboveground and belowground suppression of parasitic nematodes, insect pests and parasitic fungi, and included disease prevention. Biodiversity included aboveground metrics for plant and insect diversity as well as belowground soil fauna, nematode and microbial diversity. Biomass production referred to net primary production, including non-marketable crop growth as well as cover crop productivity.

Of monitored services, 10 ecosystem services were regulating, 7 were supporting services and 3 were provisioning services (Appendix B - Supplementary Information 2.2). Whereas nutrient cycling was investigated in 36% of studies, greenhouse gas (GHG) regulation was reported in <1% of studies (Figure 2.4, Figure 2.5.a). Descriptive statistics revealed a 10-fold research gap between the 5 most-commonly reported ES (nutrient cycling, soil C, N mineralization, water dynamics and biodiversity) and the 7 least-reported ES (soil retention, economic profitability, arbuscular mycorrhizal fungi (AMF) colonization, pollination, wildlife habitat, NO_3^- leaching and GHG regulation). In Figure 2.4, hot spots in research coverage reveal common scientific pathways and a systemization of knowledge production. The heterogenous distribution of research among pairwise ES linkages reveals a non-randomization of scientific observations and therefore, a valuation of knowledge. We observed limited or no representation of certain ES. Of 153 potential pairwise ES associations, nearly a third of ES-interactions (47/153) remain unexplored (Appendix B – Supplementary Information 2.3). Cover crop assessments followed weighed systems of ES valuation, reflecting the different interests and goals of the studies with respect to sustainability (Figure 2.6). Our analysis revealed that 90% (256/285) of articles could be categorized into two specialized frameworks of cover crop ES assessment: the first is a "nutrient management framework", which valued linkages between soil resource management services (Figure 2.6): nutrient cycling, N mineralization, soil C, water dynamics, soil structure, soil retention, AMF colonization, NO_3^- leaching and GHG regulation. The second framework, referred to as the "biological management framework", attributed greater value to linkages among biological services: pollination, wildlife habitat, pest suppression, beneficial insect conservation and weed suppression. Thus, we observe that cover crop knowledge is systematized by scientific domain. Between these two domains, service interactions were poorly explored, delimiting two distinct, mutually exclusive frameworks of cover crop assessment. Crop yields were reported in 49% of nutrient management studies but only 22% of biological management studies. Instead, biological management studies attributed greater value to biodiversity services, monitored in 68% of studies, compared to only 22% in nutrient management frameworks. Thereby, beyond the systemization of knowledge within specialized scientific domains, the two frameworks display separate approaches to sustainability: the first one focused on economic productivity and the second towards biological conservation.

Cover crop species selection and diversity

Our results reveal that cover crop studies conducted in perennial systems included on average 2 species per cover crop in addition to the cash crop and 4 ES per assessment. Of 638 distinct cover crops reported in the literature, 73% (463/638 covers) were single species. Furthermore, 43% of studies (123/285 studies) only studied one cover crop design, half of which (63/123 designs) were single species cover crops. Our results indicate that literature for perennial systems has relied heavily on a limited subset of species in its assessment of cover crop ES. Of 1,446 cover crop trials, ~80% used species belonging to either the Fabaceae, Poaceae or Asteraceae plant families (Figure 2.8). All other plant families (n=46) appeared in ≤13% of trials (Figure 2.8). Of 441 tested species, the five most-studied species (*Trifolium repens, Medicago sativa, Lolium perenne, Trifolium pratense* and *Trifolium subterraneum*) were used in 16% of trials. Overall, *Trifolium* was the most common plant genus, regardless of the intended use of the cover crop. We suggest that the reliance of research on only a handful of cover crop species reflects the limited availability of seed varieties. Our results highlight the need to expand breeding programs as well as seed distribution, so as to broaden the diversity of available cover crop seed options.

Discussion

Evidence of divergent paradigms

While nutrient management frameworks are primarily based on supporting services, biological management frameworks are structured on regulating services. Thus, ES are fragmented categorically by their supporting and regulating value (MEA, 2005). Supporting value suggests an underlying paradigm of ableism and exists on a discrete scale, whereby ecosystem states are differentiated on the basis of an ability to serve. The paradigm of regulation is the preservation of multiple processes and ecosystem qualities: the purpose of regulation is one of moderation and balance, on a continuous scale. Thereby, we observe that each specialized framework abides to separate logics. The first logic, associated with nutrient management frameworks, favors profitability over biodiversity. It ascribes to an anthropogenic view of agriculture (Purvis *et al.*, 2018; Callicott & Mumford, 1997), whereby resource conservation is valued for its ability to sustain socio-economic growth. The second logic, associated with biological management, attributes a higher value to the preservation of nature and its biodiversity, in addition to continued productivity, thereby taking a more biocentric approach. Figure 2.7 further illustrates the divide in cover crop assessment structures, defined by researchers' approach to yields. Comparing across frameworks, we notice strong similarities between productivity and nutrient management frameworks, and noticeable differences between conservation and biological management frameworks. Notably, only the biological management framework links biological processes to gains in net primary production. The fragmentation of scientific research across distinct sustainability paradigms leaves the immensely complex work of interpretation to practitioners. We suggest that addressing lags in the uptake of science-driven solutions requires negotiating a shared strategy, across differential value systems.

Lags in cover crop design

Much of the rationale behind the use of multi-species cover crops is based on the tested diversity-productivity theory, whereby increased diversity is expected to increase cover crop primary productivity and ES, through higher resource use efficiency (Tilman *et al*., 1997). In 1997, foundational work by Tilman *et al*. demonstrated that ecosystem processes not only depend on the identity of species but also the number of species within an ecosystem (Tilman *et al*., 1997). It was shown that the integration of diverse mixtures of species within an ecosystem could support a suite of ecosystem services. At the time, it had been established that productivity could accrue with the addition of up to 5 species. Tilman's later work demonstrated increases in ecosystem productivity with up to 16 species (Tilman *et al*., 1997; Tilman *et al*., 2012). Although these studies were conducted in natural systems, other studies suggest that intentionally increasing plant diversity through cover cropping could substantially augment agroecosystem services (Schipanski *et al*., 2014; Finney & Kaye, 2017). Our results indicating an average of 2 species per cover crop in addition to the cash crop and 4 ES per assessment are in contradiction with Tilman's diversity-productivity theory. The limited use of polycultures may be attributed to the limited availability of improved seed varieties for cover cropping and existing lags in breeding programs for cover crop cultivar development. With unimproved seed varieties, the establishment of species-rich assemblages is especially challenging, due to poor germination and antagonistic interactions between species, limiting productivity. Yet, the use of simplified one- to two-species cover crops restrains our capacity to evaluate the full benefits of higher diversity and of the ecosystem services, supported by polycultures.

Reaching a consensus on the rationale of cover cropping

The lack of marketability of certain ES limits research advancements, which in turn impact stakeholders' valuation and their willingness to invest in these services. We observe that many of unexplored ES linkages pertain to conservation measures and that these ES associations have not been presently ascribed a marketable value. Although some ES linkages may not have enough substance for investigation in research, exploring some of these data gaps could bring valuable updates to our current conception of marketable ES. In his work, Swinton *et al*. discuss the importance of public engagement in valuing ecosystem services for agriculture (2006). Swinton *et al*. suggest that the development of measurement systems is key to create markets and policies, which support the provision of ecosystem services and considers them as outputs (Swinton *et al*., 2006). Frameworks have been developed specifically for cover cropping to account for ES bundles and co-occurrences (Schipanski *et al*., 2014). Beyond the definition of indicators and metrics, assessment structures need to account for dynamics between services in the form of synergies and tradeoffs. Frameworks such as the Sustainable Intensification Framework provide a set of methods, practices, and principles to account for ecosystem dynamics (Musumba *et al*., 2017). This framework integrates social services in its environmental assessment, which evaluates provisioning, regulating and supporting services. Our results indicated that social and cultural services are especially under-represented in the scientific literature. Due to the low representation of knowledge diffusion and cultural services in the articles of our study, these services were not included within our final ES visualization (Appendix A – Supplementary Information 2.4 - Pearson *et al*., 2003; Sastre *et al*., 2017). However, we recognize their importance and the esthetic, spiritual and cultural value of perennial agro-ecosystems.

Dendoncker *et al*. (2018) suggest that the transition towards agroecological practices requires the development and use of integrated ES valuation systems in science. The Sustainable Intensification Framework proposes a set of methods to integrate socio-cultural services with the assessment of agro-ecosystem sustainability (Musumba *et al*., 2017). Other frameworks and processes have also been developed to integrate different motivations for cover cropping: the ES assessment framework for agroecological transitions in practice (Dendoncker *et al*., 2018), the goal-oriented indicator framework (Olsson *et al*., 2009), the adaptive learning process (Reed *et al*., 2006) and the multi-criteria, multi-stakeholder assessment for cover cropping (Ravier *et al*., 2015). Although not yet applied to cover cropping, system-based modelling efforts have developed multi-level storylines and participatory socio-environmental modules to better represent different realities and perspectives within agro-environmental sustainability assessments (Nassar *et al*., 2020). Our dataset reveals that distinct schools of thought have commonly adopted the language of "cover crops". Due to existing differences in the selection of metrics, particularly yields and economic indicators, integrating each realm of research into tradeoff assessments and comprehensive frameworks may be particularly challenging.

Although cover crop knowledge frameworks are intricately contextualized and systematized, the design of cover crops is not. Addressing barriers to cover crop adoption requires that seed design rationales be integrated within cover crop sustainability discourse. Indeed, formal literature rarely explicitly describes researchers' processes of seed selection or clarify the chosen design criterion of tested cover crops. Our analysis reveals that, within ES assessments, primary production services have largely been recognized as the core component of ES provision. Biomass production was the most-reported ES, monitored in 64% of studies. In comparison, biodiversity was monitored in only 36% of studies (Figure 2.4, Figure 2.5.a). Emerging research has revealed that, aside from net primary productivity, plant functional traits (i.e., biological N fixation, leaf area index, floral display) are reliable predictors of cover crop ES (Finney & Kaye, 2017; Smith *et al*., 2014; Blesh, 2017). Advancements in the understanding of the linkages between multifunctionality and plant functional diversity open new opportunities to elaborate cover crop seed selection rationales (Tribouillois *et al*., 2015; Faucon *et al*., 2017). This highlights new opportunities to optimize cover crop selection, to meet stakeholders' desired outcomes.

The widespread adoption of cover cropping is delayed by sets of catch-22s. With limited economic compensation for cover cropping, seed costs constitute an important opportunity cost for farmers, leading research to focus on low-cost mixes of one to two species. We observe a noticeable lag in development of new cover crop cultivars, despite the need for improved seed varieties. Poor germination, winter-kill and indeterminate flowering limit the beneficial outcomes of unimproved seed varieties. The use of simplified mixtures in cover cropping restrains our capacity to capitalize on the synergetic effects of higher diversity for ES delivery, predicted by Tilman's diversity-productivity theory (Tilman *et al*., 1997). Thereby, the transition towards cover cropping is held by a valuation-optimization bind, whereby development is constrained by lack of perceived value and value is limited by lack of optimization. Considering the socio-cultural process of catch-22s, addressing these complexities will require recognizing shared priorities and negotiating a common vision, across differential value systems. We propose that reaching a consensus over the rationale of cover cropping for sustainable agriculture requires that decision-processes in seed selection be elucidated and integrated within the broader sustainability discourse. With clear and comprehensive systems of ES valuation, optimization can integrate experiential feedback to scientific knowledge, and develop seed selection, which reflects practitioners' system-based objectives. This will require the important engagement of the seed industry to establish breeding programs and regional optimization trials, as well as the work of seed distributors to secure widespread availability of improved cover crop varieties.

Limitations and Future Research

Our keyword selection procedure had limitations. Future research would need to verify the representativeness of our subset of studies. There likely exist additional relevant cover crop research articles for perennial systems. These articles may have used the terms "cover-crops", "cover crops", "soil health practice", "soil management practice", "conservation practice" to refer to the same practice. Our selection process may not have collected these articles. There likely exist more than 285 studies reporting on this subject.

In total, research investigated cover cropping effects across 44 commodities and 36 countries. Although these data provide important insight into the distribution of this research across the agricultural landscape, it may not reflect countries' respective contribution to the research, as lead and/or partnering institutions, nor does it report on the distribution of research between industry, governmental and university sectors. It is important to note that our database presented a regional data gap, as there were no studies conducted in Russia. Prior literature indicates that considerable work was conducted by researchers of the Soviet Union on the role of cover crops in supporting biological control in orchards (Altieri & Schmidt, 1985). In particular, we were unable to access works of Telenga (1958) and Chumakova (1960). Furthermore, although some of the literature included was in Portuguese, Chinese and French, the vast majority of literature included in this study was in English and therefore may not have encompassed the full breadth of knowledge available internationally.

Conclusion

In this time of transformative change, we must reflect upon the relevance of the leading normative and cognitive systems of knowledge production and the decision frameworks they support. By doing so, we may reconcile for the asymmetries in social realities and cultural meaning, to build a more inclusive conceptualization of agricultural sustainability. Conceptual growth comes from negotiating meaning, sharing multiple perspectives of reality and creating a shared vision. In this study, we take a constructivist approach to explore the socio-cultural constructs through which cover crop knowledge has been developed, and how this social quality shapes our appreciation of this practice. We bring to light the disparate nature of the two leading scientific rationales for cover cropping, and their distinct visions of sustainable agriculture: anthropogenic conservation and biocentric preservation. The anthropogenic conservation approach is directed towards natural resource conservation for sustainable consumption. The ecological preservation approach assumes nature is inherently valuable, irrespective of immediate profitability. This leaves the risks and challenges of interpretation to practitioners, who must make multi-disciplinary decisions. Although cover crop ES are intricately systematized, the design of the practice is not. We suggest that the increased adoption of cover cropping is held by a valuation-optimization bind whereby confounding ES value systems and considerable lags in seed design optimization delays cover crop utilization. Unlocking this bind will require the engagement of the seed industry to develop optimized seed varieties and to ensure their widespread distribution. This can only occur with a two-way conversation of value systems between researchers and practitioners, over the rationale of cover cropping as a pillar of sustainable agriculture.

References:

The articles used for the meta-analysis are listed in Appendix B – Supplementary Information 2.4

Altieri, M.A. and Schmidt, L.L. 1985. Cover crop manipulation in Northern California orchards and vineyards: Effects on arthropod communities: Biological agriculture & Horticulture 3:1-24.

Blesh, J. 2017. Functional traits in cover crop mixtures: biological nitrogen fixation and multifunctionality. Journal of Applied Ecology 55:38-48.

Byrnes, J.E. *et al*. 2014. Investigating the relationship between biodiversity and ecosystem multifunctionality: Challenges and solutions. Methods Ecol. Evol. 5(2):111–124.

Callicott, J.B. and Mumford, K. 1997. Ecological Sustainability as a conservation concept. Conservation Biology 11:32-40.

Castellano-Hinojosa, A. and Strauss, S.L. 2020. Impact of cover crops on the soil microbiome of tree crops. Microorganisms 8:328.

Chumakova, B.M. 1960. Supplementary feeding as a factor increasing the activity of parasites of harmful insects. Trudy-Vsesoyznogo Nauchno-issledovatel-scogo Instituta Zashchity Rastenii 15:57-70.

Costanza, R. *et al*. 1997. The value of the world's ecosystem services and natural capital. Nature 387:253-260.

Daily, G. 1997. Nature's Services: Societal Dependence on Natural Ecosystems. Island Press. Washington D.C., USA.

Dendoncker, N. *et al*. 2018. How can integrated valuation of ecosystem services help understanding and steering agroecological transitions? Ecology and Society 23(1):12.

Department for Environment, Food and Rural Affairs (DEFRA). 2017. Ecological Focus Areas: features on farms in England 2015/2016. Department for Environment, Food and Rural Affairs. London, UK.

Eilittä, M. *et al*. 2004. Green Manure/Cover Crop Systems of Smallholder Farmers. Springer Netherlands.

Faucon, M.P., Houben, D. and Lambers, H. 2017. Plant Functional Traits: Soil and Ecosystem services. Trends in Plant Science 22:385-394.

Finney, D.M. and Kaye, J.P. 2017. Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system. Journal of Applied Ecology 54:509-517.

Garnet, T. *et al*. 2013. Sustainable intensification in agriculture: premises and policies. Science 341:33-34.

Halbrendt, J. *et al*. 2014. Differences in farmer and expert beliefs and the perceived impacts on conservation agriculture. Global Environmental Change 28:50-62.

Hector, A. and Bagchi, R. 2007. Biodiversity and ecosystem multifunctionality. Nature 448:188–190.

International Food Policy Research Institute (IFPRI). 2020. Global Food Policy Report: Building Inclusive Food Systems. International Food Policy Research Institute. Washington, D.C., USA.

Jabbour, R., *et al*. 2013. Mental models of organic weed management: comparison of New England US farmer and expert models. Renew. Agric. Food Syst. 29:319-333.

Kinyua M. *et al*. 2019. Green manure cover crops in Benin and Western Kenya - A review. CIAT Publication No. 481. International Center for Tropical Agriculture (CIAT). Nairobi, Kenya.

Manning, P. *et al*. 2018. Redefining ecosystem multifunctionality. Nature Ecology & Evolution 2:427-436.

Middendorf, G. and Busch, L. 1997. Inquiry for the public good: Democratic participation in agricultural research. Agriculture & Human Values 14:45-57.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and Human Well-Being: Synthesis. Island Press. Washington D.C., USA.

Moher, D., Liberati, A., Tetzlaff, J. and Altman, D.G. 2009. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. Ann. Intern. Med. 154:264-269.

Musumba, M., Grabowski, P., Pal,, C. and Snapp, S. 2017. Guide for the Sustainable Intensification Assessment Framework. Available at: https://www.k-state.edu/siil/resources/framework/index.html

Nassar, J.A.B., Malard, J., Adamowski, J.F., Ramirez, M.R., Medema, W. and Tuy, H. 2020. Multi-level storylines for participatory socio-hydrological modelling – involving marginalized communities in Tz'oloj Ya', Mayan Guatemala. Hydrol. Earth Syst. Sci. 25:1283-1306.

Neill, S.P. and Lee, D.R. 2001. Explaining the adoption and disadoption of sustainable agriculture: the case of cover crops in Northern Honduras. J. Econ. Dev. Cult. Change 49 (4):793–820.

OECD. 2001. Multifunctionality: Towards an Analytical Framework. OECD Publications. France.

Olsson, J.A., Bockstaller, C., Stapleton, L.M., Ewert, F., Knapen, R., Therond, O., Geniaux, G., Bellon, S., Correira, T.P., Turpin, N. and Bezlepkina, I. 2009. A goal oriented indicator framework to support integrated assessment of new policies for agri-environmental systems. Environmental Science & Policy, 12(5):562-572.

Pullin, A.S. and Stewart, G.B. 2006. Guidelines for systematic review in conservation and environmental management. Conserv. Biol. 20:1647-1656.

Purvis, B., Mao, Y. and Robinson, D. 2018. Three pillars of sustainability: in search of conceptual origins. Sustainability Science 14:681-695.

Ravier, C., Prost, L., Jeuffroy, M.-H., Wezel, A., Paravano, L. and Reau, R. 2015. Multi-criteria and multi-stakeholder assessment of cropping systems for a result-oriented water quality preservation action programme. Land Use Policy 42:131-140.

Reed, M.S., Fraser, E.D.G., Dougill, A.J. 2006. An adaptive learning process for developing and applying sustainability indicators with local communities. Ecological Economics 59:406-418.

Reuter, T. 2018. Understanding food system resilience in Bali, Indonesia: a moral economy approach. Culture, Agriculture and Environment 41:4-14.

Schipanski, M.E. *et al*. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agricultural Systems 125:12-22.

Smith, R.G., Atwood, L.W. and Warren, N.D. 2014. Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. PLoS ONE 9:e97351.

Suppe, F. 1988. The limited applicability of agricultural research. Journal of Agricultural Economics Research 40:1-14.

Swinton, S.M., Lupi, F., Robertson, G.P. and Landis, D.A. 2006. Ecosystem services from agriculture: Looking beyond the usual suspect. Amer. J. Agr. Econ. 88:1160-1166.

Telenga, N.A. 1958. Biological methods of pest control in crops and forest plants in the USSR. Report of the Soviet Delegation. 9th International Conference on Quarantine and Plant Protection, 15.

Tilman, D., Balzer, C., Hill, J. and Befort, B.L. 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108:20260–20264.

Tilman, D., Lehman, C.L. and Thomson, K.T. 1997. Plant diversity and ecosystem productivity: Theoretical considerations. PNAS 94:1857-1861.

Tilman, D., Reich, P.B. and Isbell, F. 2012. Biodiversity impacts ecosystem productivity as much as resources, disturbance, or herbivory. PNAS 109:10394-10397.

Tomich, T.P. *et al*. 2011. Agroecology: A review from a global-change perspective. Annu. Rev. Environ. Resour. 36:193-222.

Tribouillois, H., Fort, F., Cruz, P., Charles, R., Flores, O., Garnier, E. and Justes, E. 2015. A functional characterisation of a wide range of cover crop species: growth and nitrogen acquisition rates, leaf traits and ecological strategies. Plos One 10(3): e0122156.

United Nations Food and Agriculture Organization (FAO). Available online: http://www.fao.org/faostat/en/#data/RL (accessed on 15 January 2021).

US Department of Agriculture (USDA) National Agricultural Statistics Service. 2017. Census of Agriculture. Chapter 2, Table 41–Land Use Practice.

Zafra-Calvo, N. *et al*. 2020. Plural valuation of nature for equity and sustainability: Insights from the Global South. Global Environmental Changes 63:102115.

Figure 2.1. Global distribution of cover crop field research for perennial systems. Field research, reported in the comprehensive literature (n=285), was distributed between 36 countries. Circle size and coloration reflect the respective number of studies per country or region, ranging from 1 to 90 studies. The differential color and size of circles reflect the heterogeneous distribution of cover crop field research among countries. This distribution shows that cover crop field research occurred within a limited set of countries. Circle diameters are proportional to the number of studies conducted per country, as indicated by the grey bars scaled from 1-100 in the legend.

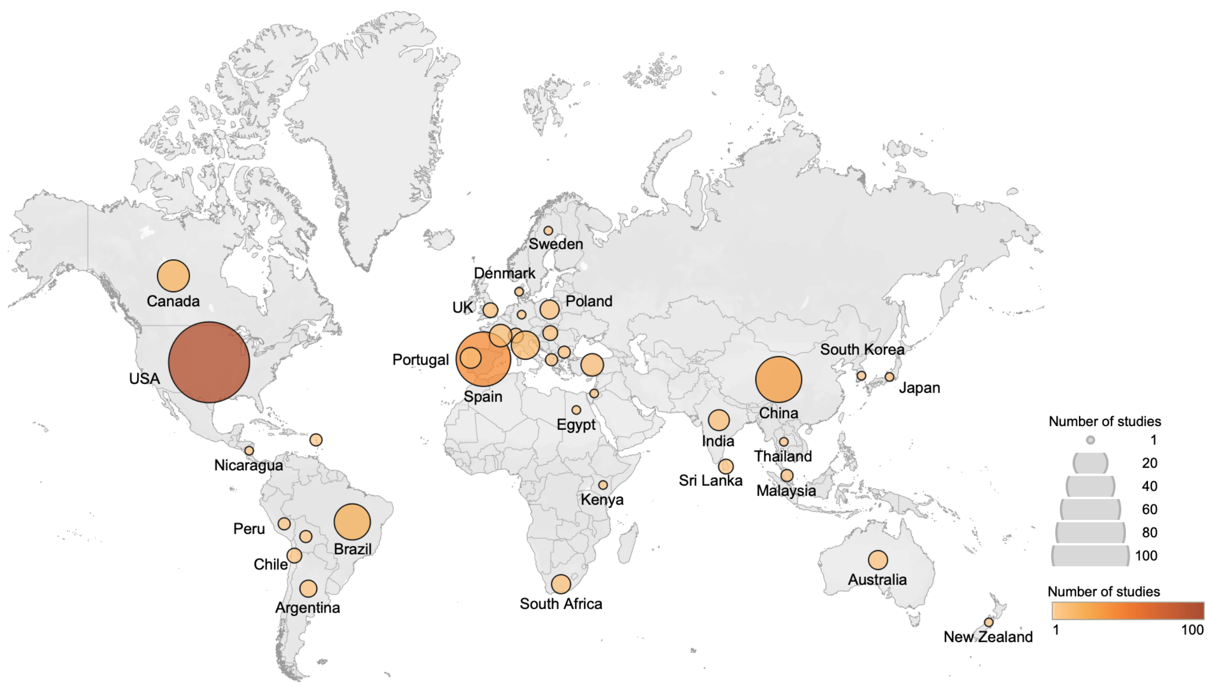


Figure 2.2. Distribution of cover crop research, by perennial system, distinct to country. Due to the high quantity of research conducted in the USA, research was presented by state. Research distribution between the types of perennial crop reveal distinct interests and priorities by country, which likely reflect different socio-economic contexts and bio-zones.

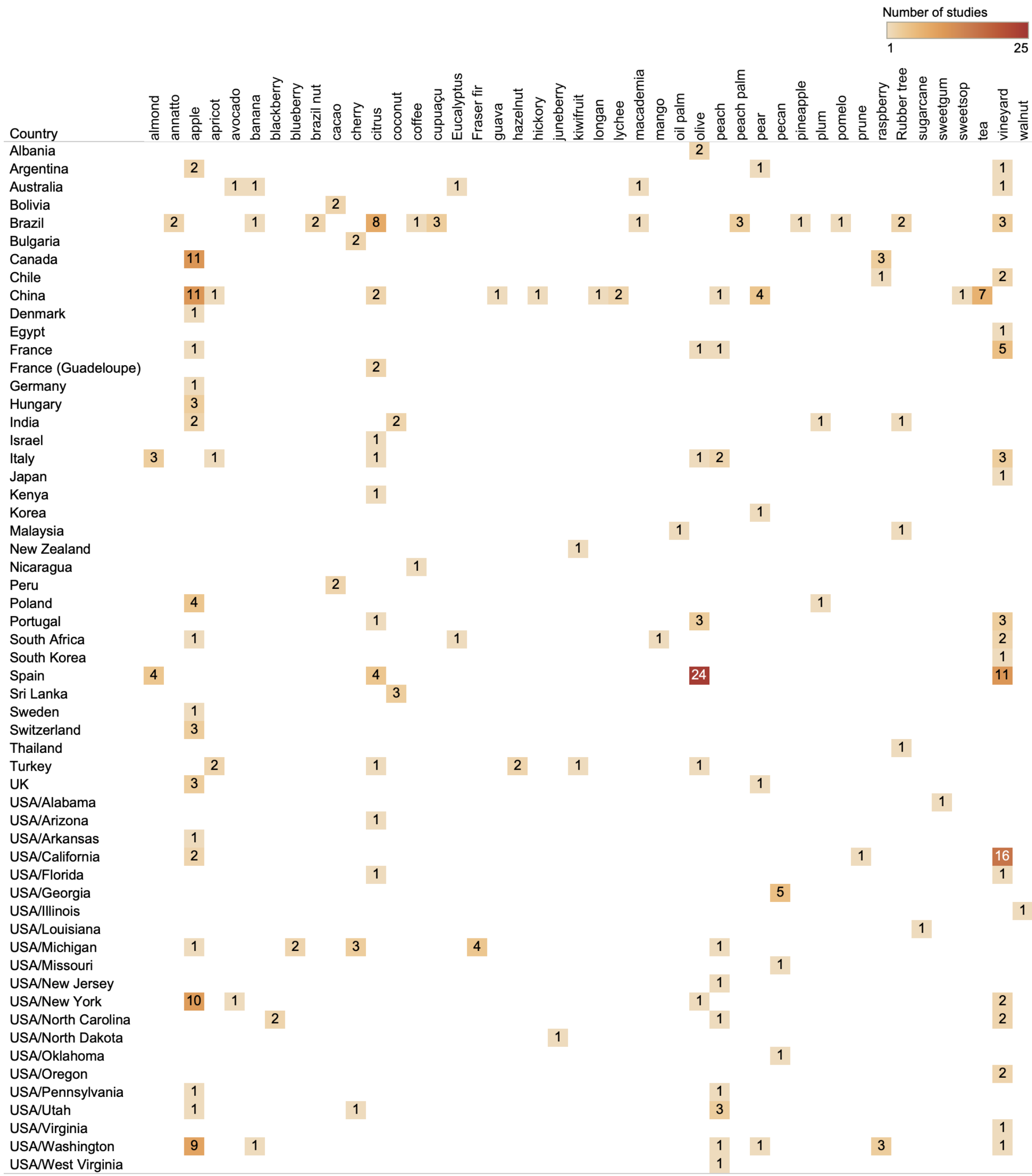


Figure 2.3. Distribution of cover crop research by perennial crops. Perennial crops are classified by yield category: 'fruit and nut' or 'other', which encompasses all other products including tea, rubber, timber, etc. Literature reported cover cropping research, conducted in 44 different perennial crops (woody and vine), suggesting a common interest for cover crops, across a diverse set of agronomic contexts. Data reveal differential research coverage by perennial crop.

