RESEARCH ARTICLE

Carbon farming can enhance pollinator resources

Carbon farming can help protect bees and other wild pollinators that are essential to California agriculture.

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Climate change is impacting California agriculture in many ways. Climate-associated shifts in ecological regimes, including rising temperatures and increased wildfires, droughts and floods, are negatively affecting populations of beneficial insects,

Carbon storage, like pollination, is an ecosystem service. Carbon farming is an array of agricultural practices that aim to reduce greenhouse gas (GHG) emissions or increase carbon sequestration (Toensmeier 2016). In rangelands and crop fields, carbon can be stored in aboveground vegetation or in the soil as soil organic matter (SOM) — a combination of roots, dead plant matter, and microbial biomass. SOM improves soil health and productivity, which can decrease inputs including synthetic nutrients and water, and help increase yields in both crop and rangeland systems (Oldfield et al. 2019; Ryals and Silver 2013). However, for pollinated crops, yields may remain low if pollinators are limited (Reilly et al. 2020). Certain carbon farming practices can bolster pollinator populations which, in turn, can help promote pollination to improve crop yield (Albrecht et al. 2020; Garibaldi et al. 2014; Garibaldi et al. 2016).

Pollinators enhance crops

One-third of crops are pollinator-dependent (Aizen et al. 2009), with approximately 75% of fruits and vegetables producing higher yields when pollinated (Klein et al. 2006). Although honey bees provide critical pollination to a vast array of crops, they are negatively impacted by disease (e.g., Traynor et al. 2016) and their pollination effectiveness is projected to decrease as rising temperatures limit their productive periods (Rader et al. 2013). A diverse pollinator community can help minimize and buffer the effects of the projected decline in honey bee availability (Brittain et al. 2013; Garibaldi et al. 2013) because wild native bees tolerate a wider variety of environmental conditions and provide ecological redundancy (Rader et al. 2013), which can contribute to resiliency.

Pollinators throughout the world are experiencing declines (e.g., Goulson 2019). Habitat destruction and degradation, pesticide exposure, disease and climate change contribute to these losses (Kjøhl et al. 2011). Although pollinators and the services they provide to agriculture are not the primary focus of carbon farming, modest modifications to many carbon storage farm practices can yield large benefits to pollinators without diminishing economic benefits to farmers or climate outcomes.

Adapting carbon farming

Numerous carbon farming practices can be adapted to benefit pollinators (fig. 1; table 1). In fact, many are

