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Review

A Sustainable Agricultural Future Relies on the Transition to Organic Agroecological Pest Management

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Abstract: The need to improve agricultural sustainability to secure yields, minimize environmental impacts and buffer environmental change is widely recognized. Investment in conventional agriculture has supported its present yield advantage. However, organic agriculture with agroecological management has nascent capacity for sustainable production and for increasing yields in the future. Conventional systems have leveraged reductionist approaches to address pests, primarily through pesticides that seek to eliminate biological factors that reduce yield, but come at a cost to human and ecosystem health, and leave production systems vulnerable to the development of pest resistance to these chemicals or traits. Alternatives are needed, and are found in organic production approaches. Although both organic and agroecology approaches encompass more than pest management, this aspect is a pivotal element of our agricultural future. Through increased investment and application of emerging analytical approaches to improve plant breeding for and management of these systems, yields and resilience will surpass approaches that address components alone.

Keywords: organic agriculture; agroecology; pest management; plant breeding; biodiversity; sustainability; host plant resistance; pesticides

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1. Achieving Needs for Agricultural Productivity and Pest Management Sustainably

There is broad recognition among agricultural scientists that a growing world population will consume greater amounts of food and fiber with fewer resources available for production [1]. This, however, cannot be separated from the global imperative to move towards a more sustainable agriculture, especially regarding methods of pest management [2]. Key aspects of sustainable agricultural systems include meeting food and fiber production needs in an economically viable manner, while improving environmental health and individual and societal well-being [3]. These tenets of sustainable agriculture are all strongly influenced by pest management activities. Whether conventional or organic agriculture is the ideal way forward is a contentious topic, where many discuss the tradeoffs between organic production systems and efficiency [4–9]. We argue that these tradeoffs diminish when there is sufficient investment in developing holistic organic alternatives. Given the complexity of our food production systems, rather than a focus on discrete innovations, we need to address the long-term goals for sustainable agriculture in the context of the whole system. Organic agriculture is a production system well suited and incentivized to lead in research and development of new sustainable pest management methods.

Organic agriculture is defined in the United States (US) [3] and internationally [4] as production systems that "foster cycling of resources, promote ecological balance and conserve diversity" and "principles of health, ecology, fairness and care", respectively. The organic label provides farm certification and product identification for approximately 1% of total agricultural land worldwide that is under organic management [10], and this branding facilitates economic benefit to organic growers through enabling consumer choice. Although there is great diversity in organic farming systems, there is substantial common ground between growing operations in best practices for pest management. A complementary movement, agroecology, addresses the study of key elements of sustainable production systems that systems like organic agriculture rely upon [11]. While not perfectly aligned, (for example, organic farming restricts synthetic and transgenic inputs and agroecology seeks to create resilient polyculture; although, organic farming and agroecology are more blended in some countries) [12,13], it is the nexus of these approaches that we believe is the future agricultural system, and we will refer to their common ground throughout as "organic agroecology".

Contrasting approaches to pest challenges in conventional and organic agricultural systems: A major challenge in all agricultural systems is the management of weed, disease and insect pests. Worldwide, yield losses from these pests range from a 34% reduction due to weeds, and 16% and 18% for plant pathogens and animal (predominately insect) pests, respectively [14]. Overall, it is estimated that pre-harvest pests lessen crop yields by about 35% [15,16]. Pest challenges vary over seasons, and it is difficult to predict how this variation will shift in the face of climate change [17], but warming has expanded previous ranges of pests from equatorial regions to farther toward the poles [18]. Resilient systems are needed for food security in response to these dynamic pressures. While all farming operations are and will continue to be challenged by pest issues, organic and conventional methods have different approaches to mitigate pest damage.

The dominant means of managing pests in conventional systems is through the purchase and application of synthetic pesticides. About $40 billion USD is spent on pesticides worldwide for application of almost 2 million metric tons of active ingredient [15,19]. In the United States alone, about $12 billion USD is spent on more than 200,000 metric tons of active ingredients, with most application (>80%) in corn, soybean, cotton, potato and wheat crops, and the most abundant pesticide type being herbicides (76% of total) [20]. Although there are not complete estimates of pesticide application on every horticultural crop, their use is ubiquitous. From the most recent years detailed US data is available, in the majority of crops surveyed, more than 50% of planted acreage of each vegetable crop and bearing acreage of each fruit crop is treated with at least one pesticide (Table 1) [21]. In sum, on horticultural crops in the US, more than 25,000 metric tons of fungicides, and 5000 metric tons each of herbicides and insecticides are applied annually [21], with the largest single users being tomatoes (*Solanum lyocpersicum*), grapes (*Vitus* spp.) and apples (*Malus x domestica*) [20,21]. It is estimated in the United States that indirect costs from negative human or ecosystem health impacts due to pesticides use rivals direct costs at $8 billion USD per year [22], and some warn these estimates may be low and dated [23]. In all, conventional agriculture has relied on purchased off-farm inputs [24] to mitigate pest problems. This approach has facilitated investment, research and development, and boosted agricultural production, but is inconsistent with sustainability goals.

Table 1. Total pesticide use in metric tons (MT) of active ingredient (AI) applied, and percent of production area treated at least once in the United States from most recent year data is available. Data compiled from the United States Department of Agriculture National Agricultural Statistics Service [21].

