Multiple Benefits from Agricultural and Natural Land Covers in California's Central Valley

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Photo: S Corey

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Executive Summary

The Central Valley of California is one of the most heavily modified landscapes in the world, with millions of acres of semi-arid grassland, desert, mesic, wetland, and riparian areas transformed into an irrigated crop production powerhouse through large-scale infrastructure and irrigation projects. Despite its reputation as an agricultural “sacrifice zone”, it remains an area of conservation focus for its varied, unique, and vibrant ecosystems, from rare vernal pools and serpentine grasslands to the extensive networks of riverine systems, riparian forests, and wetlands that converge at the Sacramento-San Joaquin Delta. While the importance of these natural areas for human-valued functions such as water supply and quality regulation, biodiversity, culture, and recreation is well established, the dominance of agricultural land covers in the Central Valley underscores the need to understand to what extent they contribute to or detract from ecosystem functions beyond crop production.

Much of the information that is available on the potential benefits from agricultural and natural land covers is not centralized. Instead, disparate reports from research activities that vary in geographic location, scope, and timeframe constitute the bulk of the literature. Furthermore, most studies implement a particular suite of metrics to characterize benefits or tradeoffs provided by a land cover depending on the objectives of the study. Therefore, a synthesis of information on multiple benefits that aggregates metrics into a single database with comparable units of measure is an important step towards incorporating multiple benefits research into concerted planning and policy-making efforts for a multifunctional Central Valley landscape.

We performed a rapid evidence assessment following a consistent search strategy and pre-determined inclusion/exclusion criteria. We limited the results of the literature search to peer-reviewed publications from 2010-2020 with a geographic focus on the Central Valley, including the Sacramento-San Joaquin Delta. We extracted published, quantitative estimates of benefits and/or tradeoffs associated with individual land covers and compiled a database consisting of metrics on: 1) climate regulation (e.g., greenhouse gas emissions, carbon storage/sequestration), 2) economy (e.g., livelihoods, production value), 3) environmental health (e.g., pollution, pesticide load), 4) water (e.g., water quality, water use), and 5) wildlife, specifically value for avian conservation. We also consulted expert panels in the fields of agricultural ecology and conservation to assess: 1) avian conservation value, and 2) vulnerability to the impacts of climate change of each of the land covers. Finally, we produced a spatially-explicit model using publicly-available datasets to visualize the distribution of ecosystem benefits and tradeoffs, including carbon storage potential, air and water quality, groundwater recharge, and socio-cultural benefits.

We found that the agricultural land covers most likely to be associated with multiple benefits were alfalfa, rice, and rangelands/pastures (including shrublands and oak woodlands managed for grazing). Alfalfa was associated with benefits such as carbon sequestration and managed aquifer recharge potential, along with minor support for biodiversity, although tradeoffs such as nitrous oxide emissions from mature stands and high consumptive water use were also noted. Flooded rice systems were notable for their high value for wildlife, particularly waterfowl, shorebirds, and waterbirds, along with their economic value in the form of relatively high wages for agricultural labor, although methane emissions and consumptive water use were also a concern. As for orchard crops, which are notable for their large increase in planted area in recent years, their important contributions to agricultural production value and agricultural livelihoods were offset by potential tradeoffs in air quality metrics, nitrate leaching risk, and consumptive water use.

Grasslands, including rangelands and pastures managed for livestock production as well as unmanaged grasslands, had high potential benefits for climate regulation via carbon storage and sequestration in soils and belowground biomass, along with high value for biodiversity and support of valuable agricultural pollination services. In contrast, annual field crops such as tomatoes, corn, and cotton were the most likely to be associated with tradeoffs such as greenhouse gas emissions, nitrate

leaching hazard, and heavy pesticide use. Natural land covers such as unmanaged grasslands, wetlands, and riparian areas were most widely associated with benefits such as support for wildlife populations, carbon storage (particularly in riparian areas) and pollutant mitigation (in the case of wetlands), while some tradeoffs in greenhouse gas emissions were noted.

The spatial distribution of benefits and tradeoffs was highly heterogeneous, although in many cases a north-south trend was evident with areas in the northern Central Valley/Sacramento Valley exhibiting more relative benefits than areas in the southern Central Valley/San Joaquin Valley. The former is noted for the concentrated production of rice, along with a mixture of tomatoes, alfalfa, and orchard crops such as almonds and walnuts. The latter, on the other hand, is associated with most of the Central Valley's production of annual row crops (e.g., cotton), oranges and lemons, table grapes, and deciduous perennial tree crops such as pistachios, almonds, peaches, and prunes. Carbon storage patterns were particularly distinctive, with hotspots in the highly organic soils of the Sacramento-San Joaquin Delta and the former Tulare lakebed. However, the distribution of carbon storage potential was inversely related to carbon storage, in agreement with research showing the Delta and Tulare lakebed to be sites of carbon loss [1].