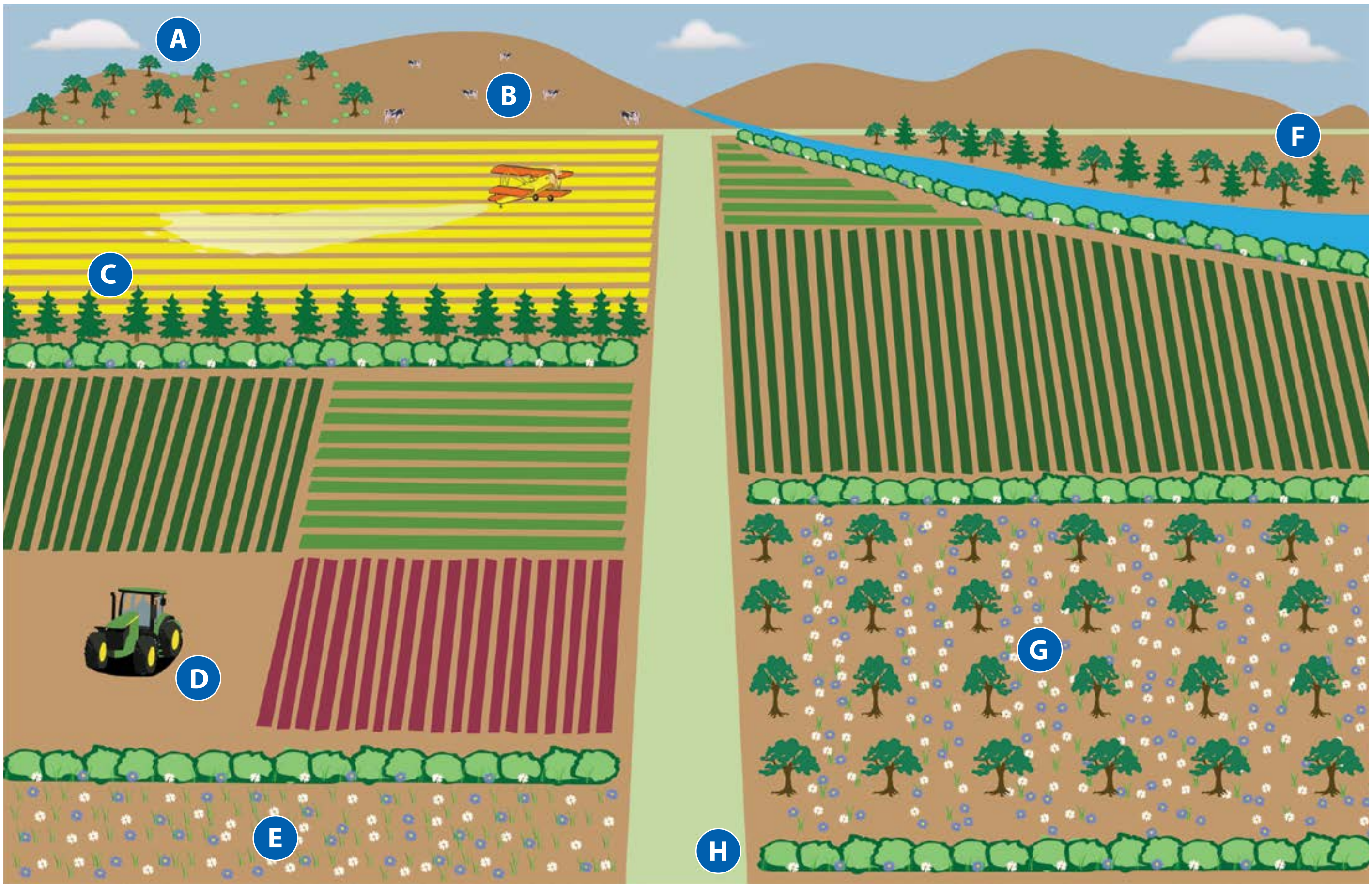

FIG. 1. Potential carbon-beneficial pollinator-friendly practices that can be implemented in agricultural landscapes. (A) Tree/shrub establishment, (B) prescribed grazing, (C) windbreak, (D) reduce/eliminate tillage, (E) field border, (F) riparian planting (woody or herbaceous), (G) cover crops, (H) hedgerow. *Illustration*: Jamie Tibbetts.

TABLE 1. Carbon farm practices approved by CDFA and NRCS that can be adapted to benefit pollinators*

Practice	CPS	Unit	Description	Pollinator-beneficial adaptation	Carbon-sequestration potential	Crop	Orchard/ vineyard	Range
Conservation Cover†	327	ac	Permanent vegetative cover of forbs, grasses and/or legumes.	Plant species that provide floral and nesting resources.	0.6	x	x	
Cover Crops†	340	ac	Temporary plantings during fallow winter or summer periods, or as a seasonal understory in perennial cropping systems.	Plant flowering species and allow them to bloom before terminating.	0.4	x	x	x
Field Border†	390	ac	A strip of permanent vegetation established at the edge of a field.	Plant species that provide floral and nesting resources.	0.9	x	x	
Hedgerow Planting†	422	lf	Establishment of woody vegetation along field edges.	Plant species that provide floral and nesting resources.	0.9	x	x	x
Prescribed Grazing	528	ac	Management of vegetation with grazing and/or browsing animals.	Manage timing, frequency, duration, or intensity of grazing to encourage flowering plants and minimize disturbance of host plants.	< 0.1			x
Range Planting	550	ac	Establishment of perennial or self-sustaining vegetation such as grasses, forbs, legumes, shrubs and trees on rangelands.	Plant flowering native or non-native species.	0.3			x
Residue and Tillage Management – No Till	329	ac	Eliminate soil disturbance and manage plant reside.	Eliminating tillage can help promote ground-nesting bees.	0.2	x		
Residue and Tillage Management – Reduced Till	345	ac	Limit soil disturbance and manage plant reside.	Reducing tillage can help promote ground-nesting bees.	0.1	x		
Riparian Forest Buffer†	391	ac	Permanent woody vegetation along riparian areas.	Plant native tree species that provide habitat or resources for pollinators.	2.0	x	x	x
Riparian Herbaceous Cover†	390	ac	Permanent herbaceous vegetative cover along riparian areas.	Plant species that provide floral and nesting resources.	0.2	x	x	
Tree/Shrub Establishment†	612	ac	Tree or shrub establishment by seeding, planting or natural regeneration.	Plant native trees and shrubs that provide floral and nesting resources.	19.0	x		x
Windbreak/ Shelterbelt Establishment†	380	lf	Single or multiple rows of trees or shrubs to achieve specific benefits.	Include trees, vines or shrubs that that provide pollen and nectar. Alternately, can be used as pesticide drift barriers, in which case, use conifers.	0.9	x	x	x

* Not a full list of the carbon farm practices currently approved by CDFA.