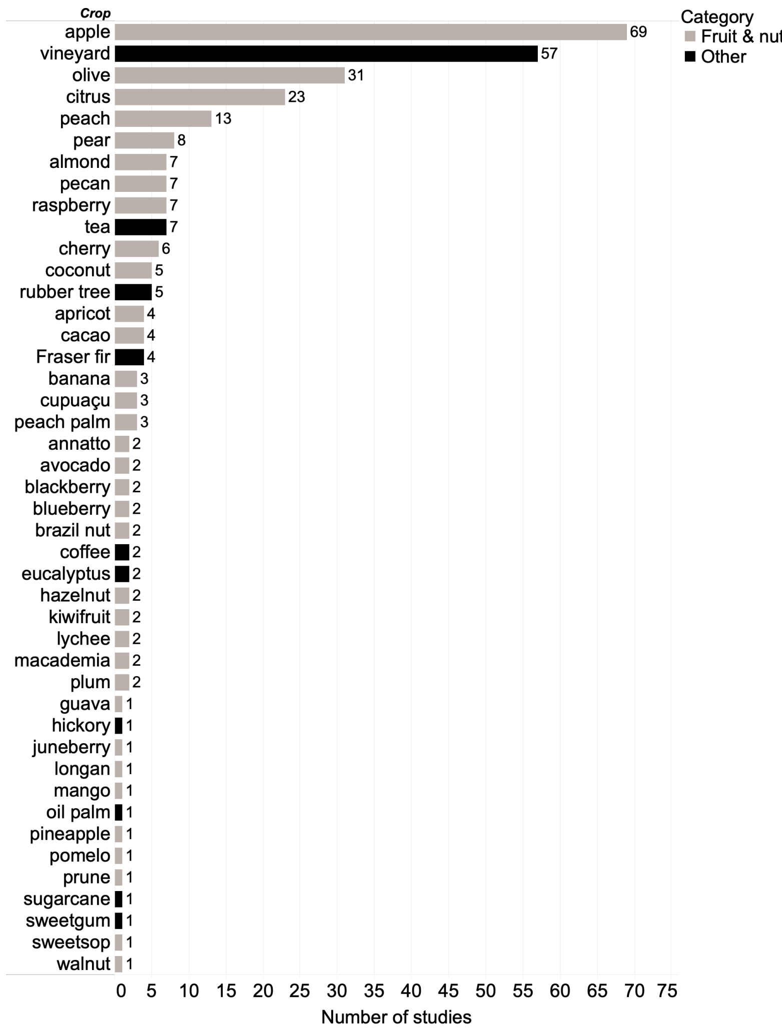
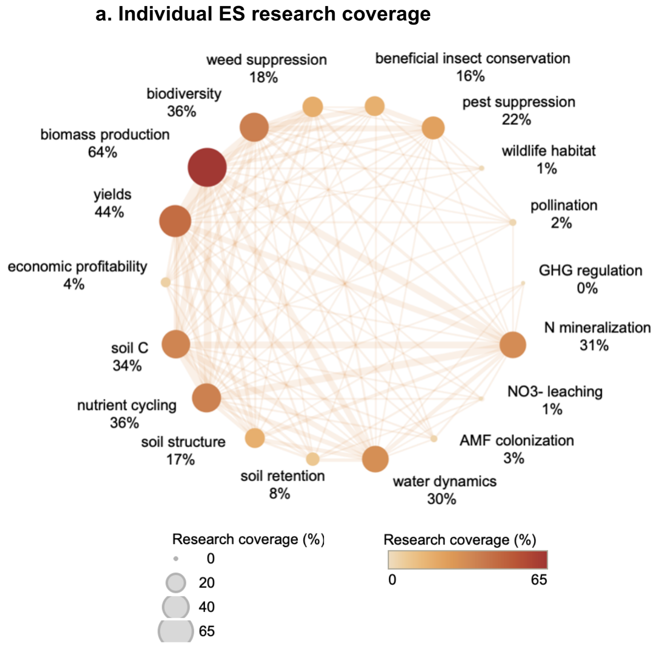


Figure 2.4. Distribution of research among pairwise ecosystem service (ES) linkages, in cover crop literature, for perennial agro-ecosystems. Cell color and annotation reflect the number of studies, which replicate the study of a given pairwise ES linkage. The heterogenous distribution of research among pairwise ES linkages reveals a non-randomization of scientific observations and a valuation of knowledge. ‘Hot spots’, illustrated by cells of darker coloration, reveal common scientific pathways and a systemization of knowledge production. These pathways shape the contours of cover crop knowledge.

ES	soil C	nutrient cycling	N mineralization	water dynamics	soil structure	soil retention	NO3- leaching	GHG regulation	AMF colonization	economic profitability	yields	biomass production	pollination	wildlife habitat	weed suppression	beneficial insect conservation	pest suppression	biodiversity
soil C		73	60	44	32	15	2	0	5	1	46	58	1	0	12	1	3	25
nutrient cycling	73		66	36	26	7	2	1	5	5	52	67	1	1	15	1	8	26
N mineralization	60	66		29	23	6	2	1	5	3	50	64	1	0	12	1	2	18
water dynamics	44	36	29		30	21	1	1	2	3	43	55	0	0	8	1	2	12
soil structure	32	26	23	30		10	0	1	0	2	20	25	0	0	1	0	1	5
soil retention	15	7	6	21	10		1	0	0	0	6	9	0	0	0	0	1	1
NO3- leaching	2	2	2	1	0	1		0	0	0	2	2	0	0	0	0	0	0
GHG regulation	0	1	1	1	1	0	0		0	0	0	0	0	0	0	0	0	0
AMF colonization	5	5	5	2	0	0	0	0		0	3	5	0	0	3	0	0	3
economic profitability	1	5	3	3	2	0	0	0	0		11	10	0	0	6	1	2	3
yields	46	52	50	43	20	6	2	0	3	11		94	5	1	23	9	12	28
biomass production	58	67	64	55	25	9	2	0	5	10	94		1	1	45	14	27	49
pollination	1	1	1	0	0	0	0	0	0	0	5	1		0	0	5	3	5
wildlife habitat	0	1	0	0	0	0	0	0	0	0	1	1	0		0	0	2	3
weed suppression	12	15	12	8	1	0	0	0	3	6	23	45	0	0		1	3	27
beneficial insect conservation	1	1	1	1	0	0	0	0	0	1	9	14	5	0	1		43	42
pest suppression	3	8	2	2	1	1	0	0	0	2	12	27	3	2	3	43		49
biodiversity	25	26	18	12	5	1	0	0	3	3	28	49	5	3	27	42	49	

Number of studies
0 100

Figure 2.5. Map of knowledge production pathways in cover crop scientific research, for perennial systems. a. Individual ecosystem service (ES) research coverage. b. Pairwise ES linkage research coverage. We define "research coverage" as the proportion of studies within the whole body of scientific literature, which replicate the study of a given service or linkage of services. Research coverage is represented either by a) node or b) link coloration and size. Link coloration follows 3-step increments: increment 1 illustrates research coverages of 1-12 %, increment 2 corresponds to 13-24% coverage, and increment 3 corresponds to 25-35% coverage.



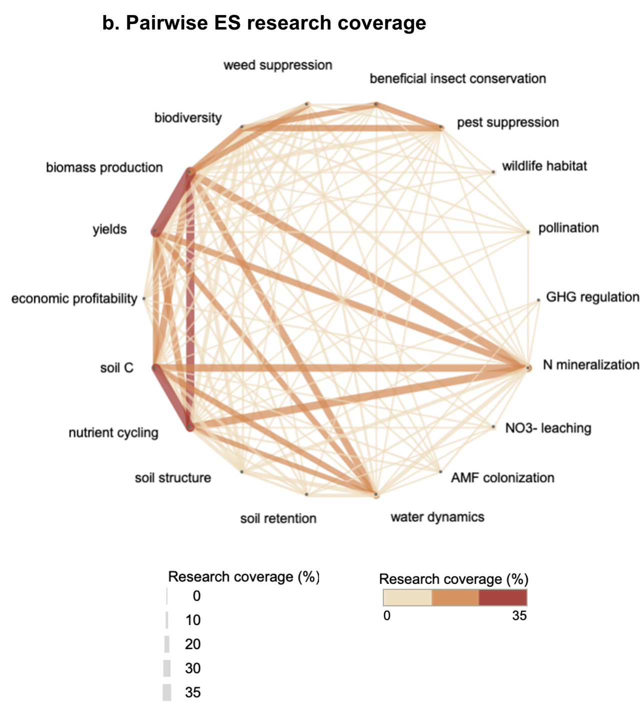


Figure 2.6. Map of specialized knowledge pathways in cover crop scientific research, for perennial systems. a. Biological management knowledge frameworks, defined as those measuring one or more of the following ES: [Pollination], [Wildlife habitat], [Pest suppression], [Beneficial insect conservation] and [Weed suppression]. b. Nutrient management knowledge frameworks, defined as those measuring one or more of the following ES: [Nutrient cycling], [N mineralization], [Soil C], [Water dynamics], [Soil structure], [Soil retention], [AMF colonization], [NO_3^- leaching] and [GHG regulation]. Common knowledge pathways within either specialized framework are differentiated by their greater research coverage and illustrated by linkages of color increments 2 and 3.

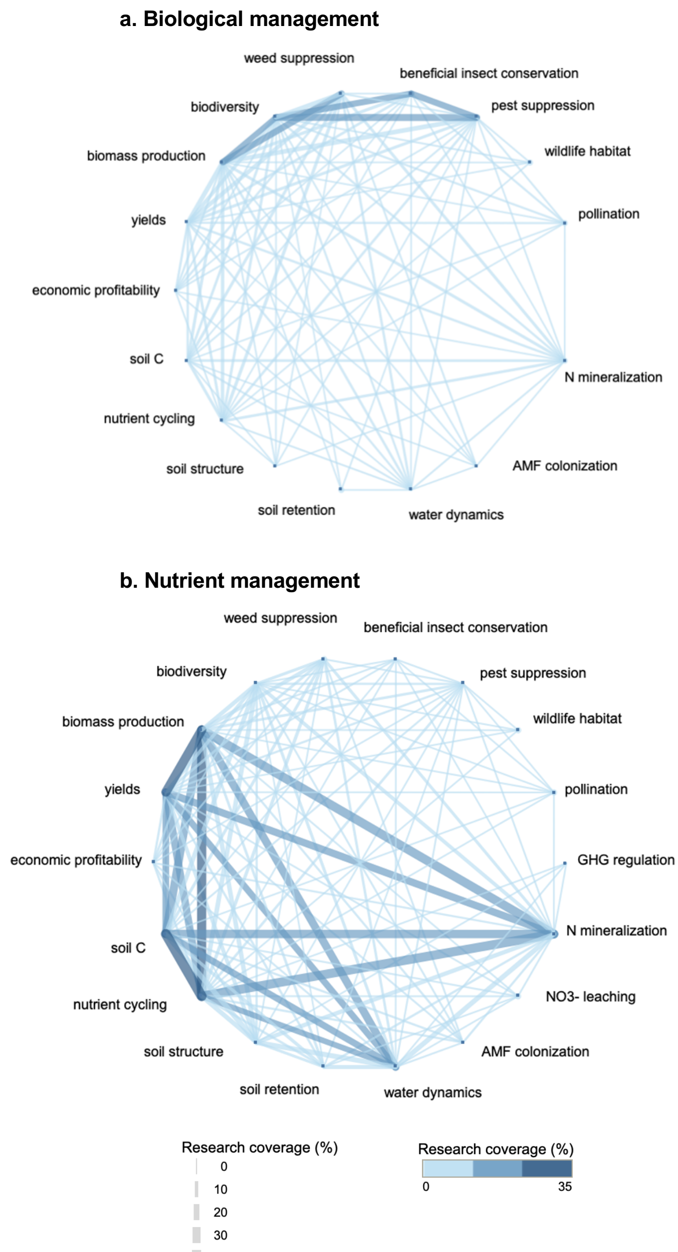


Figure 2.7. Map of knowledge pathways, distinct to research focus in cover crop literature for perennial systems. a. Knowledge frameworks associated to a conservation focus, defined as research, which did not report agronomic yields. b. Knowledge frameworks associated to a productivity focus, defined as research reporting yields. Common knowledge pathways associated with each focus are illustrated by larger link sizes and darker coloration. Data demonstrate that the fragmentation of research, on the basis of yields, generated distinct systems of knowledge production.

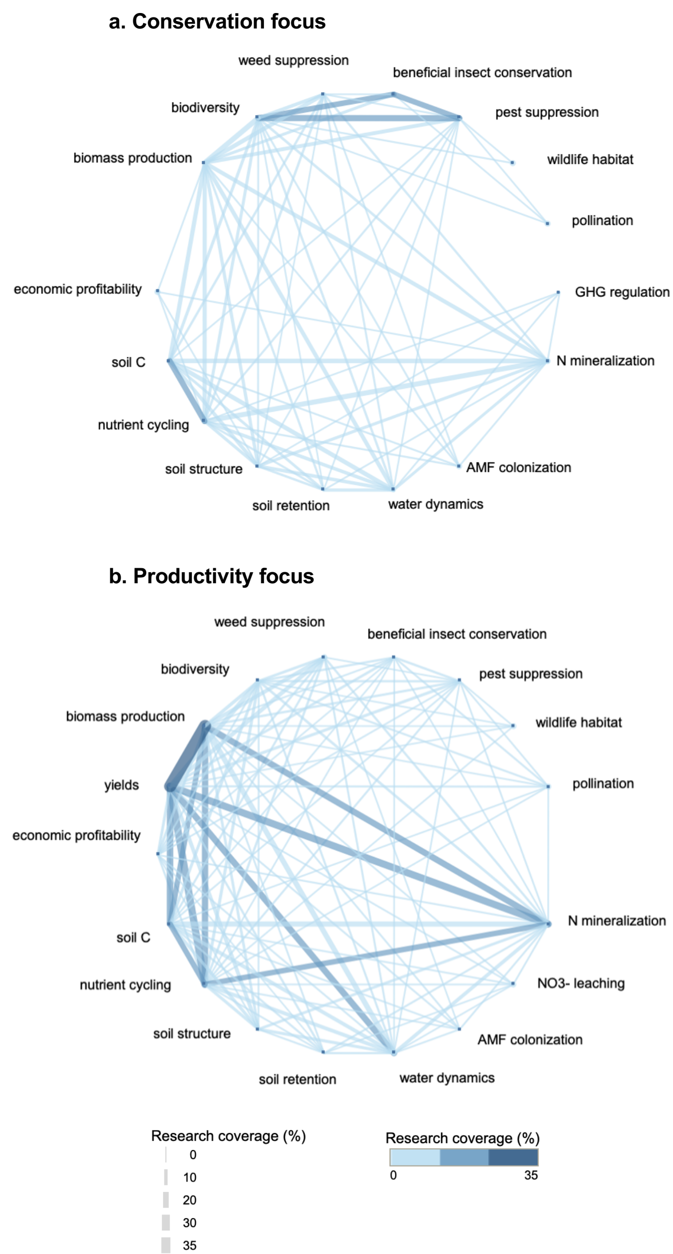
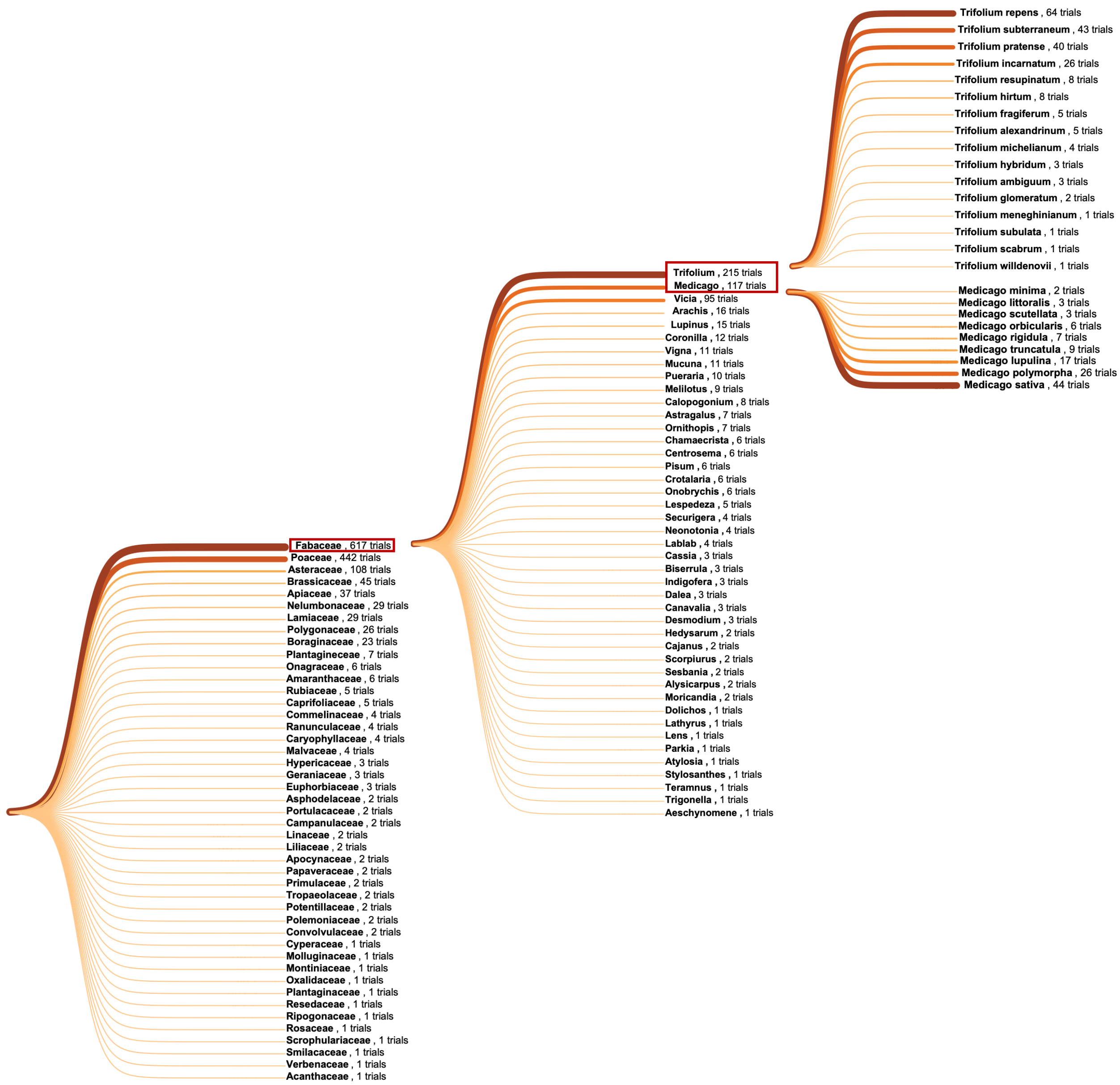


Figure 2.8. Dendrogram indicating the number of research trials conducted per cover crop plant family, genus and species. Common research pathways are illustrated by larger link sizes and darker coloration. Data were aggregated from cover crop studies conducted in perennial systems (woody and vine). We define 'trial' as an individual study of a cover crop species within diverse specie assemblages, published in research literature.



Chapter 3: Ecosystem service measurements reveal that the sustainable use of cover crops is specific to perennial crop type

Abstract

Cover crops have been touted for their capacity to enhance multifunctionality and ecosystem services (ES). Ecosystem services are benefits which people obtain from ecosystems. Despite nearly a century of cover crop research, there has been low adoption of the practice in perennial systems of many parts of the world. Emphasis on the multi-functional dimension of cover crop outcomes may misrepresent the practice as a panacea for sustainable agriculture and distract from the need to tailor the practice to specific contexts and differing value systems. In this study, we explore how cover crop ecosystem service frameworks reflect the distinct environmental realities of perennial agriculture. We considered that ES value systems are manifested through the non-randomization of research coverage. Therefore, value systems can be elucidated through evidence-based systematic mapping. Our analysis revealed differential systems of ES valuation specific to perennial crop types. While ES frameworks are heavily contextualized, the design of seed mixes is not. We suggest that cover crop adoption could be enhanced by clearly acknowledging the different conceptualizations of agricultural sustainability addressed by various cover crops. Furthermore, explicitly delineating the competing desires of stakeholders is a crucial step in rationally selecting between various cover crop seed mix options.

Introduction

After more than a century of cover crop field research, scientific discourse has acknowledged the important contribution of cover cropping to the sustainability of food systems. The rationale behind the use of multi-species cover crops in support of agricultural sustainability is based on Tilman's diversity-productivity theory. Tilman demonstrated that increased diversity could augment cover crop primary productivity and ES through higher resource use efficiency (Tilman *et al*., 1997). Thereby, ecosystem processes are not only dependent on the identity of species, but also on the number of species within a given ecosystem. Although initial studies suggested increased productivity with up to five species within an ecosystem, later work demonstrated benefits with up to 16 species (Tilman *et al*., 1997; Tilman *et al*., 2012). These studies were originally applied to natural ecosystems and then to cover crop studies for agro-ecosystems (Smith al., 2020; Housman *et al*., 2021; Florence *et al*., 2019). More recent research demonstrates that, beyond improvements in resource use efficiency, increased diversity may benefit ecosystem functioning by supporting diverse plant functional traits (biological N fixation, floral display, leaf area index and ground coverage) (Finney & Kaye, 2017; Smith *et al*., 2014; Blesh, 2017). These recent findings highlight opportunities to align cover crop seed selection and design to meet differential conceptualizations of agricultural sustainability.

The outcomes of cover cropping have been broadly introduced across the scientific literature as a cumulative suite of ecosystem services: soil retention, pollinator habitat provision, weed control, improved soil physical properties, carbon sequestration, biocontrol services, enhanced water quality and improved nutrient cycling (Vicente-Vicente *et al*., 2016; Vukicevich *et al*., 2016; Gomez, 2017). Recent literature demonstrates that cover crop services occur in bundles (Finney *et al*., 2017; Raudsepp-Hearne *et al*., 2010). However, comprehensive studies verifying the co-occurrence of these many services remain scarce (Shackelford *et al*., 2019). Managing for the co-occurrence of multiple ecosystem services holds challenges—for instance, mowing N-rich vegetative covers to improve nutrient cycling may be incompatible with the provision of floral resources to increase pollinators. In turn, promoting flowering of cover crops may come at the cost of higher water consumption for an orchard. Perennial agro-ecosystems (woody and vine) provide unique opportunities to explore the benefits of a wide variety of cover crop uses and functions (Bugg *et al*., 1991; Altieri & Schmidt, 1985; Garcia *et al*., 2018; Pardini *et al*., 2002). Perennial systems represent an enormous diversity of cropping systems, varying in planting design (i.e., square, offset and hedgerow configurations), harvest strategies (i.e., mechanical harvests in cherry systems compared to dry floor harvests in almond) and pruning (i.e., removal of pruning residues compared to on-site mulching) (Ramos, 1997; Micke, 1996). These diverse agronomic practices reflect the different climates, soil types and economic contexts of perennial production systems and have immediate implications for the management of cover crops and their associated ES (Power, 2010; Demestihas *et al*., 2017; Kragt & Robertson, 2014; Syswerda & Robertson, 2014). These differences in management directly influence cover crop management, including the timing of cover crop seeding, the feasibility of berm cover, the degree of soil surface coverage and the ease of mowing operations (Ingels, 1998; Grant *et al*., 2006). Compared to annuals or biennials, the perennial nature of woody and vine systems provides opportunities to study cover crops across multiple seasons and to explore different termination dates. In perennial systems, cover cropping can potentially fulfil a diversity of functions within these systems (i.e., pest suppression, soil retention, etc.), and take different forms, based on varying ecosystem service valuation systems.

Although ecological rationales for cover cropping have been elucidated, the implementation of the practice lags. There has been slow and limited adoption of cover cropping in many parts of the world (i.e., only 1.7% in US farmlands) (Neill & Lee, 2001; Eilittä *et al*., 2004; DEFRA, 2017; USDA, 2017; Kinyua *et al*., 2019). This disconnect is important because to address societal imperatives (i.e., large-scale initiatives like the Soils for Food Security and

Climate 4/1000 Initiative, the UN Sustainable Development Goals and the UN Convention on Biological Diversity), the widespread adoption of sustainable agricultural approaches must occur, and cover cropping is a cornerstone practice. We believe a major gap between the establishment of scientific evidence and the actual uptake of sustainable agronomic practices is hindering progress. We suggest that lags in cover crop adoption reveal a mismatch between the scientific discourse and the relevance of the practice to growers. Surveys and focus group studies of practitioners have explored key factors involved in the decision to use cover crops. These factors include barriers (i.e., difficult management of the cover crop, cost of establishment and market forces) (O'Connell *et al*., 2015; Moore *et al*., 2016; Dunn *et al*., 2016; Roesch-McNally *et al*., 2018) and motivators (i.e., increased soil organic matter, support of biodiversity) (O'Connell *et al*., 2015; Moore *et al*., 2016). Although the literature contains reports on the logic of practitioners for cover cropping, very little work has been done on the production of scientific knowledge, in which information can be similarly systematized to reflect scientists' values. We suggest that the dissemination of cover crop knowledge from scientists to extensionists and stakeholders may reflect differential value systems, which obscure the benefits of multi-species covers and penalize them for economic constraints. We consider that lags in cover crop adoption are not solely due to knowledge gaps and uncertainties, but are the result of differing ES valuation systems and, particularly, different prioritizations of economic profitability, relative to other ecosystem services.

A large body of literature has attempted to create a consensus in terms of a common, coherent definition of sustainability (Purvis *et al*., 2018; Seager, 2018). However, some claim that sustainability as a concept is inherently malleable, due to its socio-cultural foundation and the existence of differing environmental realities (i.e., soil type, bio-zones and vulnerabilities to climate change, etc.). Hence, the meaning of sustainability exists on a spectrum of interpretations.