Crop [1]	Fungicide		Herbicide		Insecticide	
	AI (MT)	Acreage (%)	AI (MT)	Acreage (%)	AI (MT)	Acreage (%)
Vegetable crop [2]						
Asparagus	16	53	41	88	20	90
Beans, snap, processing	36	49	138	97	11	58
Broccoli	17	38	61	46	31	68
Carrots, fresh market	188	75	73	77	3	35
Carrots, processing	28	100	5	100	0	100
Cauliflower	2	11	7	47	8	76

Table 1. *Cont.*

Crop [1]	Fungicide		Herbicide		Insecticide	
	AI (MT)	Acreage (%)	AI (MT)	Acreage (%)	AI (MT)	Acreage (%)
Celery	20	65	9	42	20	71
Eggplant	1	71	0	21	0	81
Garlic	16	88	29	89	4	58
Lettuce, (excluding head)	206	71	111	42	56	85
Lettuce, head	207	76	52	52	66	90
Melons, cantaloupe	99	79	42	54	31	85
Melons, honeydew	22	87	3	24	31	92
Melons, watermelon	282	84	31	52	114	80
Onions, dry	287	88	176	92	125	91
Peas, green, processing	2	14	60	98	2	29
Peppers, bell	199	84	17	44	46	81
Pumpkins	75	69	22	76	7	32
Spinach, fresh market	29	75	11	41	6	79
Squash	79	76	7	51	9	53
Sweet corn, processing	6	31	163	97	10	71
Tomatoes, field, processing	5073	87	268	69	216	79
Total, vegetable crops	*6890*		*1326*		*816*	
Fruit crop (bearing) [3]						
Apples	2545	81	122	37	704	91
Apricots	18	70	7	55	5	77
Avocados	ND	ND	28	35	4	40
Blackberries	36	76	10	95	4	83
Blueberries	223	86	82	66	90	85
Cherries, sweet	627	83	48	36	150	83
Cherries, tart	252	95	14	54	30	90
Dates	0	-	3	23	0	8
Figs	0	-	19	60	0	-
Grapefruit	193	84	198	70	452	94
Grapes [4]	13,590	83	854	55	269	53
Kiwifruit	0	-	11	50	0	12
Lemons	25	34	51	60	53	74
Nectarines	73	55	16	49	7	55
Olives	50	43	23	39	2	26
Oranges	744	72	1890	72	2246	90
Peaches	824	82	46	43	68	78
Pears	566	90	24	45	564	92
Plums	27	51	14	47	3	70
Prunes	132	63	48	57	5	63
Raspberries	65	92	14	91	12	94
Strawberries	620	96	11	27	159	93
Tangelos	25	96	11	75	29	97
Tangerines	140	72	78	76	185	88
Total, fruit crops	*20,775*		*3622*		*5041*	

[1] In all cases, totals for crops represent select states surveyed by the USDA NASS, and these states are listed in Table S1. [2] Vegetable crop totals are from 2016 data, with the exception of eggplant, which is from 2010. [3] Fruit crop totals are from 2015 data, with the exception of strawberries, where fungicide and herbicide totals are from 2016, and insecticide data from 2014. [4] Grape types include table, juice, raisin, and wine grapes.

In contrast, organic agroecological pest management is best characterized by an emphasis on preventive, not curative, measures and the long term goal to "amplify agro-ecological system resilience" by developing on-farm management approaches rather than purchasing external products [25]. This goes beyond substituting one conventional chemical with one organic practice to solve the same problem [25–27]. Although product solutions are common inputs in conventional agriculture, organic agroecology is much more focused on management approaches. Pest management techniques in organic systems share similar principles with integrated pest management (IPM) [28], but it is only in organic production that these practices are exclusively agroecological. Organic agroecological pest management can be summarized as a systems approach that incorporates plant-based resistance, farm-scale cultural practices, or crop-targeted intervention with biological, mechanical or natural control agents (Table 2). This sustainable, holistic approach mitigates the risks from synthetic pesticides and must be the foundation of agricultural pest management.

Table 2. Summary of organic agroecological pest management practices.

	Practice or Trait	Results
Plant based resistance	Physical traits	• Deter or impede mobility of insect pests [29] or colonization of plant pathogens (i.e., cuticle composition) [30] • Canopy architecture can shade weeds [31], or alter environmental conditions (i.e., humidity) to slow pathogen growth [32]
	Chemical traits	• Volatile deterrents for insect pests [33] • Harmful or deterrent secondary metabolites for pathogen and insect pests [34–36], and allelopathic compounds inhibit weed growth [37,38] • Volatile cues for insect predators or parasitoids about location of prey [39–41] • Qualitative gene-for-gene interactions [34,42] or quantitative resistance traits [42,43]
	Tolerance	• Plants exhibit no apparent yield or fitness cost to pest damage [44,45]
Farm scale cultural practices	Sanitation	• Clean planting material and equipment stop inoculum from entering farm (pathogens, weeds and insects) [46,47]
	Crop rotation	• Disrupt pest lifecycles (pathogens, weeds and insects) [46,48,49]
	Applying botanical diversity	• Trap crops or push-pull systems rely on differential plant attractiveness to lure and, or repel insect pests from main marketable crop [50,51] • Provide habitat and alternate food sources for plant beneficial insects [49] • Modify epidemiological factors to slow the spread of pathogens through crop rotations, intercropping, companion planting or growing a crop mixture [46]
Crop targeted interventions	Beneficial organisms	• Beneficial insects that are predatory on pests, and nematodes and effective microbes can further suppress insect pest and pathogen populations [49,52,53]
	Mechanical interventions	• Cultivation, thermal and mechanical measures to manage weeds or pathogens [46,54] • Specific passive traps (like trenches) or active control like vacuuming to manage particular insect pests [55]
	Naturally-derived products	• Non-synthetically derived products like oils, soaps, or extracts, can be used to supplement pest management efforts [46,49]

Concerns about productivity loss by moving away from conventional pest management: Concerns about the risks of conventional pesticide use have been overshadowed in recent scientific literature [4–9] by discussion of whether organic or conventional agriculture is the best choice to feed the growing world population. The main concerns have been balancing yield with environmental impact; for instance, how to reduce synthetic fertilizers and pesticides without increasing land use and greenhouse gases [8]? One answer is to stop wasting thirty percent of all of the food we grow, especially the higher proportion of 40–50% of fruits and vegetables [56]. Although some of this is attributable to losses in the field, much in North America, Europe and increasingly in Asia, are wasted post-consumer and includes cosmetic blemishes, not edibility issues [56,57], suggesting there is a path to double these yields without needing to increase production through changes in distribution and consumer habits.