† Supported by CDFA's Pollinator Habitat program.

The carbon-sequestration potential for each conservation practice standard (CPS) was calculated using CDFA's version of COMET-planner. Carbon-sequestration potential, measured in metric tonnes CO_2 per year per unit, was calculated at either the 1-acre (ac) or 500 linear feet (lf) scale depending on the NRCS standard practice unit. The x's indicate whether a practice is applicable to crop, orchard/vineyard, or rangeland production systems.

already utilized to support pollinators. Agricultural practices that help sequester carbon and protect pollinators on farms can be grouped into two general categories: habitat management and farm production practices.

On-farm habitat can consist of perennial or annual vegetation within or along fields to achieve specific agronomic or conservation outcomes. Woody vegetation maximizes carbon-storage potential because woody plants have secondary persistent growth and often achieve greater biomass than herbaceous species (Blaser et al. 2014; De Stefano and Jacobson 2017). As a result, the USDA Natural Resources Conservation Service's (NRCS) Riparian Forest Buffer conservation practice standard (CPS 391), which introduces woody vegetation adjacent to waterways, is estimated to have 10 times the carbon sequestration potential of Riparian Herbaceous Cover (CPS 390) (table 1; Swan et al. 2018).

Carbon-sequestering habitat can be adapted to support pollinators by including species that provide floral resources and nesting or breeding sites for pollinators. Most pollinators exclusively feed on pollen and nectar, though different species vary in seasonal activity and flower preference. Offering numerous flowering species that bloom throughout the year introduces floral resource diversity and continuity to the farmed environment that is capable of supporting an array of pollinating species (Mallinger et al. 2016). Including plants used for nesting (e.g., pithy-stemmed species) creates nest locations that are often lacking in intensively farmed landscapes that contain little remnant vegetation (Forrest et al. 2015).

Some pollinators are trophic specialists, exclusively provisioning pollen to their young from one or a few related plant species. Incorporating these plants into habitat areas can help support selective, often more imperiled, pollinators (Sutter et al. 2017). Other pollinators depend on host plants during immature life stages, such as the reliance of monarch butterfly larvae on milkweed. Some host plants support a wide array of invertebrate pollinators. Oaks (*Quercus* spp.) are among the most effective tree species at sequestering carbon (SFEI 2017); they are also the host plant for many lepidopteran species and provide an important source of pollen for pollinators (Williams et al. 2007; Yourstone et al. 2021), despite being predominantly wind pollinated. Incorporating plant species that have high carbon sequestration potential and serve as an important pollinator resource will increase the multifunctional benefits of habitat. Additional research is needed to identify multi-beneficial plant species in order to streamline project design.

Providing habitat may also help pollinators adapt to climate change by creating structural diversity. Plantings can create varied microclimates that buffer pollinators from the impacts of extreme temperatures (Papanikolaou et al. 2017). For example, monarchs take refuge in shaded areas during periods of high heat (Landis 2014). Access to shade is likely to become increasingly important for bees and other insects as temperatures continue to rise (Sunday et al. 2014).

Managing for pollinators

Farm production management practices, including disking, applying pesticides, and grazing, have both direct and indirect impacts on both pollinators and GHG emissions. Adopting practices that sequester carbon and protect floral and nesting resources is critically important to reduce carbon emissions and conserve pollinators on farms.

Disking and cultivating farm fields mechanically agitates and redistributes soil, impacting soil structure, vegetative cover, root structure, soil microbes, and other soil organisms (Schmidt et al. 2018). Minimizing tillage through conservation tillage practices can increase soil organic carbon, though results vary by soil type (Ogle et al. 2012). Conservation tillage practices can also protect bees that nest within crop fields. Tillage can kill bee larvae in their underground nests. Although the exact depth will vary by bee species, tillage depths >15 inches have been shown to increase larval mortality by up to 50% for squash bees (*Peponapis purinosa*) (Ullmann et al. 2016). By contrast, surface tilling may have a reduced impact. Reducing or eliminating tillage-related disturbance protects underground nests by allowing bees to safely emerge.