Ecosystems services refer to the many additional services beyond food production, which society gains from agroecosystems. We propose that the ways in which ecosystem services are valued in cover crop assessments reflect different conceptualizations of agricultural sustainability. In the first section, we provide a literature review of cover crop developmental history, to consider how the development of the practice has historically reflected shifts in societal preferences and sustainability goals. In the second section, we conduct a meta-analysis of cover crop literature conducted in perennial systems and ask whether the nature of the ecosystem services measured within cover crop studies are dependent on commodity type. We ask how the malleability of cover crop assessment structures is reflected in the selection of cover crop plant species presented in the scientific literature. We consider that acknowledging the differential interpretations of sustainability expressed in the diverse uses of cover crops is key to the future development of the practice.

Materials and Methods

Historical review of cover crop research and development

To contextualize perennial field research within the broader history of cover crop research, we performed a detailed literature review. We studied the socio-cultural contexts in which different uses of cover cropping were developed, as well as shifts in cover crop designs in response to changes in societal goals. In this review section, we consider cover cropping as applied more broadly to both annual and perennial agroecosystems. We considered that cover crop developments in annual systems largely contributed to those of perennial systems. We explored the United States' history specifically as a case study of cover crop research and development. Our historical review begins in 1900, when the use of "cover crop" as a term was first recorded. However, we recognize that this practice is ancient, with records of cover cropping dating back over a millennium. Our analysis considered existing cover crop reviews, particularly the works of Bugg and Waddington (1994), Groff (2015), Hartwig and Ammon (2002), Peshin *et al*. (2014), and Altieri and Schmidt (1985), as well as more eco-sociological works, such as the work of Cochrane (1993). In studying these works and others, we focused on socio-economic events and scientific discoveries, which influenced the emergence of specialized cover crop uses, particularly nutrient management and biological management applications. In doing so, we considered the development of cover crop rationales across specialized scientific disciplines, and how their associated methodological approaches may have shaped the design and uses of cover cropping.

Meta-analysis

Identification process: Selection of studies

A literature search was conducted following the methodology described in the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) process (2009). This process includes four steps: identification, screening, eligibility and inclusion, as detailed in Figure 3.1. Data were extracted on 05/05/2020 primarily through Web of Science (Clarivate Analytics ®). We used a keyword-based approach to identify relevant articles, assuming this method would provide a roughly representative sample of the literature. The following keyword combinations were used as Core Collection Topic entries: (1) "cover crop" x "orchard", 198 results, (2) "cover crop" x "woody", 27 results, (3) "orchard" x "floor management", 135 results, (4) "woody" x "floor management", 135 results, (5) "perennial" x "floor management", 25 results and (6) "perennial" x "cover crop", 264 results (Figure 3.1). The timespan selected included 1900 to 2020. Web of Science Topic entries searches article titles, abstracts, author keywords, as well as data in Keywords Plus, defined as words or phrases which frequently appear in the titles of the referenced articles, but which are not present within the title of the article itself. Therefore, the identification of articles was limited by our keyword selection and the efficacy of keyword indexing. To partially amend for this limitation, we complemented our Web of Science database with searches through BioOne, PLOS, JSTOR, ScienceDirect, Oxford Journals, Springer Link, Taylor and Francis Journals, Wiley Online and WorldCat. We extracted a total of 859 published studies. Following the screening and eligibility process detailed in Figure 3.1, 285 articles remained.

Screening and eligibility process: Field experiment characteristics

Our analysis included only studies conducted under field conditions. Cover cropping was defined as a vegetative cover within orchard alleyways and also included research where tree berms were seeded. Studies where cover crops were not integrated within the orchard, such as hedge row trials, were excluded. Native vegetation covers were included only when plant species were identified. We defined "perennial agro-ecosystems" as land-use systems, in which woody and vine perennials are managed as agricultural crops. Our definition overlaps with certain definitions of "agroforestry systems" (FAO, ICRAF), but does not include linear agroforestry systems (i.e., riparian forest, buffers, windbreaks, etc.) (USDA). Our analysis did not include creeping vine crops or herbaceous climbing plants, such as vanilla (*Vanilla planifolia*), hops (*Humulus lupulus*) and cucumber (*Cucumis sativus*). Following inclusion, 285 cover crop articles remained, of which the source references are detailed in Appendix B – Supplementary Information 2.4. Although most material was peer-reviewed, our selection also included land-grant university extension articles and conference materials.

The selected field research included orchard-, grove- and plantation-based cover crop studies. Review- and model-based articles were excluded in the screening process. Greenhouse, glasshouse and pot studies were not included. Nursery studies, pre-plant studies and pre-mature orchard trials were excluded. The remaining studies were conducted either on commercial crop land or in experimental field stations. Due to the different spatial scales of ecological processes (Kremen *et al*., 2012), our study selection integrated different investigative approaches and scales of study. For instance, soil studies are often conducted with replications of ~4000 sq. meters, whereas pollination studies required landscape separations of 1 km to capture variations in bee foraging. Indeed, entomological studies have higher potential for community crossover and mobility between treatment replications. As such, randomized block designs or split plot designs, conducted within single orchard plots or at a small scale are often not appropriate for entomological studies. Due to the different motivations that compel researchers to study cover crops, our meta-analysis also integrated different experimental controls. For example, nutrient resource management studies compare the use of cover crops to fertilizer products and tillage practices, whereas biological management studies compared use of cover crops to synthetic pesticide application or other biological agents, used as controls.

Study inclusion process

Following the study identification, screening and eligibility processes, 285 studies remained, of which the annotated source references are detailed in Appendix B – Supplementary Information 2.4. We recognize that this may represent a low retention of the broader cover crop literature. We consider that this low retention is primarily due the different usage of the term “cover crops” within literature. We defined “cover crops” as seeded covers and included resident covers for which plant species had been identified. Therefore, we used a more restrictive definition of cover crops, compared to its broader definition as an established vegetative cover. Furthermore, although our analysis included studies, which referred to cover crops as catch crops, green manure, living mulch, sod, inter-crops and service crops, our search was based on the keywords “cover crop” and “floor management”. Therefore, our keyword selection restricted the type of cover crop studies selected within our study, which may in part explain the relatively low retention of studies.

Data extraction

Ecosystem services associated with cover cropping

Much cover crop research predates the introduction of the concept of “ecosystem services”, first introduced by Daily (1997) and Costanza (1997). Although the term “ecosystem service” was not always explicitly used, most cover crop studies reported and monitored the impacts of cover crop ecosystem functions and services. In our evaluation of the perennial agro-ecosystem literature, we recorded 19 ecosystem services associated with cover cropping. Of these services, 10 were regulating services (beneficial insect conservation, biodiversity support, greenhouse gas (GHG) regulation, nitrate (NO_3^-) leaching control, pest suppression, pollination support, soil retention, water dynamics regulation, weed suppression and wildlife habitat provision), 7 were supporting services (arbuscular mycorrhizal fungi (AMF) colonization, biomass production, water dynamics regulation, N mineralization, nutrient cycling, soil carbon and soil structure) and 3 were provisioning services (crop yield, economic profitability and knowledge diffusion) (Appendix B - Supplementary Information 2.2). Our characterization of cover crop-mediated ecosystem services and their classification was based on the Millennium Ecosystem Assessment (2005), and based on the framework for cover crop assessment, described by Schipanski *et al*. (2014).

We defined biomass production as net primary production, including non-marketable, vegetative crop growth metrics, and cover crop productivity metrics. In contrast to other studies, we considered biodiversity as an ecosystem service. Biodiversity services included aboveground metrics (i.e., insect biodiversity, plant species biodiversity) as well as below-ground metrics (i.e., soil food web biodiversity, microbial biodiversity). Biodiversity plays a central role in supporting other ecosystem services and is often included as a supporting service in ecosystem service frameworks (Power, 2010; Kremen & Miles, 2012). Pest suppression services included aboveground and belowground suppression of pests, including parasitic nematodes, insect pests, and parasitic fungi. Due to the low research coverage of knowledge diffusion and other cultural services, these services were not included in our evaluation of ES. However, we recognize their importance and the esthetic quality of perennial agricultural systems.

Country of study site and commodity type

To understand the different agronomic and socio-economic contexts of cover crop use, we recorded the countries in which cover crop field research was conducted. For meta-studies indicating multiple field sites, we recorded each country represented in the study. Comprehensive literature reports cover crop research conducted in 36 countries (Figure 3.2). We recorded the number of cover crop articles available per commodity group. The literature reported cover crop research that had been conducted in 44 different perennial crops, suggesting a common interest in the practice, across a diverse set of agronomic contexts (i.e., planting densities, pruning management, etc.) (Figure 3.3).

Cover crop mix design and optimization

Based on Tilman's diversity-productivity theory (Tilman *et al.*, 1997), we assumed that ecosystem processes are dependent on the identity of the species and the number of species within a given ecosystem. For each article, we recorded the number of cover crop mixes tested, the number of species assembled per mix and the identification of cover crop mix species. Plant identification included family, genus and species. In our study, we define “cover crop optimization” as the process of calibrating the practice and assembling a mix of species to enhance the cover crop’s response to system-based needs. We define cover crop “trial” as an individual study of a cover crop species within diverse species assemblages, as published in the research literature. We consider that diverse uses of cover cropping, adapted to different ES valuation systems, should be reflected in species mix designs (i.e., species identification and number of species).

Data analysis: Research coverage and ES valuation

In contrast to conventional meta-analyses, we focused on the constructs of scientific research pathways rather than on the impact of service outcomes. We deconstructed articles into multiple ES observations to explore the knowledge frameworks by which cover crops have been analyzed. For each study, we recorded individual ecosystem service observations as well as pairwise service linkages. We consider that the constructs of ES frameworks within cover crop articles are intrinsically tied to scientific interests. We propose that the non-randomization of research coverage reveals socio-cultural constructs, shared situational awareness, and common scientific interests. These often-overlooked social processes define the contours of the mental frameworks and knowledge pathways of researchers. We define “research coverage” as the proportion of studies within the entire body of scientific literature, which replicate the study of a given ecosystem service or linkage of services. We use the term “ES frameworks” to refer to shared pathways of scientific inquiry in cover crop research. As such, we provide a view of the research distribution across different pathways of scientific inquiry and shed light into the ways in which cover crop knowledge has been developed.

Data visualization

Descriptive statistics were used to characterize the whole population. For data analyses, we used a combination of Microsoft Excel (Version 16.43), to organize and format data, and Tableau Data Analytics and Visualization Software (Version 2020.2.1) for the preparation of geographical maps, and heatmaps. Because our focus was on the whole population, our process did not involve data randomization or blinding. We aggregated ecosystem service observations to provide a system-wide visualization of cover crop assessments and common ES frameworks, specific to commodity type, as detailed in Figure 3.3 & 3.4. Hot spots illustrated by darker cell colorations indicate higher research coverage for a given ecosystem service, specific to commodity groups. In Figure 3.5, a heatmap is used to illustrate the number of cover crop designs tested per commodity type. Additionally, commodity-specific cover crop designs are indicated by the number of species assembled within mixes. For each commodity, the cell's coloration and annotation in the heatmap reflect the number of cover crops tested per species count. Systematic mapping supports integration of the narrative and visual significance of the research distribution across ecosystem services explored, to draw a more comprehensive picture of cover crop-meditated services, *in lieu* of fully exhaustive ecosystem service assessments.

Results and Discussion

Review: History of cover crop development in US agriculture

In the United States, the term "cover crop" was first introduced by Dr. Bailey at Cornell University around 1900 (Waite, 1909). The initial motivation for the use of cover crops was "*to protect the soil from washing and leaching and to protect the roots of trees from freezing*" (Waite, 1909; Hedrick, 1926). The concept of plant functional traits was established early in modern history with key discoveries, including that of biological nitrogen fixation (BNF), supported by legume species (Beijerinck, 1901). This understanding of the role of plants in N cycling was followed by the discovery of the Haber Bosch process in 1909. Improved knowledge of the N cycle and plant nutrition played an undeniable role in the development of cover crop practices. During the Green Revolution, advancements in N fertilization methods paired with plant breeding led to spectacular improvements in productivity. Much of cover crop research revolved around N partitioning and focused particularly on two distinct functions: improvements in N fixation and the reduction of N leaching (Hartwig & Ammon, 2002). Within this context, cover crops were evaluated as a soil nutrient management strategy, in support of agricultural productivity.

Following the devastating erosion events of the Dust Bowl in the 1920s and 1930s, cover crops gained attention as a soil conservation practice. The Dust Bowl led to shifts in societal imperatives and contributed to the establishment of soil conservation policy in the United States. Early in the establishment of land-grant university research, there were records of cover crop trials in orchard systems (UCCE, 1921; Johnson, 2003). Writings at that time were focused on use of cover crops to protect soils: "*to support soil conservation and to prolong the life of agriculture*". Similarly, early records of the Soil Science Society of America include cover crop research to improve soil quality (Hester *et al*., 1936; Karraker & Bortner, 1938). However, as plentiful and inexpensive N synthetic fertilizer became readily available in the 1950s, the interest in cover cropping declined (Rifkin, 1983; Crookston, 1984; MacRae & Mehuys, 1985; Karlen *et al*., 1994). By the mid-1960s, the practice was widely discontinued (Groff, 2015; Frye *et al*., 1985).

In 1973, the oil embargo generated spikes in the prices of fuel and fuel-based agrichemicals. The strong dependency of Green Revolution agriculture on fuel became painfully apparent, generating renewed interest in research conservation practices (Hartwig & Ammon, 2002). In 1984, Odell *et al*. warned of rapid losses in soil organic matter, highlighting the sharp decline in U.S. corn belt SOM from 12% to <6%, in just 100 years of crop production (Odell *et al*., 1984). In 1988, with the rise in awareness of the harmful effects of global warming, the International Panel on Climate Change (IPCC) was established (Lipper & Zilberman, 2018). As the public became aware of the daunting effects of climate change, carbon cycling and sequestration became increasingly integrated within cover crop research. Climate disruptions induced a change in the way that conservation had been previously perceived. Conservation assumed that environments were relatively stable over management periods. However, projected shifts in species diversity and ecosystem functions challenged this concept. Cover crop studies reflected this change. With increased knowledge of C sequestration mechanisms, research efforts were directed towards the development of cover crops, as a climate-smart agriculture strategy (FAO, 2009).

A second, parallel branch of cover crop research focused on integrated pest management (IPM) and biological management for agro-ecosystems. In the 19th century, the outbreak of the potato blight in Europe was pivotal in consolidating research efforts towards the development of pest management strategies. Agriculture moved away from traditional practices (manual and/or cover crops) towards the integration of inorganic chemicals for insect pests, diseases and weeds. Lead arsenate was used at the beginning of the 20th century for insect control, at the expense of soil contamination. At the time, work on plant functional traits identified biochemical processes among organisms and the concept of "allelopathy" was introduced by Molisch (1937), establishing a foundation for later weed suppression research. However, as land tenures were consolidated and monoculture expanded, agriculture became increasingly vulnerable to damage from dominant pest species and diseases.

By 1940–1950, the use of synthetic pesticides became the common practice for pest control in the U.S. and the use of cover crops was largely discontinued (Peshin *et al*., 2014; Hartwig & Ammon, 2002). However, by 1960, the environmental damage caused by chemical pest control and fuel-dependent agri-chemicals gained attention among environmental groups. In 1962, Rachel Carson's book 'Silent Spring' denounced the environmental repercussions of intensive agricultural production methods and raised public awareness about the detrimental effects of DDT (Carson, 1962). Other critical pieces including Ehrlich's *The Population Bomb* (1968) and the Ecologist's *A Blueprint for Survival* (1972) made way for the rise of modern environmental activism.

Responding to the increased need for conservation strategies, the first concepts of "integrated pest management" was first introduced by Stern *et al.* (1959), which initially integrated both chemical and biological solutions. In Stern's foundational work, cover crops were presented as a way to *"create refuge areas"* through "*string treatments with chemicals"*. As such, it is important to note that initial designs did not immediately integrate cover crops within inter-rows, but rather used hedge strips for insect refuge. Thus, these initial designs did not allow for weed suppression co-benefits. Although primarily developed for the control of invertebrate pests, original principles of integrated pest management were later successfully adapted for the control of diseases, parasitic nematodes and, at a later stage, for weed control (Edwards *et al*., 1991). Some have attributed the later application of IPM for weed control to concerns over water and nutrient competition with the primary crop (Echtenkamp & Moomaw, 1989).

As the oil embargo of 1973 pushed the agricultural community away from fuel-intensive practices, farmers converted to minimum tillage practices (Hartwig & Ammon, 2002). Reduced-tillage systems presented problems, including difficult weed control. Cover crop designs were revisited to account for weed suppression (Hartwig, 1977; Hartwig, 1989). By the 1990s, research moved away from combined chemical-biological solutions towards fully biological solutions, leading to considerable advancements in cover crop biological control (Else & Ilnicki, 1989). The term "biofumigation" was coined in 1993 by J.A. Kirkegaard to describe the effect of isothiocyanate release from *Brassica* species on soil properties (Kirkegaard *et al*., 1993). In 1994, Dr. Robert Bugg published important work on the use of trophic associations of pest arthropods, as well as beneficial and neutral arthropods, for biological control.

Concepts of "plant-soil feedback" were also introduced at the time to describe mutual interactions between plants and soil organisms, further advancing cover crop research (Bever, 1977; Bever *et al*., 1997). Recent methods in metagenomics have provided new tools to characterize soil biodiversity and have created opportunities to better understand linkages between above and belowground biological control. These new methods and scientific instruments may further promote the uses and applications of cover cropping, in support of ecosystem services.

Concepts of sustainability and cover crop design

Although the concept of 'sustainable yields' was first introduced by foresters in the 17th century, the term 'sustainability' only made its way into the public sphere in the 1980s. Thus, the use of cover crops predates the introduction of 'sustainability', as a concept in modern agriculture. As a concept, productivity and conservation narratives merged and established three foundational pillars of sustainability: environmental, social and economic sustainability (Purvis *et al*., 2018). Agriculture's stance towards sustainability is unique from other environmental disciplines, due to its societal imperatives. We observe that cover crop research developed in response to socio-economic events, and evolved to meet societal shifts in sustainability goals. Cover crop research for agricultural sustainability has been particularly marked by historical shifts in the valuation of productivity-conservation tradeoffs. Nevertheless, despite the heavy contextualization of cover crop uses throughout their developmental history, the formal literature rarely details researchers' seed design decisions or their intended uses for cover crops. We suggest that important lags in cover crop adoption are not solely due to knowledge gaps but rather, are the result of confounding rationales for cover cropping, presented in the literature, and a lack of clarity in the seed selection process.

For perennial agriculture, yield productivity is dependent on a number of ES, provided by natural ecosystems (i.e., pollination, biological control, etc.). Agronomic decisions are rarely unilateral but rather involve complex assessments of multiple tradeoffs and opportunity costs. Economic factors are inevitably central to cover crop decisions. However, our results indicate an inexplicably low inclusion of economic profitability metrics in cover crop assessments, proportionally to the reporting of other services (Figure 3.4). We propose that the optimization of cover crops must account for diverse realities and perceptions of risk gains. Indeed, the augmentation of selected ecosystem services may come at an opportunity cost, affecting other services within agro-ecosystems. Meeting commodity-specific ES needs will require a differentiation of cover crop objectives and designs. We highlight that multiple uses of the term "cover crop" exist: although some designate an aboveground biological control practice, others refer specifically to the coverage of soil for conservation purposes. Each reveals differential conceptualizations of agricultural sustainability. An emphasis on the multi-functional dimension of cover crop outcomes may misrepresent the practice, as a panacea for sustainable agriculture, and thus distract from the need to tailor the practice to specific value systems. We suggest that the optimization of cover crops will require the practice to be recognized as a mediator of opportunities and tradeoffs.

Commodity-specific ES frameworks for cover cropping

As indicated in Figure 3.4, we found that research coverage was not randomized in the reporting of ecosystem services and of commodities. The majority of commodities reported in our study were fruit or nut crops. Of the 44 cropping systems, 10 systems represented other types of yield, including alcohol production, coffee, tea, rubber, gum production, oil, sugar crops, palm heart, tannins and timber. In apple systems, the effects of cover cropping on nutrient cycling received more research coverage than its effects on water dynamics (n = 28, n = 18 studies respectively), whereas water dynamics outcomes were at the forefront of research conducted in olive systems. In olive systems, only one article (n = 1) measured weed suppression, whereas this was more frequently measured in apple systems. This may be indicative of greater water scarcity concerns in olive systems and perceivably less competition from weed species. Stimulant crops are predicted to be vulnerable to pollination losses (Gallai *et al*., 2009). However, throughout the literature, pollination services were only reported in five cropping systems (apple, mango, citrus, blueberry and almond), none of which were stimulant crops. Regarding stimulant crops, studies on tea exclusively explored services related to biological management (i.e., beneficial insect conservation and pest suppression) (Figure 3.4). In comparison, studies on cacao and coffee production were focused on nutrient management (i.e., soil C, N mineralization), as well as weed suppression services (Figure 3.4).

The different ES frameworks of assessment in the scientific literature indicate two principle uses of cover crops within perennial agriculture—biological management and nutrient management. We defined biological management ES frameworks as those including one or more of the following services—pest suppression, beneficial insect conservation, weed suppression and pollination. We defined nutrient management ES frameworks as those including nutrient cycling, N mineralization, soil carbon, water dynamics, soil structure, soil retention, AMF colonization, NO_3^- leaching and/or GHG regulation. Substantially more studies addressed the use of cover crops for nutrient management (n = 171 articles) than for biological management (n = 118). We suggest that the non-randomization of observations and differences in ES research coverage reveal shared scientific interests and valuation systems. Our analysis suggests different priorities and challenges faced by specific commodity groups. This contextualization of knowledge reveals the malleable uses and functions of cover crops among commodity groups and generates opportunities for crop-specific optimization.

It is important to note that our study suggests a considerable gap in research coverage among perennial crops. Apple systems represented 24% of articles (n = 69/285). Although this may be linked to our article selection procedure, the disproportionately low research coverage of other perennial crops is noteworthy. In our study, for nearly a third of the perennial systems, we found only one cover crop article. This may suggest opportunities to diversify cover crop research. The specialized use of cover crops for certain commodities may be a consequence of the narrower span of research identified for these systems. In our study, the five-most researched cropping systems (apple, vineyard, olive, citrus and peach) comprised 67% of all studies. Despite this greater research coverage, the distribution of research was not randomized among ES within these systems, revealing different ES valuation systems. In apple systems, in contrast to olive, vineyard, peach and citrus, there were studies of beneficial insect conservation services. In contrast, olive and vineyard systems prioritized water dynamics services. These patterns reflected relatively narrow research foci for different commodities. In 1993, Cochrane suggested that this specialization in agricultural research occurred in response to the specialization of farms for one or two crops and also the influence of commodity groups, advocating for crop-specific research needs (Cochrane, 1993). Our data suggest that commodification may be apparent in cover crop ES frameworks.

Cover crop seed designs

Of 1446 trials, ~80% trials belonged to either the Fabaceae, Poaceae or Asteraceae plant families. Although most articles explored multiple cover crop mix designs, 43% of articles (123/285 articles) only reported one cover crop, half of which (63/123 cover crops) were single species. Of the 638 cover crops recorded throughout the literature, 73% were single species. It is important to note that although certain aromatic plant species (i.e., *Mentha haplocalyx, Indigofera hendecaphylla*) were exclusively used for biological management uses (i.e., promotion of beneficial insects), other species were relatively omnipresent within cover crop research and were used for a multitude of functions (i.e., weed suppression, pest suppression and carbon sequestration). These include *Trifolium pratense, Trifolium repens, Trifolium incarnatum, Lolium multiflorum, Festuca arundinaceae, Festuca rubra, Secale cereale* and *Vicia villosa*. Of all reported plant species (n=441 species), *Trifolium repens* (n=64 trials), *Medicago sativa* (n=44 trials) and *Lolium perenne* (n=42 trials) were the most frequently used species for cover cropping. The top 10 cover crop species accounted for 25% of cover crop trials. We may question whether the use of a restricted subset of species may be due to limited seed options and their availability for cover cropping. As illustrated in Figure 3.5, the majority of cover crops tested in perennial agriculture were single species, in contradiction to concepts introduced by Tilman (1997). For certain cropping systems including cacao, hazelnut and juneberry, cover crop outcomes were solely tested on single species designs. Thereby, although we observed malleability in the uses and functions assessed for cover crops, this contextualization was not reflected in the design of cover crop seed mixes (i.e., the number of species and species identifications). Our analysis highlights important opportunities for cover crop optimization, to enhance the response of cover crops to system-based needs.

Climate change considerations

It is important to note the gaps in the research distribution among commodity crops—21% of nutrient cycling and 23% of soil C assessments for cover cropping were conducted in apple systems. Considering the wide variety of agronomic operations employed in perennial systems, particularly with regards to pruning, gaps in data about cover crops in many commodities may pose challenges in climate change mitigation. Compared to annual systems, residues in perennial systems may differ in their lignocellulosic content due their longer life cycle and different climates. Lignin and cellulose compounds play an important role in carbon cycling and contribute to recalcitrant soil carbon pools (Frei, 2013). These compounds vary in their use of bacterial and fungal mediated pathways of decomposition (Wilhelm *et al*., 2019). We could expect different mechanisms of C sequestration within perennial systems. Of 44 total perennial crops reported in the literature, 17 crops, including walnut, plum and hazelnut, had no coverage of soil C in their cover crop assessments. In many of these systems, cover crops were not valued as a soil-building strategy but rather as a biological management practice. Tea and blueberry systems used aromatic cover crops exclusively for pest suppression, as well as beneficial insect conservation, whereas for sweetgum, sugarcane, plum, pineapple, oil palm, juneberry and hazelnut, the weed suppression outcomes of cover cropping were primarily valued. The diversity of cover crop uses reflects a variety of values pertaining to different systems.

The presence of gaps in countries and bio-zones in which cover crop research has been conducted is a particularly important issue in the context of global climate change adaptation efforts. Crops of high importance to smallholder farmers, particularly tropical staples and perennials, were either not studied (argan, shea, marula, etc.) or received little coverage within the cover crop literature. The least-studied cropping systems were primarily tropical tree crops (i.e., guava, mango, pineapple and sweetsop). Bananas, sugarcane and coffee, despite their economic importance, received limited research coverage—these systems are important export crops in a number of countries (Thrupp, 1988). Smallholder farmers face distinctive climate stressors. Projections suggest that they have particularly high vulnerability to climate change (Cohn *et al*., 2017). Their adaptive capacity is particularly tied to regional socio-economic development (Cohn *et al*., 2017). Exploring the role of cover cropping across different socio-economic realities is key for our understanding of its use within different cap-and-trade regulations, carbon credit markets and other GHG mitigation initiatives. Therefore, although cover cropping is well-established as a climate-smart strategy, there remain important opportunities to adapt the practice to the wide diversity of perennial systems (McNunn *et al*., 2020).

