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FEATURE

# Developing cover crop systems for California almonds: Current knowledge and uncertainties

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Almond (*Prunus amygdalus*) orchard systems are highly productive and widespread in Mediterranean climates and dominate the California agricultural landscape. However, current intensive monocultural bare soil production practices limit the potential to support nonproduction functions (i.e., multifunctionality) and long-term sustainability of the orchard system (Aizen et al. 2019; Fenster et al. 2021). Managing orchards for multifunctional benefits includes maintaining ecologically and economically viable yields while prioritizing water quality, soil health, reduced input use, and support for biodiversity. Recent studies in almond demonstrate that diversification, including planted or spontaneous (resident) vegetation in orchard alleys, can improve multifunctionality by enhancing nonproduction functions in the orchard without reducing crop yield, thereby providing opportunities to enhance sustainability and resilience (Fenster et al. 2021; Morugán-Coronado et al. 2020).

Cover crops have been used in some Mediterranean orchards to accomplish a variety of goals for centuries (Proebsting 1958; Paine and Harrison 1993). In California, on-farm studies, such as the Biologically Integrated Orchard Systems (BIOS) for Almond program (Bugg et al. 1994; Bentley et al. 2001), developed valuable baseline information for cover crop implementation in modern almond orchard systems. Subsequent research suggests multiple avenues by which planted winter cover crops or resident vegetation can increase Mediterranean agroecosystem multifunctionality, though there is limited evidence from almonds. Synthesizing the information that exists could increase a shared understanding of expected benefits and trade-offs of integrating cover crops into almond orchards and clarify persistent knowledge gaps. Establishing this updated understanding can guide continued work to enable transformation toward multifunctional sustainable agroecosystems.

Cover crops have three main components that can be managed for potential benefit in the orchard system: roots, aboveground vegetative biomass, and flowers. The following review uses these three components to organize a synthesis of current knowledge about how cover crop inclusion in an orchard can lead to biophysical changes that can contribute to a multifunctional orchard system (figure 1). With a focus on almond systems, we review how these components are managed according to two major management decisions: species selection and management timing, and consider major possible trade-offs for cover crop use.

## ROOTS: BELOWGROUND IMPACTS

Although cover crop management decisions about species selection and timing often focuses on aboveground biomass and flowers, roots contribute to soil multifunctionality in agricultural systems (Faucon et al. 2017).When the multiple possible functions mediated by roots are targeted, species selection is key because different species have distinct root functional traits. Additionally, management timing should maximize the length of time that living roots are in soil as well as the biomass of roots that will decompose after cover crop termination. If root functions are targeted but aboveground biomass is undesirable, there are species (e.g., clovers [*Trifolium* spp.]) that produce less aboveground biomass, and cover crop biomass can be limited through mowing or grazing without impediment to belowground function.

***Enhancing Water Infiltration.*** Cover crop roots improve water infiltration by physically loosening soil and building stable soil structure pores and channels (Araya et al. 2022). In almonds, cover cropping in orchard alleys can lead to increased water infiltration amounts and rates compared to bare soils (Folorunso et al. 1992). Cover crops in almonds are typically grown during the winter rainy season in Mediterranean climates, when trees are dormant and not irrigated. Living roots during high precipitation events can enhance infiltration; reduced runoff can contribute to water savings goals and also reduce erosion and off-site movement of pesticides and fertilizers. A recent study in California almond systems found that despite water use by cover crops, the effects on soil moisture and evapotranspiration in almond orchards can be negligible (DeVincentis et al. 2021). Similarly, native grasses in a vineyard ecosystem increased water content at lower soil depths, presumably by increasing water infiltration (Daane et al. 2018), and a review of cover crops in Mediterranean vineyard and olive