Planting herbaceous flowering plants between rows of annual crops can increase pollination within fields. *Photo*: Sam Earnshaw.

Planting summer and winter cover crops that include flowering plants can provide additional floral resources between rows in orchards as well as during crop rotations in annual field crops (Ellis and Barbercheck 2015). On the other hand, weed control practices (e.g., mowing, disking, burning or spraying) on vegetated field borders can remove floral resources, depending on implementation and timing. Timing weed control practices to avoid bloom periods or dividing habitat into sections managed over consecutive years or seasons will help provide refuges for pollinators (Morandin et al. 2014; Sardiñas et al. 2018), especially those that may not be able to relocate nest sites in the absence of floral resources. A more permanent solution would be to replace weedy field edges with native California flowering plants that can outcompete weeds (Wilkerson 2014).

Selective management practices in rangelands can also impact pollinator and climate conservation goals. The rangelands that encircle California's Central Valley function as source habitat, exporting pollinators to crop fields (Chaplin-Kramer et al. 2011). Timing or intensity of grazing can affect the diversity and abundance of both flowering plants (Black et al. 2011) and pollinators (Lázaro et al. 2016; Shapira et al. 2020). Seasonal grazing can limit competition from weedy species and allow persistence of desirable plants (Bartolome et al. 2014). Rotational grazing reduces grazing pressure, helping to increase plant biomass and leaf litter, which in turn increases SOM and carbon sequestration (Gosnell et al. 2020) and can increase the overall productivity of the grassland system.

Integrated pest management (IPM) strategies can also protect pollinators while mitigating climate impacts. Some IPM practices such as planting pest and disease resistant varieties, using crop rotation to break pest-disease cycles, and the use of selective pesticides that protect natural enemies can help reduce pesticide use (Biddinger and Rajotte 2015). This in turn can potentially limit GHG emissions by reducing sprays and volatile organic compounds (VOCs) (Heeb et al. 2019). On-farm habitat can also attract natural enemies of crop pests, including insects and birds that enhance pest control in adjacent fields (Heath and Long 2019; Kross et al. 2016; Morandin et al. 2014), which can further reduce reliance on pesticides. Synergistic effects between pest control and pollination services can increase crop yields (e.g., Lundin et al. 2013; Morandin et al. 2016). Subsequent reductions in crop losses can enhance carbon assimilation by the retained crops (Heeb et al. 2019). Another win-win example is intercropping, which entails planting strips of habitat between crop rows to support natural enemies and pollinators (e.g., Brandmeier et al. 2021). Planting windbreaks composed of non-flowering woody vegetation (e.g., conifers) to shelter habitat and pollinators from pesticide drift also creates benefits to pollinators while increasing carbon sequestering via on-farm woody biomass (Lee-Mäder et al. 2020).

Balancing outcomes

Although promoting multiple ecosystem services from the same practice can amplify benefits, some practices may create neutral or negative outcomes for either pollinators or carbon storage (fig. 2). For example, Prescribed Grazing (CPS 528) can benefit pollinators, but the quantifiable carbon benefits of the practice are low (fig. 2). However, by restoring woody or herbaceous plants in grasslands (e.g., Range Planting CPS 550) a rancher can achieve dual carbon- and pollinator-beneficial outcomes, though this practice must be balanced with a need for forage production.

Alternatively, it may be preferential to limit the maximum potential of each service to ensure some level of each service. For example, many nitrogen-fixing cover crops are mowed or reincorporated into fields before they flower to capture their maximum nitrogen value. However, when terminated before bloom, they cannot provide forage for pollinators. Where it is compatible with management and primary crop phenology, waiting until a cover crop has achieved 50% bloom can benefit pollinators while still benefiting soil nutrients. Perennial crops like orchards and vineyards are more likely to allow for such timing than many annual row crops, although late-seeded crops such as winter squash may also be well suited to this strategy. In any production system, if a flowering cover crop might bloom during a season when regular pesticide applications occur, it may be preferable to terminate the cover crop and force pollinators to find different floral resources