Our results suggest gaps in the research coverage of services, relating to GHG regulation and climate change, within the comprehensive scientific literature. These missing links are important, as they may be the cause of blind spots in the form of unexplored synergies, tradeoffs and/or feedbacks for climate change mitigation. For instance, the effects of cover crops on the colonization of roots by mycorrhizal fungi may also reduce N_2O emissions (Bender *et al*., 2013), thereby reducing the environmental footprint of production systems. However, higher yields potentially enhanced by cover cropping may generate increased GHG emissions, creating a tradeoff between productivity and conservation. Overall, we observe that GHG regulation was the least reported ES (n=1 article, in vineyard systems). Another gap is that commercial yields were not reported in 14 commodity crops including walnut, prune, pecan, coffee and avocado systems whereas other ES, such as soil C services were reported. Without yield measurements, the tradeoffs of supporting other services could not be assessed. Overall, ecosystem disservices were largely underrepresented in the literature and only reported in 7/285 articles or 2% of articles (Appendix B – Supplementary Information 2.4 – Olthof, 1986; Malik *et al*., 2001; Granatstein *et al*., 2008; Valdes-Gomez, 2011; Licznar-Malanczuk *et al*., 2015; Klodd *et al*., 2016; Whaley *et al*., 2019). Provisioning services of economic profitability and knowledge diffusion were also rarely reported in the literature (12/285 and 1/285 articles, respectively). Without comprehensive ecosystem service assessments, it becomes difficult to make widely applicable recommendations relevant to cover crop management, as tradeoffs cannot be taken fully into account. While certain ES frameworks focused on yield gains, other systems of assessment assume that ecosystem services are inherently valuable, regardless of immediate profitability. Recognizing differentials in the valuation of ecosystem services within the scientific literature is especially important, in the context of climate change. Indeed, instigating effective climate change action will require creating a shared vision, across differential value systems.

Limitations and Future Research

The identification of articles may have been limited by the selection of keywords. Our process only used the keywords “cover crop” and “floor management” to refer to the practice. It is possible that our selection may have missed works, which used the terms “soil management”, “soil health practices”, “catch crop”, “vegetative refuge” or the plurals of these terms, in reference to the same practice. Requests on certain search engines may be more restrictive. For example, the keywords “cover crop”, “cover-crop”, “cover crops” may have generated different reference lists than for the keyword “cover cropping”. Therefore, our selection procedure may have affected the results, depending on the representativeness of our subset of articles relative to the whole body of literature. Another potential limitation is that we did not consider the distinctions between ecosystem services and functions, nor did we discuss the association between plant functional traits and services in the design of cover crop mixtures (De Bello *et al*., 2010; Tancoigne *et al*., 2014; Blesh, 2017). This may have affected our results. Our database presented a regional data gap, as there were no studies conducted in Russia. The prior literature indicates that considerable work was conducted by researchers from the Soviet Union on the role of cover crops in supporting biological control in orchards (Telenga, 1958; Chumakova, 1960). Overall, most of the articles contained in our study were written in English, with some works written in Portuguese, Chinese or French. Therefore, we acknowledge that our data repository may not fully represent the breadth of cover crop work, available internationally.

Conclusion

Cover cropping, as a practice is unique in its plasticity and capacity to adapt to evolving societal goals. Our meta-analysis of ES frameworks for perennial agriculture revealed the malleable nature of cover crop use, as illustrated in the scientific literature. Beyond its use for soil improvements, cover crop research has considered a variety of intended functions, reflecting specific ES priorities apparent across commodity types: biological management, weed suppression and resource conservation, etc. The differences in ES frameworks of assessment suggest contrasting interpretations of sustainability within cover crop research. Only 44% of ES frameworks reported yield measurements. Therefore, although the practice has been touted for its multi-functional benefits, we emphasize the need to address differing sustainability goals and value systems in cover crop implementation. Our analysis of scientific ES frameworks revealed distinct knowledge pathways and confounding rationales for cover cropping in perennial systems. Promising avenues remain for cover crop optimization, both in research design and in mix species selection. In terms of research design, scientific knowledge pathways reveal the delimitation of commodity-specific ES priorities and indicate interest in specialized cover crop assessments. In turn, the specialized assessment of cover crop outcomes can inform the design of cover crop mix species. This highlights multiple potential avenues for concerted research efforts and for effective, trans-disciplinary collaboration in cover crop design optimization in order to account for diverse value systems.

References

The articles used for the meta-analysis are listed in Appendix B – Supplementary Information 2.4

Altieri, M.A. and Schmidt, L.L. 1985. Cover crop manipulation in Northern California orchards and vineyards: Effects on arthropod communities. Biological agriculture & Horticulture 3:1-24.

Beijerinck, M.W. 1901. Über oligonitrophile Mikroben. Zbl. Backt. 7:561-582.

Bender, S.F., Plantenga, F., Neftel, A., Jocher, M., Oberholzer, H.-R., Kohl, L., Giles, M., Daniell, T.J., and Van der Heijden, M.G.A. 2013. Symbiotic relationships between soil fungi and plants reduce N_2O emissions from soil. The ISME Journal 8:1336-1345.

Bever, J.D. 1994. Feedback between plants and their soil communities in an old field community. Ecology 75:1965-1977.

Bever, J.D., Westover, K.M., and Antonovics, J. 1997. Incorporating the soil community into plant population dynamics: the utility of the feedback approach. J. Ecol. 85:561–573.

Blesh, J. 2017. Functional traits in cover crop mixtures: biological nitrogen fixation and multifunctionality. Journal of Applied Ecology 55:38-48.

Bugg, R.L., Sarrantonio, M., Dutcher, J.D. and Phatak, S.C. 1991. Understory cover crops in pecan orchards: possible management systems. Am. J. Alt. Agric. 6:50–62.

Bugg, R. and Waddington, C. 1994. Using cover crops to manage arthropod pests of orchards: A review. Agriculture, Ecosystems & Environment 50:11-28.

Carson, R. 1962. Silent Spring. Boston: Houghton Mifflin.

Chumakova, B.M. 1960. Supplementary feeding as a factor increasing the activity of parasites of harmful insects. Trudy-Vsesoyznogo Nauchno-issledovatel-scogo Instituta Zashchity Rastenii 15:57-70.

Cochrane, W.W. The development of American agriculture: a historical analysis. 2nd edition. Minneapolis: University of Minnesota Press, 1993.

Cohn, A.S., Newton, P., Gil, J.D.B., Kuhl, L., Samberg, L., Ricciardi, V., Manly, J.R. and Northrop, S. 2017. Smallholder agriculture and climate change. Annual Review of Environment and Resources 42:347-75.

Costanza, R. *et al*. 1997. The value of the world's ecosystem services and natural capital. Nature 387:253-260

Crookston, R. K. 1984. The rotation effect. Crop Soils 36:12-14.

Daily, G. Nature's Services: Societal Dependence on Natural Ecosystems. Island Press, 1997. Washington D.C., USA.

De Bello, F., Lavorel, S., *et al*. 2010. Towards an assessment of multiple ecosystem processes and services via functional traits. Biodivers. Conserv. 19:2873-2893.

Demestihas, C., Plénet, D., Génard, M., Raynal, C. and Lescourret, F. 2017. Ecosystem services in orchards. A review. Agron. Sustain. Dev. 37:12.

Department for Environment, Food and Rural Affairs (DEFRA). 2017. Ecological Focus Areas: features on farms in England 2015/2016. Department for Environment, Food and Rural Affairs. London, UK.

Dunn, M., Ulrich-Schad, J.D., Prokopy, L.S., Myers, R.L., Watts, C.R. and Scanlon, K. 2016. Perceptions and use of cover crops among early adopters: Findings from a national survey. Journal of soil and water conservation 71:29-40.

Echtenkamp, G.W. and Moomaw, R.S. 1989. No-till corn production in a living mulch system. Weed Technol. 3:61-266.

Edwards, C.A., David Thurston, H.D. and Janke, R. 1991. Integrated Pest Management for Sustainability in Developing Countries. In: Toward Sustainability: A plan for collaborative research on agriculture and natural resource management. National Academies Press.

Eilittä, M. *et al*. 2004. Green Manure/Cover Crop Systems of Smallholder Farmers. Springer Netherlands.

Else, M.J. and Ilnicki, R.D. 1989. Crops and mulch systems effect upon weeds in corn. Abstr. Weed Sci. Soc. Am. 29:68.

FAO. 2009. Food Security and Agricultural Mitigation in Developing Countries: Options for Capturing Synergies. UN FAO Publication: Italy. Available at: http://www.fao.org/3/i1318e/i1318e00.pdf

Finney, D.M. and Kaye, J.P. 2017. Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system. Journal of Applied Ecology 54:509-517.

Finney, D.M., Murrell, E.G., White, C.M., Baraibar, B., Barbercheck, M.E., Bradley, B.A., Cornelisse, S., Hunter, M.C., Kaye, J.P., Mortensen, D.A., Mullen, C.A. and Schipanski, M.E. 2017. Ecosystem services and disservices are bundled in simple and diverse cover cropping systems. Agricultural and Environmental Letters 2:170033.

Florence, A.M., Highley, L.G., Drijber, R.A., Francis, C.A. and Lindquist, J.L. 2019. Cover crop mixture diversity, biomass productivity, weed suppression and stability. PLoS ONE 14(3): e0206195.

Frei, M. 2013. Lignin: Characterization of a Multifaceted Crop Component. The Scientific World Journal 2013:1-25.

Frye, W.W., Smith, W.G., and Williams, R.J. 1985. Economics of winter cover crops as a source of nitrogen for no-till corn. J. Soil Water Conserv. 40:246–249.

Gallai, N., Salles, J.M. and Vaissiere, B.E. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollination decline. Ecol. Econ. 68:810-821.

Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdes-Gomez, H. and Metay, A. 2018. Management of service crops for the provision of ecosystem services in vineyards: a review. Agriculture, Ecosystems and Environment 251:158-170.

Gomez, J.A. 2017. Sustainability using cover crops in Mediterranean tree crops, olives and vines - Challenges and current knowledge. Hungarian Geographical Bulletin 66:13-28.

Grant, J., Anderson, K. and Prichard, T. Cover crops for Walnut orchards. University of California, Division of Agriculture and Natural Resources, Publication 21627e, 2006. Oakland, CA.

Groff, S. 2015. The past, present, and future of the cover crop industry. Journal of soil and water conservation 70:130A-133A.

Hartwig, N.L. 1977. Nutsedge control in no-tillage corn with and without a crownvetch cover crop. Proc. Northeast. Weed Sci. Soc. 31:20–23.

Hartwig, N.L. 1989. Influence of crownvetch living mulch on dandelion invasion in corn. Proc. Northeast. Weed Sci. Soc. 43:25–28.

Hartwig, N.L. and Ammon, H.U. 2002. Cover crops and living mulches. Weed Science 50:688-699.

Hedrick, U.P. 1926. Tendencies in deciduous orcharding. Indiana Horticultural Society Annual Meeting 21-31.

Hester, J.B., Carolus, R.L. and Blume, J.M. 1936. A study of the availability of phosphorus and potash and their influence upon vegetable crop production and fertilizer practices on coastal plain soils. Soil Sci. Soc. Amer. Proc. 1:233-242.

Housman, M., Tallman, S., Jones, C., Miller, P. and Zabinski, C. 2021. Soil biological response to multi-species cover crops in the Northern Great Plains. Agriculture, Ecosystems & Environment 313:107373.

Ingels, C. Cover cropping in vineyards: A grower's handbook. University of California, Division of Agriculture and Natural Resources, Publication 3338, 1998. Oakland, CA.

Johnston, W.E. 2003. Cross sections of a diverse agriculture: profiles of California's agricultural production regions and principal commodities. In: Siebert, J. (Ed.) California Agriculture: Dimensions and Issues. pp. 29-55.

Karlen, D.L., Varvel, G.E., Bullock, D.G. and Cruse, R.M. 1994. Crop rotations for the 21st century. Advances in Agronomy 53:1-45.

Karraker, P.E. and Bortner, C.E. 1938. Nitrogen leaching in soil on the experiment station farm at Lexington. Soil Science Society of America Journal 2:393-398.

Kinyua M. *et al*. 2019. Green manure cover crops in Benin and Western Kenya - A review. CIAT Publication No. 481. International Center for Tropical Agriculture (CIAT). Nairobi, Kenya.

Kirkegaard, J.A., Gardner, P.A., Desmarchelier, J.M. and Angus, J.F. 1993. Biofumigation - using Brassica species to control pests and diseases in horticulture and agriculture. Proceedings of the 9th Australian Research Assembly on Brassicas 77-78.

Kragt, M.E. and Robertson, M.J. 2014. Quantifying ecosystem services trade-offs from agricultural practices. Ecol. Econ. 102:147-157.

Kremen, C., Iles, A. and Bacon, C. 2012. Diversified farming systems: an agroecological, systems-based alternative to modern industrial agriculture. Ecology and Society 17(4):44.

Kremen, C. and Miles, A. 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecology and Society 17:40.

Lipper, L. and Zilberman, D. 2018. A Short History of the Evolution of the Climate Smart Agriculture Approach and Its Links to Climate Change and Sustainable Agriculture Debates. In: Lipper L., McCarthy N., Zilberman D., Asfaw S., Branca G. (eds) Climate Smart Agriculture. Natural Resource Management and Policy, vol 52. Springer, Cham.

MacRae, R.J. and Mehuys, G.R. 1985. The effect of green manuring on the physical properties of temperate area soils. Adv. Soil Sci. 3:71-94.

McNunn, G., Karlen, D.L., Salas, W., Rice, C.W., Mueller, S., Muth, D. Jr. and Seale, J.W. 2020. Climate smart agriculture opportunities for mitigating soil greenhouse gas emissions across the U.S. Corn-Belt. Journal of Cleaner Production 268:122240.

Micke, W.C. Almond Production Manual. University of California, Division of Agriculture and Natural Resources, Publication 3364, 1996. Oakland, CA.

Millennium Ecosystem Assessment (MEA). Ecosystems and Human Well-Being: Synthesis. Island Press, 2005. Washington D.C., USA.

Moher, D., Liberati, A., Tetzlaff, J. and Altman, D.G. 2009. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. Ann. Intern. Med. 154:264-269.

Molisch, H. 1937. The effect of plants on each other. Fischer Jena 31:12-16.

Moore, V.M., Mitchell, P.D., Silva, E.M. and Barham, B.L. 2016. Cover crop adoption and intensity on Wisconsin's organic vegetable farms. Agroecology and Sustainable Food Systems 40:693-713.

Neill, S.P. and Lee, D.R. 2001. Explaining the adoption and disadoption of sustainable agriculture: the case of cover crops in Northern Honduras. J. Econ. Dev. Cult. Change 49 (4):793–820.

O'Connell, S., Grossman, J., Hoyt, G., Shi, W., Bowen, S., Marticorena, D., Fager, K.L. and Creamer, N.G. 2015. A survey of cover crop practices and perceptions of sustainable farmers in North Carolina and the surrounding region. Renewable Agriculture and Food Systems 30(6):550-562.

Odell, R.T., Melsted, S.W. and Walker, W.M. 1984. Changes in organic carbon and nitrogen of Morrow Plot soils under different treatments, 1904-1973. Soil Sci. 137:160-171.

Pardini, A., Faiello, C., Longhi, F., Mancuso, S. and Snowball, R. 2002. Cover crop species and their management in vineyards and olive groves. Adv. Hort. Sci. 16:225-234.

Peshin, R., Jayaratne, K.S.U. and Sharma, R. 2014. IPM Extension: A global overview. Integrated Pest Management 493:527.

Power, A.G. 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. Lond., Ser. B.: Biol. Sci. 365:2959-2971.

Purvis, B., Mao, Y. and Robinson, D. 2018. Three pillars of sustainability: in search of conceptual origins. Sustainability Science 14:681-695.

Ramos, D.D. Walnut production manual. University of California, Division of Agriculture and Natural Resources, Publication 3373, 1997. Oakland, CA.

Raudsepp-Hearne, C., Peterson, G.D. and Bennett, E.M. 2010. Ecosystem services bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. USA 107(11):5242–5247.

Rifkin, J. 1983. "Algeny." Viking, New York.

Roesch-McNally, G., Basche, A., Arbuckle, J., Tyndall, J., Miguez, F., Bowman, T. and Clay, R. 2018. The trouble with cover crops: Farmers' experiences with overcoming barriers to adoption. Renewable Agriculture and Food Systems 33(4):322-333.

Schipanski, M.E. *et al*. 2014. A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agricultural Systems 125:12-22.

Seager, T.P. 2018. The sustainability spectrum and the sciences of sustainability. Bus. Strat. Env. 17:444-453.

Shackelford, G.E., Kelsey, R. and Dicks, L.V. 2019. Effects of cover crops on multiple ecosystem services: Ten meta-analyses of data from arable farmland in California and the Mediterranean. Land Use Policy 88:104204.

Smith, R.G., Atwood, L.W. and Warren, N.D. 2014. Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. PLoS ONE 9:e97351.

Smith, R.G., Warren, N.D. and Cordeau, S. 2020. Are cover crop mixtures better at suppressing weeds than cover crop monocultures? Weed Science 68:186-194.

Stern, V.M., Smith, R.F., van den Bosch, R. and Hagen, K.S. 1959. The integrated control concept. Hilgardia 29:81–101.

Syswerda, S.P. and Robertson, G.P. 2014. Ecosystem services along a management gradient in Michigan (USA) cropping systems. Agric. Ecosyst. Environ. 189:28-35.

Tancoigne, E., Barbier, M., Cointet, J.-P. and Richard, G. 2014. The place of agricultural sciences in the literature on ecosystem services. Ecosystem Services 10:35-48.

Telenga, N.A. 1958. Biological methods of pest control in crops and forest plants in the USSR. Report of the Soviet Delegation. 9th International Conference on Quarantine and Plant Protection 15.

Tilman, D., Lehman, C.L. and Thomson, K.T. 1997. Plant diversity and ecosystem productivity: Theoretical considerations. PNAS 94:1857-1861.

Tilman, D., Reich, P.B. and Isbell, F. 2012. Biodiversity impacts ecosystem productivity as much as resources, disturbance, or herbivory. PNAS 109:10394-10397.

Thrupp, L.A. 1988. Pesticides and policies: approaches to pest-control dilemmas in Nicaragua and Costa Rica. Latin American Perspectives 15:37-70.

University of California, Cooperative Extension (UCCE). Cover crop variety test. 1921. Merced county, UC Cooperative Extension Records, Box 175. UC Cooperative Extension Archives, UC Merced Library, Merced, CA. https://calisphere.org/collections/27012

US Department of Agriculture (USDA) National Agricultural Statistics Service. 2017. Census of Agriculture. Chapter 2, Table 41–Land Use Practice (2017).

Vicente-Vicente, J.L., Garcia-Ruiz, R., Francaviglia, R., Aguilera, E. and Smith, P. 2016. Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: a meta-analysis. Agric. Ecosyst. Environ. 235:204-214.

Vukicevich, E., Lowery, T., Bowen, P., Urvez-Torres, J. and Hart, M. 2016. Cover crops to increase soil microbial diversity and mitigate decline in perennial agriculture: A review. Agron. Sustain. Dev. 36:48.

Waite, M.B. 1909. Fertilizing the orchard. Annual Report – Virginia Department of Agriculture and Commerce.

Wilhelm, R.C., Singh, R., Eltis, L.D. and Mohn, W.W. 2019. Bacterial contributions to delignification and lignocellulose degradation in forest soils with metagenomic and quantitative stable isotope probing. The ISME Journal 13:413-429.

Figure 3.1. Study review and selection flow chart. Peer-reviewed studies were collected following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) process, adapted by Moher *et al*. (2009).

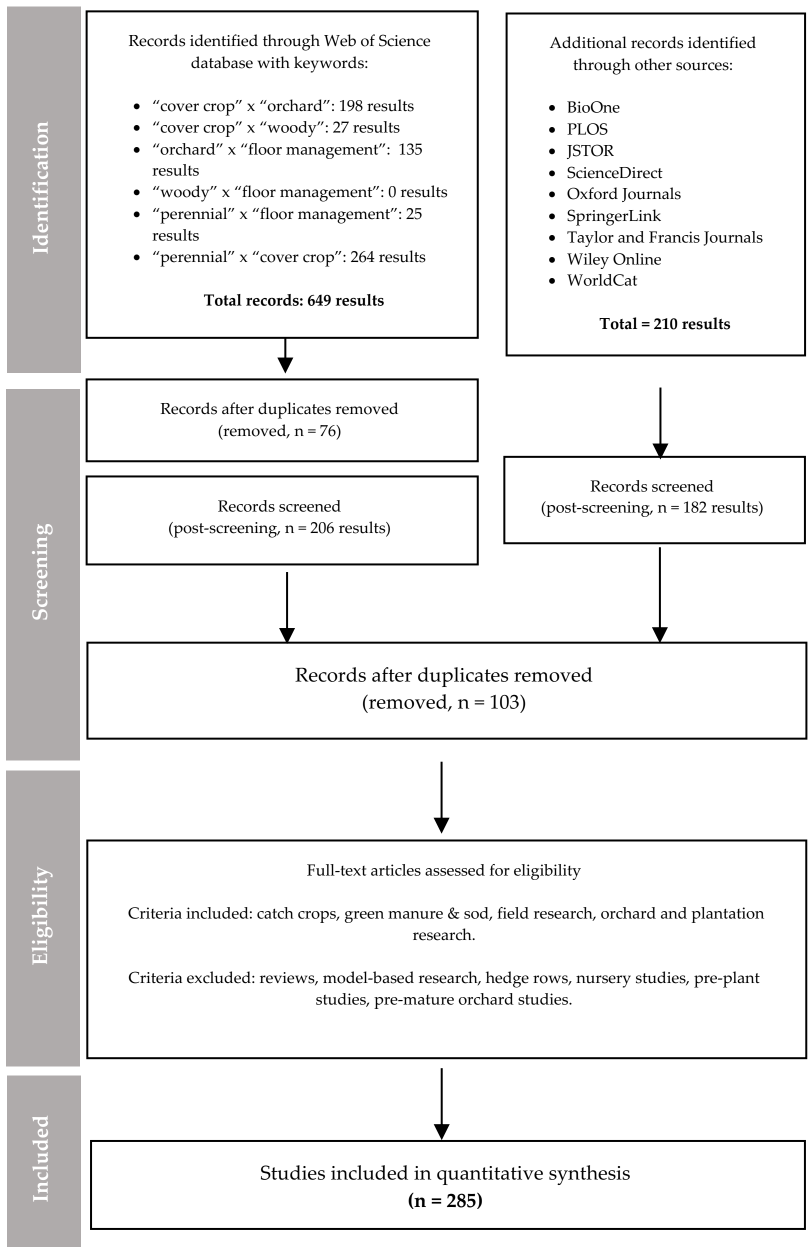


Figure 3.2. a. Geographical distribution of cover crop field research conducted in perennial agro-ecosystems, indicated by the number of published peer-reviewed articles per country. b. due to the high research coverage in the United States, the research distribution is presented by state.

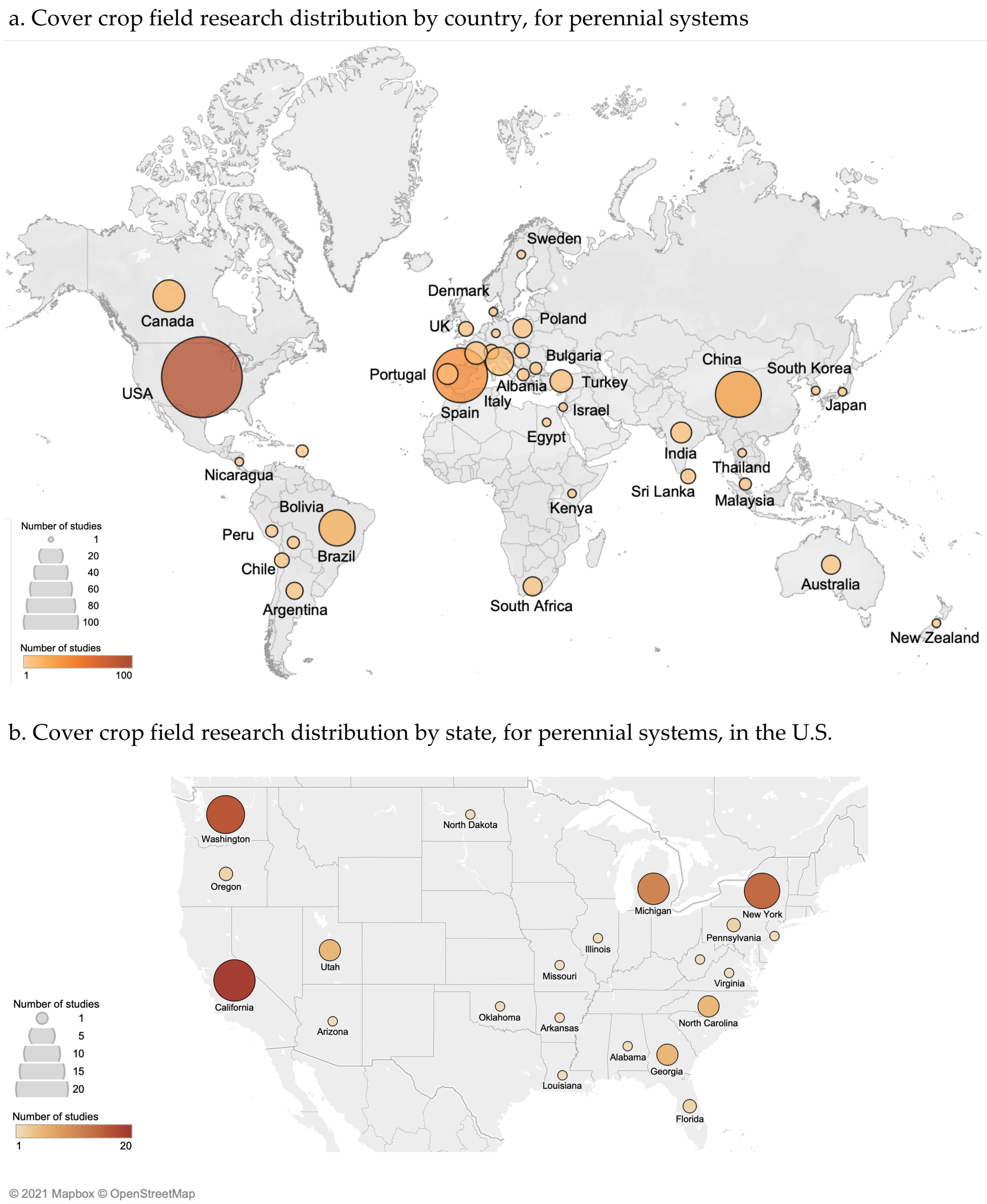


Figure 3.3. Distribution of cover crop research, by perennial system, distinguished by country. Due to the high quantity of research conducted in the USA, research is presented by state for that country. It is important to note that due to our definition of cover cropping, which included only seeded or covers with identified plant species, many published cover crop studies were excluded from our analysis. Our keyword selection may also have missed other relevant studies.