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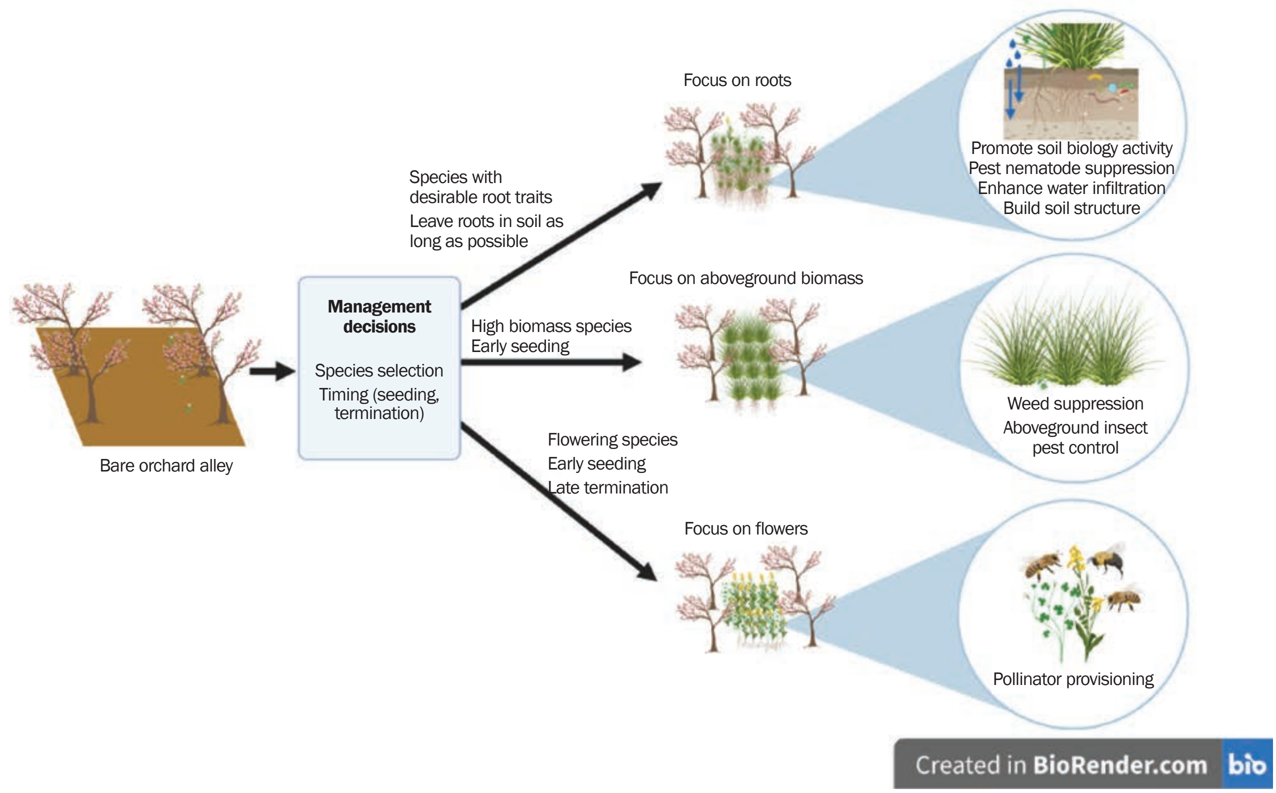
**Figure 1**

**Conceptual model of moving from a bare soil orchard to one with cover crops, and how a focus on flowers, aboveground biomass, or roots influences the effects of cover crops in almond orchard systems, as well as how the main management decisions in the orchard will change based on which part of the cover crop is the focus.**




(*Olea europaea*) systems found increased water use efficiency with cover crops by increasing deep soil rooting (Novara et al. 2021). While transpiration losses are low in fallow fields and probably also in bare orchard alleys, evaporation and runoff can limit water savings in unvegetated sites. Depending on location, cover crop management, and rainfall pattern, fields with cover crops could have similar water dynamics as fallow fields. Quantifying cover crop water balance and the underlying balance under modern orchard production practices, especially high-efficiency irrigation systems, remains a critical knowledge gap that should be addressed in collaboration with growers.

***Building Soil Structure and Carbon.*** Cover crops can contribute to improved soil structure and increased soil organic matter. Living roots physically break up compaction and increase soil aggregates with root biomass and exudates (Roberson et al. 1991). After cover crop termination, root and shoot biomass further promote soil aggregation by adding soil carbon (C) and stimulating microbial activity. In almond orchards, soil compaction and crusting decreased by 41% with cover crops (Folorunso et al. 1992), and in prune (*Prunus domestica*), cover crops increased resistance of macroaggregates to slaking (Roberson et al. 1991).

