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Forum

Orchard systems offer low-hanging fruit for low-carbon, biodiversity-friendly farming

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Abstract

As core constituents of healthy diets, fruits are often cultivated in temporally stable and structurally complex ecosystems that harbor high levels of biodiversity. However, high-intensity orchard management can lessen the human and environmental health benefits of fruticulture. In the present article, we argue that increased emphasis on biological control could contribute to preventative management of fruit pests, weeds, and diseases, resulting in pesticide phasedown. Carefully calibrated orchard management can increase the provision of ecosystem services by above- and belowground biota, improve soil health, and store atmospheric carbon. When tactically integrated with agroecological measures, behavior-modifying chemicals, or digital tools, biological control helps to conserve pollinator or soil fauna, protect vertebrate communities, and improve vegetation restoration outcomes. Its implementation can, however, give rise to scientific and social challenges that will need to be explored. By resolving the adoption hurdles for biological control at scale, human society could enjoy the myriad benefits of nature-friendly fruit production.

Keywords: ecological intensification, agroecology, One Health, biological control, pesticide pollution

Humankind is facing a mounting triple challenge through climate change, biodiversity loss, and malnutrition. Food and farming find themselves at the core of this challenge (Willett et al. 2019). Since its earliest origins, agriculture has provided supplies of nutrient-dense food, forming one of the cornerstones of complex civilizations. However, over the past century, agriculture has changed substantially and now poses important risks for the Earth system's resilience and stability. Energy-intensive industrial agriculture notably contributes to global warming, biodiversity loss, ecosystem decay, and human health hazards (Jaureguiberry et al. 2022, Wyckhuys et al. 2022). It is pushing the Earth system beyond its safe operating space (Richardson et al. 2023), compromising One Health—that is, the combined health of people, plants, animals, and ecosystems (Falkenberg et al. 2022)—and degrading societal well-being (Sachs et al. 2023). The wholesale transformation or planet proofing of agriculture in order to keep it within planetary boundaries (Rockstrom et al. 2020) requires urgent attention and bold action. In such an endeavor, a balance needs to be struck among its ecological, socioeconomic, and cultural spheres (Sachs et al. 2023). An effective rerouting or redesign of farming systems demands holistic perspectives and integrative systems approaches (Vandermeer et al. 2018, Barrios et al. 2020, Leclère et al. 2020), which should be coordinated across geographic, disciplinary, and crop boundaries (Willett et al. 2019, Mehrabi et al. 2022).

A redesign of farming systems entails more than extracting maximum yields through top-down control and simple recipes (DeFries and Nagendra 2017); it also involves a careful manipulation of their biotic constituents, structure, and functioning (Garibaldi et al. 2021). This process poses significant challenges, given the increasing homogeneity and interconnectedness of agroecosystems and their exposure to recurrent anthropogenic disturbance (Tooker et al. 2020). In particular, synthetic pesticides are often liberally applied on farmland (Tang et al. 2021), where they replace ecosystem-provided population regulation services and lead to a state of coerced resilience (Rist et al. 2014). As such, many farming systems have now become inflexible and ecologically brittle (Tittonell 2020), requiring constant intervention to maintain desirable outcomes (Rist et al. 2014). Simplified, chemically intensified, and disturbed farmland is inhospitable to many plant, animal, and microbial biota (Wagner et al. 2021, Edlinger et al. 2022), with cascading impacts on ecosystem integrity, human health, and well-being. For instance, pollinator deficits reduce global fruit and nut production by 3%–5% and could

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potentially cause over half a million excess deaths from human malnutrition and associated diseases every year (Smith et al. 2022). Equally, agrochemical inputs negatively affect the richness of nontarget biota (Qi et al. 2020), many of which play a vital role supporting ecosystem services and upholding ecological resilience (Keyes et al. 2021). To retain humanity's options for an increasingly unpredictable future, with climatic upheaval and biotic shocks (Moore and Schindler 2022), these farmland ecosystems urgently need to be transformed.

Impacts wrought on by high-intensity farming are pervasive and not restricted to frontier zones but feature poorly on biodiversity conservation, ecosystem restoration, and nutrition agendas. Those impacts can be offset by harnessing biodiversity and agroecological processes through so-called ecological intensification (Kleijn et al. 2019). This involves a careful tuning of on-farm practices (LaCanne and Lundgren 2018, Finger and Möhring 2024), establishment of ecological infrastructures such as hedgerows (Albrecht et al. 2020), reconfigured landscapes, reduced field sizes, and more diverse cropland (Tscharntke et al. 2021). Those measures allow farmers to exploit landscape-level spillover of beneficial organisms (Larsen et al. 2024), especially in ephemeral production systems. However, most farming landscapes miss the critical 20% of natural or seminatural habitat cover to uphold prime ecosystem services such as pollination or natural pest regulation across space and time (Garibaldi et al. 2021). In those settings, judiciously managed perennial agroecosystems, including tree-based production, prove a powerful lever to reconstitute landscape-level service delivery (Barrios et al. 2018, Ickowitz et al. 2022), reverse biodiversity loss (Villar 2023), and wield food as a restorative force.

In this article, we outline the potential for fruit orchards to be transformed from intensively managed, externality-generating production systems into productive but resilient landscape hubs for ecosystem service-providing biodiversity, by integrating biological pest control with other management methods. We discuss those actions that should be targeted; provide examples of their potential or realized benefits for ecosystems, consumers, and growers alike; and discuss how these actions could be achieved at different scales. Although this Forum article is centered on fruits and nuts, many elements readily apply to other orchard crops, such as cacao, coffee, tea, and olives.

Perennial fruit orchards as prime levers for healthy ecosystems and people

Given their temporal stability, perennial fruit orchards carry ample promise to serve as landscape hubs for service providers and could thus enhance resilience of the surrounding ephemeral agroecosystems. However, there are also pitfalls associated with high-intensity orchard management. In the below paragraphs, we elaborate further on the exact promise and pitfalls of the kinds of systems.

Promise

Fruits and nuts (which we simply call *fruits* in the present article) are key constituents of sustainable healthy diets (Willett et al. 2019). Given the elevated contents in nutrients, vitamins, and phytochemicals, their dietary intake can alleviate the human disease burden (Glabska et al. 2020). Tree-sourced fruits in particular carry up to ninefold higher titers of vitamin A and C than other foods (Jansen et al. 2020) and assume a central role in resolving malnutrition among underprivileged populations in food-deficient regions (Omotayo and Aremu 2020, Aburto et al. 2022, Ickowitz et al. 2022). For example, fruit tree portfolios have been developed to face the challenge of seasonal availability, therefore providing year-round micronutrient to smallholder farmers (McMullin et al. 2019). Aside from directly improving human nutrition and health, an increased global consumption and cultivation of perennial fruit crops may also reduce the land-use requirements and diminish the environmental footprint of agriculture.

Specifically, perennial fruit orchards may complement the area-wide role of natural habitat in biodiversity conservation (Wang et al. 2021), ecosystem service delivery (Ickowitz et al. 2022), and ecological resilience. These patterns derive from ecological theory, in which temporal constancy and spatial or structural heterogeneity lend stability among a varied tapestry of ecosystems (May 1974). Temporally homogeneous systems such as fruit orchards are highly stable and prone to bear high biodiversity (Worm and Duffy 2003), which, in turn, can bolster ecosystem multifunctionality. Indeed, extensively managed fruit orchards constitute agroecosystems with high levels of temporal stability. It is primarily foliage or fruit loss (or harvesting) that upsets the continuity of on-farm interactions (Wiedenmann and Smith 1997), and even such impacts are minimal in tropical settings. Moreover, other layers of vegetative and nonvegetative complexity can be added to orchards to reinforce or magnify the resource continuity (Iuliano and Gratton 2020). Vegetational diversity per se benefits various trophic guilds, such as carnivores (Root 1973), omnivores (Ebeling et al. 2018), and pollinators (Ebeling et al. 2008); soil health and fertility (Furey and Tilman 2021); and multitrophic control of arthropod herbivory (Barnes et al. 2020).