We propose that there is an additional variable that could be added to these studies: plant breeding for regional organic agroecological systems. Conclusions of a yield gap in current organic systems do not reflect the intrinsic potential of the two systems, but rather a research and development investment gap (Figure 1). These studies reflect the use of relatively unimproved, non-adapted seeds for organic systems that *force* the tradeoff of investing in undesirable practices like tillage, or increasing land use for cultivation to meet yield requirements [8]. Research and investment in organic agroecological production systems, including plant breeding for organic systems, has only gained attention relatively recently, such as through programs like the Organic Agriculture Research and Extension Initiative program (OREI, US Dept. of Agriculture, National Institute of Food and Agriculture) [58]. This can clearly be seen in the frequent use of heirloom cultivars in organic systems, especially prior to the 2000s when organic plant breeding began gaining traction in the US [58]. While heirloom crops may be a reservoir of flavor [59], they have, by definition, not been improved with recent advances for yield or yield stability traits like pest and disease resistance. Transgenic crops are not allowed in organic systems [60,61], thereby promoting the use of more durable, polygenic solutions (see Section 2).

In plant breeding, genotype by environment interactions are key to achieving optimal performance for both yield and host resistance so cultivars should be selected in the environment of intended use to maximize plant breeding gains [62]. As organic and conventional environments differ in many factors, breeding for and within organic systems are key to achieving superior yields with elevated sustainability benefits. Crops that have had the highest level of support for plant improvement for conventional systems have enjoyed the highest yield differential currently [6], suggesting that equivalent plant breeding investment in organic systems would erase this yield gap. By investing in plant breeding for organic systems, we can develop cultivars that perform best in organic environments [63–66]; direct selection in organic systems can increase the yield by 30% or more compared with conventionally bred cultivars [63]. Therefore, adapted cultivars from organic plant breeding efforts are key investments to sustainably boost yield and offset the yield gap between conventional and organic.

Toward a more sustainable agricultural future, we must move away from pesticide-based agriculture. While reductionist approaches supported pesticides as a tool, this approach is harmful and limited. In Section 2, we highlight the costs to human health, ecosystem stability and production systems and provide examples of organic agroecological practices addressing these challenges. The current yield advantage of conventional agriculture is likely to change as we move to more sustainable expectations for agriculture, reduce pesticide use, and growing seasons become more variable. In contrast, with investment to develop systems approaches including plant breeding, organic agroecology is well positioned to gain efficiency and address these needs. Comparisons of yield and efficiency of these two approaches reveal there is a current difference between average productivity, but they do not take into account the potential benefits of investing in organic agriculture. The increased accessibility of data (i.e., more affordable genome sequencing) and attention on employing agroecological concepts is allowing us to integrate the biological complexity of organic farming systems into accessible management techniques. By investing in organic agroecological systems research (Section 3), a new truly sustainable agriculture in on the horizon.