Carbon storage via cover cropping in agricultural soils has been proposed to decrease atmospheric C while providing other co-benefits (Lal 2015). In Mediterranean climates, the extent to which soil C can be increased is countered by rapid mineralization (Garcia-Gonzalez et al. 2018; Proebsting 1958) necessitating strategic use of cover crops to contribute to soil C (Moukanni et al. 2022). In almonds, C accrual may be favored when cover crops are combined with compost or other organic matter addition (Vicente-Vicente et al. 2016). Effects of cover crops on C pools and cycling at multiple depths remain unknown.

***Promoting Soil Biological Activity.*** Soil organisms, including bacteria, fungi such as arbuscular mycorrhizae (AMF), nematodes, protozoa, worms, and soil arthropods, support healthy and productive tree crops and ecosystem health (Delgado-Baquerizo et al. 2020; Sofo et al. 2020). Cover crops can promote soil biodiversity and reduce pathogens (Vukicevich et al. 2016). In Mediterranean perennial cropping systems, cover crops, among a suite of soil health practices, contributed to increased abundance of soil biota such as earthworms and AMF (Montanaro et al. 2017). Living roots also have demonstrated effects on nematode communities, which are important indicators of biological functioning in soils (Zhang et al. 2017).

Cover crops enhance almond root AMF colonization (Vasilikiotis et al. 2020) and could help trees access nutrients and water (Basu et al. 2018). Fungal hyphae, along with larger soil organisms, have the capability to move bacteria through the soil (Yang and van Elsas 2018), which may overcome the spatial gap between the cover crop and the almond tree row, though almond roots are found in the alleys as well as the berm. Additional research is needed to determine the impacts of biological enrichment of the alley on tree health and nutrition, especially under different irrigation contexts (e.g., drip versus microsprinklers) that may affect almond root exploration of the alley. The impact of cover crops on microbial community functions and how those functions translate to orchard multifunctionality also remains understudied (Castellano-Hinojosa and Strauss 2020). Additional research is needed to determine how cover crop termination timing should be altered to optimize benefits from living versus decomposing root biomass.

***Pest Nematode Suppression.*** Cover crop roots and aboveground biomass can both suppress pest nematodes by releasing natural nematicides (Zasada et al. 2010), especially the by-products of glucosinolates from brassicas (Haramoto and Gallandt 2004). Maximizing this suppressive effect requires proper timing. For instance, breakdown of glucosinolates in the biomass into nematicidal compounds requires plant tissue maceration and warm, moist soils (Matthiessen et al. 2004). Glucosinolate concentration is highest in cover crops roots at early vegetative stages, and highest in the aboveground biomass at flowering (Kruger et al. 2013). To balance suppressive benefits along with other root benefits, cover crop termination at or before flowering may be most effective, but further research is necessary to quantify trade-offs.

Though the benefits of nematode-suppressive cover crops have been demonstrated in vineyards (Kruger et al. 2013), such benefits may be limited in almond orchards by spatial separation between alley-planted cover crops and the tree rows, which are usually kept vegetation free. Opportunities that may increase benefits include planting cover crops during the fallow period before orchard (re)planting or in strips alongside trees, but research is needed to evaluate the short- and long-term effects of these strategies on pest nematode populations and on other orchard management goals. Additionally, the ability of various cover crop species to host plant parasitic nematodes and support nematode reproduction is important information for almond growers concerned about buildup of pest nematodes (Sikder and Vestergård 2020).

## BIOMASS: VEGETATION AND RESIDUE QUALITY

Cover crop vegetation and decomposing residue can be considered a management nuisance by growers desiring to limit plant residue at almond harvest. Managing residues for harvest ease may conflict with management for maximal biomass and flowering benefits and root accumulation, especially for cover crop species with semiwoody stems at maturity. However, cover crop aboveground biomass can support multiple management and sustainability goals while being managed to avoid negatively impacting harvest; this may be achieved by choosing species that decompose quickly or adjusting termination timing.

***Aboveground Insect Pest Control.*** Cover crop aboveground biomass can help with management of aboveground insect pests by providing habitat for natural enemies (Landis et al. 2000) and/or by diluting host-location cues (Andow et al. 1991). However, using on-farm habitat diversity to enhance biological control in perennial systems has had mixed results (LeTourneau et al. 2011). Insect pest management outcomes are highly dependent on the cropping system, target organisms, and landscape context (Batary et al. 2011; Chaplin-Kramer et al. 2011; Eilers and Klein 2009).

