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Cover Cropping: A Malleable Solution for Sustainable Agriculture? Meta-Analysis of Ecosystem Service Frameworks in Perennial Systems

Cynthia M. Crézé * and William R. Horwath

Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA; wrhorwath@ucdavis.edu
* Correspondence: cmcreze@ucdavis.edu

Abstract: Cover crops have been touted for their capacity to enhance multifunctionality and ecosystem services (ESs). 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 (ES) 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.

Keywords: cover crop; ecosystem services; sustainability; perennial agroecosystems; nutrient management; biological control; productivity–conservation tradeoffs; valuation systems; optimization

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1. 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 [1]. 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 [1,2]. These studies were originally applied to natural ecosystems and then to cover crop studies for agro-ecosystems [3–5]. 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) [6–8]. 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 (ESs): soil retention, pollinator habitat provision, weed control, improved soil physical properties, carbon sequestration, biocontrol services, enhanced water quality and improved nutrient cycling [9–11]. Recent literature demonstrates that cover crop services occur in bundles [12,13]. However, comprehensive studies verifying the co-occurrence of these many services remain scarce [14]. 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 [15–18]. 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) [19,20]. 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 ESs [21–24]. 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 [25,26]. 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 (ES) valuation systems.

Although ecological rationales for cover cropping have been elucidated, the implementation of the practice lags behind. There has been slow and limited adoption of cover cropping in many parts of the world (i.e., only 1.7% in US farmlands) [27–31]. 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) [32–35] and motivators (i.e., increased soil organic matter, support of biodiversity) [32,34]. 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 [36,37]. 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.

2. Materials and Methods

2.1. 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 [38], Groff [39], Hartwig and Ammon [40], Peshin et al. [41] and Altieri and Schmidt [16], as well as more eco-sociological works, such as the work of Cochrane [42]. 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.

2.2. Meta-Analysis

2.2.1. 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 [43]. This process includes four steps: identification, screening, eligibility and inclusion, as detailed in Figure 1. Data were extracted on 5 May 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" × "orchard", 198 results, (2) "cover crop" × "woody", 27 results, (3) "orchard" × "floor management", 135 results, (4) "woody" × "floor management", 135 results, (5) "perennial" × "floor management", 25 results and (6) "perennial" × "cover crop", 264 results (Figure 1). The timespan selected included 1900 to 2020. Web of Science Topic entries search 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 1, 285 articles remained.

Records identified through Web of Science database with keywords:

- "cover crop" x "orchard": 198 results
- "cover crop" x "woody": 27 results
- "orchard" x "floor management": 135 results
- "woody" x "floor management": 0 results
- "perennial" x "floor management": 25 results
- "perennial" x "cover crop": 264 results

Total records: 649 results

Additional records identified through other sources:

- BioOne
- PLOS
- JSTOR
- ScienceDirect
- Oxford Journals
- SpringerLink
- Taylor and Francis Journals
- Wiley Online
- WorldCat

Total = 210 results

Records after duplicates removed (removed, n = 76)

Records screened (post-screening, n = 206 results)

Records screened (post-screening, n = 182 results)

Records after duplicates removed (removed, n = 103)

Full-text articles assessed for eligibility

Criteria included: catch crops, green manure & sod, field research, orchard and plantation research.

Criteria excluded: reviews, model-based research, hedge rows, nursery studies, pre-plant studies, pre-mature orchard studies.

Studies included in quantitative synthesis **(n = 285)**

Figure 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. [43].

2.2.2. 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 in which tree berms were seeded. Studies in which cover crops were not integrated within the orchard, such as hedgerow 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 A. Although most material was peer-reviewed, our selection 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 cropland or in experimental field stations. Due to the different spatial scales of ecological processes [44], our study selection integrated different investigative approaches and scales of study. For instance, soil studies are often conducted with replications of ~4000 m^2, whereas pollination studies require landscape separations of 1 km to capture variations in bee foraging. Indeed, entomological studies have higher potential for community crossover and mobility amongst 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 compare the use of cover crops to synthetic pesticide application or other biological agents, used as controls.

2.2.3. Study Inclusion Process

Following the study identification, screening and eligibility processes, 285 studies remained, of which the annotated source references are detailed in Appendix A. 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.

2.2.4. Data Extraction

Ecosystem Services Associated with Cover Cropping

Much cover crop research predates the introduction of the concept of "ecosystem services", first introduced as a concept in 1997 by Daily [45] and Costanza [46]. 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). Our characterization of cover crop-mediated ecosystem services and their classification was based on the Millennium Ecosystem Assessment [47], and based on the framework for cover crop assessments, described by Schipanski et al. [48].