As a result, perennial fruit orchards offer complementary resources and serve as refuges for species-rich communities of functionally important plant, animal, and microbial biota (Kreitzman et al. 2022). Elevated levels of biodiversity translate into superior pollination, pest control, and insect- or even snail-mediated vectoring of yeasts (Stefanini et al. 2012), decisive factors of fruit quality. Low-input systems such as *Opuntia* fruit orchards offer foraging habitat for apex predators such as bobcats, bears, and foxes (Borchert et al. 2008) and act as stepping stones or corridors for multiple taxa (Riojas-López et al. 2018), maintaining habitat connectivity and upholding service delivery across scales (Nogeire and Davis 2015). By favoring functional biota, perennial fruit systems could catalyze a transition toward low-carbon, nature-friendly, and pest-resilient farming if only their ecological facets and (taxon- or context-specific) the impacts of orchard management were properly investigated (Rosas-Ramos et al. 2020, Giffard et al. 2022).

Pitfalls

Fruits can be health-giving, but their social–environmental benefits can be partially or wholly offset by high pesticide usage intensity, mechanization, and habitat simplification (van Der Meer et al. 2020). Globally, the hazard load of insecticide usage in fruit systems is 5 to 466 times higher than that of other crop categories (figure 1; Wyckhuys et al. 2023). Its adverse impact on nontarget biota such as mammals markedly exceeds that of other agrifood items and is felt beyond orchard boundaries (García et al. 2022). A wide set of synthetic fungicides, herbicides, acaricides, and insecticides are used in fruit production, uniquely but imperfectly mirrored by the residue profiles of harvested produce. Multiple residues are most commonly found in berries (65%–86%), citrus fruit (73%), and grapes (68%) in the European Union and in 70%–76% of China pears and peaches (Wyckhuys et al. 2020). These

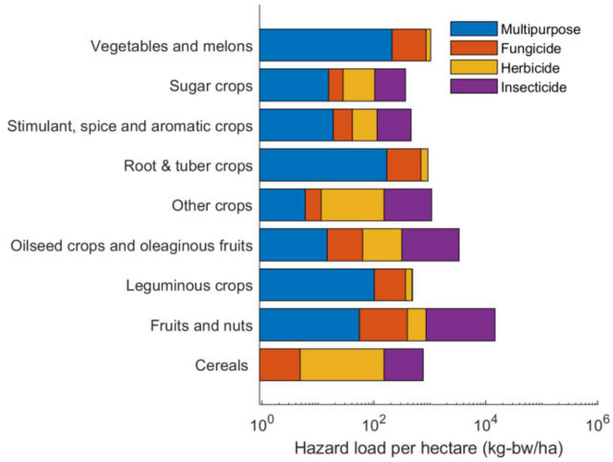


Figure 1. Hazard load per hectare of the various pesticide classes that are applied in the world's agricultural crops. For each crop group c and pesticide class p, the hazard load (HL, in the unit of kilograms of body weight) was calculated as $HL(c, p) = \sum_i [M_i/(NOAEL_i \times 365)]$, where i represents the active ingredients within pesticide class p that are applied to crops in crop group c, M_i is the total mass of active ingredient i accumulated in the environment, and NOAEL is its no observed adverse effect level in nontarget organisms. The values of M_i were calculated on the basis of spatially explicit, crop-specific, and active ingredient–specific application rates for 2015, obtained from PEST-CHEMGRIDS v1.0 (Maggi et al. 2019), and the corresponding degradability of each active ingredient was determined using a spatially explicit process-based model (see Tang et al. 2022 for a detailed description). The hazard load accounts for both the degradability and the toxicity of pesticides, and it reflects the mass of nontarget biota (i.e., birds and mammals) that is needed to absorb the applied pesticides without adverse effects. The total hazard load for each crop group c and pesticide class p was then divided by the global total crop area of all crops within the crop group c. The nine categories of agricultural crops are defined on the basis of the Indicative Crop Classification by the Food and Agriculture Organization of the United Nations.

can pose immediate hazards for food safety and human health. No less than 56% and 61% of domestically produced fruits respectively in Argentina and the Middle East surpass maximum residue limits—the highest legally tolerated residue of a given pesticide (MacLoughlin et al. 2018, Philippe et al. 2021). Meanwhile, at least 20 single pesticide applications are made per season in today's Canadian apple orchards, 20%–55% higher spraying frequencies than in the late 1900s (Chouinard et al. 2021). In Brazil, 63% of passionfruit pulp samples carry pesticide residues with 70% of the detected compounds not authorized for local use (de Oliveira Mozzaquatro et al. 2022). Under these conditions, it is unclear whether the actual health benefits of regular fruit consumption, such as by infants outweigh its protracted risks (Landrigan et al. 2019, Vigar et al. 2019, but see Fantke et al. 2012).

Crop value drives pesticide usage intensity in the fruit sector (Rosenheim et al. 2020), and this intensity is deepened by the high cosmetic standards of industrialized nations, high-end suppliers, or export markets (Zakowski and Mace 2022). Pesticide overreliance can weaken ecological safeguards such as natural biological control and can therefore induce pest outbreaks or facilitate resistance development—that is, hallmark features of a pesticide treadmill. Treadmills often start with the launch of new pesticidal compounds against endemic pests or pathogens (Beers et al. 2016), climate-triggered issues, or the appearance of invasive ones. Following the arrival of the invasive stink bug *Halyomorpha halys*, Asian citrus psyllid *Diaphorina citri*, or spotted-wing drosophila *Drosophila suzukii*, insecticide spraying frequency in invaded areas increased by more than four times (Leskey et al. 2012, Haye et al. 2016, Joshi et al. 2022), often in smallholder systems that had historically remained pesticide free. Aside from sometimes being ineffective and unnecessary, such routine or calendar-based applications tend to aggravate pest problems (Qureshi and Stansly 2009) and cause human health impacts (Jones 2020). Therefore, regardless of its crop protection benefits in the short-term, chemical crop protection can diversify the negative impacts of invasive pests to include inflated monetary costs, the loss of native biodiversity, and human health hazards. These impacts can be substantial: Invasive tephritid fruit flies such as *Bactrocera dorsalis* (or *Bactrocera invadens*) inflict more than US$2 billion losses per year across Africa—not accounting for the additional approximately 10% expenditure on insecticides (Ekesi et al. 2016). Those monetary impacts are compounded by social–environmental ones, which all too often remain unquantified. Invasive pest issues and pesticide-induced externalities are likely to deepen in the near future. Globalization and the resulting cross-border trade, as well as transformed environments and societies, lead to the recurrent emergence, spread, and proliferation of crop-feeding herbivores worldwide (Seebens et al. 2017, Hulme 2021). Among those polyphagous fruit pests such as *H. halys*, *D. suzukii*, and *Bactrocera* spp. challenge fruit growers and severely compromise the One Health benefits of fruit growing.

Aside from pesticide-related issues, common management practices jeopardize the overall integrity and functioning of perennial fruit orchards. These are most severe in technified and intensified systems with low-stem fruit cultivars—that is, those that have been bred to be of low stature in order to simplify management and facilitate picking (van der Meer et al. 2020). Although the diverse vegetation and multistrata designs of traditional orchards offer complementary benefits (Perfecto et al. 1996, Rosas-Ramos et al. 2020, Mockford et al. 2022), more simplified arrangements drastically affect resident biota. In vineyards, mowing negatively affects spider and grasshopper diversity and affects small mammals, whereas tillage and herbicide use lowers biodiversity and ecosystem service delivery by 20% (Winter et al. 2018). Heavy machinery used during fertilizer and pesticide application or for irrigation causes soil compaction and organic matter loss (Giffard et al. 2022) with cascading impacts on aboveground biodiversity and trophic interactions. The removal of structural diversity and ecological infrastructures such as hedgerows exerts taxon- and context-specific impacts on pollinator and natural enemy communities (Rosas-Ramos et al. 2020). Finally, expansive, genetically uniform fruit orchards increase the abundance of invasive pests with limited dispersal abilities, such as mealybugs. Well-calibrated management may enhance biodiversity and reconstitute service delivery at spatial scales far beyond those of individual orchards—that is, at the landscape level (Borchert et al. 2008, Pumariño et al. 2015, Riojas-López et al. 2018).