Navel orangeworm (NOW) is one of the primary insect pests of almonds in California (Wilson et al. 2020), and management can be either impeded or facilitated by cover crops. This species overwinters as larvae in remnant "mummy" nuts that remain in the orchard after harvest. Winter sanitation (i.e., dislodging mummy nuts from the tree and shredding them) is key to NOW suppression (Haviland et al. 2021). While increased water infiltration due to cover crops may improve conditions for extended winter orchard access, effective sanitation is facilitated by bare alleys, which allow machinery to effectively gather and destroy mummy nuts. As such, cover crops may impede NOW sanitation efforts if this orchard management cannot be completed prior to cover crop establishment. However, mortality of overwintering NOW larvae is increased when mummy nuts on the orchard floor are in cover crop vegetation, likely due to increased decomposition of mummy nuts and/or changes in microclimate (Wilson et al. 2022). Cover crops may also reduce spring egg deposition of first flight moths by interfering with oviposition on mummy nuts on the ground. This requires that the cover crop remain in place through the spring flight period.

Use of cover crops for insect pest control therefore has unresolved effects on species selection and management timing. The potential benefits of winter cover crops to NOW or other pest management must be weighed against other agronomic trade-offs. Furthermore, the contribution of winter cover crops to management of other key arthropod pests, such as mites and plant bugs, remains largely unknown. As such, quantifying mechanistic links and associated management opportunities between cover crops and pest insects as well as the marginal value of alternative management practices are critical areas for collaborative research with growers.

***Limiting Weeds.*** Cover crops can suppress weeds through direct competition or by reducing weed seed germination, and can facilitate weed management because the activities of cover crop management can also manage weeds. In annual cropping systems, cover crop residues can reduce weed germination at rates comparable to mechanical and chemical methods (Osipitan et al. 2018). In limited studies in perennial systems, cover crops have competed directly with emerged weeds to decrease their growth. In a study in California wine grapes, cover crop competition generally decreased weed biomass in alleys without impairing other aspects of vineyard management (Baumgartner et al. 2008). In recent orchard research, management practices that influenced cover crop establishment had a larger impact on weed competition than the specific cover crop mix (Haring and Hanson 2022). Cover crops are not likely to fully control weeds in orchard alleys but direct competition with weeds and the weed control benefits of cover crop termination will contribute to weed control goals over the multiyear lifespan of an almond orchard. Managing a weed-suppressing cover crop requires timely planting and termination, and may entail some trade-offs with other desired cover crop functions in the orchard system.

## FLOWERS: NECTAR AND POLLEN RESOURCES

***Pollinator Provisioning.*** Most commercial almond growers depend on managed honey bees (*Apis mellifera*) to provide pollination services for the brief time window of almond bloom, but monoculture almond orchards lack diverse pollen and nectar resources that benefit bee health (DeGrandi-Hoffman et al. 2018; Alaux et al. 2010). Flowering cover crops can expand access to nutritional resources for honey bees. Research on orchard-adjacent wildflower plantings in California showed no negative effects on crop pollination (Lundin et al. 2017), suggesting that cover crops can benefit bees without negatively affecting almond pollination.

Cover crops can also support wild non-*Apis* bee populations (Boyle et al. 2020; Norfolk et al. 2016). Currently, their populations are absent from most large-scale almond orchards in the United States (Reilly et al. 2020), and lack of natural or seminatural habitat may be a primary cause (Klein et al. 2012). Some non-*Apis* bees are more efficient almond pollinators than honey bees (Koh et al. 2018), and their presence in orchards can increase honey bee pollination effectiveness by encouraging cross varietal pollen transfer (Brittain et al. 2013). This positive outcome requires sufficient support for wild bee densities during almond bloom. Improving orchard conditions for wild and honey bee populations with flowering cover crops could therefore benefit growers, beekeepers, and bee biodiversity.