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 above-ground 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 maintaining ecosystem processes and is often included as a service in ecosystem assessment frameworks [21,49]. Pest suppression services included above-ground and below-ground suppression of pests, including parasitic nematodes, insect pests and parasitic fungi. It is important to note that ecosystem disservices were largely underrepresented in the comprehensive literature and were only reported in an estimated 7/285 articles or 2% of articles (Appendix A List A1) [50–56]. Provisioning services of economic profitability and knowledge diffusion were also rarely reported in the literature (12/285 and 1/285 articles, respectively). Due to the low research coverage of knowledge diffusion and other cultural services, these services were not included in our evaluation of ESs. However, we recognize their importance and the esthetic quality of perennial agricultural systems.

Country of Study Site

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 2).

Commodity Type

We recorded the number of cover crop articles found 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).

Cover Crop Mix Design and Optimization

Based on Tilman's diversity-productivity theory [1], 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 mixed designs (i.e., species identification and number of species).

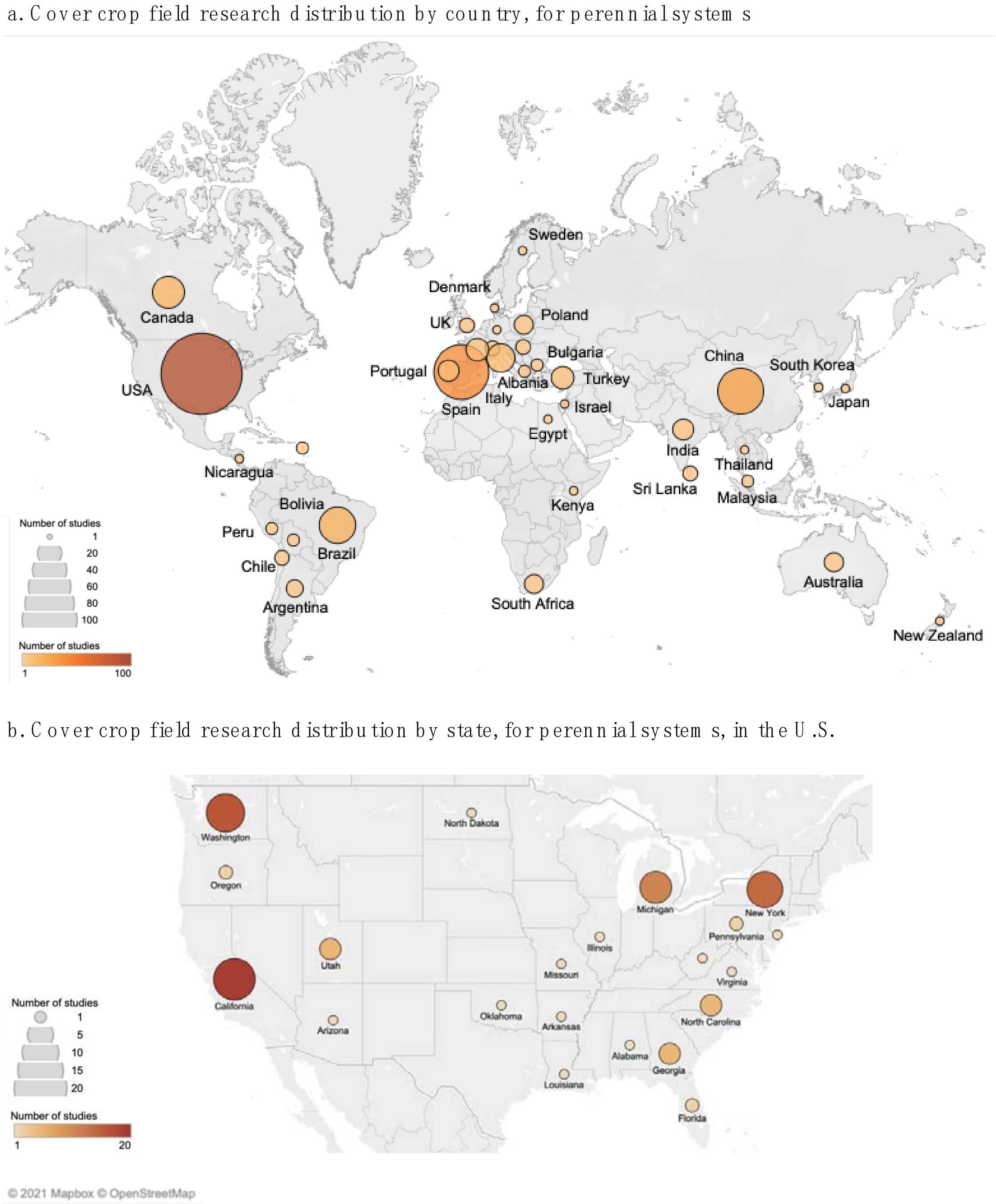

Figure 2. (**a**) Geographical distribution of cover crop field research conducted in perennial agro-ecosystems, indicated by the number of published peer-reviewed articles per country; (**b**) due to the high research coverage in the United States, the research distribution is presented by state.