Redesigning fruit production systems for enhanced service delivery

Anthropogenic disturbances degrade biodiversity-driven ecosystem processes, functions, and services in farming landscapes. Offering temporally stable habitats, perennial fruit orchards constitute unique testing grounds for conservation and restoration action (Tooker et al. 2020). Through an ecological intensification of orchard systems (Kleijn et al. 2019), human-made perennial habitats can become central pivots of self-sustaining multifunctional landscapes (Asbjornsen et al. 2014, Winkler et al. 2017). With functionally important biota spilling over into adjacent farmland (Larsen et al. 2024), their benefits accrue far beyond the orchard boundaries.

Box 1. Designing climate-resilient, pest-suppressive banana cropping systems.

Bananas are globally important food crops that are increasingly affected by climate change and biotic stressors (Bebber 2023). The banana weevil, *Cosmopolites sordidus*, is the main pest of banana and causes substantial yield losses (Gold et al. 2001). Weevil grubs bore galleries into the banana rhizome, weakening plants and vectoring or facilitating the entry of phytopathogens (Guillen Sánchez et al. 2021).

Invertebrate and microbial natural enemies contribute substantially to *C. sordidus* management. Histerid beetles, ants, earwigs and spiders prey on *C. sordidus* eggs and larvae (Abera-Kalibata et al. 2006, Mollot et al. 2014, Dassou et al. 2023), whereas vertebrates such as shrews, lizards and toads are voracious predators of adult stages. Entomopathogenic nematodes affect weevil larvae and adults (Tabima et al. 2023). Insect-killing fungi such as *Beauveria* spp. or *Metarhizium* spp. exert important levels of larval mortality in laboratory settings (Membang et al. 2020), can easily be mass cultured (Mascarin and Jaronski 2016) and act as antagonists against pathogenic fungi such as *Fusarium oxysporum* f. sp. *cubense* (Mascarin et al. 2022), but their efficacy against *C. sordidus* in the field proves more variable (Tresson et al. 2021).

By deploying biological control within integrated or agroecological management packages, such as IPM, its full potential can be tapped. Delivery of insect-killing fungi can be enhanced through attract-and-kill approaches involving pseudostem traps (Gold et al. 2001), aggregation pheromones and their endophytic establishment in plant tissues (Akello et al. 2009). Volatile attractants or repellents can be used in concert with fungi via a push–pull strategy similar to that used against the Asian citrus psyllid in orange orchards (Eduardo et al. 2023), or can help to recruit natural enemies into pest infestation hotspots (Tinzaara et al. 2007). Biological control agents constitute the first line of defense in IPM and are smartly integrated with physical, cultural and agroecological tactics. This involves deploying LED-equipped traps for adult weevils (Kannan et al. 2020) or diversifying banana orchards (Dassou et al. 2023). The latter can be achieved through use of cover or intercrops, addition of noncrop habitats and agroforestry arrangements (Mollot et al. 2014, Collard et al. 2018, Carval et al. 2022). The addition of crop residues or mulching provide refuges to natural enemies (Gold et al. 2001) and benefit water infiltration, plant nutrition and yield, though its impacts in terms of pest suppression are inconsistent across sites (Gold et al. 2006).

Cover crops are a so-called climate-smart solution, because they add structural complexity and plant diversity to banana monocrops (Carval et al. 2022) which, in turn, raises overall resilience. Their impacts in terms of *C. sordidus* control are highly context- or species-specific and depend on spatial configureuration of crop and noncrop habitats (Collard et al. 2018). Although certain intercrops positively affect biological pest control (Duyck et al. 2011), others benefit crop performance through nitrogen fixation or prevent soil erosion but do not consistently lower pest damage (Carval et al. 2022). Along the same vein, polycultures of banana with maize, cocoyam or gourds and agroforestry arrangement also harbor more speciose natural enemy communities, experiencing enhanced levels of biological control and lowered susceptibility to biotic, abiotic shocks (Poeydebat et al. 2017).
Overall, a systems perspective is instrumental in building pest-suppressive, climate-resilient banana systems. Interdisciplinary research is imperative to fully account for the effects of plant diversity, soil coverage, habitat structure or landscape-level flows of natural enemies (Poeydebat et al. 2017, Tresson et al. 2021) without discounting its social–environmental dimensions, such as human well-being, farmer revenue, agrochemical pollution and environmental integrity.

To ecologically intensify fruit production, an array of tactics has been defined, trialed, and validated. These include agroecological measures such as agroforestry, cover cropping, conservation tillage, and organic matter addition, as well as landscape-level interventions. Given the pervasive, uneven impact of pesticide-intensive crop protection on ecosystem integrity and functioning, nonchemical management alternatives represent a main leverage point. Regardless of the potential of individual measures such as biological pest or disease control (Urbaneja et al. 2023) and orchard grazing (Paut et al. 2021), their standalone implementation tends to spawn limited outcomes. Meanwhile, their tactical integration can achieve pesticide phasedown, pollinator, and wildlife conservation; enhanced soil health; and carbon sequestration (box 1; Barrios et al. 2018). Practices such as organic manuring and efficient water management can even raise the titers of health-promoting phytochemicals (Yan et al. 2023), directly benefiting human health.

Harnessing nature for biological pest control

Naturally occurring (vertebrate, invertebrate, or microbial) consumer organisms keep pest populations within bounds, providing the universally valid service of pest population regulation or biological control (Hairston et al. 1960). Those so-called natural enemies bring balance to ecosystems, with their action valued at US$95.5 billion per year across biomes (Costanza et al. 2014; adjusted for inflation) and vital to restoration success (Villar 2023). As such, they underpin economically profitable agrifood production in a wide portfolio of systems (Naranjo et al. 2019). In perennial fruit orchards, resident natural enemies uphold photosynthetic capacity or primary productivity, fruits' nutritional quality, and growers' profits (Jacas and Urbaneja 2010). For example, in vineyards and apple orchards, insectivorous bats alone raise revenues by up to US$263 or US$ 594 per hectare per year (Rodriguez-San Pedro et al. 2020, Ancillotto et al. 2024). Although microbial antagonists of *Erwinia amylovora*, the causal agent of fire blight in apple orchards, are readily delivered through natural precipitation (Mechan Llontop et al. 2020), farmers can actively manipulate the spatiotemporal abundance, activity, and impacts of many other natural enemies. The service of biological control has therefore been ingeniously exploited by man, and its scientific underpinnings are robust (figure 2; Peña et al. 2002). Biodiversity can be harnessed under three different biological control modalities—that is, conservation, classical, and augmentation biological control (Heimpel and Mills 2017, Wyckhuys et al. 2024). These tactics are ideally to be bundled with agroecological measures (Deguine et al. 2023) and other compatible technologies, such as robotics,

Figure 2. Scientific underpinnings of biological control in 35 globally important fruit or nut crops. Per fruit or nut crop, we plot the number of all-time scientific publications on biological control of arthropod pests. Underlying queries were run on Web of Science over 1900–2023. Search strings were designed to capture scientific output on biological control in the particular crop: TS=((“biological control” OR biocontrol) AND crop AND (pest* OR herbivore*)). Per crop, the number of logged publications is reflective of overall technoscientific progress, cropping area, and pest incidence or severity. The crop categories are defined on the basis of the Indicative Crop Classification by the Food and Agriculture Organization of the United Nations.

precision agriculture or decision-support tools to manage pests or diseases preventatively.