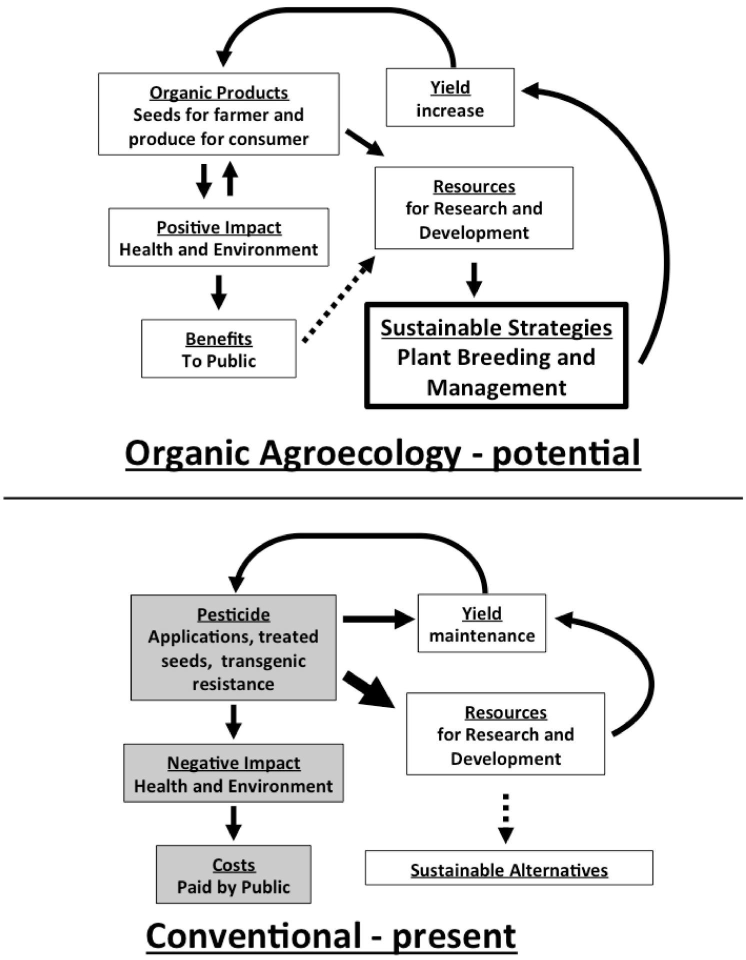

Figure 1. Toward increased investment in sustainable strategies in organic agriculture. In an organic agroecological system, increasing investment in sustainable plant breeding and management strategies will have an outsized impact on increasing yield. Increasing use of organic seed will promote further resources for research and development. The adoption of organic practices is beneficial to human and environmental health, which benefit the public. As the public increasingly values sustainable strategies (for instance, by influencing government agricultural research budgets), increased funding will allow for shifting more production to organic agroecological management. In conventional agriculture, the use of pesticides (including treated and transgenic seed) maintain yield, which reinforces the continued use of these products with little incentive for pursing sustainable alternatives. Resources from these sales lead to research and development to support new pesticide related products. The use of pesticides has negative impacts on human health and the environment and leads to hidden costs paid indirectly by the public. Plant breeding in conventional systems, (not shown), is important but is done in the context of pesticide-managed environments during selection. Solid arrows indicate flow of resources or influence between elements of model. Dashed arrows indicate connections that would benefit from further development.

2. Issues with Managing Agricultural Pests through Pesticides

2.1. Pesticides Impact Human Health

Pesticide use poses risks to human health from the application of the pesticide to consumption of the produced food. Broadly, agricultural workers and pesticide applicators face the most severe health risks due to close and repeated exposures to pesticides, especially with concentrated pesticide product [67]. Physician-diagnosed pesticide poisonings in agricultural workers can be as high as 20,000 incidents per year in the United States [68]. Negative health outcomes can be due to acute exposure or chronic effects [67]. While chronic effects are difficult to measure, there are associations between chronic pesticide exposure in adults and incidence of different types of cancer [69–71]. Other chronic impacts on endocrine, reproductive and neurological health are also active areas of investigation [70]. Risks regarding occupational exposure to farm workers, especially immigrant communities, also fits into a broader discussion of environmental and social justice issues [72].

There are also risks from non-occupational pesticide exposure. For instance, children of agricultural workers tend to have greater exposure to pesticides in their home environment [73]. Children with prenatal pesticide exposure also have increased risks for certain cancers in childhood and neurodevelopmental effects [70,74]. Consumers are exposed to pesticide residue on food products, but in the United States, the Environmental Protection Agency (EPA) regulates acceptable residue levels to a "reasonable certainty of no harm" as mandated by the Food Quality Protection Act of 1996 [75]. Washing produce as recommended can also remove more than 50% of residue [76,77]. Still, metabolites from pesticide residue consumption are widely detected in the U.S. general population [78–80].

Consumers primarily choose organic produce because of the perceived health benefits, including reduced exposure to pesticide residue as compared to conventional produce [81]. Organic produce does have less pesticide residues than conventional produce [82,83], and people consuming organic diets had fewer detectable urinary pesticide metabolites [84–86]; however, the clinical effects of reducing consumption of residues already below EPA regulated levels is still unknown [85,86]. Importantly, at least one study supports organic farming as being safer for growers: A study in Portugal found that organic growers had fewer negative health markers, like chromosomal aberrations, as compared to conventional growers who used pesticides [87].

Reduced pesticide exposure for growers and consumers of organic produce can be attributed to prohibition of the use of synthetic pesticides on organic farms, as well as use of safer alternatives like biopesticides, biologically derived substances, when needed [88]. For example, microbial-based products, including *Trichoderma* spp., that can outcompete or antagonize plant-pathogenic fungi [52,89], and pose no known health risks to all non-target organisms, including humans (i.e., *Trichoderma harzianum* T-22 strain [90]). This is not to say that insecticidal or antimicrobial compounds do not exist in organic agriculture (i.e., spinosad, pyrethrin, and copper products), but control measures cannot rely exclusively on these products [60,61]. While the safer crop-targeted controls are important tools for organic growers, this does not imply that organic management is simply an input substitution for conventional chemicals, nor that organic agroecological approaches center around the applications of these products over employing preventive strategies. Instead, it demonstrates that there is incentivized, active research in organic systems for lower toxicity means of pest management that could be incorporated as one aspect of agroecological growing operations.

2.2. Pesticides Disrupt Ecosystems and Ecosystem Services for Agriculture

Pesticides can also weaken ecosystem stability via detrimental off-target effects on other organisms. Pesticide use has been shown to diminish diverse insect communities to only a few species [91,92]. Population reductions of pollinators [93,94], and natural enemies of pests like predators and parasitoids [28,95–97], as well as sub-lethal effects on these insects [98] have all been associated with pesticide use. Insects are not the only organisms affected on farms: the use of fungicides reduces functional diversity rhizosphere-associated microbial populations [99,100].

There is a known agricultural economic imperative to protect these insect species that provide ecosystem services like pollination, or predation of pests—the value of ecosystem services in the United States by wild insects alone (i.e., excluding honey bee colonies) tops $57 billion USD [101]. In one study in small grains, it was posited that the insect predators that were lost to insecticide spray could have kept pest populations in check [97], and thereby saved (at minimum) the cost of application. Economic losses associated with ecosystem services provided by soil microbes are yet unknown.

In addition, the effects of pesticide are not contained on farmland; there is an ecological (and economic) burden to a broad loss of insect species diversity and abundance. Substantial declines in abundance of flying insects [102] were recently reported and may be attributed in part to pesticide use. Pesticide run-off into waterways also reduces stream invertebrate biodiversity, even when concentrations are at or below regulated levels [103]. In addition, reduction in bird species diversity was associated with increased fungicide and insecticide use [95].