Our ability to draw general conclusions on the relative benefits or tradeoffs associated with Central Valley land covers was limited by the single-intervention nature of most of the quantitative research available on benefit/tradeoff related metrics. Experimental designs often must restrict activities to a single or few related land covers and investigate the impacts of an intervention on the metric of interest. For the purposes of cross-system comparisons, there were very few studies that addressed variability in benefit/tradeoff metrics across multiple land covers from a multiple benefits or multi-functional landscapes perspective. Many studies were focused on a few key metrics of known importance for a particular land cover, e.g., methane emissions in rice, rather than a broader survey of potential benefits and tradeoffs. Furthermore, most experimental analyses are spatially biased and not representative of the entire Central Valley landscape. These challenges highlight the need for more research on human-valued benefits across land covers from a multiple benefits perspective, preferably with a common set of metrics and indicators relevant to most or all of the land covers under consideration.

The following report synthesizes the most recent, Central-Valley-specific literature available on multiple benefit and tradeoff metrics. Section I presents individual land cover profiles, with a compilation of published, quantitative estimates for benefit/tradeoff metrics relative to other land covers, and where relevant, discussion of additional metrics not included in benefit/tradeoff analysis. Section II provides further details on a benefit/tradeoff analysis across land covers using data extracted from the published literature, along with the results of expert panel scoring on relative avian conservation value and climate change vulnerability among land covers. Finally, Section III presents results for spatial models of benefits and tradeoff metrics, including carbon storage, air, water, and habitat quality, groundwater recharge potential, and socio-cultural benefits across the Central Valley. Appendices are included for detailed coverage of methods for the rapid evidence assessment, benefit/tradeoff analyses, and index development. **The complete database and code in R script associated with this report are freely available on the Dryad repository under DOI: https://doi.org/10.25338/B8061X**

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Table of Contents

Figures and Tables

Background

Multiple benefits and multifunctional landscapes

All human economies rely on healthy landscapes to provide a multitude of services and benefits, from clean air and water, to food production, to places to enjoy recreational and cultural activities. However, it is difficult to adequately account for these multiple benefits when making economic, policy, and planning decisions without defining explicit metrics by which we can understand their relative contributions to human health and livelihood. Furthermore, we need ways to consider multiple metrics simultaneously to understand the net benefits and potential tradeoffs associated with an individual land cover relative to another. This includes, for example, understanding how land covers managed for human purposes such as food production can provide more than one service or benefit beyond their primary purpose. Such awareness can create opportunities for managing and planning landscapes that are "multi-functional" and promote the co-existence of complementary land covers that collectively provide a range of services for the greatest good to all who use and enjoy the landscape.

Past research has attempted to quantify the multiple benefits or services associated with different land covers. Research on ecosystem service "hotspots," for example, uses land cover maps, ecosystem process models, and public databases to map areas of relatively high provisioning of 5 or more ecosystem services [2,3]. Ecosystem service "bundles" are a related concept, with benefits and tradeoffs that occur repeatedly together being mapped across ecosystem management units [4,5]. Both are spatially explicit approaches that, via cluster analysis, Principle Components Analysis, or other advanced statistical techniques can relate the spatial distribution of land covers to the spatial distribution of service/benefit hotspots or bundles. Similarly, dynamic modeling approaches have been used to determine the relative provisioning of different services or benefits, including carbon storage and water yield, by leveraging combinations of biogeochemical and hydrological process models [6].

More often, however, research is not spatially explicit but rather conducted within a single land cover and for objectives that, though complementary to a multiple benefits perspective, are not necessarily designed with benefit quantification and comparison in mind. Collectively, this knowledge base represents a vast, underexploited resource that can inform and supply quantitative estimates to multiple benefits analyses in complex, diverse landscapes.

Challenges in managing for multiple benefits in the Central Valley, CA

A multifunctional landscape perspective is particularly relevant to the Central Valley of California, a vast region of over 18,000 square miles that is not only rich in natural heritage but also one of the most productive and valuable agricultural production regions in the world (**Figure 1**). Several competing levers of change are at work in the Central Valley. These include a rapidly growing population, urban/suburban expansion and the resulting fragmentation of natural and working lands, and an agricultural landscape that is transitioning away from annual row crops to high-value perennials such as fruit and nut trees and vineyards.