Managing orchard habitats to benefit resident biota

The density, performance, and action of natural enemies can be enhanced by manipulating on- and off-farm habitat (Landis et al. 2000, Judt et al. 2023), a practice that has been refined for millennia. As early as 304 CE, date palm and citrus growers in Yemen and subtropical Asia built up the populations of resident predatory ants using kitchen scraps (van Mele 2008). Its basic premise includes favoring natural enemy populations through added shelter, floral or extrafloral nectar or pollen, alternative host or prey items, and suitable microclimates (Landis et al. 2000). Vegetation management is pivotal in these efforts: Cover crops, long-lived flower strips, or hedgerows can be highly effective (Albrecht et al. 2020, Judt et al. 2023) and are often paired with sugar dispensers, artificial pollen dustings, or behavior-modifying volatiles. Natural vegetation within and near the orchard also benefits natural enemy populations (Álvarez et al. 2019, 2024). Flower strips, when they are established in alleyways, nearly double natural enemy abundance and reduce pest pressure by 25% in cherry orchards (Mateos-Fierro et al. 2021). Interrow strips of flowers, grasses, or rice straw can enhance natural enemy action in vineyards by 50% (Berndt et al. 2006) and raise predator-mediated fruit fly control by one-third (Cruz-Miralles et al. 2022). In citrus, sown wildflower strips in alleyways with high structural heterogeneity of vegetation increase the abundance and nutritional status of parasitoids twofold (Mockford et al. 2022). Their usage is not restricted to invertebrates; adding coarse sand in planting holes benefits insect-killing nematodes and raises citrus yield by 60% (Duncan et al. 2013), and white mustard covers lower root disease incidence (Richards et al. 2020). Ant management can also enhance the biological control of sap-feeding herbivores such as aphids, scales, and mealybugs (Anjos et al. 2022), because ants protect these herbivores from natural enemy attack in return for access to their sugar-rich honeydew excretions. Conserving resident natural enemies also pays off. Washington apple growers that consciously protect natural enemies by using selective insecticides annually save $671 per hectare (Gallardo et al. 2016), whereas Australian mango growers that conserve weaver ants enjoy 55% higher profits (Peng and Christian 2006). However, some pest species such as *D. suzukii* can even benefit from natural enemy conservation measures (Santoiemma et al. 2018), and their impacts are often crop, pest, and context specific. One such example is the conservation or reintroduction of noncommercial fruit trees in the orchard periphery, to act as alternative hosts for pest or nonpest fruit flies and their parasitoids (Aluja et al. 2014). By acting as a locally preferred host of *Anastrepha obliqua*, the native tree *Spondias mombin* enhances natural the densities of four species of fruit fly parasitoids and bolsters biological control in guava- and mango-growing areas of Brazil (de Sousa et al. 2021).

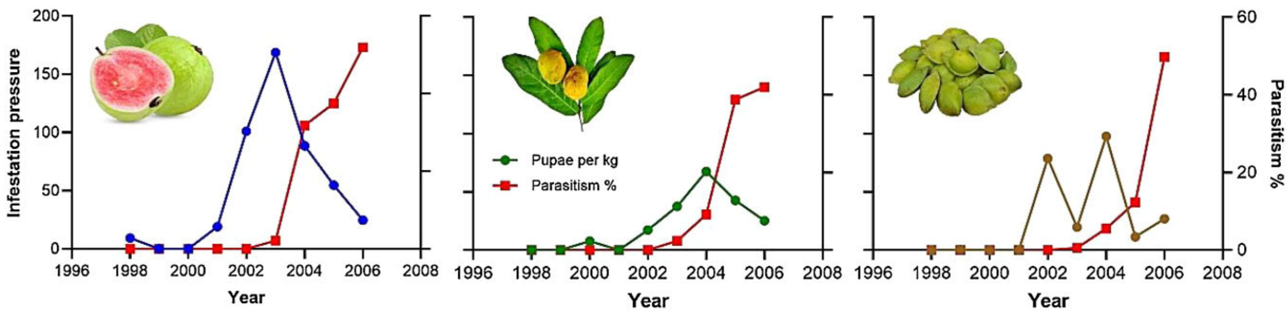


Figure 3. Tephritid infestation dynamics on three culturally important fruit or nut crops in Tahiti, French Polynesia following the release of the nonnative parasitoid Fopius arisanus. Year by year infestation pressure of the invasive fruit fly Bactrocera dorsalis (as the number of pupae per kilogram of fruit) are shown for guava Psidium guava, Polynesian chestnut Inocarpus fagifer, and Malabar almond Terminalia catappa (Vargas et al. 2007). Infestation dynamics are contrasted with temporal patterns in F. arisanus parasitism (as a percentage) on each fruit crop, depicted with a square markers in each graph.

However, in areas where S. *mombin* is absent or where pest or nonpest fruit fly species exhibit varying seasonal dynamics or are less prevalent, this strategy proves futile. Similarly, although raptors such as American kestrels show high occupancy of nest boxes in North American cherry orchards (approximately 93%; Shave and Lindell 2017), occupancy is much lower (approximately 31%) in blueberry fields 300 kilometers away (Hannay et al. 2023). Field-level effects of promising tactics are often inordinately shaped by landscape context, farm management, locally abundant biota, or cropping history (Paredes et al. 2015). If one aims to generate desirable social–ecological outcomes, conservation biological control practices need to be promoted with due regard for farming context—something that is often forgotten (Giller et al. 2021).

Restoring balance in invaded fruit systems

Because the success of some invasive pests is thought to be tied to their release from coevolved natural enemies (Liu and Stiling 2006), their long-term suppression in invaded ecosystems often relies on a scientifically guided restoration of ecological balance (Hoddle 2004). By introducing host-specific natural enemies from the pest's region of origin, perpetual, self-sustaining control can sometimes be attained. Since its first effective use in the late 1800s to resolve invasive pest issues in California citrus orchards (Caltagirone and Doutt 1989), this form of biological control has been globally deployed against a suite of invasive fruit pests, diseases, and weeds. Perennial systems in particular are well suited for this practice mainly because they represent comparatively stable ecosystems (Kenis et al. 2017). Guided releases of one single parasitoid species enabled declines of a factor of 16 in invasive African citrus psyllid *Trioza erytreae* incidence on the Canary Islands (Pérez-Rodríguez et al. 2024) and lowered *Bactrocera doralis* fruit fly densities on guava by up to 98% in Tahiti (figure 3; Vargas et al. 2007). Across the Caribbean, the parasitic wasp *Anagyrus kamali* reduced invasive mealybug numbers by 95%–99% on soursop and *Spondias* plum (Kairo et al. 2000, Roltsch et al. 2006). Mycoviruses of an invasive blight fungus restored the commercial viability of chestnut production in Europe (Rigling and Prospero 2018). Nonnative natural enemies often arrive accidentally (box 2; Weber et al. 2021). For instance, the cosmopolitan predator *Amblyseius largoensis* provides fortuitous biological control of the invasive red palm mite on coconut (Carrillo et al. 2014). Meanwhile, the economic dividends of intentional releases can be immense: The biological control of invasive mealybugs annually yields US$86 million gains for Benin's mango growers at a 145:1 benefit–cost ratio (Bokonon-Ganta et al. 2002).