Flowering cover crops can support both managed and wild bee populations (Saunders et al. 2013) but insecticide and fungicide applications during cover crop bloom increase the risk of pesticide exposure and injury to bees and other beneficial insects (Boyle et al. 2019). Therefore, cover crops and chemical pest management must be comanaged to limit pesticide exposure and injury risk for nontarget insects (May et al. 2015). More research is needed to close persistent knowledge and regulatory gaps regarding bee-toxic agrochemicals (Durant 2020).

Managing cover crops for pollinators may entail trade-offs with management for other goals. Species selection for pollinators is limited to those that flower, such as legumes, brassicas, and other forbs. Management includes seeding as early as possible to promote prompt flowering, and delaying termination to maximize flowering period. However, cover crop nitrogen (N) content decreases in cover crops after 50% flowering, leading to increased C:N ratios (Clark 2013). Cover crops with high C:N in aboveground biomass may be slow to decompose and, if terminated in late spring or early summer, residues may persist as a nuisance at harvest.

Finally, flowering potential of cover crops may be limited by current recommendations related to frost injury risk. Current recommendations for California almonds are to terminate cover crops in the event of frost risk because they reduce soil temperatures compared to bare soils (Snyder and Connell 1993). This may lead growers to mow cover crops shortly before almond bloom, thus preventing cover crop flowering. However, the effects of cover crops on canopy temperatures remains unknown; quantifying these effects would provide growers with more information about when termination is necessary. Choosing cover crops for the flower resource benefits they provide to pollinators must therefore be balanced against potential trade-offs with other priorities of orchard management.

## SUMMARY

Extant literature on cover cropping in orchard systems suggests that the greatest benefits for multifunctionality comes from growing multiple cover crop functional groups grown for the longest period possible. For example, flowering species support pollinators, and high biomass will outcompete weeds, so a combination that has both features can provide more benefit than a single species, such as the multispecies cover crop pictured in figure 2. However, there are also trade-offs between benefits that a cover crop can accrue because optimal management of one component can interfere with other components and orchard activities. For example, optimal management for pollinator benefits may conflict with desirable termination timing for nematode suppression. Additionally, when focusing on navel orangeworm management, cover crops may interfere with mummy sanitation practices or other winter orchard operations. Therefore, cover crop management for multifunctional orchard outcomes may not simultaneously achieve all functions and must be tailored to the main target management goals within a specific orchard. Continued research is necessary to clarify how management and species selection can support multifunctional outcomes while minimizing trade-offs.

## COVER CROPS IN A SYSTEM

Cover crops are one ecologically focused tool that can be part of perennial agroecosystem management (Reynolds et al. 2021). Current knowledge suggests that cover crops can contribute to multiple ecosystem functions in Mediterranean orchard systems, and management can be adapted to fit the constraints and opportunities of a specific orchard context (Wauters et al. 2021), though many trade-offs and effects remain understudied both for production and nonproduction functions. Some constraints that limit the viability and benefits of cover crops, such as lack of water and degraded soil conditions, may point to broader unsustainable conditions for orchard cropping systems, or more appropriate application of other complementary practices, such as agroforestry, or mixed crop-livestock systems. Other constraints may be outside the biophysical realm, such as documented among citrus growers, where resistance to cover crops has been shown to stem from norms about the benefits of a "clean" or "tidy" orchard and assumptions that cover crops confer societal, but not farm-level, benefits (Cerdà et al. 2018). Similar assumptions are likely held by some almond growers who may view cover crops as a cost without direct return in the form of yield increases. Addressing the

**Figure 2**

**Cover crop growth over the winter. Photos taken in November, February, March, and May (top to bottom), showing emergence, growth stage during almond bloom, peak growth, and post-termination condition of an annual winter cover crop composed of functionally diverse species (a brassica, a grass, and a legume).**

broader implication of biophysical and sociopolitical constraints is an important collaborative opportunity for growers, agricultural researchers, and rural sociologists. In particular, it is an opportunity for robust cocreative knowledge development that acknowledges the depth and breadth of informal knowledge held by farmers (Šumane et al. 2018). Growers with a robust systemic understanding of how biodiversity management impacts their orchards can therefore both inform and be supported by research.

Within a larger biophysical and sociopolitical context, broader transformation is needed for agricultural land to be managed to form part of a sustainable, biodiversity-supporting landscape matrix (Perfecto et al. 2019). Cover crops, when managed appropriately, can contribute to this transformation in Mediterranean orchard production.

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