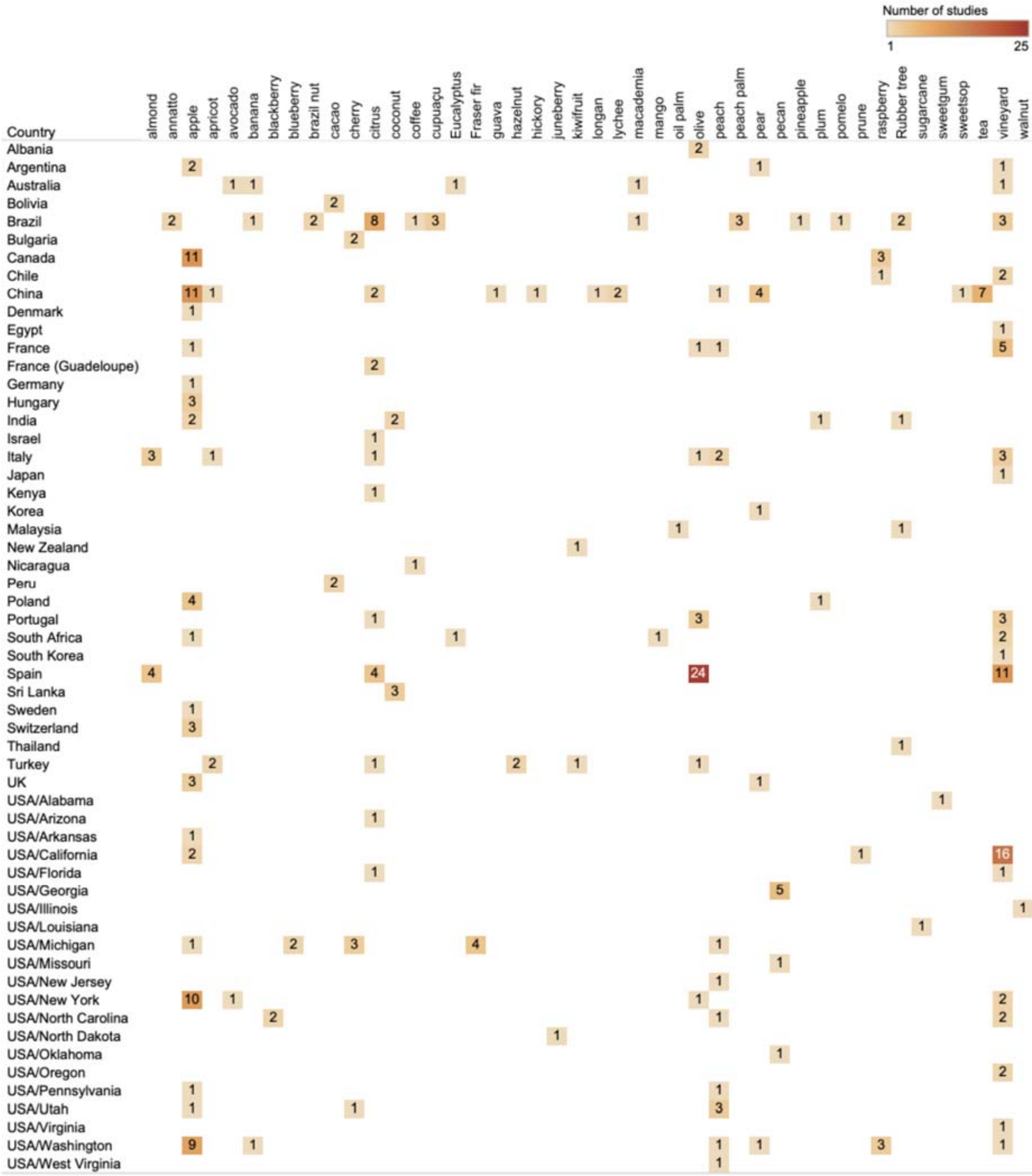

Figure 3. Distribution of cover crop research, by perennial system, distinguished by country. Due to the high quantity of research conducted in the USA, research is presented by state for that country. The research distribution amongst perennial crops reveals distinct interests and priorities divided by country, which likely reflect different socio-economic contexts and bio-zones. The non-randomized distribution of cover crop research, distinct to different countries, reveals the contextualization of cover crop knowledge. 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.

2.2.5. 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.