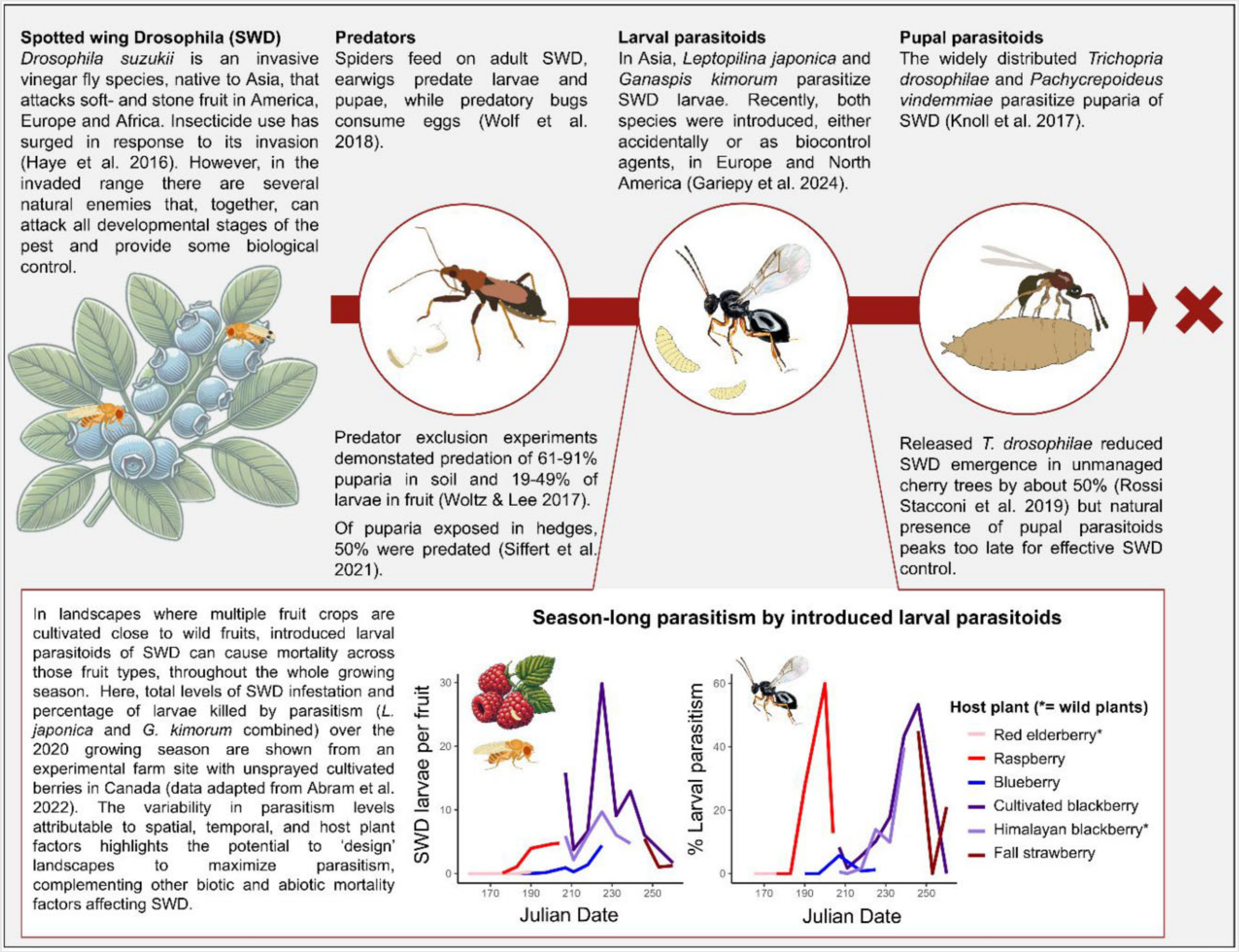
Fortifying inherent defenses with mass-reared beneficials

A third form of biological control involves inoculative or recurrent releases of mass-produced, endemic natural enemies either invertebrate or microbial. Extensively used in greenhouse horticulture, this tactic has considerable potential in perennial fruit orchards (Lacey and Shapiro-Ilan 2008). Predatory mites that are grown in biofactories, for example, provide 80%–92% control efficacy of the European red mite *Panonychus ulmi* in Chinese apple orchards (Zhou et al. 2014). Earwigs, reared on dogfood and protected by artificial refuges, cause 40- to 60-fold declines in aphid numbers on apple or kiwifruit as compared to untreated control plots (Carroll and Hoyt 1984, Logan et al. 2011). Scheduled releases of minute parasitic wasps at 0.3 individuals per square meter kill 74% of the nymphs of the Asian citrus psyllid *Diaphorina citri* (Marin et al. 2023), whereas drones distribute predatory mites with high levels of precision in vineyards. Single, soil-directed sprayings of entomopathogenic fungi kill up to 82% of citrus coddling moth *Thaumatotibia leucotreta*, and these natural enemies persist for 5 months after application (Coombes et al. 2016). Often, biological control proves competitive with pesticide pricing, and growers even receive price premiums for residue-free produce (Khan et al. 2018, Wittwer et al. 2021). Such produce is highly coveted in export markets, which has enabled the implementation of augmentation biological control on more than 20,000 hectares of mango crops in southeastern Mexico (Liedo et al. 2021). However, its implementation in open-field systems such as fruit orchards can face unique sociotechnical challenges such as a heightened likelihood of agent dispersal beyond proprietary boundaries, eventual interference with orchard management or naturally occurring biota, and farmers' limited knowledge of and familiarity with biodiversity-based practices (Michaud 2018, Wyckhuys et al. 2019). To spur widespread adoption, additional societal support may be needed.

Cross-scale benefits of biological control

Perennial woody plants assume central roles in global water, energy, carbon, and nutrient cycles (Ellison et al. 2017), and fruit-bearing trees prove popular in climate change mitigation efforts (Martin et al. 2021). Perennial fruit orchards constitute valued carbon sinks (Eddy and Yang 2022): Vineyards, for example, annually increase carbon storage by 43% by mass (Wiliams et al. 2020). Biodiversity-based and agroecological interventions such as biological control can lower the energy-use intensity and

Box 2. Native and (fortuitously) introduced natural enemies provide Drosophila suzukii biological control in small fruits.



carbon footprint of farm operations (Wyckhuys et al. 2022), enhance carbon sequestration rates, and simultaneously sustain broader bundles of ecosystem services that derive from fruit growing (Kreitzman et al. 2022, Ickowitz et al. 2022, Deguine et al. 2023). Cover cropping, in particular, greatly augments the carbon storage potential of perennial fruit crops (Zumkeller et al. 2022, Leonel et al. 2024). When established in banana monocultures; shade-tolerant forage grasses; or legumes such as *Brachiaria* spp., *Panicum* spp., *Arachis* spp., *Neonotonia wightii* or *Paspalum notatum* may also suppress weeds, retain soil moisture, lower disease susceptibility, and enhance overall resilience to climate change (box 1; Carval et al. 2016, Dassou et al. 2023). Pairing cover crops with an array of regenerative farming practices in US almond orchards increased carbon storage, improved water infiltration by 600%, and doubled profit (Fenster et al. 2021).

Biological control in fruit systems can help to achieve area-wide pest management—that is, suppression of pest populations beyond the confines of single fields or orchards (Hendrichs et al. 2021). First, such can be achieved by exploiting the cross-habitat movement of natural enemies (Larsen et al. 2024), in which orchards are prime source habitats for pest regulation services at broad spatial scales (Bianchi 2022). In landscape matrices, the spatial cover of structurally complex traditional orchards and organic vineyards increases landscape-level abundance and diversity of insectivorous birds, spiders, and predatory beetles (Horak et al. 2013, Paiola et al. 2020). High-intensity orchard management cancels out such organismal flows and the associated cross-scale benefits (Clemente-Orta et al. 2020). Another option is to exploit pest phenology, dietary breadth, or habitat affinities to use orchards as the main loci for pest management interventions (Lu et al. 2024). Orchard leaf litter, for example, teems with winter-active predators (Niedobová et al. 2024), which can be used to suppress (dioecious) aphids or polyphagous mirids before they colonize adjacent field crops (De Roincé et al. 2013, Gajski et al. 2024). On the other hand, however, it also harbors fungal pathogens that can facilitate the infection or reinfection of orchards with diseases such as apple scab (Gomez et al. 2007).

Furthermore, ecosystem-friendly interventions to mitigate aboveground pest threats benefit the belowground realm of agroecosystems (Veen et al. 2019). Soil health is pivotal to human and environmental health (Banerjee and Van Der Heijden 2023), and this certainly applies to perennial fruit systems (Giffard et al. 2022). In addition to the soil microbiome, macrofauna are critical to the sustainability of orchard systems and define plant nutrition (Sofo et al. 2020). As agrochemical inputs and tillage exert strong negative impacts (Sánchez-Moreno et al. 2015, Giffard et al. 2022), their deliberate reduction restores soil health even in the absence of organic management regimes (Daelemans et al. 2022). Cover crops, mulching, and organic manuring further boost microbial biomass, earthworm abundance (Morugán-Coronado et al. 2020, Fenster et al. 2021, Webber et al. 2022, Castellano-Hinojosa et al. 2023), soil stability (Gomez et al. 2018), and fruit yield, especially in nonarid, fertile settings (Novara et al. 2021). Soil-mediated processes also define fruit quality and titers of health-promoting antioxidants in grapes or blueberries (Wang et al. 2008, Mezzasalma et al. 2018).

Cross-guild benefits and leverage points

Perennial fruit orchards, especially when combined with seminatural or natural areas, flower strips, and hedgerows offer a suitable habitat for pollinator diversity conservation (Eeraerts et al. 2021, von Königslöw et al. 2022, Leclercq et al. 2023), and can also benefit the conservation of birds, mammals and even vascular plants. In the following paragraphs, we outline how orchard systems offer important leverage points for biodiversity conservation at large.