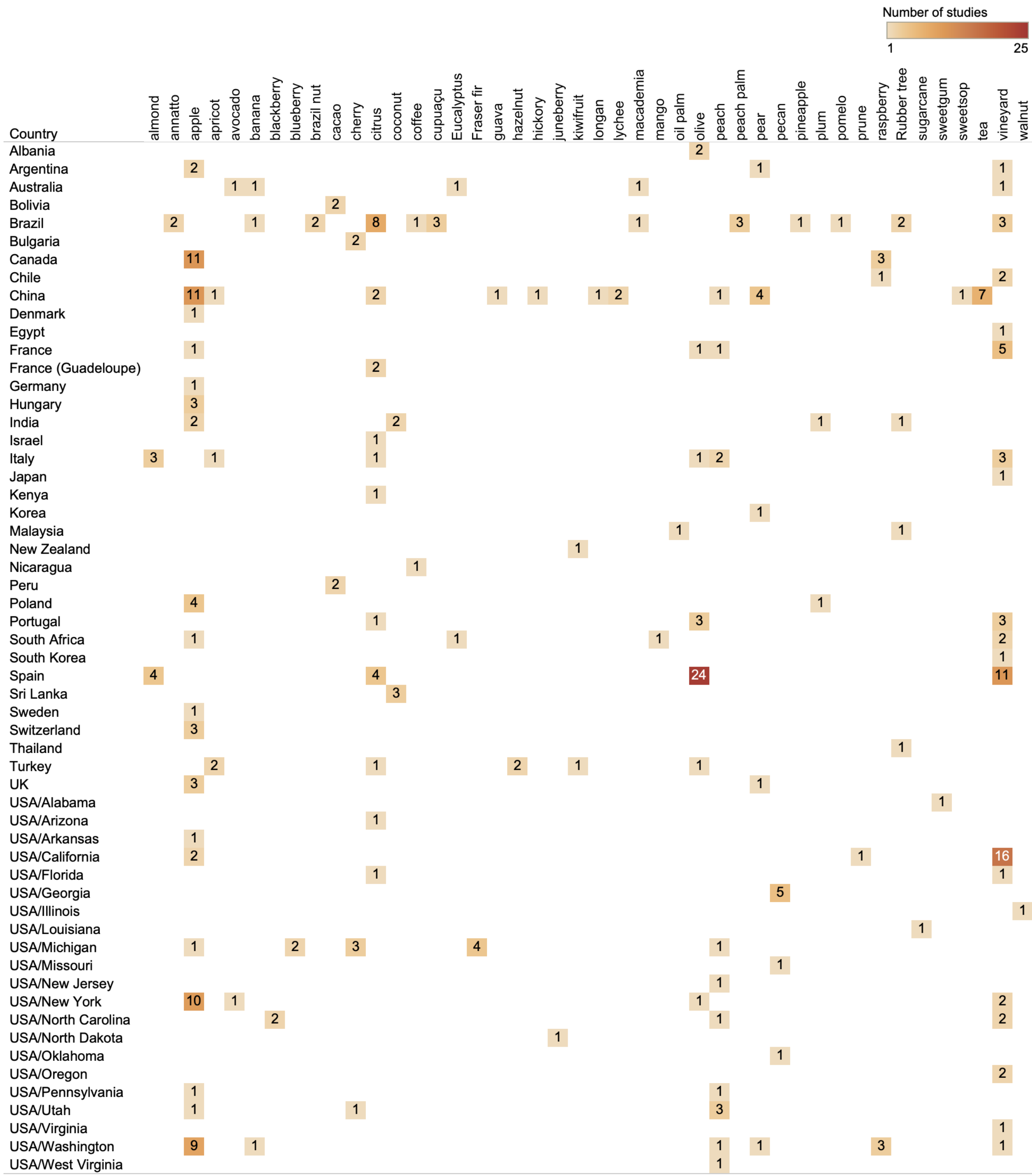


Figure 3.4. Research coverage of ecosystem services distinct to perennial cropping system in the comprehensive cover crop literature.

Number of studies
1 45

	AMF colonization	beneficial insect conservation	biodiversity	biomass production	economic profitability	GHG regulation	N mineralization	NO3- leaching	nutrient cycling	pest suppression	pollination	soil C	soil retention	soil structure	water dynamics	weed suppression	wildlife habitat	yields
almond	0	1	3	4	0	0	4	0	5	1	1	5	1	3	3	2	0	4
annatto	0	0	1	2	0	0	1	0	1	0	0	0	0	1	1	0	0	1
apple	1	16	31	45	0	0	22	2	24	21	2	23	1	12	18	8	1	37
apricot	0	0	0	3	1	0	0	0	3	0	0	3	0	2	3	1	0	3
avocado	0	0	0	2	0	0	1	0	1	0	0	1	0	0	0	0	0	0
banana	0	0	1	2	0	0	1	0	2	0	0	2	0	1	1	0	0	1
blackberry	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2
blueberry	0	2	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1
brazil nut	0	0	1	2	0	0	1	0	1	0	0	0	0	1	1	0	0	1
cacao	1	0	2	1	0	0	2	0	3	0	0	2	0	0	0	1	0	1
cherry	0	0	2	6	2	0	3	0	2	1	0	1	0	0	2	1	0	4
citrus	0	5	10	11	2	0	6	0	9	7	1	6	1	3	3	7	0	8
coconut	0	0	2	3	1	0	2	0	2	0	0	2	0	0	3	2	0	1
coffee	0	0	2	2	0	0	0	0	0	0	0	1	0	0	0	2	0	0
cupuaçu	0	0	1	2	0	0	2	0	2	0	0	1	0	2	1	0	0	2
Eucalyptus	0	0	1	1	1	0	0	0	1	0	0	1	0	0	0	1	0	1
fraser fir	0	0	0	3	0	0	2	0	3	0	0	3	0	0	3	0	0	2
guava	0	0	0	1	1	0	1	0	1	0	0	0	0	1	0	0	0	0
hazelnut	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	2	0	1
hickory	0	0	1	1	0	0	1	0	1	0	0	1	0	1	0	0	0	0
juneberry	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
kiwifruit	0	0	1	1	0	0	1	0	2	0	0	2	0	1	1	1	0	1
longan	0	0	0	1	1	0	1	0	1	0	0	0	0	1	0	0	0	0
lychee	0	0	0	2	1	0	1	0	1	0	0	1	0	1	1	0	0	0
macadamia	1	0	0	2	0	0	0	0	1	0	0	1	0	0	0	0	0	1
mango	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
oil palm	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1
olive	0	2	6	14	0	0	9	0	9	4	0	16	13	8	18	1	1	10
peach	0	1	4	10	1	0	4	0	4	2	0	5	0	3	4	3	0	4
peach palm	0	0	1	2	0	0	2	0	2	0	0	1	0	2	1	0	0	2
pear	0	5	6	2	0	0	2	0	3	5	0	2	0	0	0	0	0	1
pecan	1	4	4	3	0	0	2	0	2	5	0	2	1	1	0	1	0	0
pineapple	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	0	0
plum	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	2
pomelo	1	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0
prune	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
raspberry	0	0	1	6	0	0	3	0	2	2	0	3	0	2	0	1	0	6
rubber tree	0	0	0	5	0	0	5	0	5	0	0	3	0	2	3	0	0	5
sugarcane	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1
sweetgum	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1
sweetsop	0	0	0	1	1	0	1	0	1	0	0	0	0	1	0	0	0	0
tea	0	6	7	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0
vineyard	4	7	18	44	2	1	17	0	15	9	0	12	6	8	24	12	1	25
walnut	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0

Figure 3.5. Design of cover crop seed mixes. Cover crop designs are indicated by the number of species assembled in each cover crop. The number of cover crops tested per design is indicated by the cell's coloration and annotation. Commodities are listed in order of research coverage.

Number of cover crops

1 50

	Number of species in cover crop																				
Crop	1	2	3	4	5	6	7	8	9	10	11	12	14	15	17	18	21	25	26	29	Total
vineyard	90	16	9	6	3	2	2		2		1		2			1					134
apple	92	12	3	3	3	1			1			1	1		1		1	1	2		122
citrus	46	5	5	1	2	3	1														63
olive	32	4	6	1						2	1	1								1	48
pear	33		2												1						36
pecan	25	1						1													27
raspberry	22	3		1																	26
peach	17	6																			23
cacao	12																				12
tea	8	1		1	1																11
cherry	2	4	4		1																11
fraser fir	9		1																		10
coconut	9																				9
rubber tree	6	1	1																		8
banana	7		1																		8
kiwifruit	6		1																		7
apricot	5	1				1															7
almond	2	1	3	1																	7
hazelnut	6																				6
walnut	4	1																			5
oil palm	2	2																			4
lychee	3						1														4
juneberry	4																				4
blueberry	3													1							4
pomelo	2	1																			3
macademia	2	1																			3
hickory	3																				3
coffee	2		1																		3
sugarcane	2																				2
prune	1	1																			2
pineapple	2																				2
peach palm	2																				2
eucalyptus		1			1																2
cupuaçu	2																				2
sweetsop							1														1
sweetgum				1																	1
plum	1																				1
mango		1																			1
longan							1														1
guava							1														1
brazil nut	1																				1
avocado		1																			1
annatto	1																				1

Appendix A. Supplementary Information to Chapter 1

Supplementary Information 1.1. Copy of the distributed survey questions

UCDAVIS
UNIVERSITY OF CALIFORNIA

California-wide Almond Survey

Participant Criteria

Who can take this survey?

Are you an almond grower?

Yes ○ No ○

Do you have 1 or more acres of almond trees?

Yes ○ No ○

PART I: Cover cropping opportunities

PART I: Cover cropping opportunities

How **knowledgeable** are you of **cover cropping** in almond orchards?

- ○ Very knowledgeable
- ○ Somewhat knowledgeable
- ○ Not knowledgeable at all

Have you previously considered using cover crops in your orchard?

Yes ○ No ○

In your opinion, which of the following are **most improved** by cover cropping?

	Not improved	Somewhat improved	Most improved
Soil structure & field access	○	○	○
Soil health	○	○	○
Tree nutrition	○	○	○
Pollinator habitat	○	○	○
Weed control	○	○	○
Water infiltration & retention	○	○	○
Aboveground pest control (NOW)	○	○	○
Belowground pest control	○	○	○

How important are the following **challenges** in your orchard?

	Not important	Somewhat important	Very important
Soil compaction/Poor water infiltration	○	○	○
Erosion/Dust	○	○	○
Poor water retention	○	○	○
Low soil health	○	○	○
Nitrogen losses	○	○	○
Soil salinity	○	○	○
Weak pollination	○	○	○
Nematode infestation	○	○	○
Navel orangeworm (NOW) infestation	○	○	○

In your opinion, are possible cover crop **benefits** mostly:

- ○ **Agronomic**: organic matter, reduces dust ...
- ○ **Operational**: earlier field access ...
- ○ **Economic**: reduces input expenses, positive economic returns...

**NOW refers to the navel orangeworm (Amyelois transitella).*

PART II: Cover cropping concerns

How **economically stable** do you consider your almond enterprise to be?

- ○ Not stable
- ○ Somewhat stable
- ○ Very stable

Are your concerns with cover crops mostly:

- ○ **Agronomic**
- ○ **Operational**
- ○ **Economic**
- ○ **Insufficient information available on cover cropping**

How would you rank the following **agronomic concerns** with cover cropping?

	Not important	Somewhat important	Very important
Frost complications	○	○	○
Difficult **pest management**	○	○	○
Difficult **weed management**	○	○	○
Impediment to **orchard sanitation**	○	○	○
Other: ______	○	○	○

How would you rank the following **operational concerns** with cover cropping?

	Not important	Somewhat important	Very important
Complicated **transition** towards cover cropping	O	O	O
Seeding equipment availability	O	O	O
Difficult **establishment**	O	O	O
Difficult **management of stand**	O	O	O
Difficult **termination**	O	O	O
Difficult almond **harvest** (debris)	O	O	O

How would you rank the following **economic concerns** with cover cropping?

	Not important	Somewhat important	Very important
High transition costs	O	O	O
Higher equipment expenses	O	O	O
Increase of labor expenses and time	O	O	O
Cost of learning new practice	O	O	O
Cost of water	O	O	O
Uncertainty of economic outcome	O	O	O

PART III: Farming operations

PART III: Farming operations

How many total acres of non-bearing almond orchards do you have?

How many total acres of bearing almond orchards do you have?

In what **zip code** are your almond orchards located?

- ☐ Zip code, number of acres: ____
- ☐ Zip code, number of acres: ____
- ☐ Zip code, number of acres: ____
- ☐ Zip code, number of acres: ____
- ☐ Zip code, number of acres: ____
- ☐ Zip code, number of acres: ____

How much **N-fertilizer** do you apply to **mature orchards** (in lbs/acre)?

____

What is the main irrigation system used in your orchard?

- ☐ **Furrow**
- ☐ **Flood**
- ☐ **Micro-sprinkler**
- ☐ **Sprinkler**
- ☐ **Single drip**
- ☐ **Double drip**

Do you use organic amendments (i.e. compost...)?

Yes	No
○	○

Of your almond acreage, what percentages are in the following categories?

- ☐ **Conventional**, %: ____
- ☐ **USDA Certified Organic**, %: ____
- ☐ **Transitioning into USDA Organic**, %: ____
- ☐ Other: ____

PART IV: Orchard soil management

PART IV: Orchard soil management

In your **non-bearing** almond orchards, what are your floor management practices?

- ☐ **Bare orchard floor**
- ☐ **Winter cover crop (October-February)**
- ☐ **In-season cover crop (March-September)**
- ☐ **Year-round cover crop**
- ☐ **Resident vegetation**

In your **bearing** almond orchards, what are your floor management practices?

- ☐ **Bare orchard floor**
- ☐ **Winter cover crop (October-February)**
- ☐ **In-season cover crop (March-September)**
- ☐ **Year-round cover crop**
- ☐ **Resident vegetation**

Which practices do you use to control **resident vegetation & weeds**?

- ☐ Herbicide application only on berms
- ☐ Herbicide application on berms and alleyway
- ☐ Cultivation
- ☐ Mowing
- ☐ Cover crop establishment to outcompete weeds
- ☐ Other: ____

Do you use cover crops in your almond orchards?

The term cover-crop here refers to a seeded vegetative cover, including either annual or perennial plant species.

Yes ○ No ○

Cover Cropping Experience

PART IV Section for cover crop users

Do you seed the cover crop annually?

○ Yes
○ No. If so, please specify the seeding time interval: [ ]

Do you rotate the plant species?

Yes ○ No ○

Do you alternate cover crop mixes in every other alleyway of the orchard?

Yes ○ No ○

Do you design your **own mix** or do you use a **pre-packaged** mix?

Own ○ Packaged ○

How many **plant species** are included in your mix?

[ ]

Which of the following are included in the mix?

- ☐ Legume
- ☐ Grass
- ☐ Brassica/mustard
- ☐ Buckwheat

What is the width of your cover crop stand in an orchard alleyway?

- ○ Less or equal to 6 feet
- ○ 6-15 feet
- ○ 15-20 feet
- ○ Fully cover-cropped/No bare berms

What were the **costs per acre** of establishing the cover crop (including seed costs)?

Did you reduce your **N-fertilizer application** with cover cropping?

- ○ Yes. If so, by **how much** (in lbs. N/acre)?
- ○ No

When do you usually **seed** your cover crop? Please indicate which month.

Why have you chosen to **seed** at that time? (Choose all that apply)

- ☐ Harvest operations were done.
- ☐ Floor preparation was done.
- ☐ Seeding must occur before winter rains start.
- ☐ To provide early bee forage in the orchard.
- ☐ Other: ________

Do you conduct sanitation after cover crop seeding?

- ○ Yes
- ○ No

How do you manage mummies and residues?

- ○ Intact mummies are left to decompose in the cover crop.
- ○ Mummies are crushed/flail mowed in the cover crop alleyways.

Do you prune the orchard after cover crop seeding?

Yes	No
○	○

Do you irrigate the cover crop?

Yes	No
○	○

Do you use compost with cover cropping?

Yes	No
○	○

Do you mow the cover crop?

Yes	No
○	○

If you mow, when do you start mowing the cover crop?

- ☐ After cover crop seeding, at regular time intervals.
- ☐ Before tree pollination.
- ☐ After tree pollination.
- ☐ At frost.
- ☐ As soon as soil dries up in the spring.
- ☐ After the cover crop goes to seed.
- ☐ Before the aboveground biomass reaches an unmanageable level.
- ☐ Other: ______

If you mow, approximately how many times per year?

______

Do you terminate the cover crop?

Yes	No
○	○

Please indicate the **month** in which you usually terminate the cover crop.

Why did you terminate the cover crop at that time?

- ☐ Before spring frost, to avoid frost damage.
- ☐ Prior to almond tree bloom.
- ☐ Prior to leaf formation in the spring.
- ☐ To avoid complications at harvest.
- ☐ To avoid competition with water.
- ☐ I do not terminate: the cover crop dies naturally due to lack of water.
- ☐ I do not terminate the cover crop: I let it reseed itself.
- ☐ Other: ______

How do you **terminate** your cover crop?

- Chemically
- Mowed
- Disked
- Terminates naturally
- Other:

How do you manage the **cover crop residue**?

- **Incorporated** in the soil
- Left on **top** of the soil
- **Removed** from site
- Other:

Did cover crops **meet your expectations** (both in benefits and encountered challenges)?

- Yes
- No. If so, please explain:

Did you notice an increase in almond yields with cover cropping?

Yes	No
○	○

Did any barriers lead you to **discontinue** using cover crops?

- Yes. If so, please explain the main **reason** for discontinuing the practice:
- No

PART V: Knowledge gaps

PART V: Knowledge gaps

Please rank the following from your **most to least important source of information** (Click and Drag).

Farm advisor/Cooperative extension specialists

PCA/CCA

Research collaboration

Other growers

Agricultural publications

Extension bulletins

Books

Websites

Almond Board of California Newsletters

Workshops/Field Days/Conferences

Other: ____________

In your opinion, where are the **most important knowledge gaps** about cover cropping, **in each category?**

Benefits of cover cropping:

- [ ] Tree nutrition
- [ ] Pollinator habitat
- [ ] Weed control
- [ ] Water retention
- [ ] Soil health
- [ ] N fixation
- [ ] Pest control

**PCA/CCA refer to pest control advisers and certified crop advisers of California.*

Tradeoffs of cover cropping:

- ☐ Water use
- ☐ Frost complications
- ☐ N immobilization
- ☐ Orchard sanitation
- ☐ Pest buildup

Operations relating to cover cropping:

- ☐ Seed selection & traits
- ☐ Seeding date
- ☐ Stand maintenance
- ☐ Termination date
- ☐ Termination operations

Economics relating to cover cropping:

- ☐ Cost to establish
- ☐ Economic risks
- ☐ Economic returns

Please leave any additional comments here:

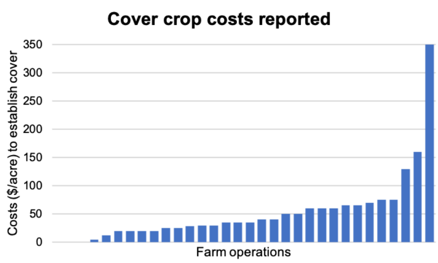
Supplementary Information 1.2. Current cover crop management practices (n=42)

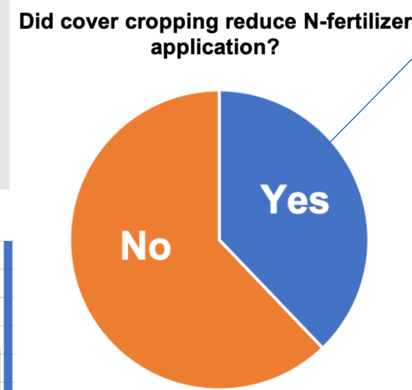
Reported Costs

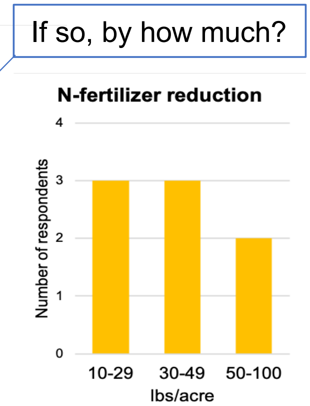
Cover crop establishment costs (including seed costs):

Range: $0 to $350/acre

Average cost: **$52.81**/acre





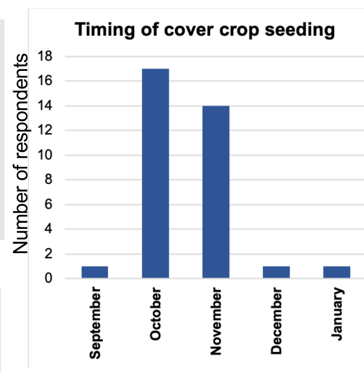


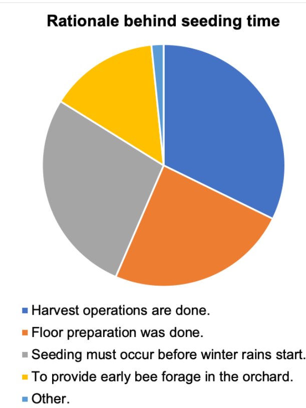
Comment from grower: "This depends on the field and the water quality."

Cover crop seeding

Seeding time

82% of growers in this survey re-seed the cover crop annually.



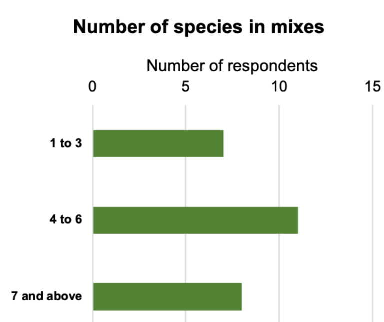


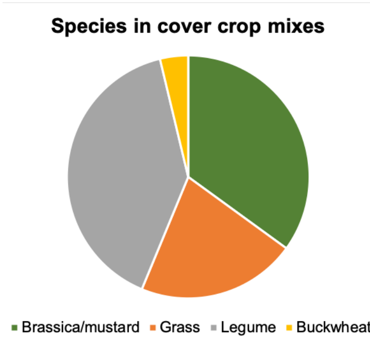
Species selection & Biodiversity

21% of growers design their own mix, whilst 79% use pre-packaged mixes

40% rotate plant species within the cover crop mix.

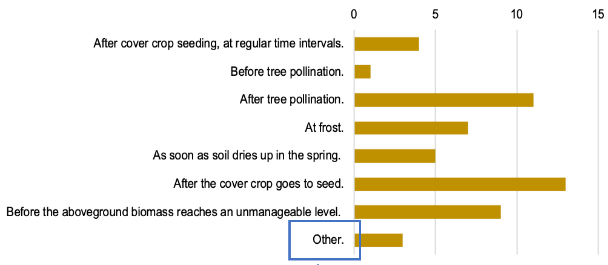
30% use different cover crop mixes within 1 orchard.





Cover crop stand management

Rationale of when to mow the cover



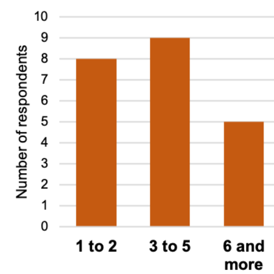
Comments from growers:
When do you mow the cover?

- *"Prior to [the cover crop] going to seed."*
- *"When the grass gets ahead of the sheep."*
- *"This depends on the field".*

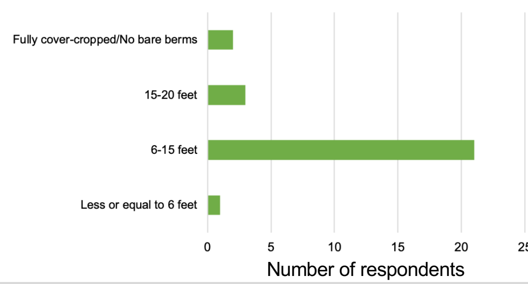
Mowing and Maintaining the stand

100% of growers mow the cover crop.

Number of mowings/year

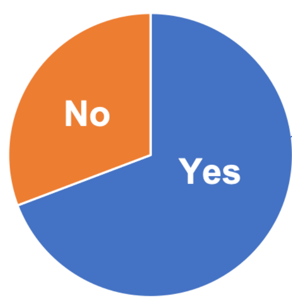


Width of the cover crop stand in orchard alleyways



Other orchard operations during cover crop establishment

Do you conduct sanitation after cover crop seeding?



38% leave intact mummies in the cover crop to decompose.

62% crush or flail-mow the mummies in the cover crop.

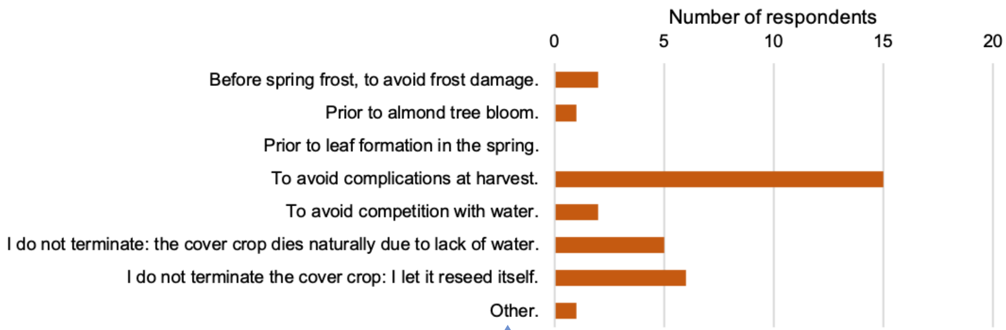
Do you compost with cover cropping?

Do you irrigate the cover crop?

Do you prune the orchard after cover crop seeding?

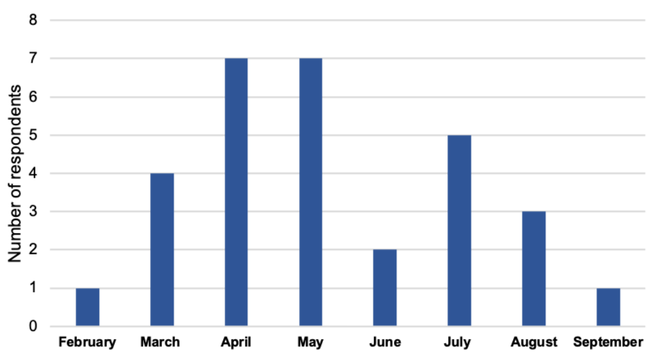
Cover crop termination

Rationale of when to terminate



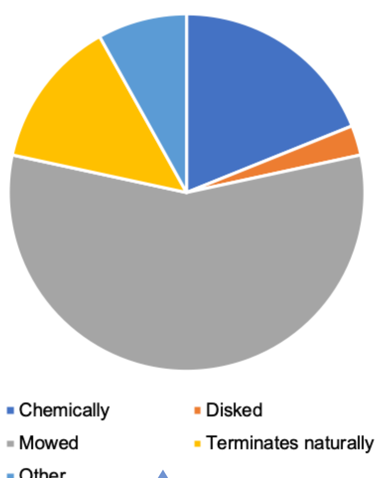
Comments from grower: "[I terminate] to prevent loss of fixed nitrogen."

Timing of Termination



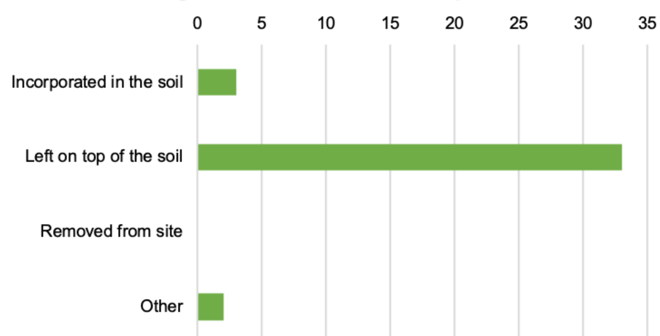
68% of growers terminated the cover crop.

How do you terminate the cover crop?



Comments from grower: "Graze it."

Management of the cover crop residue



Comments from growers:
"[Let it] go to seed, mow and let it dry up."
"[I use] a roller."

Cover crop results & Feedback from growers

Comments from growers:
"Previously used legume mix and experienced a blowup of the pocket gopher population."

"Sometimes we have to take a year off of cover cropping to do floor maintenance (float) for harvest purposes."

"Water."