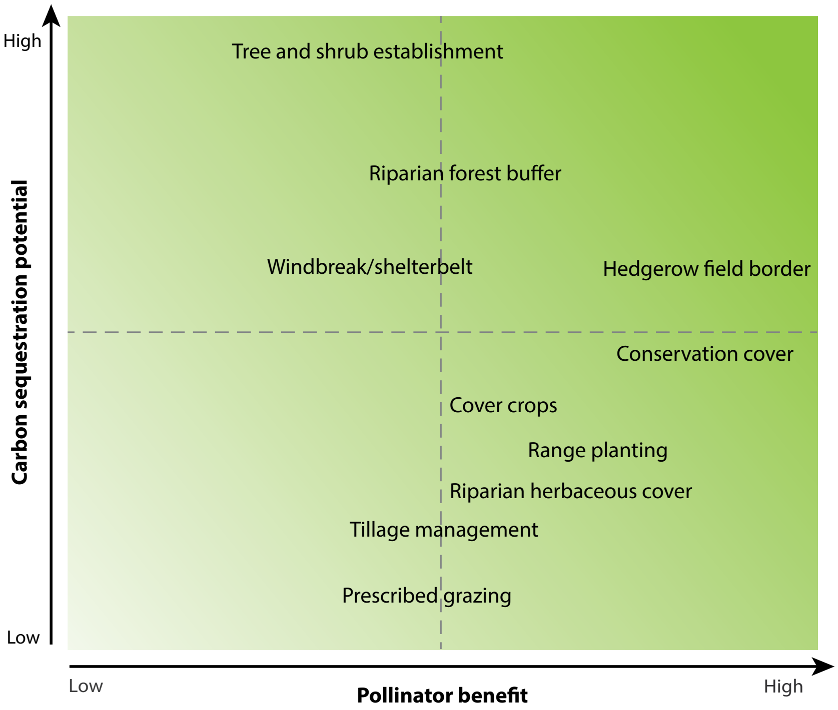

FIG. 2. Four-box model of the relative carbon sequestration potential of individual carbon farm practices compared to the relative pollinator benefit of the same practices. Notice some practices will vary in benefit depending on specific aspects. For example, the pollinator value of tree and shrub plantings for pollinators will vary according to the plant species chosen, thus there is a range of potential benefits associated with pollinator practices instead of a discrete value (corresponding to the width of the text). As the four-box layout emphasizes, certain practices trade off high values in one dimension against the other (top left and lower right regions; e.g., riparian herbaceous cover and tree and shrub establishment, which provide high pollinator benefits but modest carbon storage in the one case versus high carbon storage but moderate pollinator benefits in the other). Other practices (top-right box) afford high function in both dimensions (e.g., hedgerows). Because of complementary habitat needs of pollinators it is also possible the multiple practices in combination could fall into the top right box when either alone does not.

Between row cover crops in vineyards or orchards can provide pollinator resources while improving soil carbon sequestration capacity by improving soil organic matter. *Photo*: Houston Wilson.

instead of exposing bees to pesticides. Almond is an example in which the yearly crop cycle can accommodate cover crops, but regular insecticide applications are generally ramped up in mid-April. In this system, if flowering cover crops are allowed to persist through spring, mowing them prior to spraying would avoid pesticide exposure for resident wild bees and could be incorporated into management activities. As this example illustrates, careful timing of management actions and weighing different production goals can be used to promote multiple benefits.

The location where practices are implemented in a field or region can also impact on-farm ecosystem service delivery as well as emergent benefits. Pollination services predominantly occur at small scales because many pollinator species are non-migratory and have relatively short foraging ranges (Greenleaf et al. 2007), and thus are reliant on nearby floral and nesting resources. Regional-scale pollination benefits can occur when sufficient habitat is created to support a metapopulation of pollinators whose dispersal movements help maintain the resiliency of the overall pollinator community over time (Iles et al. 2018; M'Gonigle et al. 2015). For carbon-sequestering practices, benefits can also accrue at the global scale because the carbon cycle is a global process.

It is important to determine the best location to implement a specific practice at field scale (Faichnie et al. 2021) because this can impact the level of agronomic or economic benefits received by farmers. At the same time, the distribution of practices across the landscape should contribute to regional resiliency (Batáry et al. 2011). Planning habitat-based carbon farm practices at both the farm and landscape level would help optimize benefits (Williams et al. 2018). Incentive programs, discussed below, could vary payment rates to encourage adoption in specific areas to generate a more even distribution of pollinator and climate benefits across agricultural landscapes.

The woody vegetation in this hedgerow maximizes carbon-storage potential because woody plants have secondary persistent growth and often achieve greater biomass than herbaceous species. Hedgerows have also been shown to support robust pollinator populations. *Photo:* Sam Earnshaw.