Pollinator conservation

In temperate zones, many fruit trees are early flowering, offering pollen and nectar at a crucial period for nest-founding bumble bees and many solitary bees (Becher et al. 2024). In addition, some fruit crops of the genus *Rubus* (e.g., raspberry, blackberry) can provide nesting habitat themselves for stem-nesting bees (Coates et al. 2022). Farmers can consciously retain or provide nesting material for (small) carpenter bees and orchard bees, *Ceratina* spp., *Xylocopa* spp. or *Osmia* spp. (table 1). Comanaging orchards for pest control and insect pollination has been the central aim of integrated pest and pollinator management (Lundin et al. 2021) and can be used in analogous ways in organic management. The key is to minimize trade-offs while maximizing cobenefits and synergies among pest control, pollinator diversity, and crop yield (table 1; Lundin et al. 2021). This can be achieved in the long term by increasing seminatural areas, providing nesting material, increasing flowering resources, and phasing down disturbances such as pesticide applications (table 1). However, not all resulting direct and indirect effects and their interactions and trade-offs are well understood. Relatively unexplored win–win outcomes include the enhancement of floral resources that benefit both pollinators and natural enemies but do not favor pests (Albrecht et al. 2020) and, at the same time, offsetting negative effects of pesticide exposure on bees by providing a diverse diet (Wintermantel et al. 2022). To what extent a diverse diet can compensate for the effects of pesticides is not fully understood, so a reduction of pesticide use should be a priority (Sponsler et al. 2019). However, there could also be trade-offs when reducing pesticide use. For instance, when using mechanical weeding instead of herbicides to keep the soil vegetation free under trees, ground-nesting bees could potentially be harmed more than by using the herbicide (Ullmann et al. 2020), although more research is needed to confirm that this effect persists in the long term. To resolve those trade-offs without resorting once again to pesticides, nonchemical solutions such as biological control need to be inserted and treated equivalently as other tools in incipient decision frameworks (Knapp et al. 2022). Pollinators do not only provide crucial pollination services (Klein et al. 2007), lifting yields and yield resilience (Hünicken et al. 2021, Senapathi et al. 2021) and improving the organoleptic characteristics of fruits (Gazzea et al. 2023), but they can also directly engage in biological control. By vectoring fungal natural enemies that are delivered through dispensers at the entrance of hives nesting tubes, managed honeybees and mason bees suppress fire blight in pear orchards (Joshi et al. 2020). Meanwhile the larvae of pollinating hoverflies are voracious predators of sap-feeding herbivores such as aphids and psyllids (Irvin et al. 2021).

Vertebrate and bird conservation

Many nonchemical management approaches have benefits for vertebrates such as insectivorous birds, bats, shrews, and raptors, which, in turn, contribute to biological control. In Dutch apple orchards, as few as three nesting pairs of great tits (*Parus major*) reduce caterpillar infestation pressure by 50% compared with areas free of *P. major* (Mols and Visser 2007). By protecting these organisms from pesticide-related harm, biological control bolsters their cost-free, self-sustaining pest control services. In turn, thriving natural enemy communities help to regulate populations of small-mammal herbivores that benefit from nonchemical orchard management, such as with vole numbers increasing by 73% when herbicide use is suspended (Sullivan et al. 1998).

The benefits of vertebrate-friendly crop protection can further be enhanced by introducing additional habitat management practices (García et al. 2021). In particular, the installation of nest boxes influences the presence or activity of cavity-nesting birds in fruit systems and, therefore, the potential to promote biological control. By installing nest boxes for western bluebirds (*Sialia mexicana*) in vinyards in California, in the United States, the removal of pest moth larvae was markedly enhanced (Jedlicka et al. 2011). The installation of nest boxes for American kestrels (*Falco sparverius*) in cherry orchards in Michigan, in the United States, led to fewer fruit-eating birds and reduced small mammal activity (Shave et al. 2018a, Shave et al. 2018b). On the basis of observations of fruit removal by fruit-eating birds, American kestrels were estimated to reduce cherry loss by 600% as compared to orchards without active nest boxes, potentially resulting in over US$2 million added to Michigan's GDP (Shave et al. 2018a). Nest boxes designed for kestrels are also readily used by other insectivores such as eastern bluebirds (*Sialia sialis*) and tree swallows (*Tachycineta bicolor*; Jasinski et al. 2021). Finally, barn owls (*Tyto javanica javanica*) in Malaysia palm oil plantations reduce rat abundance and associated fruit damage to levels comparable to that achieved by rodenticides. Their establishment further keeps palm fruit damage below the 5% threshold at which rat control programs are economically justified (Zainal Abidin et al. 2021). In addition to nest box establishment, amended orchard management could enhance bird-mediated biological control, but its scientific underpinnings require strengthening.

Vegetation restoration

For vascular plants, structural vegetation diversity is a sound proxy of biodiversity (Sullivan and Sullivan 2006). Diversified, traditional orchards with a varied canopy architecture harbor species-rich weed communities (Norfolk et al. 2013), and those are further enhanced by heterogeneous cover crops (Gomez et al. 2018, Mockford et al. 2022) and herbicide phasedown (Terzi et al. 2021). Functionally diverse cover crops effectively increase vegetation cover, lower weed pressure, and sustain plant community composition (Haring et al. 2023), with cascading benefits for flower visitors such as pollinators and parasitoids (Kammerer et al. 2016, Vaca-Uribe et al. 2021, Mockford et al. 2022). The termination of cover crops, such as by roller-crimpers, offers a valid alternative to herbicides in vineyards and the resulting mulch aids weed control (Recasens 2024), although mowing and

Table 1. Measures to enhance pollinator activity and pollination rates in fruit orchards and their respective synergies with biological control of pests, weeds and pathogens.

Measure	Examples and effects on pollinators	Synergies and trade-offs
Seminatural areas	SNA can provide complementary floral and nesting resources to fruit orchards (Eeraerts et al. 2021) and act as reservoirs for pollinators of crops (Ortego et al. 2024). SNA can boost bumblebee colony development in apple orchards (Proesmans et al. 2019) and dense tropical forest cover around coffee plantations increased the richness of flower visiting wild bees (Moreaux et al. 2022). Nearby agroforestry settings enhance pollinator visits in cacao orchards (Toledo-Hernández et al. 2021). Indirect effects: SNA can buffer negative effects of pesticide use in apple orchards (Park et al. 2015).	Synergy: SNA can serve as reservoirs of both pollinators and natural enemies for nearby agricultural landscapes (Ortego et al. 2024).
Increasing floral resources	Hedges and flower strips can be complementary food resources in fruit orchards (von Königslöw et al. 2022) and can increase flower visitors (Dhandapani et al. 2024) especially when implemented over several years (Blaauw and Isaacs 2014). A simple measure in fruit orchards can be to mow alleys less frequently. Wild bees can also be supported by summer flowering cover crops in vineyards (Wilson et al. 2018). Indirect effects: A diverse diet can offset negative sublethal effects of pesticides on wild pollinators (Knauer et al. 2022, Wintermantel et al. 2022).	Synergy: Floral strips and cover crops can enhance natural enemies and pest regulating services (Geldenhuys et al. 2021, Mateos-Fierro et al. 2021).
Crop and cultivar diversity	Crop diversity benefits pollinator communities in landscapes with SNA (Aguilera et al. 2020). Bees can spill over from an earlier flowering to a later flowering crop (Grab et al. 2017) but coblooming crops can also compete for pollinators (Osterman et al. 2021). Increasing cultivar diversity in fruit orchards can prolong crops‘ flowering time and providing flowering resources over a longer period, supporting even different pollinator communities (Eeraerts 2022).	Synergy: Crop diversification can promote natural enemies (Jaworski et al. 2023) and favour the control of pests and diseases (Parisi et al. 2013).
Beekeeping	Beekeeping can increase visitation rates of honeybees to crops (Osterman et al. 2023) but might be dependent on landscape hive density rather than on-field densities (Eeraerts 2022). Indirect effects: Managed bees might be competing with wild bees (Angelella et al. 2021).	Synergy: Managed bees can be used as “flying doctors” to vector fungal natural enemies (Joshi et al. 2020).
Nesting material	Provisioning of nesting material can increase *Osmia* flower visitation rate in cherry orchards (Osterman et al. 2023) and are used to promote *Xylocopa* spp. for passion fruit orchards (Junqueira et al. 2013). More different types of nesting material should be tested, as stink stations (i.e., dead fish or meat) can boost blow fly visitation rates in mango orchards (Finch et al. 2023) and straw bales can provide suitable nesting habitats for bumblebees (Lindström et al. 2022).	Synergy: Nesting material could potentially host natural enemies (Gilpin et al. 2022) and consequently reduce pest pressure.
Pesticide reduction	Pesticide use can negatively affect wild bees (Park et al. 2015). However, the reduction of pesticides is often indirectly investigated, by comparing, such as organic with IPM or industrial production systems. In organic apple orchards more bee species were found compared to in IPM systems (Samnegård et al. 2019), whereas organic vineyards can benefit butterfly species richness (Puig-Montserrat et al. 2017). Indirect effects: Some management alternatives,, such as tillage, could be harmful for ground-nesting bees (Ullmann et al. 2016).	Synergy: Increase in natural enemies in apple orchards (Samnegård et al. 2019). Trade-off: Can increase pest pressure (Samnegård et al. 2019).