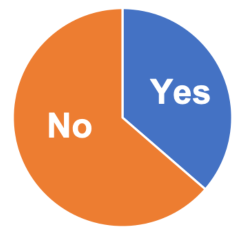
"Water."

"Cumbersome."

"Main barrier was low germination rate but we will give it another try."

36% of growers say that they noticed an increase in almond yields with cover cropping.

Did you notice an increase in almond yields with cover croppings?



Comments from growers:
"Not enough growth. [Does not] bloom in time for bees."

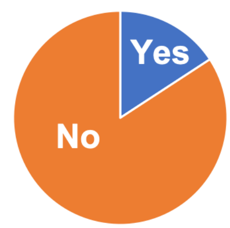
"Poor germination due to lack of water."

"Does not establish well, lack of water."

"Planting challenges with winter rains used as only irrigation source."

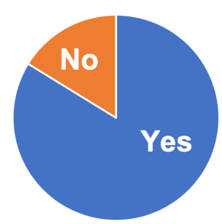
"Although we know of well documented benefits of cover crops, what really discouraged us from continuing trying to implement a cover crop (despite its increased potential factor in frost, increased labor, and an increased water demand) was the cover crops low germination rate. Not sure if we just got a bad seed mix or why there was such low germination rate. Suggestion: I would really like to see a more detailed study on cover crops and the effect of ground cover in the orchard. For example does planting a cover crop 6 feet wide in the row center actually benefit your trees in your orchard? Or does the cover crop need to be right under the tree canopy to even have any beneficial effect in the orchard?"

Did any barriers lead you to discontinue using cover crops?



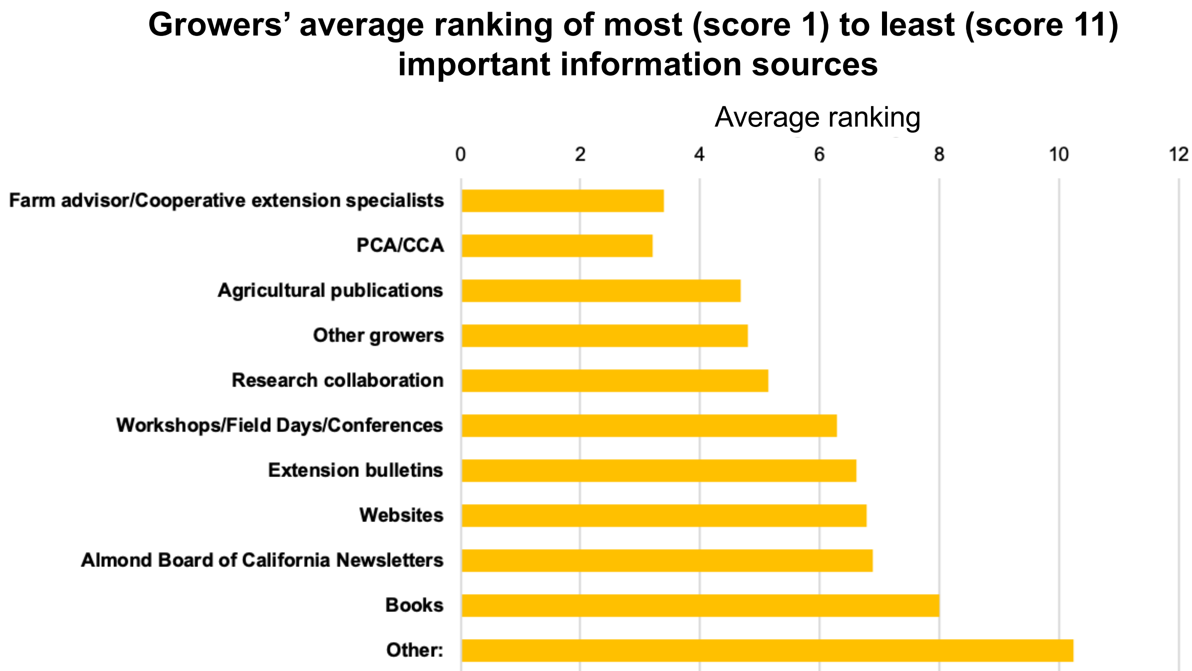
16% of growers discontinued using cover crops because of barriers.

Did cover crops meet your expectations?



84% of growers say that cover crops met their expectations.

Supplementary Information 1.3. Current cover crop information sources and knowledge gaps (n=82). **PCA/CCA refer to pest control advisers and certified crop advisers of California.*



Comments from growers:

"NRCS"

"Seed industry experts"

"Project APIS M"

"Project APIS representative"

"Private advisor/consultant"

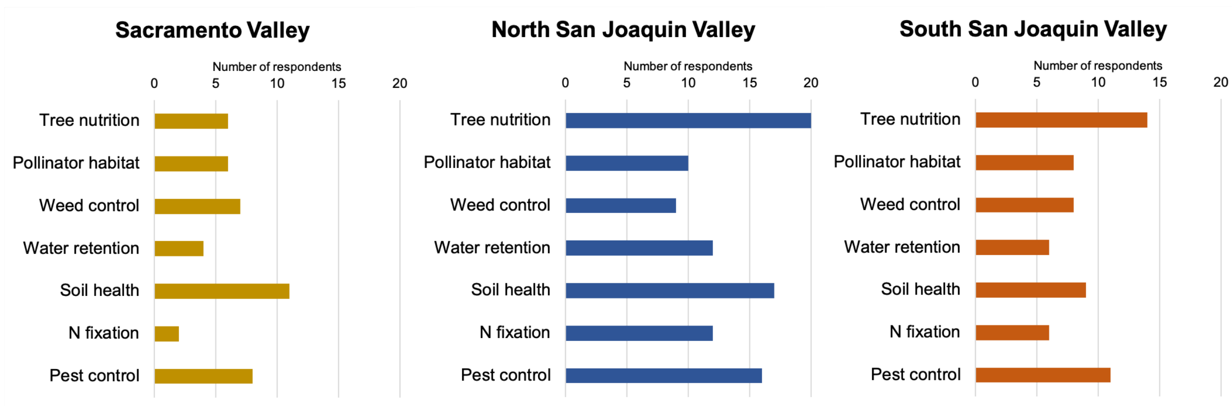
"Education in pomology"

"My experience"

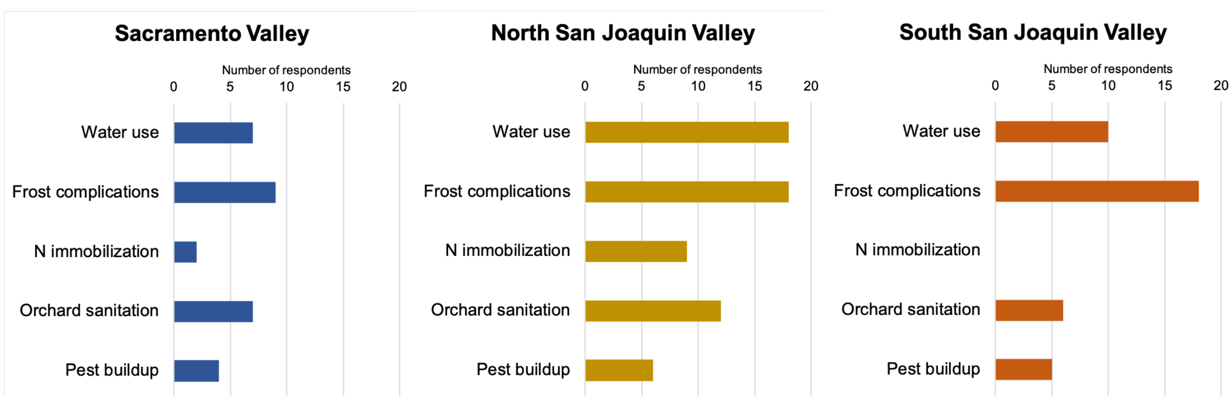
"Several generations of farming; Rodale Press for developing equipment, and the EFA (Ecological Farming Association) conference, which inspired us to grow weeds."

Most important knowledge gaps by region

Benefits of cover cropping

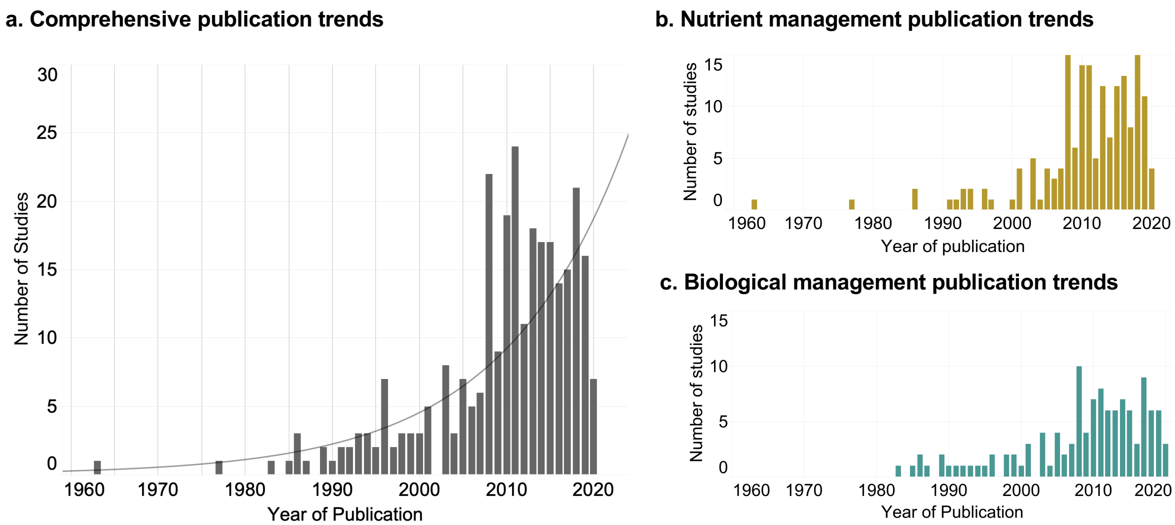


Tradeoffs of cover cropping



Appendix B. Supplementary Information for Chapter 2 and 3

Supplementary Information 2.1. Publication trends of cover crop research conducted in perennial systems. Trends are indicated by the number of studies published per year, from 1960 to May 2020. a. Comprehensive publication trends. b. Publication trends for nutrient management frameworks. c. Publication trends for biological management frameworks. Publication trends demonstrate that nutrient and biological management frameworks of cover crop research co-evolved from the 1960s to today, with a noticeable increase in publication around 2000. Yearly publication trends indicate a stronger research coverage of nutrient management frameworks over time, as compared to biological management frameworks.



**The earliest cover crop scientific article found in nutrient management corresponds to: Miller, D.E., Bunger, W.C., Proebsting, E.L. 1963. Agronomy Journal, 188-191.*

Supplementary Information 2.2. Classification of ecosystem services, observed in cover crop research. Our definition of ecosystem services and their classification were based on the Millennium Ecosystem Assessment (2005) and on the framework described by Schipanski *et al*. (2014). Regulating services were those gained from the regulation of ecosystem processes. Supporting services were those required for the production of other services. Provisioning services referred to products, beneficial to human societies, provided by ecosystems. Comprehensively, scientific research observed ten regulating ecosystem services, seven supporting services and three provisioning services, associated with cover cropping in perennial systems.

Ecosystem services and Millennium Assessment categories		
Regulating services	Supporting services	Provisioning services
Beneficial insect conservation	AMF colonization	Crop yield
Biodiversity	Biomass production	Economic profitability
GHG regulation	N mineralization	Knowledge diffusion
NO_3^- leaching	Nutrient cycling	
Pest suppression	Soil carbon	
Pollination	Soil structure	
Soil retention	Water dynamics	
Water dynamics		
Weed suppression		
Wildlife habitat		

Supplementary Information 2.3. Unexplored co-occurring pairwise ecosystem services within cover crop literature. Field studies were conducted in perennial systems. Of 153 potential pairwise associations between the 18 ES reported in the comprehensive literature, not including knowledge diffusion services, nearly a third of ES-interactions (47/153) remain unexplored.

NO3- leaching economic profitability
soil retention GHG regulation
soil retention pollination
NO3- leaching biodiversity
soil retention weed suppression
soil retention wildlife habitat
NO3- leaching beneficial insect conservation
soil structure AMF colonization
soil structure beneficial insect conservation
N mineralization wildlife habitat
soil retention economic profitability
NO3- leaching GHG regulation
soil retention beneficial insect conservation
soil retention AMF colonization
soil structure NO3- leaching
NO3- leaching pest suppression
soil structure pollination
GHG regulation yields
GHG regulation wildlife habitat
soil C wildlife habitat
soil structure wildlife habitat
GHG regulation weed suppression
GHG regulation pollination
NO3- leaching pollination
GHG regulation pest suppression
GHG regulation economic profitability
GHG regulation biomass production
NO3- leaching weed suppression
GHG regulation biodiversity
NO3- leaching wildlife habitat
GHG regulation beneficial insect conservation
water dynamics pollination
pollination wildlife habitat
water dynamics wildlife habitat
soil C GHG regulation
AMF colonization wildlife habitat
AMF colonization pollination
AMF colonization pest suppression
AMF colonization NO3- leaching
wildlife habitat beneficial insect conservation
AMF colonization GHG regulation
pollination economic profitability
wildlife habitat economic profitability
AMF colonization economic profitability
wildlife habitat weed suppression
pollination weed suppression
AMF colonization beneficial insect conservation

Supplementary Information 2.4. List of studies included in the meta-analysis (n=285). Records were extracted on 05/05/2020.

Abraham, J. and Joseph, P. 2016. A new weed management approach to improve soil health in a tropical plantation crop, rubber (Hevea brasiliensis). Expl. Agric. 52:36-50.

Aengelo Rodrigues, M., Dimande, P., Pereira, E.L., Ferreira, I.Q., Freitas, S., Correia, C.M., Moutinho-Pereira, J. and Arrobas, M. 2015. Early-maturing annual legumes: an option for cover cropping in rainfed olive orchards. Nutrient Cycling in Agroecosystems 103:153-166.

Aguilar-Fenollosa, E., Ibanez-Gual, M. V., Pascual-Ruiz, S., Hurtado, M. and Jacas, J. A. 2011. Effect of ground-cover management on spider mites and their phytoseiid natural enemies in clementine mandarin orchards (I): Bottom-up regulation mechanisms. Biological Control 59:158-170.

Aguilar-Fenollosa, E. and Jacas, J.A. 2013. Effect of ground cover management on Thysanoptera (thrips) in clementine mandarin orchards. Journal of Pest Science 68:469-481.

Aguilar-Fenollosa, E., Pascual-Ruiz, S., Hurtado, M. A. and Jacas, J.A. 2011. Efficacy and economics of ground cover management as a conservation biological control strategy against *Tetranychus urticae* in clementine mandarin orchards. Crop Protection 30:1328-1333.

Almagro, M., De Vente, J., Boix-Fayos, C., Garcia-Franco, N., Melgares de Aguilar, J., Gonzalez, D., Sole-Benet, A. and Martinez-Mena, M. 2013. Sustainable land management practices as providers of several ecosystem services under rainfed Mediterranean agroecosystems. Mitig. Adapt. Strateg. Glob. Change. https://www.doi.org/10.1007/s11027-013-9535-2

Alston, D.G. 1994. Effect of apple orchard floor vegetation on density and dispersal of phytophagous and predaceous mites in Utah. Agriculture, Ecosystems and Environment 50:73-84.

Altieri, M.A. and Schmidt, L.L. 1986. Cover crops affect insect and spider populations in apple orchards. Calif. Agric. 40:15-17.

Altieri, M.A. and Schmidt, L.L. 1985. Cover crop manipulation in Northern California orchards and vineyard – Effects on Arthropod communities. Biological Agriculture and Horticulture 3:1-24.

Anderson, J.J., Bingham G.E. and Hill, R.W. 1992. Effects of permanent cover crop competition on sour cherry tree evapotranspiration, growth and productivity. Acta Hort 313:135–142.

Angelo Rodrigues, M., Correia, C.M., Claro, A.M., Ferreira, I. Q., Barbosa, J. C., Moutinho-Pereira, J.M., Bacelar, E. A., Fernandes-Silva, A.A. and Arrobas, M. 2013. Soil nitrogen availability in olive orchards after mulching legume cover crop residues. Scientia Horticulturae 158:45-51.

Atucha, A., Merwin, I.A. and Brown, M.G. 2011. Long-term Effects of Four Groundcover Management Systems in an Apple Orchard. HortScience 46:1176-1183.

Atucha, A., Merwin, I.A., Brown, M.G., Gardiazabal, F., Mena, F., Adriazola, C., Goebel, M. and Bauerle, T. 2013. Root distribution and demography in an avocado (*Persea americana*) orchard under groundcover management systems. Functional Plant Biology 40:507-515.

Atucha, A., Merwin, I.A., Purohit, C.K. and Brown, M.G. 2011. Nitrogen Dynamics and Nutrient Budgets in Four Orchard Groundcover Management Systems. HortScience 46:1184-1193.

Balota, E.L. and Auler, P.A.M. 2011. Soil microbial biomass under different management and tillage systems of permanent intercropped cover species in an orange orchard. R. Bras. Ci. Solo 35: 1873–1883.

Balota, E.L. and Martins Auler, P.A. 2011. Soil carbon and nitrogen mineralization under different tillage systems and permanent groundcover cultivation between orange trees. Rev. Bras. Fructic. 33:637-648. https://www.doi.org/10.1590/S0100-29452011005000071

Basinger, N.T., Jennings, K.M., Monks, D.W., Mitchem, W.E., Perkins-Veazie, P.M. and Chaudhari, S. 2017. In-row Vegetation-free Strip Width Effect on Established 'Navaho' Blackberry. Weed Technol. 32:85-89.

Baumgartner, K., Fujiyoshi, P., Smith, R. and Bettiga, L. 2010. Weed flora and dormant-season cover crops have no effects on arbuscular mycorrhizae of grapevine. Weed Research 50:456-466.

Baumgartner, K., Steenwerth, K.L. and Veilleux, L. 2007. Effects of organic and conventional practices on weed control in a perennial cropping system. Weed Science 55:352-358.

Baumgartner, K., Steenwerth, K.L. and Veilleux, L. 2008. Cover-crop systems affect weed communities in a California vineyard. Weed Science 56:596-605.

Beizhou, S., Jie, Z., Jinghui, G., Hongying, W., Yun, K. and Yuncong, Y. 2011. Effects of intercropping with aromatic plants on the diversity and structure of an arthropod community in a pear orchard. Pest Manag. Sci. 67:1107-1114.

Belding, R.D., Majek, B.A., Lokaj, G.R.W., Hammerstedt, J. and Ayeni, A.O. 2003. Orchard floor preparation did not affect early peach tree performance on aura sandy loam soil. HortTechnology 13:321-324.

Blaauw, B.R. and Isaacs, R. 2014. Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. Journal of Applied Ecology 51:890–898.

Bowen, P. and Freyman, S. 1995. Ground covers affect raspberry yield, photosynthesis, and Nitrogen nutrition of primocanes. HortScience 30:238-241.

Bradshaw, L. and Lanini, W.T. 1995. Use of perennial cover crops to suppress weeds in Nicaraguan coffee orchards. International Journal of Pest Management 41:185-194.

Bremer Neto, H., Victoria Filho, R., Alves Mourao Filho, F.A., de Menezes, G.M. and Canali, E. 2008. Nutritional status and production of 'Pera' sweet orange related to cover crops and mulch. Pesq. agropec. Bras. 43:29-35.

Broughton, W.J. 1977. The effect of various covers on soil fertility under *Hevea brasiliensis* Muell. Arg. and on growth of the tree. Agro-Ecosystems 3:147–170.

Brunetto, G., Ceretta, C.A., Bastos de Melo, G.W., Kaminski, J., Trentin, G., Girotto, E., Avelar Ferreira, P.A., Miotto, A. and Ocheuze Trivelin, P.C. 2014. Contribution of nitrogen from agricultural residues of rye to 'Niagara Rosada' grape nutrition. Scientia Horticulturae 169:66-70.

Bugg, R.L., Dutcher, J.D. and McNeill, P.J. 1991. Cool-season cover crops in the pecan orchard understory: effects on Cocconellidae (Coleoptera) and pecan aphids (Homoptera: Aphididae). Biol. Control. 1:8-15.

Bugg, R.L. and Dutcher, J.D. 1989. Warm-season cover crops for pecan orchards: horticultural and entomological implications. Biol. Agric. Hortic. 6:123-148.

Bugg, R.L. and Dutcher, J.D. 1993. *Sesbania exaltata* (Rafinesque-Schmaltz) Cory (Fabaceae) as a Warm-Season Cover Crop in Pecan Orchards: Effects on Aphidophagous Coccinellidae and Pecan Aphids. Biological Agriculture and Horticulture 9:215-229. https://www.doi.org/10.1080/01448765.1993.9754637

Bugg, R.L., McGourty, G., Sarrantonio, M., Lanini, W.T. and Bartolucci, R. 1996. Comparison of 32 cover crops in an organic vineyard on the north coast of California. Biological Agriculture and Horticulture 13:63-81. https://www.doi.org/10.1080/01448765.1996.9754766.

Buyer, J.S., Baligar, V.C., He, Z. and Arevalo-Gardini, E. 2017. Soil microbial communities under cacao agroforestry and cover crop systems in Peru. Applied Soil Ecology 120:273-280. http://www.doi.org/10.1016/j.apsoil.2017.09.009

Campbell, A.J., Wilby, A., Sutton, P. and Wackers, F. 2017. Do sown flower strips boost wild pollinator abundance and pollination services in a spring-flowering crop? A case study from UK cider apple orchards. Agriculture, Ecosystems and Environment 239:20-29.

Campbell, A.J., Wilby, A., Sutton, P. and Wackers, F. 2017. Getting more power from your flowers: multi-functional flower strips enhance pollinators and pest control agents in apple orchards. Insects 8:101.

Cardenas, M., Castro, J. and Campos, M. 2012. Short-term response of soil spiders to cover-crop removal in an organic olive orchard in a Mediterranean setting. Journal of Insect Science 12:61.

Carpio, A.J., Castro, J., Mingo, V. and Tortosa, F.S. 2017. Herbaceous cover enhances the squamate reptile community in woody crops. Journal for Nature Conservation. http://www.doi.org/10.1016/j.jnc.2017.02.009

Carpio, A.J., Castro, J. and Tortosa, F.S. 2018. Arthropod biodiversity in olive groves under two soil management systems: presence versus absence of herbaceous cover crop. Agricultural and Forest Entomology 21:58-68. http://www.doi.org/10.1111/afe.12303

Carpio, A.J., Lora, A., Martin-Consuegra, E., Sanchez-Cuesta, R., Tortosa, F.S. and Castro, J. 2020. The influence of the soil management systems on aboveground and seed bank weed communities in olive orchards. Weed Biology and Management 20:12-23.

Carpio, A.J., Soriano, M.-A., Guerrero-Casado, J., Prada, L.M., Tortosa, F.S., Lora, A. and Gomez, J.A. 2017. Evaluation of an unpalatable species (*Anthemis arvensis L.*) as an alternative cover crop in olive groves under high grazing pressure by rabbits. Agriculture, Ecosystems and Environment 246:48-54.

Carvalheiro, L.G., Seymour, C.L., Nicolson, S.W. and Veldtman, R. 2012. Creating patches of native flowers facilitates crop pollination in large agricultural fields: mango as a case study. Journal of Applied Ecology 49:1373–1383.

Castro, J., Fernandez-Ondono, E., Rodriguez, C., Lallena, A.M., Sierra, M. and Aguilar, J. 2008. Effects of different olive-grove management systems on the organic carbon and nitrogen content of the soil in Jaen (Spain). Soil and Tillage Research 98:56-67.

Celano, G., Dumontet, S., Xiloyannis, C., Nuzzo, V. and Dichio, B. 1997. Responses of peach-orchard system to green manuring and mineral fertilization. Acta Hort. 448:289-296.

Celette, F. and Gary, C. 2013. Dynamics of water and nitrogen stress along the grapevine cycle as affected by cover cropping. Europ. J. Agronomy 45:142-152.

Celette, F., Gaudin, R. and Gary, C. 2008. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. European Journal of Agronomy 29(4):153-162.

Centinari, M., Filippetti, I., Bauerle, T., Allegro, G., Valentini, G. and Poli, S. 2013. Cover crop water use in relation to vineyard floor management practices. Am. J. Enol. Vitic. 64:522-526. https://www.doi.org/10.5344/ajev.2013.13025

Chen, L., Lin, S., You, M., Chen, S., Vasseur, L. and Ye, S. 2011. Effects of cover crops on mite communities in tea plantations. Biodiversity Science 19:353-362.

Chen, L.L., Yuan, P., You, M.-S., Pozsgai, G., Ma, X., Zhu, H. and Yang, G. 2019. Cover crops enhance natural enemies while help suppressing pests in a tea plantation. Annals of the Entomological Society of America: 1-8.

Chen, L.L., Yuan, P., Pozsgai, G., Chen, P., Zhu, H. and You, M-S. 2018. The impact of cover crops on the predatory mite *Anystis baccarum* (Acari, Anystedae) and the leafhopper pest *Empoasca onukii* (Hemiptera, Cicadellidae) in a tea plantation. Pest Management Science 75:3371-3380.

Chen, L.-L., You, M.-S. and Chen, S.-B. 2011. Effects of cover crops on spider communities in tea plantations. Biological Control 59:326-335.

Chen, L.-L., Yuan, P., Pozsgai, G., Chen, P., Zhu, H. and You, M.-S. 2018. The impact of cover crops on the predatory mite *Anystis baccarum* (Acari, Anystidae) and the leafhopper pest *Empoasca onukii* (Hemiptera, Cicadellidae) in a tea plantation. Pest Manag. Sci. 75:3371-3380. https://www.doi.org/10.1002/ps.5489

Clermont-Dauphin, C., Suvannang, N., Pongwichian, P., Cheylan, V., Hammecker, C. and Harmand, J.-M. 2016. Dinitrogen fixation by the legume cover crop Puerara phaseoloides and transfer of fixed N to *Hevea brasiliensis* - Impact on tree growth and vulnerability to drought. Agriculture, Ecosystems and Environment 217:79-88. https://www.doi.org/10.1016/j.agee.2015.11.002

Corleto, A. and Cazzato, E. 2008. Effects of Different Soil Management Practices on Production, Quality and Soil Physico-Chemical Characteristics of an Olive Grove in Southern Italy. Acta Hort. 767: 319-328.

Costello, M.J. and Daane, K.M. 2003. Spider leafhopper (Erythroneura spp.) response to vineyard ground cover. Environ Entomol 32:1085-1098.

Costello, M.J. 2010. Grapevine and Soil Water Relations with Nodding Needlegrass (*Nassella cernua*), a California Native Grass, as a Cover Crop. HortScience 45:621-627.

Costello, M.J. 2010. Growth and Yield of Cultivated Grape with Native Perennial Grasses Nodding Needlegrass or California Barley as Cover Crops. HortScience 45:154-156.

Cotes, B., Castro, J., Cardenas, M. and Campos, M. 2009. Responses of epigeal beetles to the removal of weed cover crops in organic olive orchards. Bulletin of Insectology 62:47-52.