An example of the ecological impacts that some conventional chemistries carry is the use of neonicotinoids in pollinator dependent crops, like cucurbit crops. Cucurbit crops include pumpkins as well as summer and winter squashes (*Cucurbita* spp.), and insect pests, like *Acalymma vittatum* (striped cucumber beetles) are commonly controlled by systemic neonicotinoid treatments [104]. Squash flowers are visited by multiple species of bees, yet systemically applied neonicotinoids have been shown to move into the nectar and pollen [105,106], at biologically active levels for bees [105]. Generally, negative effects on traits like foraging behavior and growth rates from sublethal neonicotinoids doses have been reported on generalist visitors like honeybees [107–109] and bumblebees [110–112]. Overall, use of neonicotinoid for insect pest control in cucurbit crops is an example of how a broad-spectrum treatment for a pest can have tangible impacts on other insects that growers are dependent on for successful crop production.

In contrast, organic growers can manage pests like *A. vittatum* while reducing off-target effects by employing multiple cultural control methods. At a small scale, growers can physically shield crops [113], or, when outbreaks are seasonably predictable, planting date could be altered to preclude co-occurrence of vulnerable plants and the pest. More importantly, there are management tactics that are ecologically based and scalable. For instance, planting cucurbit crops in a polyculture was shown to reduce pest damage [114]. Perimeter trap cropping, planting highly attractive plants around the field border to draw pests away from the marketable crop, can be seen as an extension of polyculture, and has been shown to provide effective pest management [115–118]. In addition, use of non-preferred cucurbit cultivars can reduce beetle damage, and is effective at farm-scale [119]. Finally, a habitat for natural enemies could be provided [113], and the role of parasitoids could be better understood and promoted [120–122]. The example of cultural practices replacing the role that neonicotinoid insecticides occupy in conventional systems typifies sustainable alternative with lessened off-target effects that organic agroecological pest management strategies can provide.

2.3. Pesticides Create Risk in Production Systems

Relying on pesticides to secure yields poses major risks to growers and food security: the direct and indirect costs of pesticide application are often under-reported, and pesticide efficacy is fragile over time. There has been an inflation-adjusted five-fold increase in direct pesticide expenditures in the United States since 1960, yet the relative price of pesticides as compared to labor or fuel has dropped, thereby limiting incentives to reduce pesticide use [20]. Health and environmental costs are incurred that are rarely factored into any price differential, but are costs borne by the public [123], and more recent analyses estimate indirect costs to exceed $8 billion USD [22]. Superficially, the lower sticker price of conventionally grown crops may be interpreted as a criticism of efficiency of organic production methods, but the full accounting reveals a great hidden cost to both growers and our food system generally [124].

In addition, the strong selective forces exerted by pesticides on pests to overcome control measures can precariously place conventional systems on a so-called "pesticide treadmill"; as pesticides are deployed, pest resistance develops, necessitating increases in dose or frequency, or replacement with new pesticides or mixtures of pesticides [125]. More than 586 species are resistant to at least one insecticide, with the number of incidences of resistance for particular insect-insecticide pair surpassing 10,000 since 1920 across all cropping systems [126]. For weeds and fungi, these occurrences exceed 300 since 1960, and 1970, respectively [126]. The evolution of resistant pests has been documented in both to synthetic insecticides [127,128] and transgenic resistant crops [129–131] in row crop systems.

The only commercialized genetically engineered Bt vegetable crop, Bt eggplant (*Solanum melongena*), has been deployed on farms in Bangladesh beginning in 2014 in response to damage from the fruit and shoot borer (*Leucinodes orbonalis*) [132], making it difficult to assess how quickly resistance will develop. Overall, loss of pesticide or transgenic efficacy is a burden to growers, with effects rippling through the supply chain.

An example of where reliance on pesticides carries a significant cost and repeated loss of pesticide efficacy is for management of cucurbit downy mildew in cucurbit crops. Cucurbit downy mildew (CDM; pathogen *Pseudoperonospora cubensis*) is a disease of all commercially grown Cucurbitaceae including watermelon (*Citrullus lanatus*), melon (*Cucumis melo*), squash (*Cucurbita* spp.), and cucumber (*Cucumis sativus*) [133]. In 2004, annual epidemics of cucurbit downy mildew that overcame resistance of cucumber cultivars and several fungicides affected the United States [134] while globally, similar pathogen dynamics were underway [135]. Over time, the pathogen has developed resistance to multiple fungicide chemistries [133–136]. Currently, there are effective pesticide regimes that rotate products and spray every 5–7 days can control the disease albeit at an additional cost of $150–$235 USD per acre [137].

Organic growers had no such option available; in general, there is a lack of curative chemical controls in organic agriculture, and resistant crops are a primary component of preventing major losses [26]. In response, researchers at Cornell University worked to develop cucumber genotypes resistant to the disease. This led to the development of some of the first documented CDM-resistant slicing cucumber varieties on the market after the 2004 outbreak [138]. Ongoing breeding efforts from this germplasm are not restricted by utility patents and have resulted in an improved CDM-resistant slicing cucumber variety [139], and ongoing work to develop CDM-resistant pickling cucumber varieties co-selected in organic and conventional production systems. This example highlights that organic plant breeding can drive research efforts to develop resistant crop varieties that can supplant the need for pesticide use.

3. Investment in Organic Agroecological Research for Sustainable Pest Management Moves toward Eliminating the Conventional-Organic Yield Gap

The central tenets of the organic agroecological agriculture movement broadly support sustainable pest management, and we have highlighted numerous examples that exemplify the positive impact of these approaches in Section 2. Moving forward, organic agroecological agriculture will continue to activate transformative research in novel sustainable pest management techniques that maintain "biologically oriented thinking that sees our agricultural efforts as participatory rather than antagonistic vis-à-vis the natural world" [140]. Organic growers cannot rely on curative conventional pesticides; instead, they must innovate or adopt agroecological-based techniques. Organic agroecological systems are ideal environments for testing new pest management techniques because of characteristics like the promotion of soil health and biodiversity. Together, these foundational principles paired with constraints from restricted practices drive innovation, experimentation and initial application to develop novel and sustainable techniques that could reduce pesticide applications across many management systems.