Note: For context-specific or place-based solutions, specific reference is made to the relevant crop or cropping system, such as IPM, organic, pesticide-free production modalities. Where relevant, examples are also provided for nonfruit orchard systems, such as coffee, cacao or tea.

low-intensity tillage may conserve floristic diversity better than the above practice (Lisek 2023). Furthermore, by favoring consumer organisms, low-input orchards may reestablish trophic cascades and improve vegetation restoration outcomes at a landscape scale (Villar 2023).

Trade-offs and limitations of biodiversity-friendly farming

Biodiversity-friendly farming aims to balance agricultural productivity or yield and natural resource conservation. However, addressing both objectives can result in limitations and trade-offs that need to be considered. First, even though orchard systems offer ample room for yield–biodiversity win–win outcomes (Gong et al. 2022), biodiversity-friendly systems often carry lower yields than industrial ones (Seufert et al. 2012). Some farmers will therefore need to accept lower yields or higher costs in return for improved social–environmental outcomes. However, nonmonetary outcomes such as bolstered ecosystem functioning or enhanced farmer health are all too often undervalued. Where relevant, lower revenues or profits can be offset through incentive payments (Canales et al. 2024), subsidies, premium pricing, such as for organic or pesticide-free produce, or reduced production costs (Sánchez et al. 2022). The rising costs of pesticides may discourage their use, whereas the effectiveness of financial incentives depends on societal awareness and a willingness and capacity to pay, either through the tax system or markets. Equally, opportunities for premium pricing may be limited because of a lack of territorial markets, consumer awareness or sufficient labeling (iPES Food 2024). Second, because biodiversity-friendly farming tends to be comparatively labor intensive, rural labor shortages or an ageing farming population can pose important hurdles. These can potentially be countered through the use of small-scale mechanization or robotics (Daum et al. 2023). Managing these trade-offs successfully involves a careful balancing of environmental benefits with economic, social, and productivity outcomes and requires a smart deployment of financial incentives, capacity development, market access improvements, and integrated policy frameworks (Piñeiro et al. 2020).

Future research directions or hypotheses

To effectively transform intensively managed fruit orchards into resilient, biodiversity-rich landscape hubs, a series of scientific and social challenges need to be resolved:

Funding and institutional support for long-term projects

Many of the proposed methods, such as the manipulation of on- and off-farm habitat or the restoration of ecological balance in invaded areas, are based on complex ecological systems and require long-term projects to be implemented and evaluated. To shed light on their multifaceted benefits, these projects will require longer time horizons than the short-cycle projects that are commonly funded.

Implementation of area-wide projects

For technologies such as classical biological control, mating disruption, or the sterile insect technique, area-wide implementation has generated immense social–ecological benefits (Hendrichs et al. 2021). When implemented at similar scales and through multistakeholder involvement, conservation or augmentation tactics are prone to deliver outcomes of similar magnitude. Multidisciplinary projects.

Multidisciplinary projects are needed to evaluate multifunctional benefits and resolve potential trade-offs that result from nonchemical pest management. For instance, the use of cover crops may exacerbate water or nutrition competition in arid or low-fertility conditions impacts that remain obscured in monodisciplinary research efforts.

Funds, infrastructure, and local technoscientific capacity

Funds, infrastructure, and local technoscientific capacity are central to the promotion of biological control, especially in developing countries. Critical momentum can be generated through consumer demand for biodiverse, low-emission ecosystems or agroecosystems or pesticide-free produce. Equally, the establishment of local biological control companies can help to ensure sufficient availability of high-quality natural enemies. In this process, targeted investments from national and international agencies or philanthropy or through markets for biodiversity credits (Antonelli et al. 2024) can lend a vital stimulus.

The complexity of orchard ecosystems

The complexity of orchard ecosystems, including the multitude of (native, invasive) herbivores, in different contexts or regions and the context specificity of management measures (e.g., Walker et al. 2024) could pose a challenge. Big data approaches (Rosenheim and Gratton 2017), although they are limited by the availability of standardized methodologies in many parts of the world, may produce useful predictive tools in the future. Networked trials, standardization of data collection methodologies, and crowdsourcing data from farmers, such as achieved that through the 1000 Farms Initiative (Brock et al. 2024) should be encouraged to make these kinds of data more available.

Novel molecular techniques

Novel molecular techniques, such as metabarcoding and next-generation sequencing, as well as automated image analysis provide, alongside with traditional tools, the opportunity to unravel trophic links faster and in more detail than ever before (Miller et al. 2021, Rondoni et al. 2024).

Multidimensional and multiscale performance criteria

Multidimensional and multiscale performance criteria are essential to holistically capture social–ecological outcomes and bundles of One Health benefits (e.g., Darmaun et al. 2023). By steering clear of yield-only metrics, stakeholders can appreciate the tangible benefits of biological control on farm-level revenue or return on investment (Naranjo et al. 2015). Also, to properly allocate resources into different strategies, opportunity costs need to be concurrently considered in monetary terms and social or nonmarket values, including human health and biodiversity or ecosystem metrics (Lee et al. 2024).

International networking and knowledge transfer

International networking and knowledge transfer is critical to the global advancement of biological control. Although national research institutions and academia feature as prominent actors (Wyckhuys and Hadi 2023), transnational institutions, such as the CGIAR and specialized UN agencies such as FAO ideally also step to the fore.

Achieving behavioral change at scale

Innovative measures, even those anchored in biodiversity or ecological processes, can be disruptive and can create gales of creative destruction that transform established sociotechnical structures (Schumpeter 1942). However, in industrial agriculture, standalone technologies such as biological control have irregularly generated net positive outcomes over space and time (González-Chang et al. 2020) and routinely face pushback from manufacturers of incumbent technologies such as agrochemicals. This has been embodied in the European Union struggle to retain pesticide reduction goals in its Farm to Fork Strategy. The latter has been marred by farmer protests, misinformation campaigns, and fickle decision-making. These issues could be defused through inclusive consultation and cocreation processes with due involvement of farmers, as well as agroecology or biological control constituencies, and by treating crop protection as an integral part of orchard or agrolandscape management. Also, the emergence of pesticide-free, nonorganic production as a disruptive third-way strategy (Finger and Möhring 2024) can lower implementation hurdles and reduce the yield penalties tied to organic production while generating traction for biological control. Equally, an enhanced recognition of the multifunctional benefits of agroforestry and cover crops (Barrios et al. 2018, Couëdel et al. 2019, Tamburini et al. 2020) can create unprecedented opportunities for their deployment as biological control solutions. Individual solutions are also to be tactically bundled—as in Tephritid fruit fly mitigation packages (table 2)—and

Table 2. Effective bundling of biological control with compatible technologies in area-wide mitigation programs for Tephritid fruit flies in the Americas and Spain.