2.2.6. 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 Figures 3 and 4. Hot spots illustrated by darker cell colorations indicate higher research coverage for a given ecosystem service, specific to commodity groups. In Figure 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 cells' 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.

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
macademia	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 4. Research coverage of ecosystem services distinct to perennial cropping systems in the comprehensive cover crop literature.

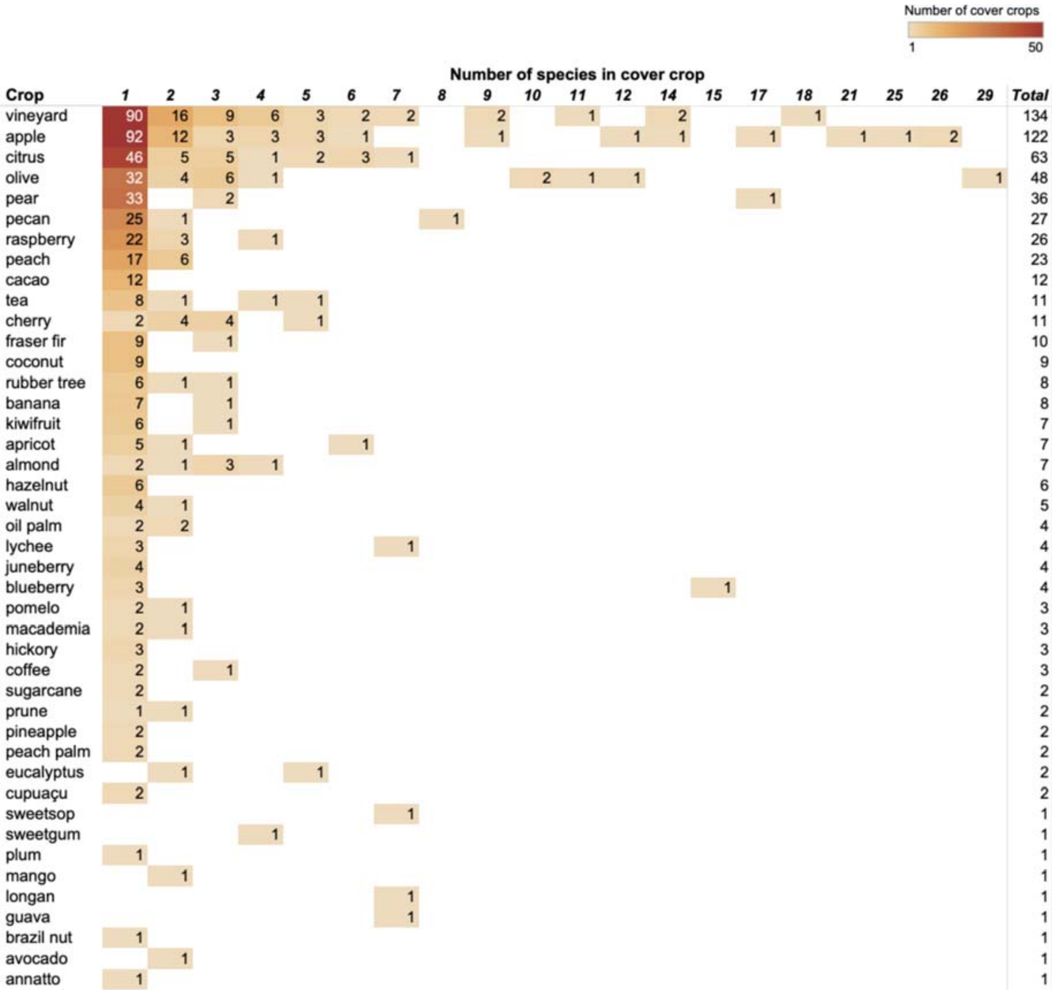

Figure 5. Design of cover crop seed mixes. Cover crop designs are indicated by the number of species assembled in each cover crop. The number of cover crops tested per design is indicated by the cells' coloration and annotation. Commodities are listed in order of research coverage.