Recently, there have been massive advances in the fields of plant breeding and selection [141], phenotyping [142], metagenomics [143], and chemical ecology [144], which can leveraged for progress in organic agroecological sustainable pest management. With these tools, organic agricultural researchers can significantly move the field of sustainable pest management forward by pursuing research in (1) understanding and promoting the healthy rhizosphere-associated microbiome fostered in organic agroecological systems, (2) increasing the use of organic seeds by leveraging transgenerational defense priming, (3) plant breeding to counter pests through indirect mechanisms, (4) plant breeding for quantitative resistance traits, (5) developing heterogeneous cultivar mixtures, (6) promoting farmscape diversity, (7) and enhancing interactions between types of defenses against pests (Figure 2). Taken together, these approaches can transform pest management on, and outside of, organically managed land by displacing the pesticide use and improving agricultural sustainability; these are among the key investment areas to eliminate the yield gap.

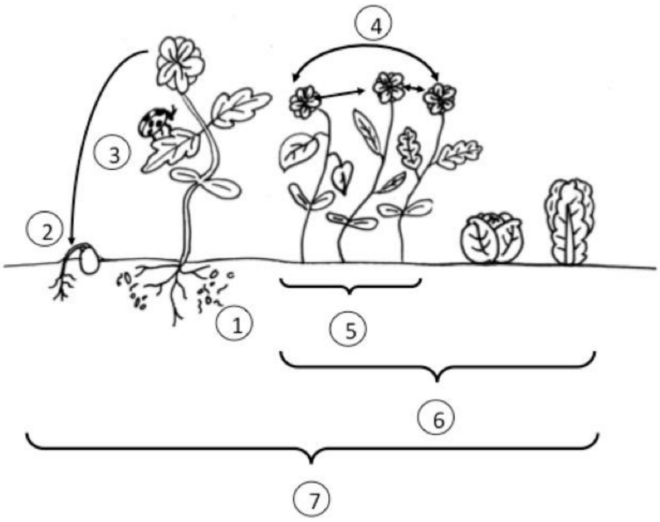

Figure 2. A summary of research directions for organic agroecological pest management: (1) understanding and fostering of beneficial rhizosphere associated microbiome; (2) study and application of transgenerational defense priming; (3) plant breeding for ecosystem services like indirect defense via predators and parasitoids; (4) plant breeding for quantitative resistance; (5) deployment of genetically diverse cultivar mixtures; (6) supporting application of interspecific botanical diversity on the farm; (7) allowing and promoting interactions between different pest management mechanisms.

3.1. Rhizosphere-Associated Microbiome

Organic farmers have long understood that soil health is important for crop health. Soil health encompasses not only functionality and productivity, but also includes fostering environmental sustainability and the health of organisms that interact with the soil [145,146]. In conventional agriculture, soil management typically focuses on soil nutrient status. However, the physical and biological status of soil is also critically important for crop growth. Crops that have access to an adequate supply of nutrient are less stressed and can better protect themselves from pests. Similarly, soil structure, drainage, and pore space are important for promoting healthy crop growth. Thus managing soil health is a foundational component of organic agroecological pest management [147].

One component of soil health in organic systems is the rhizosphere associated microbial community. The soil microbiome on organic farms can have greater functional diversity and activity [99], greater evenness [148], or even greater taxonomic diversity [100] as compared to conventional farms. Furthermore, recent and extensive reviews have indicated that soil microbes do substantially affect plant phenotype [149–153], with specific attention to modes by which microbe interactions allow plants to acquire immunity to pests [154–157]. In addition, the microorganisms that may be responsible for disease-suppressive soils are topics of active investigation [158,159]. Importantly, it has also been shown for a wide range of row and horticultural crops that soil-borne disease are less problematic on organic farms, owing to greater soil health [46]. It is widely accepted that the rhizosphere-associated microbiome promotes healthier plants, as such we must better understand and foster these microbiomes via management techniques for sustainable agriculture [160,161].

We are at a pivotal time where interest in harnessing the benefits derived from the soil microbiome has surged, and new technologies from imaging [162,163], metabolomics [164], as well as genomics and transcriptomic tools [165,166] have become available to enable the detailed study of these microbial interactions.

Future research questions:

1. Which soil microbes contribute to disease suppressive soils [167], and in what context are they effective in significant disease suppression on organic farms?
2. Can plant—soil microbe interactions be improved through selecting plant genotypes that have increased beneficial interactions (i.e., increased resistance to pests, or better nutrient uptake) with soil microbes [53,168,169]?
3. How widespread and effective is the role of soil microorganisms in facilitating plant to plant communications in response to pest interactions [170,171], and how can this be translated into organic agroecological management recommendations?

3.2. Trans-Generational Defense Priming

Currently, the US and international organic standards encourage the use of organic seed [60,61] because organic agroecological systems are best served not only by organically bred seed, but also organically produced seed. By producing seed organically, the seeds may be better prepared for future pest pressures via transgenerational defense priming or induction. Priming refers to a state where a plant is able to respond more rapidly and intensely to a biotic stress [172], whereas induction refers to already activated defenses. The mechanisms of transgenerational induction and priming are not yet fully understood, but research indicates that heritable epigenetic changes are responsible [173–176]. Either state can be highly advantageous to mitigate damage from insects and disease, and "plant vaccination" via priming has been advocated for as a key IPM technique [28]. However, our focus is on the transgenerational effects from parent plant (grown at organic seed farm) to offspring seed (grown at organic production farm).