		Pest management strategies				
Species	**Country**	**Baited traps**	**Cultural**	**Chemical**	**Biological**	**Sterile insect technique**
Anastrepha ludens	M	X	X	X	X	X
Anastrepha obliqua	M	X	X	X	X	X
	Br, Co, E				–	–
Anastrepha serpentina	M	X	X	X	X	–
Anastrepha striata	Co, M	X	X	X	–	–
Anastrepha suspensa	–	X	X	X	–	–
Anastrepha grandis	Br, Pa	X	X	X	–	–
Anastrepha fraterculus	A, Br, E, Co, Pe	X	X	X	X	–
Bactrocera oleae	S, U	X	X	X	X	–
Bactrocera carambolae	Br	X	–	X	X	–
Ceratitis capitata	A, Br, Bo, E, Ch, Co, G, M, Pe, S, U	X	X	X	X	X

Note: Programs target various *Anastrepha*, *Bactrocera* and *Ceratitis* spp. in citrus, mango, hog plum, guava, sapodilla, mamey sapote, olive, apple or cucurbits, among others. Traps are baited with nontoxic lures, such as torula yeast pellets, protein hydrolysate, ammonium bicarbonate, or sex pheromones. Cultural practices involve the periodic removal of infested or unharvested fruits (eventually to be transferred to mesh-covered augmentoria, from which small-bodied parasitoids can escape; Deguine et al. 2011), whereas chemical control entails an attract-and-kill approach using spot applications of spinosad-based bait sprays. Biological control relies on resident biota or scheduled releases of laboratory-reared parasitoids, such as *Diachasmimorpha longicaudata*, *Psytallia humilis*, or *Psytallia lounsburyi*. Phytosanitary regulations, such as the delineation of fruit fly free areas and postharvest treatments, are not listed. *Abbreviations*: A, Argentina; Bo, Bolivia; Br, Brazil; Ch, Chile; Co, Colombia; E, Ecuador; G, Guatemala; M, Mexico; Pa, Panama; Pe, Peru; S, Spain; U, United States.

integrated with emerging technologies. This involves pairing natural enemy releases with nectar-bearing plants (Patt and Rohrig 2017, Tougeron et al. 2023) or artificial food sources (Tena et al. 2015), exploiting synergies between microbial and invertebrate natural enemies (Koller et al. 2023, but see Heve et al. 2021), and concurrently harnessing ecosystem processes that occur above and below ground. It also entails combining natural enemy-based measures with scheduled releases of sterile males (i.e., the sterile insect technique), volatile mating disruption or mass trapping (Horner et al. 2020, Stupp et al. 2021), exclusion netting or glue strips (Marshall and Beers 2023, Lu et al. 2024), behavior-based precision treatments (Blaauw et al. 2015), bred or engineered varietal resistance, robotics, or sensor-equipped early-warning systems. As standalone technologies, the sterile insect technique reduced codling moth populations in New Zealand apple orchards by 90%–99% over a 6-year time frame (Horner et al. 2020), whereas perimeter sprayings can keep the invasive *H. halys* at bay with up to 61% lower insecticide volumes (Blaauw et al. 2015). Therefore, in early stages of pesticide phase down, border-only sprayings against herbivores that exhibit strong edge effects (Blaauw et al. 2015) can promote biological control by leaving most of the crop unsprayed and therefore hospitable for natural enemies. New fruit crop varieties, such as fungus resistant grape varieties, could reduce fungicide use by 60%–90% in vineyards (Finger et al. 2023), and their integration with alternative pest and weed management can generate further benefits. Laser-guided sprayings or drone-based delivery of biopesticides can then provide curative control where needed (Chen et al. 2020). However, not all technologies are mutually compatible or benefit different functional guilds to equal extent: High-density plantings (Lang 2019) and netting in high-value crops (Manja and Aoun 2019) can enhance biological control but may hamper insect pollination. Overall, the effective deployment or codeployment of this diverse range of tools imposes in-depth ecological insights or so-called ecological literacy on behalf of scientists and growers alike (Wyckhuys et al. 2019). Indeed, when compared with technological fixes such as synthetic pesticides, biodiversity-based strategies tend to be knowledge intensive. Ultimately, success derives from a combination of multiple compatible practices into a functioning orchard system (Fenster et al. 2021, Baaken 2022) and routinely translates into added social–ecological resilience and wider profit margins for farmers.

Fruits' elevated pesticide hazard load (figure 1) underscores how a large-scale adoption of nature-based crop protection is critically lagging. Indeed, its global diffusion is hampered by reductionism, silo approaches, and insufficient collaboration with the social sciences (Mansfield et al. 2023, Wyckhuys et al. 2023). Closer farmer–scientist interaction, such as through participatory on-farm trials or living laboratories could engage fruit growers (Belien et al. 2021), enable discovery-based learning, and fortify ecological literacy. Indeed, although farmers may very well appreciate the role of pollinators (e.g., managed honeybee; Park et al. 2020) and the agronomic benefits of cover crops (Cosgray et al. 2023), they possess scant knowledge of natural enemies and ways to deploy them (Wyckhuys et al. 2019). There are, however, exceptions: Oregon pear growers readily value biological control and are even willing to pay an extra US$109 per hectare to protect resident natural enemies (Gallardo and Wang 2013). Knowledge cocreation approaches also play a crucial role in generating locally specific and context-appropriate knowledge (Coe et al. 2014, Hölting et al. 2022), which is especially important given the high levels of spatiotemporal variability in agroecological systems. To tap the area-wide service of nature-friendly orchard management, a critical mass of adopters or so-called mass action is often needed (Nahar et al. 2024). Also, to steer decision-making, scientists need to record decision-relevant endpoints, such as profit or return on investment (Kleijn et al. 2019), and to communicate the superior product quality that results from biological control (Martínez-Sastre et al. 2020) to value chain actors such as retailers (Macfadyen et al. 2015) and consumers (Wyckhuys et al. 2020). Overall, multicriteria analyses that capture win–win outcomes (or large wins and small losses) in terms of fruit yield, harvest quality, revenue, biodiversity recovery, or food safety hazards are central in farmer extension and policy advocacy alike. Furthermore, the lowering of cosmetic standards for certain food items and consumers' or retailers' acceptance of imperfectly shaped or blemished produce could go a long way in phasing down pesticide usage. Finally, when pursuing regulatory change and advocating for alternative forms of agrifood production at national or regional scales, regulators are to be properly insulated from public or private sector pressure, popular perceptions or misperceptions, and populist excesses (Kuran and Sunstein 1998). Much is to be improved in this domain.

On many fronts, enabling pesticide policies and regulations offers an important leverage point to advance biodiversity-friendly orchard management. Most countries have implemented legislative frameworks to regulate pesticide registration and approval and to establish maximum residue limits for pesticide residues on commodities used for food or feed (Handford et al. 2015). Some jurisdictions have also established guideline values to regulate pesticide concentrations in the soil (Jennings and Li 2014), on the surface, and in the ground water (Li and Fantke 2022) and atmosphere (Huang and Li 2024). However, despite harmonization efforts by several international bodies (Handford et al. 2015, Kubiak–Hardiman et al. 2023), pesticide legislation varies widely across jurisdictions. Regulatory values can vary by orders of magnitude (Li and Fantke 2022), with Global North countries generally having more stringent pesticide regulations than those in the Global South, where limited resources and expertise hinder effective implementation and enforcement (Handford et al. 2015). Even within the Global North, disparities exist; for example, the European Union has stricter pesticide regulations and sets markedly lower maximum residue limits than the United States (Handford et al. 2015). Meanwhile, the registration process for low-risk alternatives such as biological control invertebrates or biopesticides is overly protracted in the European Union while being streamlined in countries such as Brazil, Kenya, and even the United States. These disparities pose challenges for the large-scale implementation of biological control strategies, because the countries with more relaxed pesticide regulations and enforcement tend to provide fewer incentives for farmers to adopt nonchemical pest management. Equally, fast-track registration procedures or even waivers are key to ensuring that best-bet approaches such as biopesticides become readily available to fruit growers.

Given the absence of critical amounts of species-rich natural habitat in most present-day farmland, sustainably managed orchards pose a powerful lever to rebuild ecosystem service delivery, increase trophic diversity, and facilitate restoration at a landscape level. In these temporally stable habitats, biological control—as integrated with complementary tools and technologies—offers a viable means to alleviate anthropogenic disturbances, harness resident biodiversity, and uplift farmer livelihoods. Integrative approaches together with international and cross-disciplinary collaboration can tap its full potential and unlock the cornucopia of One Health benefits of fruticulture worldwide.

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