Cruz, A.F., Pires, M.C., Beda do Nascimento, L.K., Gerosa Ramos, M.L., Oliveira, S.A., Bassay Blum, L.E. and Yamanishi, O.K. 2019. Cover cropping system and mulching can shape soil microbial status in fruit orchards. Sci. Agri. 77: e20180316

Cucci, G., Lacolla, G., Crecchio, C., Pascazio, S. and De Giorgio, D. 2016. Impact of long-term soil management practices on the fertility and weed flora of an almond orchard. Turk. J. Agric. For. 40:194–202. https://www.doi.org/10.3906/tar-1502-87

Culumber, C.M., Reeve, J.R., Black, B.L., Ransom, C.V. and Alston, D.G. 2019. Organic orchard floor management impact on soil quality indicators: nutrient fluxes, microbial biomass and activity. Nutr. Cycl. Agroecosyst. 115:101-115.

Cummings, J. and Reid, N. 2008. Stand-level management of plantations to improve biodiversity values. Biodivers Conserv 17:1187-1211.

Daane, A., Thomson, L.J., Sharley, D.J., Penfold, C.M. and Hoffman, A.A. 2010. Effects of native grass cover crops on beneficial and pest invertebrates in Australian Vineyards. Entomological Society of America 39:970-978.

Daane, K., Hogg, B., Wilson, H. and Yokota, G. 2018. Native grass ground covers provide multiple ecosystems services in California vineyards. Journal of Applied Ecology 55:2473-2483. https://www.doi.org/10.1111/1365-2664.13145

Daane, K.M. and Costello, M.J. 1998. Can cover crops reduce leaf hopper abundance in vineyards? California Agriculture 52:27-33.

De Giorgio, D. and Lamascese, N. 2005. Long-term comparison among different soil tillage systems and weed control methods on almond tree growing in southern Italy. Options Méditerranéennes 63:257-264.

De Leijster, V., Santos, M.J., Wassen, M.J., Ramos-Font, M.E., Robles, A., Dias, M., Stall, M. and Verweij, P.A. 2019. Agroecological management improves ecosystem services in almond orchards within one year. Ecosystem Services 38:1009948.

De Matos, A.P., Sanches, N.F., Souza, L.F.S., Elias Junior, J., Teixeira, F.A. and Siebeneichler, S.C. 2009. Cover Crops on Weed Management in Integrated Pineapple Production Plantings. Acta Hort. 822:155-160.

Demir, Z. and Isik, D. 2019. Effects of cover crop treatments on some soil quality parameters and yield in a kiwifruit orchard in Turkey. Fresenius Environmental Bulletin 28:6988-6997.

Demir, Z., Tursun, N. and Isik, D. 2019. Effects of Different Cover Crops on Soil Quality Parameters and Yield in an Apricot Orchard. International Journal of Agriculture and Biology 21:399-408. https://www.doi.org/10.17957/IJAB/15.0000

Dib, H., Libourel, G. and Warlop, F. 2012. Entomological and functional role of floral strips in an organic apple orchard: Hymenopteran parasitoids as a case study. J. Insect Conserv. 16:315–318. https://www.doi.org/10.1007/s10841-012-9471-6

Dinesh, R., Suryanarayana, M.A., Ghoshal Chaudhuri, S., Sheeja, T.E. and Shiva, K.N. 2005. Long-term effects of leguminous cover crops on biochemical and biological properties in the organic and mineral layers of soils of a coconut plantation. European Journal of Soil Biology 42:147-157.

Du, S., Bai, G. and Yu, J. 2015. Soil properties and apricot growth under intercropping and mulching with erect milk vetch in the loess hilly-gully region. Plant Soil 390:431-442.

Eckert, M., Mathulwe, L.L., Gaigher, R., Joubert-van der Merwe, L. and Pryke, J.S. 2019. Native cover crops enhance arthropod diversity in vineyards of the Cape Floristic Region. Journal of Insect Conservation. https://www.doi.org/10.1007/s10841-019-00196-0

English-Loeb, G., Rhainds, M., Martinson, T. and Ugine, T. 2003. Influence of flowering cover crops on Anagrus parasitoids (Hymenoptera : Mymaridae) and Erythroneura leafhoppers (Homoptera : Cicadellidae) in New York vineyards. Agricultural and Forest Entomology 5:173-181.

Espejo-Perez, A.J., Rodriguez-Lizana, A., Ordonez, R. and Giraldez, J.V. 2013. Soil Loss and Runoff Reduction in Olive-Tree Dry-Farming with Cover Crops. Soil Sci. Soc. Am. J. 77:2140–2148. https://www.doi.org/10.2136/sssaj2013.06.0250

Espindola, J.A.A., Guerra, J.G.M., de Almeida, D.L., Teixeira, M.G. and Urquiaga, S. 2006. Decomposition and nutrient release of perennial herbaceous legumes intercropped with banana. R. Bras. Ci. Solo 30:321-328.

Fell, V., Matter, A., Keller, T. and Boivin, P. 2018. Patterns and Factors of Soil Structure Recovery as Revealed From a Tillage and Cover-Crop Experiment in a Compacted Orchard. Frontiers in Environmental Science 6:134. https://www.doi.org/10.3389/fenvs.2018.00134

Fernandez, D.E., Cichon, L.I., Sanchez, E.E., Garrido, S.A. and Gittins, C. 2014. Effect of different cover crops on the presence of arthropods in an organic apple (*Malus domestica* Borkh) orchard. Journal of Sustainable Agriculture 32:197-211. http://www.doi.org/10.1080/10440040802170624

Ferraj, B., Teqja, Z., Susaj, L., Fasllia, N., Gjeta, Z., Vata, N. and Balliu, A. 2011. Effects of different soil management practices on production and quality of olive groves in Southern Albania. Journal of Food, Agriculture and Environment 9:430–433.

Ferrari, F.N. and Parera, C.A. 2015. Germination of six native perennial grasses that can be used as potential soil cover crops in drip-irrigated vineyards in semiarid environs of Argentina. Journal of Arid Environments 113:1-5.

Fidalski, J., Scapim, C.A. and Colauto Stenzel, N.M. 2007. Divergence of 'Folha Murcha' orange tree rootstocks as influenced by two groundcover crops. R. Bras. Ci. Solo 31:353-360.

Firth, D.J., Whalley, R.D.B. and Johns, G.G. 2003. Legume groundcovers have mixed effects on growth and yield of Macadamia integrifolia. Australian Journal Experimental Agriculture 43: 419–423.

Fitzgerald, J.D. and Solomon, M.G. 2004. Can Flowering Plants Enhance Numbers of Beneficial Arthropods in UK Apple and Pear Orchards? Biocontrol Sci. Technol. 14:291–300. https://www.doi.org/10.1080/09583150410001665178

Flores, L., Dussi, M.C., Fernandez, C., Azpilicueta, C., Aruani, C. and Sugar, D. 2015. Impact of Alleyway Management and Vegetation Diversity on Nematode Abundance in Pear Agroecosystems. Acta Hort. 1094:341-350.

Fourie, J.C. 2011. Soil Management in the Breede River Valley Wine Grape Region, South Africa. 3. Grapevine Performance. S. Afr. J. Enol. Vitic. 32:60-70.

Fracchiolla, M., Terzi, M., Frabboni, L., Caramia, D., Lasorella, C., De Giorgio, D., Montemurro, P. and Cazzato, E. 2015. Influence of different soil management practices on ground-flora vegetation in an almond orchard. Renewable Agriculture and Food Systems 31:300-308.

Francia, J.R., Durán Zuazo, V.H. and Martinez, A. 2006. Environmental impact from mountainous olive orchards under different soil management systems (SE Spain). Sci Total Environ. 358:46-60.

Frechette, B., Cormier, D., Chouinard, G., Vanoostruyse, F. and Lucas, E. 2008. Apple aphid, *Aphis* spp. (Hemiptera:Aphididae), and predator populations in an apple orchard at the non-bearing stage: The impact of ground cover and cultivar. Eur. J. Entomol 105:521-529.

Freyman, S. 1989. Living mulch ground covers for weed control between raspberry rows. Acta Horticult. 262:349-356.

Fye, R.E. 1983. Cover crop manipulation for building pear psylla (Homoptera, Psyllidae) predator population in pear orchards. J. Econ. Entomol. 76:306-310.

Gago, P., Cabaleiro, C. and García, J. 2007. Preliminary study of the effect of soil management systems on the adventitious flora of a vineyard in northwestern Spain. Crop Protection 26(4):584–591.

Garcia-Orenes, F., Roldan, A., Morugan-Coronado, A., Linares, C., Cerda, A. and Caravaca, F. 2016. Organic Fertilization in Traditional Mediterranean Grapevine Orchards Mediates Changes in Soil Microbial Community Structure and Enhances Soil Fertility. Land Degrad. Develop. 27:1622-1628. https://www.doi.org/10.1002/ldr.2496

Garland, G.M., Suddick, E., Burger, M., Horwath, W. and Six, J. 2011. Direct N_2O emissions following transition from conventional till to no-till in a cover cropped Mediterranean vineyard (*Vitis vinifera*). Agriculture, Ecosystems and Environment 141:234-239.

Giese, G., Velasco-Cruz, C., Roberts, L., Heitman, J. and Wolf, T.K. 2014. Complete vineyard floor cover crops favorably limit grapevine vegetative growth. Scientia Horticulturae 170:256-266.

Giese, G., Wolf, T.K., Velasco-Cruz, C., Roberts, L., and Heitman, J. 2014. Cover Crop and Root Pruning Impacts on Vegetative Growth, Crop Yield Components, and Grape Composition of Cabernet Sauvignon. American Journal of Enology and Viticulture 66:2. https://www.doi.org/10.5344/ajev.2014.14100

Glenn, D.M., Welker, W.V. and Greene, G.M. 1996. Sod competition in peach production. 1. Managing sod proximity. J. Amer. Soc. Hort. Sci. 121(4):666–669.

Gómez, J.A., Llewellyn, C., Basch, G., Sutton, P.B., Dyson, J.S. and Jones, C.A. 2011. The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. Soil Use Manage. 27:502-514.

Gómez, J.A., Campos, M., Guzmán, G., Castillo- Llanque, F., Vanwalleghem, T., Lora, A. and Giráldez, J.V. 2017. Soil erosion control, plant diversity, and arthropod communities under heterogeneous cover crops in an olive orchard. Environmental Science Pollution Research 25:977-989. https://www.doi.org/10.1007/s11356-016-8339-9

Gomez, J.A., Gema Guzman, M., Giraldez, J.V. and Fereres, E. 2009. The influence of cover crops and tillage on water and sediment yield, and on nutrient, and organic matter losses in an olive orchard on a sandy loam soil. Soil and Tillage Research 106:137-144.

Gontijo, L.M., Beers, E.H. and Snyder, W.E. 2013. Flowers promote aphid suppression in apple orchards. Biological Control 66:8:15.

Granatstein, D., Kirby, E. and Davenport, J. 2013. Direct Seeding Legumes into Orchard Alleys for Nitrogen Production. HortScience 1001:329-334.

Granatstein, D., Davenport, J.R. and Kirby, E. 2017. Growing Legumes in Orchard Alleys as an Internal Nitrogen Source. HortScience 52:1283-1287.

Granatstein, D. and Mullinix, K. 2008. Mulching options for northwest organic and conventional orchards. HortScience 43:45-50.

Griffin, J.L., Miller, D.K. and Salassi, M.E. 2006. Johnsongrass (*Sorghum halepense*) control and economics of using glyphosate-resistant soybean in fallowed sugarcane fields. Weed Technology 20:980-985.

Guzman, G., Perea-Moreno, A.-J., Alfonso Gomez, J., Angel Cabrerizo-Morales, M., Martinez, G. and Vicente Giraldez, J. 2019. Water Related Properties to Assess Soil Quality in Two Olive Orchards of South Spain under Different Management Strategies. Water 11:367. https://www.doi.org/10.3390/w11020367

Haley, S. and Hogue, E.J. 1990. Ground cover influence on apple aphid, *Aphis pomi* DeGeer (Homoptera: Aphididae), and its predators in a young apple orchard. Crop Prot. 9:225-230.

Hall, H., Li, Y., Comerford, N., Arevalo Gardini, E., Zuniga Cernades, L., Baligar, V. and Popenoe, H. 2010. Cover crops alter phosphorus soil fractions and organic matter accumulation in a Peruvian cacao agroforestry system. Agroforest. Syst. 80:447-455.

Herencia, J. F. 2014. Enzymatic activities under different cover crop management in a Mediterranean olive orchard. Biological Agriculture and Horticulture 31:45-52. http://www.doi.org/10.1080/01448765.2014.964318

Herencia, J.F. 2017. Soil quality indicators in response to long-term cover crop management in a Mediterranean organic olive system. Biological Agriculture and Horticulture 34:211-231. https://www.doi.org/10.1080/01448765.2017.1412836

Hernandez, A.J., Lacasta, C. and Pastor, J. 2005. Effects of different management practices on soil conservation and soil water in a rainfed olive orchard. Agricultural Water Management 77:232–248.

Hoagland, L., Carpenter-Boggs, L., Granatstein, D., Mazzola, M., Smith, J., Peryea, F. and Reganold, J.P. 2008. Orchard floor management effects on nitrogen fertility and soil biological activity in a newly established organic apple orchard. Biol. Fertl. Soils. 45:11-18.

Hogue, E.J., Cline, J.A., Neilsen, G. and Neilsen, D. 2010. Growth and Yield Responses to Mulches and Cover Crops under Low Potassium Conditions in Drip-irrigated Apple Orchards on Coarse Soils. HortScience 45:1866-1871.

Hussain, S., Sharma, M. K., War, A.R. and Hussain, B. 2020. Weed Management in Apple Cv. Royal Delicious by Using Different Orchard Floor Management Practices. International Journal of Fruit Science. https://www.doi.org/10.1080/15538362.2019.1700405

Ingels, C.A., Scow, K.M., Whisson, D.A. and Drenovsky, R.E. 2005. Effects of cover crops on grapevines, yield, juice composition, soil microbial ecology, and gopher activity. Am. J. Enol. Vitic. 56:1.

Ismaili, H., Gixharl, B., Dodona, E. and Vorpsi, V. 2015. Study of some biological indicators in different systems of vegetation management of olive. Journal of environmental protection and ecology 16(2):643-651.

Jiang, D.J., Xu, L.Y. and Cheng, Z.P. 2014. Effects of green manure intercropping on parasitoids and *Empoasca vitis* (Gothe) in tea plantations. Wuyi Sci. J. 30:154-161.

Jones, J., Savin, M.C., Rom, C.R. and Gbur, E. 2017. Denitrifier community response to seven years of ground cover and nutrient management in an organic fruit tree orchard soil. Applied Soil Ecology 112:60-70.

Jordan, L.M., Bjoerkman, T. and Vanden Heuvel, J.E. 2016. Annual under-vine cover crops did not impact vine growth or fruit composition of mature cool-climate 'Riesling' grapevines. Hortechnology 26: 36–45.

Kairis, O., Karavitis, C., Kounalaki, A., Salvati, L. and Kosmas, C. 2013. The effect of land management practices on soil erosion and land desertification in an olive grove. Soil Use and Management 29:597–606. https://www.doi.org/10.1016/j.still.2009.04.008

Karl, A., Merwin, I.A., Brown, M.G., Hervieux, R.A. and Vanden Heuvel, J.E. 2016. Impact of undervine management on vine growth, yield, fruit composition, and wine sensory analyses in cabernet franc. American Journal of Enology and Viticulture 67:269–280.

Kitis, Y.E., Koloren, O. and Nezihi Uygur, F. 2011. Evaluation of common vetch (*Vicia sativa* L.) as living mulch for ecological weed control in citrus orchards. African Journal of Agricultural Research 6:1257-1264.

Klodd, A.E., Eissenstat, D.M., Wolf, T.K. and Centinari, M. 2016. Coping with cover crop competition in mature grapevines. Plant Soil 400:391-402.

Korte, N. and Porembski, S. 2010. Suitability of Different Cover Crop Mixtures and Seedlings for a New Tree Row Management in an Organic Orchard. Gesunde Pflanzen 62:45-52.

Kremer, R.J. and Kussman, R.D. 2011. Soil quality in a pecan-kura clover alley cropping system in the Midwestern USA. Agroforest. Syst. 83:213-223.

Kuhn, B.F. and Lindhard Pedersen, H. 2009. Cover Crop and Mulching Effects on Yield and Fruit Quality in Unsprayed Organic Apple Production. Europ. J. Hort. Sci. 74:247-253.

Larsen, K.J. and Whalon, M.W. 1987. Crepuscular movement of Paraphlepsius irroratus (Say) (Homoptera: Cicadellidae) between the groundcover and cherry trees. Environ. Entomol. 16:1103-1106.

Le Bellec, F., Damas, O., Boullenger, G., Vanniere, H., Lesueur Jannoyer, M., Tournebize, R. and Ozier Lafontaine, H. 2012. Weed Control with a Cover Crop (*Neonotonia wightii*) in Mandarin Orchards in Guadeloupe (FWI). Acta Hort 928:359-366.

Lee, S.E., Park, J.M., Park, Y.E. and Choi, D.G. 2016. Effect of cover crop species and SCB liquid manure application on leaf mineral content, fruit quality, and soil chemical properties in an Asian pear (*Pyrus pyrifolia*) orchard. Acta Hortic 1146:57-62.

Licznar-Malanczuk, M. 2015. Suitability of blue fescue (*Festuca ovina L.*) as living mulch in an apple orchard – preliminary evaluation. Acta Sci. Pol. Hortorum Cultus 14(6):163-174.

Linares, J., Scholberg, J., Boote, K., Chase, C.A., Ferguson, J.J. and McSorley, R. 2008. Use of the cover crop weed index to evaluate weed suppression by cover crops in organic citrus orchards. HortScience 43(1):27-34.

Linares, R., de la Fuente, M., Junquera, P., Ramon Lissarrague, J. and Baeza, P. 2014. Effects of soil management in vineyard on soil physical and chemical characteristics. BIO Web of Conferences 3:01008.

Lisek, J. and Buler, Z. 2018. Growth and yield of plum trees in response to in-row orchard floor management. Turk. J. Agric. For. 42:97-102.

Liu, Z., Lin, Y., Lu, H., Ding, M., Tan, Y., Xu, S. and Fu, S. 2013. Maintenance of a Living Understory Enhances Soil Carbon Sequestration in Subtropical Orchards. Plos One: e76950.

Lopez-Vicente, M., Garcia-Ruiz, R., Guzman, G., Vicente-Vicente, J.L., Van Wesemael, B. and Gomez, J.A. 2016. Temporal stability and patterns of runoff and runon with different cover crops in an olive orchard (SW Andalusia, Spain). Catena 147:125-137.

Lopez-Vicente, M. and Alvarez, S. 2018. Stability and patterns of topsoil water content in rainfed vineyards, olive groves, and cereal fields under different soil and tillage conditions. Agricultural Water Management 201:167-176.

Mailloux, J., Le Bellec, F., Kreiter, S., Tixier, M.-S. and Dubois, P. 2010. Influence of ground cover management on diversity and density of phytoseiid mites (Acari: Phytoseiidae) in Guadeloupean citrus orchards. Exp. Appl. Acarol. 52:275-290.

Malik, R.K., Green, T.H., Brown, G.F., Beyl, C.A., Sistani, K.R. and Mays, D.A. 2001. Biomass production of short-rotation bioenergy hardwood plantations affected by cover crops. Biomass and Bioenergy 21:21-33.

Marconi, L. and Armengot, L. 2020. Complex agroforestry systems against biotic homogenization: The case of plants in the herbaceous stratum of cocoa production systems. Agriculture, Ecosystems and Environment 287:106664.

Markó, V., Jenser, G., Kondorosy, E., Ábrahám, L. and Balázs, K. 2013. Flowers for better pest control? The effects of apple orchard ground cover management on green apple aphids (Aphis spp.) (Hemiptera: Aphididae), their predators and the canopy insect community. Biocontrol Sci. Technol. 23:126–145. https://www.doi.org/10.1080/09583157.2012.743972

Markó, V., Jenser, G., Mihályi, K., Hegyi, T. and Balázs, K. 2012. Flowers for better pest control? Effects of apple orchard groundcover management on mites (Acari), leafminers (Lepidoptera, Scitellidae), and fruit pests. Biocontrol Sci. Technol. 22:39–60. https://www.doi.org/10.1080/09583157.2011.642337

Markó, V. and Keresztes, B. 2014. Flowers for better pest control? Ground cover plants enhance apple orchard spiders (Araneae), but not necessarily their impact on pests. Biocontrol Sci. Technol. 24:574–596. https://www.doi.org/10.1080/09583157.2014.881981

Marques, M.J., Garcia-Munoz, S., Munoz-Organero, G. and Bienes, R. 2010. Soil conservation beneath grass cover in hillside vineyards under Mediterranean climate conditions (Madrid, Spain). Land Degradation and Development 21:122-131.

Marrereo, D.F., Pulido Delgado, L.E., Ianez, N.C., Calero, C.M., Rodriguez, M.L., Perez, L.R. and Rodriguez, L.C. 2009. Cover crop with Teramnus labialis in a citrus orchard: effects on some physical properties of the soil. Ciencias Agraras 30:1073-1082.

Martinelli, R., Monquero, P.A., Fontanetti, A., Conceicao, P.M. and Azevedo, F.A. 2017. Ecological Mowing: An Option for Sustainable Weed Management in Young Citrus Orchards. Weed Science Society of America 31:260-268.

Martins Auler, P.A., Fidalski, J., Pavan, M.A. and Vieira Janeiro Neves, C.S. 2008. Fruit yields of 'pera' orange under different soil tillage and interrow management systems. R. Bras. Ci. Solo 32:363-374.

Martins, B.H., Araujo-Junior, C.F., Miyazawa, M., Vieira, K.M. and Milori, D.M. 2015. Soil organic matter quality and weed diversity in coffee plantation area submitted to weed control and cover crops management. Soil and Tillage Research 153:169-174. https://www.doi.org/10.1016/j.still.2015.06.005

Mauro, R.P., Anastasi, U., Lombardo, S., Pandino, G., Pesce, R., Alessia, R. and Mauromicale, G. 2015. Cover crops for managing weeds, soil chemical fertility and nutritional status of organically grown orange orchard in Sicily. Italian Journal of Agronomy 10:641.

Mazzola, M. and Mullinix, K. 2005. Comparative field efficacy of management strategies containing *Brassica napus* seed meal or green manure for the control of apple replant disease. Plant Disease:1207-1213.

Mennan, H., Ngouajio, M., Isik, D. and Kaya, E. 2006. Effects of alternative management systems on weed populations in hazelnut (*Corylus avellana* L.). Crop Protection 25:835-841.

Mennan, H. and Ngouajio, M. 2012. Effect of Brassica Cover Crops and Hazelnut Husk Mulch on Weed Control in Hazelnut Orchards. HortTechnology 22(1):99-105.

Mercenaro, L., Nieddu, G., Pulina, P. and Porqueddu, C. 2014. Sustainable management of an intercropped Mediterranean vineyard. Agriculture, Ecosystems and Environment 192:85-104.

Merwin, I.A. and Stiles, W.C. 1994. Orchard ground cover management impacts on apple tree growth and productivity, and soil nutrient availability and uptake. J. Amer. Soc. Hortic. Sci. 119:216-222.

Merwin, I.A. and Ray, J.A. 1997. Spatial and temporal factors in weed interference with newly planted apple trees. HortScience 32(4):633-637.

Merwin, I.A., Ray, J.A. and Curtis, P.D. 1999. Orchard groundcover management systems affect meadow vole populations and damage to apple trees. HortScience 34(2):271-274.

Merwin, I.A., Stiles, W.C. and Vanes, H.M. 1994. Orchard groundcover management impacts on soil physical-properties. J. Amer. Soc. Hort Sci. 119(2):216-222.

Meyer, A.H., Wooldridge, J. and Dames, J.F. 2015. Effect of conventional and organic orchard floor management practices on arbuscular mycorrhizal fungi in a 'Cripp's Pink'/M7 apple orchard soil. Agriculture, Ecosystems and Environment 213:114-120.

Meyers, S.L., Jennings, K.M., Monks, D.W. and Mitchem, W.E. 2014. Effect of Weed-Free Strip Width on Newly Established 'Navaho' Blackberry Growth, Yield, and Fruit Quality. Weed Technology 28:426-431.

Miller, D.E., Bunger, W.C. and Proebsting, E.L. 1963. Properties of soil in orchard as influenced by travel and cover crop management systems. Agronomy Journal 55:188-191.

Montanaro, G., Tuzio, A.C., Xylogiannis, E., Kolimenakis, A. and Dichio, B. 2010. Effects of soil-protecting agricultural practices on soil organic carbon and productivity in fruit tree orchards. Land degradation and development 21:132-138.

Monteiro, A., Lopes, C.M., Machado, J.P., Fernandes, N., Araujo, A. and Moreira, I. 2008. Cover cropping in a sloping, non-irrigated vineyard: I - Effects on weed composition and dynamics. Ciencia Tec. Vitiv. 23:29-36.

Monteiro, A. and Lopes, C.M. 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agriculture, Ecosystems and Environment 121:336-342.

Monzo, C., Molla, O., Vanaclocha, P., Monton, H., Melic, A., Castanera, P. and Urbaneja, A. 2011. Citrus-orchard ground harbours a diverse, well-established and abundant ground-dwelling spider fauna. Spanish Journal of Agricultural Research 9:606-616.

Mulinge, J.M., Saha, H.M., Mounde, L.G. and Wasilwa, L.A. 2018. Effect of legume cover crops on orange (*Citrus sinensis*) fruit weight and Brix. International Journal of Plant and Soil Science 21:1-9. https://www.doi.org/10.9734/IJPSS/2018/39298

Mullinix, K. and Granatstein, D. 2011. Potential Nitrogen Contributions from Legumes in Pacific Northwest Apple Orchards. International Journal of Fruit Science 11:74-87.

Neilsen, G.H. and Hogue, E.J. 2000. Comparison of white clover and mixed sodgrass as orchard floor management. Can. Journal of Plant Science 80:617-622.

Neilsen, G., Forge, T., Angers, D., Neilsen, D. and Hogue, E. 2014. Suitable orchard floor management strategies in organic apple orchards that augment soil organic matter and maintain tree performance. Plant Soil 378:325-335.

Nicholls, C.L., Parrella, M.P. and Altieri, M.A. 2000. Reducing the abundance of leafhoppers and thrips in a Northern California organic vineyard through maintenance of full season floral diversity with summer cover crops. Agric. For Entomol 2:107-113.

Niether, W., Schneidewind, U., Fuchs, M., Schneider, M. and Armengot, L. 2019. Below- and aboveground production in cocoa monocultures and agroforestry systems. Science of the Total Environment 657:558-567.

Nikiema, P., Nzokou, P. and Rothstein, D. 2012. Effects of groundcover management on soil properties, tree physiology, foliar chemistry and growth in a newly established Fraser fir (Abies fraseri [Pursh] Poir) plantation in Michigan, United States of America. New Forests 43:213-230.

Nikiema, P., Nzokou, P., Rothstein, D.E. and Ngouajio, M. 2012. Soil microbial biomass as affected by groundcover management in a Fraser fir (Abies fraseri [Pursh] Poir) plantation after 1 year. Biol Fertil Soils 48:727-733.

Novara, A., Gristina, L., Saladino, S.S., Santoro, A. and Cerda, A. 2011. Soil erosion assessment on tillage and alternative soil managements in a Sicilian Vineyard. Soil and Tillage Research 117:140–147.

Nzokou, P., Wilson, A.R. and Lin, Y. 2014. Effect of Cover Crop Management on Organic Matter Production and Soil Fertility in an Abies fraseri Plantation. Acta Hort. 1018:407-414.