In the ecological literature, there are many examples of trans-generational defense induction and priming from prior herbivory. Since the seminal paper with wild radish (*Raphanus raphanistrum*) [177], herbivory on maternal plants has been shown to prime offspring for future infestations in a diverse group of plant species [178–181], with mechanisms explored in depth with model plants *Arabidopsis thaliana* and *Solanum lycopersicum* [182]. In addition, it has been shown that the maternal abiotic environment can affect how the progeny plants respond to the biotic stress of pathogen infection [183]. In addition to seed transmission, potato (*Solanum tuberosum*), demonstrates overcompensation in response to herbivory by the Guatemalan potato moth (*Tecia solanivora*), leading to higher yield in the damaged plant [184]. It would be intriguing to explore if these overcompensation effects would persist through clonal propagation over seasons. Overall, further study of this phenomenon could lead to important discoveries for the organic seed industry and growers alike.

Future research questions

1. What underlying conserved mechanisms are responsible for transgenerational defense priming?
2. What are the biotic and abiotic triggers of plant defense priming, and how effective is the response to the broad spectrum of pests the progeny may encounter? Does this have ramifications for where and how we could produce organic seed?
3. Are certain plant genotypes best suited for a response to transgenerational priming?

3.3. Plant Breeding for Indirect Resistance

A forefront for pest management innovation in organic agroecological systems is breeding plants for indirect resistance. There are specific plant traits that can augment indirect resistance, including traits that benefit insect predators by providing a signal about prey location or habitat or food resources, or muddle herbivore host finding [39]. While breeding for favorable plant volatile profiles could be a target for plant breeders, the genetic variation for the resistant volatile profiles present in wild ancestors and landraces is largely absent in the elite cultivars used today [185–188], making introgression of these traits a significant challenge. The means by which plant volatiles can aid or disrupt insect pest host finding is still largely unknown [189], and organic plant breeders and chemical ecologists should seek to learn how effective it could be in an agricultural setting.

Future research questions:

1. How can we identify unique volatiles that affect insect behavior (pests, and natural enemies) in a high-throughput manner? Of these volatiles, is there sufficient variation to select for enhanced phenotypes within cultivated plants?
2. What procedures should be developed to ensure enhanced volatile phenotypes are effective at field scale for pest management while ensuring minimal disruption to other beneficial organisms of the plant (i.e., pollinators) [190]?
3. How quickly will pest communities evolve to overcome disruptions in host finding via volatiles? How durable can we expect this pest management method to be?

3.4. Quantitative Resistance

Agricultural pests continue to demonstrate a remarkable ability to evolve resistance to control measures, most notably to conventional pesticides [126–128] or genetically engineered resistance traits [129–131]. Since it is predictable that given a high selective pressure, a pest will overcome any resistance trait, the organic community should lead in developing effective management strategies that lower selective pressure on pests for durable resistance through plant breeding.

Plant breeders should select for quantitative resistance, an incomplete level of resistance conferred from multiple genes, instead of qualitative resistance, a complete resistance caused by a single gene [191]. The general advantage of breeding for quantitative resistance is that pests are less likely to rapidly evolve to overcome multiple minor selective forces at one time, thereby increasing the longevity of the effectiveness of plant resistance [43,192]. Breeding for quantitative resistance to both pathogen and insect pests is complicated by an incomplete understanding of molecular mechanisms and challenges with accurate phenotyping [43,193], especially in discrete components of plant-insect interactions [194], and durability of resistance is ultimately also dependent on the pest population [195]. Overall, diverse plant breeding efforts to manage pests through lower selective pressure should be a priority for organic plant breeders.

Future research questions:

1. What is the best method for breeding for quantitative resistance in organic agroecological systems? How can we improve our ability to detect and select quantitative resistance traits in an agroecosystem with extensive biological diversity?
2. Will there be tradeoffs between selecting for quantitative resistance, and other quantitative traits important to fruit and vegetable crops, including flavor and yield?
3. Can we breed for any quantitative resistance traits that provide protection to multiple disease or insect pest pressure [196]?

3.5. Genetically Diverse Cultivars

A wealth of ecological literature indicates that intraspecific diversity is important for resilient natural and agricultural systems [197]. Use of cultivar mixtures is widely accepted as a successful plant disease management technique [198], and work in small grains and soybean has shown that intraspecific diversity can increase the abundance of natural enemies of insect pests [199,200]. These examples indicate that intraspecific plant genetic diversity can be leveraged to slow pest outbreaks.

From another angle, there is intrinsic value in intraspecific diversity, both via preserving the effectiveness of plant resistance traits by applying a more diffuse selective pressure on the pest and thereby lessening the likelihood of the pest to overcome the resistance as compared to monocultures [26,28,201], and also preserving population variation to allow for continued future selection [201]. This capability is essential for responding to new or changed pest pressure. It is especially important in preparing for a changing climate where we can expect changes in plant-insect interactions such as changes in plant phenology that may impact co-occurrence with herbivores or pollinations, more generations of pests per year, and differences in plant primary and secondary metabolism under elevated carbon dioxide levels [202].

Adoption of genetically diverse cultivars can be improved by plant breeding for mixing ability [203,204] or improvement of plant populations [205]. Strategies for breeding for crop mixtures were recently reviewed [204], and include screening large numbers of genotypes for final performance traits, or building on ecological knowledge of functional traits to structure mixtures. Using tools like genomic selection [141] to select only the most promising plant genotypes to submit to intensive field trails may allow plant breeders to make rapid progress.