Farm management decisions will vary based on the importance of field-scale goals related to farm economic sustainability. The value of a given practice to a farmer — which is likely to determine whether they adopt the practice — varies in relation to the agricultural system (crops versus livestock, organic versus conventional), crop type, water availability, and economics (Albrecht et al. 2020). A farmer growing pollinator-reliant crops may adopt a different suite of practices than one growing self-fertilizing, wind-pollinated, or non-pollinated crops. Identifying management scenarios for specific sets of practices for different cropping systems will require additional targeted study or modelling to help maximize benefits. Co-management of benefits and tradeoffs will also require clear goal setting and prioritization.

Incentivizing conservation

Farmers face costs in both adopting new and adapting existing carbon-farming practices to benefit pollinators. To recognize the regional and global value of these on-farm efforts, government-sponsored incentive programs can provide cost-sharing opportunities to offset costs or supplement forgone income. In California, farmers have opportunities to apply for funding from the state government via the California Department of Food and Agriculture's (CDFA) Healthy Soils Program

FIG. 3. Different habitats impact ecosystem service delivery at different scales. Habitat implemented at the local scape (within and along fields) can scale up to have landscape-level pollinator-beneficial effects. *Photos (L-R)*: Houston Wilson, Jessa Kay-Cruz, Sam Earnshaw, Deedee Soto, Kelly Gill.

(HSP) or the Pollinator Habitat Program (PHP) as well as from the federal government through the Natural Resources Conservation Service's Environmental Quality Incentives Programs (EQIP). The HSP is funded by California's Greenhouse Gas Reduction Fund, which is generated from auction proceeds from California's carbon emissions cap-and-trade program, whereas the the PHP is a new program developed by the state legislature (SB 170, Skinner) that was developed in 2021 and rolled out in 2022. EQIP is funded through the Farm Bill.

If an HSP- or EQIP-funded practice provides an added benefit to farms, the cost-share rate is enhanced above the regular reimbursement rate for the same practice. Practices supported by these programs include hedgerow plantings, cover crops, reduced tillage, and range plantings. The PHP notes co-benefits like carbon sequestration are likely outcomes of pollinator-focused projects but does not award additional points during their application process (though past performance in other climate smart programs like HSP may be taken into account during the selection process) nor provide increased rates for projects that create such co-benefits. Increased integration between programs like the HSP and PHP could provide more holistic funding opportunities for growers in California.

Along with financial incentives, demonstration projects help showcase implementation and benefits. Demonstration programs can be particularly effective when they encourage farmer-to-farmer dissemination of information (Garbach and Long 2017). HSP, PHP and EQIP technical assistance programs also provide site-specific support to farmers for planning, implementation and maintenance of pollinator-friendly carbon farming techniques. Technical assistance has also been shown to enhance farmer adoptions rates of conservation practices (Garbach and Long 2017).

Certification programs and voluntary carbon taxes represent consumer-driven avenues that can incentivize farmers to adopt climate-friendly or pollinator-beneficial practices. The nonprofit Zero Foodprint developed an opt-in for restaurants to divert 1% of a customer's bill to a fund that supports planning and implementation of carbon farming practices. Pollinator-focused certifications are a value-added marketing tool. Food companies are increasingly incorporating certified pollinator-beneficial ingredients into their supply chains to address consumer demand for products that protect pollinators. Although existing pollinator-related certification programs such as Bee Better and Bee Friendly require flower-rich habitat, they do not formally recognize the carbon-sequestration co-benefits of the practices they require. To date, carbon-related certifications have focused on emissions (e.g., climate neutral), rather than on-the-ground habitat creation (though a small-scale niche program Fibershed is pioneering a carbon-beneficial certification for wool products). If such programs start to emphasize the dual benefits of their efforts, both pollination and carbon sequestration could benefit.

Carbon farming is a win-win

Carbon farming encompasses a wide range of conservation practices that are readily adaptable to a variety of crops. Although the carbon-sequestration potential of carbon farming practices varies depending on soil type and precipitation levels, implementation of carbon farming practices can enhance wild pollinator populations in agricultural fields. This, in turn, can sustain the production of pollinator-dependent crops and thereby help California remain a top region for global food production. Thus, carbon farming is a critical tool to help support pollinators, which are essential for reliable production of many of California's highest value crops. It is imperative to encourage and incentivize the adoption of the pollinator-beneficial carbon farming strategies outlined here to increase California's agricultural resiliency in the face of ongoing climate change.

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