3. Results and Discussion

3.1. 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 [57]. 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" [57,58]. 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 [59]. 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–the support of N fixation and the reduction of N leaching [40]. 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 consolidation 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 [60,61]. Writings at that time were focused on the use of cover crops to protect soil: "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 [62,63]. However, as plentiful and inexpensive N synthetic fertilizer became readily available in the 1950s, the interest in cover cropping declined [64–67]. By the mid 1960s, the practice was widely discontinued [39,68].

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 resource conservation practices [40]. In 1984, Odell et al. warned of rapid losses in soil organic matter, highlighting the sharp decline in US corn belt SOM from 12% to <6% in just 100 years of crop production [69]. In 1988, with the rise in awareness of the harmful effects of global warming, the International Panel on Climate Change (IPCC) was established [70]. 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 [71].

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 amongst organisms and the concept of "allelopathy" was introduced by Molisch [72], 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 US. [41]. The use of cover crops was largely discontinued [40]. However, by 1960, the environmental damage caused by chemical pest control and fuel-dependent agri-chemicals gained attention amongst 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 [73]. 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 resource conservation strategies, the first concepts of "integrated pest management" were first introduced by Stern et al. [74], 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 [75]. Some have attributed the later application of IPM for weed control to concerns over water and nutrient competition with the primary crop [76].

As the oil embargo of 1973 pushed the agricultural community away from fuel-intensive practices, farmers converted to minimum tillage practices [40]. Reduced-tillage systems presented problems, including difficult weed control. Cover crop designs were revisited to account for weed suppression [77,78]. By the 1990s, research moved away from combined chemical-biological solutions towards fully biological solutions, leading to considerable advancements in cover crop biological control [79]. The term "biofumigation" was coined in 1993 by J.A. Kirkegaard to describe the effect of isothiocyanate release from *Brassica* species on soil properties [80]. 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 [15,38].

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 [81,82]. Recent methods in metagenomics have provided new tools to characterize soil biodiversity and have created opportunities to better understand linkages between above- and below-ground biological control. These new methods and scientific instruments may further promote the uses and applications of cover cropping, in support of ecosystem services.

3.2. 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 [36]. 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, yields are dependent on a number of ESs 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 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 resource 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.

3.3. Commodity-Specific ES Frameworks for Cover Cropping

As indicated in Figure 4, we found that research coverage was not randomized in the reporting of ecosystem services and amongst 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 [83]. 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. Amongst stimulant crops, studies on tea exclusively explored services related to biological management (i.e., beneficial insect conservation and pest suppression) (Figure 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 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 amongst commodity groups and generates opportunities for crop-specific optimization.

It is important to note that our study suggests a considerable gap in research coverage amongst 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 amongst ESs 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 [42]. Our data suggest that commodification may be apparent in cover crop ES frameworks.

3.4. Climate Change Considerations

It is important to note the gaps in the research distribution amongst 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 [84]. These compounds vary in their use of bacterial and fungal mediated pathways of decomposition [85]. 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 [86]. Smallholder farmers face distinctive climate stressors. Projections suggest that they have particularly high vulnerability to climate change [87]. Their adaptive capacity is particularly tied to regional socio-economic development [87]. 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 [88].

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, thereby reducing the environmental footprint of production systems [89]. 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 ESs, such as soil C services, were reported. Without yield measurements, the tradeoffs of supporting other services could not be assessed. 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 focus 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.

3.5. Cover Crop Seed Designs

Of 1446 trials, ~80% trials belonged to either the Fabaceae, Poaceae or Asteraceae plant families. While 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., beneficial insect conservation), 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 5, the majority of cover crops tested in perennial agriculture were single species, in contradiction to concepts introduced by Tilman [1]. For certain cropping systems including cacao, hazelnut and juneberry, outcomes were solely tested for single species cover crops. 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.

3.6. 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, referring 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. We assumed that our subset of articles was a roughly representative sample of 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 [8,90,91]. This may have affected our results. Our database presented a regional data gap, as it had 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 [92,93]. 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.

4. Conclusions

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 measurements of yields. 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 mixed 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 mixes. 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.

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Appendix A

List A1. Complete list of studies included in the meta-analysis (*n* = 285).

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