Future research questions:

1. For cultivar mixtures, what is the most effective method to screen mixture combinations? Can we employ genomic tools to predict mixing ability to make the most rapid progress?
2. For plant populations, how can we ensure that genetic diversity is maintained to respond to evolving pressures?
3. How can participatory breeding methods be best employed to develop plant populations for organic growers?
4. Can development of plant populations be incentivized in the private sector; what market changes would allow plant populations greater fit into the business model of seed companies? Are there resources for public plant breeders to meet this need?

3.6. Diverse Farmscapes

Ecosystem services, like reliable predation and parasitism of pests can be augmented on the farm through providing habitats for beneficial insects [206]. Individual crops are a fickle habitat for many predatory insects, either lacking in undisturbed shelter, or providing a source of food for only a brief window. Having multiple plant species on the farm, either in separate plots or in a intercropping context is a well-documented method to enhance ecosystems services and has been thoroughly reviewed [26,197,203,207–211]. Organic farms are also noted to have greater species evenness [92] and richness [91] of communities of beneficial predatory insects. Specific examples of successful pest management via intercropping in organic horticultural systems include increased top-down herbivore control by intercropping cornflowers (*Centaurea cyanus*) with brassicas [212], and increased bird predation of insect pests when sunflowers (*Helianthus annuus*) were intercropped in organic vegetables [213]. These plantings broadly support sustainable pest management by facilitating ecosystem services and by establishing an environment that handicaps an establishment of overwhelming pest populations [49,91].

In addition to augmenting ecosystem services, there are other mechanisms by which a diverse species composition of plants can reduce pest pressure. Diverse species mixtures may have physical characteristics that produce more favorable microclimates, like a reduction in humidity that could lower fungal pest pressure, or even being an impediment to rapid movement of an insect pest [26,208]. In addition, interspecific diversity may also reduce the ability of a pest to find a susceptible host [208]. For example, a reduction in winged aphids was found in potatoes (*Solanum tuberosum*) when cropped with onions (*Allium cepa*), as a result of onion-induced increased terpenoid volatile production in potatoes [214]. Overall, the widespread use of diversified crops on the farm is a core tenet of organic agroecology, and an increased understanding of how to develop and deploy the most effective species mixtures will allow this practice to flourish.

Future research questions:

1. How can we effectively identify functional groupings of botanical diversity for organic growers, given the contextual dependency of the field, farm, and landscape on the relative effect of adding botanical diversity to the farm?
2. Are diverse organic agroecological farming operations scalable? How can we drive innovation in harvesting equipment and food distribution to allow growers to enhance the degree to which intercropping strategies, for example, are deployed on farm? While excellent local production models exist, can we develop a system to allow efficient coalescence into major markets, like cities?
3. Can we develop strategies to augment botanical diversity on organic farms, without increasing the total area of land under cultivation?

3.7. Interactions between Modes of Defense

Finally, in addition to each individual practice of a sustainable pest management system working in concert with the farm agro-ecosystem, the interactions between practices can have synergistic effectiveness. The central thesis of a recent excellent review on integrated pest management was the importance of studying the interactions between practices [28]; we agree, and believe that this can be best studied and applied in the thriving agroecosystems of organic farms.

Interactions between indirect defenses with direct plant defenses and plant biodiversity has been recently reviewed [215]. Briefly, examples of these interactions include that direct plant defenses may slow growth of insect pests that give the predators or parasitoids (indirect defense) a longer time window to find and consume their prey, and, as previously discussed, on-farm biodiversity can provide a needed habitat for these natural enemies [28]. We wish to specifically highlight the connection between soil health and plant defenses against biotic pests as the most intriguing example of pest management synergies for organic agroecological systems. In multiple systems, soil health has been connected to top-down control of insect pests [216–218]. Detangling this interaction to understand how growers can augment pest management may further promote soil health practices across management systems.

Future research questions:

1. There are innumerable combinations of modes of defense on organic farms. Can we leverage citizen science data or empirical grower knowledge to best identify the most promising areas of research for organic agroecological systems?
2. How do other organic pest-related (i.e., adding biological control) and non-pest related (i.e., tillage) management practices impact these synergistic interactions?

We wish to stress that synergies between defense types can allow organic growers to achieve pest management with lower selective pressure strategies. Overall, these topics are rooted in a system where there is already a culture of ecological stewardship and relies on integrating advances in multiple fields to make the most rapid progress. Organic agroecological research can lead the entire agricultural community in development and deployment of these ideas.

4. Conclusions

We need to invest in agricultural systems that will give us sufficient yields to nourish humanity while minimizing environmental impacts. The great yields from conventional agriculture today are inextricable from hidden cost to the environment through the detrimental effect of pesticides. While scaling organic agriculture to feed the world is still maturing, organic agroecological approaches hold the potential to provide for our world population sustainably by driving research and development of these pesticide alternatives. Our responsibility as agricultural scientists is not to maintain the status quo, but rather to continue path of innovations of previous generations for securing the productivity that currently supports our population. Indeed, agriculture is a human invention that has been in flux for millennia as new crops became available, growing techniques were developed, pest and environmental challenges emerged, new lands opened to cultivation, and markets expanded. Importantly, our knowledge of the effects of synthetic agricultural pesticide use has also shifted since their widespread introduction in the 20th century. How will we change our management techniques in response to improve the sustainability of our agricultural production? Can we move to more complex and multi-pronged strategies that are resilient and responsive to the living agroecosystems? By reframing the yield gap between conventional and organic agriculture as an investment gap, we can focus on the questions we need to answer toward the use of organic agroecological approaches in plant breeding and crop management for organic agricultural systems.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/10/6/2023/s1, Table S1: List of US states from which USDA NASS chemical pesticide application data is available.

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