O'Neal, M.E., Zontek, E.L., Szendrei, Z., Landis, D.A. and Isaacs, R. 2005. Ground predator abundance affects prey removal in highbush blueberry (*Vaccinium corymbosum*) fields and can be altered by aisle ground covers. BioControl 50:205-222.

Oliveira, M.T. and Merwin, I.A. 2001. Soil physical conditions in a New York orchard after eight years under different groundcover management systems. Plant and Soil 234:2333-237.

Olmstead, M.A., Wample, R.L., Greene, S.L. and Tarara, J.M. 2001. Evaluation of potential cover crops for inland Pacific Northwest vineyards. Am. J. Enol. Vitic. 52:4.

Olthof, T.H.A. 1986. Damage to an apple orchard cover crop of creeping red fescue (Festuca-rubra) associated with Meloidogyne-microtyla. Plant Disease 70:436-438.

Ordonez-Fernandez, R., Rodrigues-Lizana, A., Jesus Espejo-Perez, A., Gonzalez-Fernandez, P. and Milagros Saavedra, M. 2007. Soil available phosphorus losses in ecological olive groves. Europ. J. Agronomy 27:144-153.

Ordonez-Fernandez, R., Repullo-Ruiberriz de Torres, M.A., Marquez-Garcia, J., Moreno-Garcia, M. and Carbonell-Bojollo, R.M. 2018. Legumes used as cover crops to reduce fertilization problems improving soil nitrate in an organic orchard. European Journal of Agronomy 95:1-13.

Ormeno-Nunez, J., Pino-Rojas, G. and Garfe-Vergara, F. 2008. Inhibition of yellow nutsedge (*Cyperus esculentus L.*) and bermudagrass (*Cynodon dactylon* (L.) Pers) by a mulch derived from rye (*Secale cereal L.*) in grapevines. Chilean Journal of Agricultural Research 68(3):238-247.

Ovalle, C., del Pozo, A., Lavín, A. and Hirzel, J. 2007. Cover crops in vineyards: performance of annual forage legume mixtures and effects on soil fertility. Agric. Técnica 67:384-392. https://www.doi.org/10.4067/S0365-28072007000400006

Ovalle, C., Gonzalez, M.I., Hirzel, J., Pino, I., del Pozo, A. and Urquiaga, S. 2008. Contribution and transfer of nitrogen from cover crops to raspberry plant using isotopic techniques with N-15. Acta Hort. 777:465-472.

Pandey, C.B. and Begum, M. 2010. The effect of a perennial cover crop on net soil N mineralization and microbial biomass carbon in coconut plantations in the humid tropics. Soil Use and Management 26:158-166.

Parker, M.L., Hull, J. and Perry, RL. 1993. Orchard floor management affects peach rooting. J. Amer. Soc. Hort. Sci. 118:714-718.

Parker, M.L. and Meyer, J.R. 1996. Peach tree vegetative and root growth respond to orchard floor management. HortScience 31(3):330-333.

Parveaud, C.-E., Gomez, C., Bussi, C. and Capowiez, Y. 2012. Effect of White Clover (Trifolium repens 'Huia') Cover Crop on Agronomic Properties and Soil Biology in an Organic Peach Orchard. Acta Hort. 933:373-380.

Pattison, A.B., Wright, C.L., Kukulies, T.L. and Molina, A.B. 2014. Ground cover management alters development of Fusarium wilt symptoms in Ducasse bananas. Australian Plant Path. 43:465-476. https://www.doi.org/10.1007/s13313-014-0296-5

Peregrina, F., Larrieta, C., Ibañez, S. and García-Escudero, E. 2010. Labile organic matter, aggregates, and stratification ratios in a semiarid vineyard with cover crops. Soil Sci Soc Am J 74:2120–2130.

Pérez-Álvarez, E.P., García-Escudero, E. and Peregrina, F. 2015. Soil nutrient availability under cover crops: effects on vines, must, and wine in a Tempranillo vineyard. American Journal of Enology and Viticulture 66: 311–320.

Ping, X.Y., Wang, T.M., Yao, C.Y. and Lu, X.S. 2018. Impact of floor management practices on the growth of groundcover species and soil properties in an apple orchard in northern China. Biological Rhythm Research 49:597-609.

Pou, A., Gulias, J., Moreno, M., Tomas, M., Medrano, H. and Cifre, J. 2011. Cover cropping in Vitis Vinifera L. CV. Manto negro vineyards under Mediterranean conditions: Effects on plant vigor, yield and grape quality. J. Int. Sci. Vigne. Vin 45:223-234.

Qian, X., Gu, J., Pan, H.-J., Zhang, K.-Y., Sun, W., Wang, X.-J. and Gao, H. 2015. Effects of living mulches on the soil nutrient contents, enzyme activities, and bacterial community diversities of apple orchard soils. European Journal of Soil Biology 70:23-30.

Rames, E.K., Pattison, T., Czislowski, E. and Smith, M.K. 2018. Soil microbial community changes associated with ground cover management in cultivation of Ducasse banana (Musa sp. ABB, Pisang Awak subgroup) and suppression of Fusarium oxysporum. Australian Plant Path 47:449-462. https://www.doi.org/10.1007/s13313-018-0578-4

Ramos, M.E., Benitez, E., Garcia, P.A. and Robles, A.B. 2010. Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: Effects on soil quality. Applied Soil Ecology 44:6-14.

Ramos, M.E., Robles, A.B., Sanchez-Navarro, A. and Gonzalez-Rebollar, J.L. 2011. Soil responses to different management practices in rainfed orchards in semiarid environments. Soil and Tillage Research 112(1):85-91.

Ranasinghe, C.S., Premasiri, R.D.N. and Silva, L.R.S. 2003. Effect of mulches and cover crops on water status and gas exchange of coconut (Cocos nucifera L.) palms in gravelly soils. COCOS 15:01-11.

Reeve, A.L., Skinkis, P.A., Vance, A.J., McLaughlin, K.R., Tomasino, E., Lee, J. and Tarara, J.M. 2018. Vineyard Floor Management and Cluster Thinning Inconsistently Affect 'Pinot noir' Crop Load, Berry Composition, and Wine Quality. HortScience 53:318-328.

Repullo-Ruiberriz de Torres, M.A., Ordonez-Fernandez, R., Giraldez, J.V., Marquez-Garcia, J., Laguna, A. and Carbonell-Bojollo, R. 2018. Efficiency of four different seeded plants and native vegetation as cover crops in the control of soil and carbon losses by water erosion in olive orchards. Land Degrad. Dev. 29:2278-2290.

Ripoche, A., Metay, A., Celette, F. and Gary, C. 2011. Changing the soil surface management in vineyards: immediate and delayed effects on the growth and yield of grapevine. Plant Soil 339:259-271.

Rizk, M.H. 2012. Effect of Some Legume Cover Crops and Organic Fertilizer on Petiole Nutrient Content, Productivity and Fruit Composition of 'Thompson Seedless' Grapevines. Acta Hort. 933:381-388.

Roberson, E.B., Sarig, S. and Firestone, M.K. 1991. Cover crop management of polysaccharide-mediated aggregation in an orchard soil. Soil Sci. Soc. Am. J. 55:734-739.

Rodrigues de Oliveira, F.E., Oliveira, J.M. and Da Silva Xavier, F.A. 2016. Changes in Soil Organic Carbon Fractions in Response to Cover Crops in an Orange Orchard. Rev. Bras. Cienc. Solo 40:e0150105.

Rose, T.J. and Kearney, L.J. 2019. Biomass Production and Potential Fixed Nitrogen Inputs from Leguminous Cover Crops in Subtropical Avocado Plantations. Agronomy 9:70.

Rudolph, R.E., DeVetter, L.W., Zasada, I.A. and Hesse, C. 2020. Effects of Annual and Perennial Alleyway Cover Crops on Physical, Chemical, and Biological Properties of Soil Quality in Pacific Northwest Red Raspberry. HortScience 55(3):344-352.

Rudolph, R.E., Walters, T.W., DeVetter, L.W. and Zasada, I.A. 2018. Contribution of a Winter Wheat Cover Crop to the Maintenance of Root Lesion Nematode Populations in the Red Raspberry Production System. HortTechnology 28(2):182-188.

Rudolph, R.E., Zasada, I.A. and DeVetter, L.W. 2017. Annual and Perennial Alleyway Cover Crops Vary in Their Effects on *Pratylenchus penetrans* in Pacific Northwest Red Raspberry (*Rubus idaeus*). Journal of Nematology 49(4):446-456.

Ruiz-Colmenero, M., Bienes, R., Eldridge, D.J. and Marques, M.J. 2013. Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in the central Spain. CATENA 104:153-160.

Ruiz-Colmenero, M., Bienes, R. and Marques, M.J. 2011. Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. Soil and Tillage 117:211-223.

Rutto, K.L., Mizutani, F., Moon, D.G., Cho, Y.S. and Kadoya, K. 2003. Seasonal fluctuations in mycorrhizal spore populations and infection rates of vineyard soils planted with five legume cover crops. J. Japan. Soc. Hort. Sci. 72:262-267.

Samedani, B., Juraimi, A.S., Abdullah, S.A.S., Rafii, M.Y., Rahim, A.A. and Anwar, M. P. 2014. Effect of Cover Crops on Weed Community and Oil Palm Yield. International Journal of Agriculture and Biology 16:23-31.

Sanchez, E.E., Cichon, L.I. and Fernandez, D. 2006. Effects of soil management on yield, growth and soil fertility in an organic apple orchard. Acta Hort. 721:49-54.

Sanchez, J.E., Edson, C.E., Bird, G.W., Whalon, M.E., Willson, T.C., Harwood, R.R., Kizilkaya, K., Nugent, J.E., Klein, W., Middleton, A., Loudon, T.L., Mutch, D.R. and Scrimger, J. 2003. Orchard floor and nitrogen management influences soil and water quality and tart cherry yields. J. Amer. Soc. Hort. Sci. 128:277-284.

Sastre, B., Angeles Perez-Jimenez, M., Bienes, R., Garcia-Diaz, A. and De Lorenzo, C. 2016. The effect of soil management on olive yields and VOO quality in a rainfed olive grove of Central Spain. Journal of Chemistry 2016:4974609.

Sastre, B., Barbero-Sierra, C., Bienes, R., Jose Marques, M. and Garcia-Diaz, A. 2016. Soil loss in an olive grove in Central Spain under cover crops and tillage treatments, and farmer perceptions. Journal of Soils and Sediments 17:873-888.

Sastre, B., Jose Marques, M., Garcia-Diaz, A. and Bienes, R. 2018. Three years of management with cover crops protecting sloping olive groves soils, carbon and water effects on gypsiferous soil. Catena 171:115-124.

Schroth, G., Salazar, E. and Da Silva, J.P. 2000. Soil nitrogen mineralization under tree crops and a legume cover crop in multi-strata agroforestry in central Amazonia: Spatial and temporal patterns. Plant and Soil 221:143-156.

Schroth, G., Teixeira, W.G., Seixas, R., da Silva, L.F., Schaller, M., Macedo, J.L.V. and Zech, W. 2000. Effect of five tree crops and a cover crop in multi-strata agroforestry at two fertilization levels on soil fertility and soil solution chemistry in central Amazonia. Plant and Soil 221:143-156.

Schumann, A.W. 1992. The Impact of Weeds and Two Legume Crops on Eucalyptus Hybrid Clone Establishment. South African Forestry Journal 160:43-48. https://www.doi.org/10.1080/00382167.1992.9630410

Senerathne, S.H.S. and Sangakkara, R.U. 2009. Effect of different weed management systems on the weed populations, and seedbank composition and distribution in tropical coconut plantations. Weed Biology and Management 9:209-216.

Shapiro-Ilan, D.I., Gardner, W.A., Wells, L. and Wood, B.W. 2012. Impact of a Clover Cover Crop on the Persistence and Efficacy of Beauveria bassiana in Suppressing the Pecan Weevil (Coleoptera: Curculionidae). Environmental Entomology 41:298-307.

Sharifi, M., Reekie, J., Hammermeister, A., Alam, M.Z. and MacKey, T. 2016. Effect of Cover Crops on Yield and Leaf Nutrient Concentrations in an Organic Honeycrisp Apple (Malus domestica 'Honeycrisp') Orchard in Nova Scotia, Canada. HortScience 51:1378-1383. https://www.doi.org/10.21273/HORTSCI10615-16

Sholberg, P.L., Hogue, E.J. and Neilsen, G.H. 1998. Effect of orchard cover crop on incidence of low-temperature-basidiomycete rot of stored Spartan Apples. Can. J. Plant. Sci. 78:125-129.

Shylla, B. and Chauhan, J.S. 2004. Influence of orchard floor management practices on cropping and quality of Santa Rosa plum grown under mid hill conditions. Acta Hort 662:213-216.

Silva, E. B., Franco, J. C., Vasconcelos, T. and Branco, M. 2010. Effect of ground cover vegetation on the abundance and diversity of beneficial arthropods in citrus orchards. Bulletin of Entomological Research 100:489-499.

Sirrine, J. R., Letourneau, D. K., Shennan, C., Sirrine, D., Fouch, R., Jackson, L. and Mages, A. 2008. Impacts of groundcover management systems on yield, leaf nutrients, weeds, and arthropods of tart cherry in Michigan, USA. Agriculture, Ecosystems and Environment 125:239-245.

Slatnar, A., Kwiecinska, I., Licznar-Malanczuk, M. and Veberic, R. 2014.The effect of green cover within rows on the qualitative and quantitative fruit parameters of full-cropping apple trees. J. Agric. Food Chem. 62:4095-4103.

Slatnar, A., Licznar-Malanczuk, M., Mikulic-Petkovsek, M., Stampar, F. and Veberic, R. 2020. Long-Term Experiment with Orchard Floor Management Systems: Influence on Apple Yield and Chemical Composition. Horticulture, Environment, and Biotechnology 61:41-49.

Smith, M.W., Arnold, D.C., Eikenbary, R.D., Rice, N.R., Shiferaw, A., Cheary, B.S. and Carroll, B.L. 1996. Influence of ground cover on beneficial arthropods in pecan. Biological Control 6:164-176.

Sofi, J.A., Dar, I.H., Chesti, M.H., Bisati, I.A., Mir, S.A. and Sofi, K.A. 2018. Effect of nitrogen fixing cover crops on fertility of apple (Malus domestica Borkh) orchard soils assessed in a chronosequence in North-West Himalaya of Kashmir valley, India. Legume Research 41:87-94.

Song, B., Tang, G., Sang, X., Zhang, J., Yao, Y. and Wiggins, N. 2013. Intercropping with aromatic plants hindered the occurrence of Aphis citricola in an apple orchard system by shifting predator–prey abundances. Biocontrol Sci. Technol. 23:381–395. https://www.doi.org/10.1080/09583157.2013.763904

Song, G.C., Ryou, M.S. and Cho, M.D. 2004. Effects of cover crops on the growth of grapevine and underground environment of vineyards. Acta Hort. 640:347-352.

St. Laurent, A., Merwin, I.A. and Thies, J.E. 2008. Long-term orchard groundcover management systems affect soil microbial communities and apple replant disease severity. Plant Soil 304:209-225.

Steenwerth, K. and Belina, K.M. 2008. Cover crops and cultivation: Impacts on soil N dynamics and microbiological function in a Mediterranean vineyard agroecosystem. Applied Soil Ecology 40:370-380. https://www.doi.org/10.1016/j.apsoil.2008.06.004

Steenwerth, K., Calderon-Orellana, A., Hanifin, R., Storm, C. and McElrone, A. 2016. Effects of various vineyard floor management techniques on weed community shifts and grapevine water relations. Am. J. Enol. Vitic. 67:153-162. https://www.doi.org/10.5344/ajev.2015.15050

Steenwerth, K. and Belina, K.M. 2008. Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem. Appl. Soil Ecol. 40:359-369.

Stefanelli, D., Zoppolo, R.J. and Perry, R. L. 2009. Organic orchard floor management systems for apple effect on rootstock performance in the midwestern United States. HortScience 44:263-267.

Sullivan, T.P., Sullivan, D.S., Hogue, E.J., Lautenschlager, R.A. and Wagner, R.G. 1998. Population dynamics of small mammals in relation to vegetation management in orchard agroecosystems: compensatory responses in abundance and biomass. Crop Protection 17:1-11.

Sweet, R.M. and Schreiner, R.P. 2010. Alleyway Cover Crops Have Little Influence on Pinot noir Grapevines (Vitis vinifera L.) in Two Western Oregon Vineyards. American Journal of Enology and Viticulture 61:240–252.

Tahir, I.I., Svensson, S.-E. and Hansson, D. 2015. Floor Management Systems in an Organic Apple Orchard Affect Fruit Quality and Storage Life. HortScience 50:434-411.

Tang, G.B., Song, B.Z., Zhao, L.L., Sang, X.S., Wan, H.H., Zhang, J., and Yao, Y.C. 2013. Repellent and attractive effects of herbs on insects in pear orchards intercropped with aromatic plants. Agrofor. Syst. 87:273–285. https://www.doi.org/10.1007/s10457-012-9544-2

Tasseva, V. 2008. Growth and Productivity of 'Van' Sweet Cherry under Different Soil Management Systems. Acta Hort. 795:747-754.

Tasseva, V. and Domozetov, D. 2008. Improved Orchard Management Systems for Sweet Cherry Production. Acta Hort. 795:755-760.

Tebeau, A.S., Alston, D.G., Ransom, C.V., Black, B.L., Reeve, J.R. and Culumber, C.M. 2017. Effects of Floor Vegetation and Fertility Management on Weed Biomass and Diversity in Organic Peach Orchards. Weed Technology 31:404-415.

TerAvest, D., Smith, J.L., Carpenter-Boggs, L., Hoagland, L., Granatstein, D. and Reganold, J.P. 2010. Influence of Orchard Floor Management and Compost Application Timing on Nitrogen Partitioning in Apple Trees. HortScience 45(4):637-642.

Trigo-Cordoba, E., Bouzas-Cid, Y., Orriols-Fernandez, I., Dias-Losada, E. and Miras-Avalos, J.M. 2015. Influence of cover crop treatments on the performance of a vineyard in a humid region. Spanish Journal of Agricultural Research 13:e0907.

Tursun, N., Isik, D., Demir, Z. and Jabran, K. 2018. Use of Living, Mowed, and Soil-Incorporated Cover Crops for Weed Control in Apricot Orchards. Agronomy 8:150.

Tworkoski, T. J. and Glenn, D. M. 2012. Weed Suppression by Grasses for Orchard Floor Management. Weed Technology 25:559-565.

Valdes-Gomez, H., Gary, C., Cartolaro, P., Lolas-Caneo, M. and Calonnec, A. 2011. Powdery mildew development is positively influenced by grapevine vegetative growth induced by different soil management strategies. Crop Protection 30:1168-1177.

Van Sambeek, J.W., Ponder Jr., F. and Rietveld, W.J. 1986. Legumes increase growth and alter foliar nutrient levels of black walnut seedlings. Forest Ecol. and Manag. 17:159-167.

Vogt, H. and Weigel, A. 1999. Is it possible to enhance the biological control of aphids in an apple orchard with flowering strips? IOBC/Wprs Bull. 22:39–46.

Vohland, K. and Schroth, G. 1999. Distribution patterns of the litter macrofauna in agroforestry and monoculture plantations in central Amazonia as affected by plant species and management. Applied Soil Ecology 13:57-68.

Walsh, B.D., MacKenzie, A.F. and Buszard, D.J. 1996. Soil nitrate levels as influenced by apple orchard floor management systems. Canadian Journal of Soil Science 76:343-349.

Walsh, B.D., Salmins, S., Buszard, D.J. and MacKenzie, A.F. 1996. Impact of soil management systems on organic dwarf apple orchards and soil aggregate stability, bulk density, temperature and water content. Can. J. Soil Sci. 76:203-209.

Wan, H.-H., Song, B-Z., Tang, G.B., Zhang, J. and Yao, Y.C. 2015. What are the effects of aromatic plants and meteorological factors on Pseudococcus comstocki and its predators in pear orchards? Agroforest Syst. 89:537-547. https://www.doi.org/10.1007/s10457-015-9789-7

Wan, N.-F., Ji, X.-Y. and Jianh, J.-X. 2014. Testing the enemies hypothesis in peach orchards in two different geographic areas in Eastern China: the role of ground cover vegetation. PLoS One 9:e99850.

Wang, L., Tang, L., Wang, X. and Chen, F. 2010. Effects of alley crop planting on soil land nutrient losses in the citrus orchards of the Three Gorges Region. Soil and Tillage Research 110:243-250.

Warburg, S., Inbar, M., Gal, S., Salomon, M., Palevsky, E. and Sadeh, A. 2018. The effects of a windborne pollen-provisioning cover crop on the phytoseiid community in citrus orchards in Israel. Pest Manag. Sci. 75:405-412.

Wardle, D.A., Yeates, G.W., Bonner, K.I., Nicholson, K.S. and Watson, R.N. 2001. Impacts of ground vegetation management strategies in a kiwifruit orchard on the composition and functioning of the soil biota. Soil Biol. Biochem. 33:893–905.

Wei, H., Zhang, K., Zhang, J., Li, D., Zhang, Y. and Xiang, H. 2018. Grass cultivation alters soil organic carbon fractions in a subtropical orchard of southern China. Soil and Tillage Research 181:110-116.

Wells, M. L. 2011. Response of Pecan Orchard Soil Chemical and Biological Quality Indicators to Poultry Litter Application and Clover Cover Crops. HortScience 46:306-310.

Whaley, A. and Reeve, J. 2019. Orchard Floor Management Practices for Establishing Organic Peaches in the Intermountain West. OSU Publication.

Willard, D. and Valenti, H.H. 2008. Juneberry growth is affected by weed control methods. HortTechnology 18:75-79

Wilson, A.R., Nzokou, P. and Cregg, B. 2010. Ground Covers in Fraser Fir (Abies fraseri [Pursh] Poir.) Production Systems: Effects on Soil Fertility, Tree Morphology and Foliar Nutrient Status. Europ. J. Hort. Sci. 75:269-277.

Wiman, M.R., Kirby, E.M., Granatstein, D.M. and Sullivan, T.P. 2009. Cover Crops Influence Meadow Vole Presence in Organic Orchards. HortTechnology 19:558-562.

Wright, G.C., McCloskey, W.B. and Taylor, K.C. 2003. Managing orchard floor vegetation in flood-irrigated citrus groves. HortTechnology 13:668-677.

Wu, J., Lin, H., Meng, C., Jiang, P. and Fu, W. 2014. Effects of intercropping grasses on soil organic carbon and microbial community functional diversity under Chinese hickory (Carya cathayensis Sarg.) stands. Soil Research 52:575-583.

Wyss, E. 1996. The effects of artificial weed strips on diversity and abundance of the arthropod fauna in a Swiss experimental apple orchard. Agric. Ecosyst. Environ. 60:47–59. https://www.doi.org/10.1016/S0167-8809(96)01060-2

Xiloyannis, C., Dichio, B. and Montanaro, G. 2010. Sustainable Apricot Orchard Management to Improve Soil Fertility and Water Use Efficiency. Acta Hort. 862:419-424.

Ling-fei, X., Peng, Z., Qing-fang, H., Zhi-hui, L., Bao-ping, Y. and Jun-Feng, N. 2013. Spatial Distribution of Soil Organic Matter and Nutrients in the Pear Orchard Under Clean and Sod Cultivation Models. Journal of Integrative Agriculture 12(2):344-351.

Yang, J., Zhang, T., Zhang, R., Huang, Q. and Li, H. 2019. Long-term cover cropping seasonally affects soil microbial carbon metabolism in an apple orchard. Bioengineered 10:207-217.

Yang, M., Liu, M., Lu, J. and Yang, H. 2019. Effects of shading on the growth and leaf photosynthetic characteristics of three forages in an apple orchard on the Loess Plateau of eastern Gansu, China. PeerJ 7:e7594.

Yao, S., Merwin, I.A., Bird, G.W., Abawi, G.S. and Thies, J.E. 2009. Orchard floor management practices that maintain vegetative or biomass groundcover stimulate soil microbial activity and alter soil microbial community composition. HortScience 44:168-175.

Yao, S., Merwin, I.A. and Brown, M.G. 2005. Apple Root Growth, Turnover, and Distribution Under Different Orchard Groundcover Management Systems. Plant and Soil 271:377-389.

Zalamena, J., Cassol, P.C., Brunetto, G., Grohskopf, M.A. and Heberle Mafra, M.S. 2013. Nutritional status, vigor and yield of grapevines intercropped with cover crops. Rev. Bras. Frutic. 35:1190-1200.

Zalamena, J., Cassol, P.C., Brunetto, G., Panisson, J., Marcon Filho, J.L. and Schlennper, C. 2013. Productivity and composition of grapes and wine of vines intercropped with cover crops. Pesq. Agropec. Bras. 48:182-189.

Zebarth, B.J., Freyman, S. and Kowalenko, C.G. 1993. Effect of ground covers and tillage between raspberry rows on selected soil physical and chemical-parameters and crop response. Can. J. Soil Sci. 73:481-488.

Zelazny, W.R. and Licznar-Malanczuk, M. 2018. Soil quality and tree status in a twelve-year-old apple orchard under three mulch-based floor management systems. Soil and Tillage Research 180:250-258.

Zhang, Z., Zhou, C., Xu, Y., Huang, X., Zhang, L. and Mu, W. 2017. Effects of intercropping tea with aromatic plants on population dynamics of arthropods in Chinese tea plantations. J. Pest. Sci. 90:227-237.

Zhao, W., Zheng, W., Zhang, B., Yu, G., Hu, S., Xu, X. and Zhanga, H. 2014. Effect of different ground cover management on spider mites (Acari: Tetranychidae) and their phytoseiid (Acari: Phytoseiidae) enemies in citrus orchards. Biocontrol Science and Technology 24:705-709.

Zheng, W., Gong, Q., Zhao, Z., Liu, J., Zhai, B., Wang, Z., Li, Z. 2018. Changes in the soil bacterial community structure and enzyme activities after intercrop mulch with cover crop for eight years in an orchard. European Journal of Soil Biology 86:34-41.

Zheng, W., Li, Y., Gong, Q., Zhang, H., Zhao, Z., Zheng, Z., Zhai, B. and Wang, Z. 2016. Improving yield and water use efficiency of apple trees through intercrop-mulch of crown vetch (Coronilla varia L.) combined with different fertilizer treatments in the Loess Plateau. Spanish Journal of Agricultural Research 14(4):e1207.

Zheng, W., Wen, M., Zhao, Z., Liu, J., Wang, Z., Zhai, B. and Li, Z. 2017. Black plastic mulch combined with summer cover crop increases the yield and water use efficiency of apple tree on the rainfed Loess Plateau. PLoS ONE 12:e0185705.

Zheng, W., Zhao, Z., Gong, Q., Zhai, B. and Li, Z. 2018. Effects of cover crop in an apple orchard on microbial community composition, networks, and potential genes involved with degradation of crop residues in soil. Biology and Fertility of Soils 54:743-759.

Zheng, W., Zhao, Z., Lv, F., Wang, R., Gong, Q., Zhai, B., Wang, Z., Zhao, Z. and Li, Z. 2019. Metagenomic exploration of the interactions between N and P cycling and SOM turnover in an apple orchard with a cover crop fertilized for 9 years. Biology and Fertility of Soils 55:365-381.

Zhou, T., Jiao, K., Qin, S. and Lyu, D. 2019. The impact of cover crop shoot decomposition on soil microorganisms in an apple orchard in northeast China. Saudi Journal of Biological Sciences 26:1936-1942.