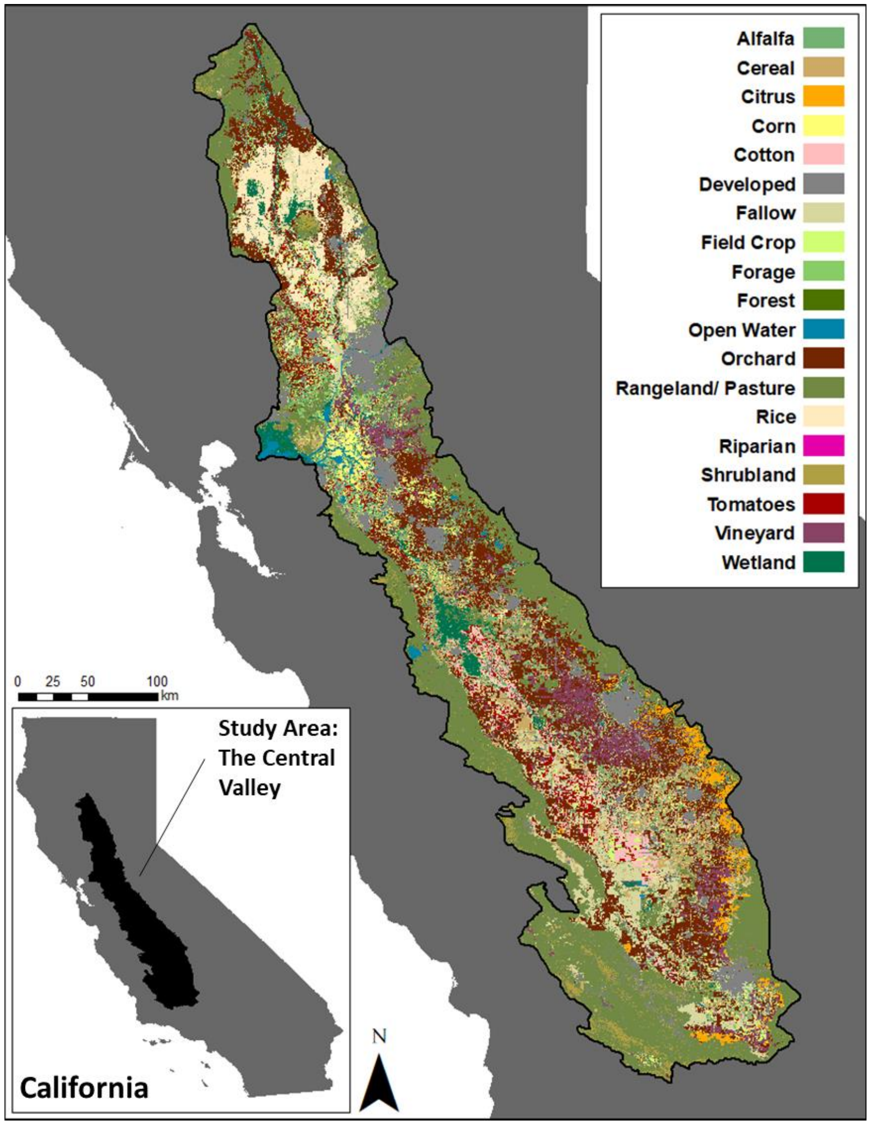

Figure 1: Agricultural and natural land covers in the Central Valley of California (CDL 2019).

Furthermore, climate change in the Central Valley is projected to have a variety of effects, including changes in precipitation regimes, increased flashiness of precipitation events, increased frequency of both floods and droughts, decreases in the amount of total precipitation provided by snow, and increases in average annual temperature, especially in the summer and in inland areas of the state [7]. These impacts will likely interact with the existing challenges noted above, and in some cases could exacerbate the conflicts over water, land, and critical natural resources that are already evident in both the private and public sectors, for example:

1. **Groundwater depletion**. Increases in drilling for groundwater following the 2014-2015 drought and increases in overall water use both for agricultural and urban purposes has led to over-withdrawal and salinization of groundwater resources, along with land subsidence. The lack of regulation and oversight of groundwater resource use led to the enactment of the California Sustainable Groundwater Act in 2014.
2. **Habitat loss.** Conversion of cropland, rangelands, and wildlands to urban, suburban, and residential use has led to the loss of habitat and connectivity for the state's biodiversity

resources, particularly in grassland ecosystems [8]. These changes have a variety of repercussions. For one, the fragmentation of once connected landscapes into private, 10-acre-or-smaller “farmettes” complicates management for resilience and multiple benefits. Furthermore, it increases the likelihood of peri-urban human-wildlife conflict and creates more dangerous conditions for wildfire as human-inhabited areas expand into fire-frequented ecosystems.

3. **“Regulatory drought.”** The 2014-2015 drought had devastating impacts on Central Valley food producers after maintenance of minimum flow requirements through the Sacramento-San Joaquin Delta required the US Bureau of Reclamation to announce zero water allocation to Central Valley Project irrigation water contracts. This complete breakdown of water allocations led Central Valley producers to proclaim the shortage as political in origin. Allocation of surface water resources remains contentious, with flow requirements and conservation baselines at odds with agricultural production and urban consumption [9].

These and other conflicts among stakeholders highlight the increasing need to emphasize management for multiple benefits across sectors in the interest of fostering a truly multifunctional landscape. The challenges inherent in balancing conservation and ecosystem health with human livelihoods in a multi-use landscape require clear, quantifiable understanding of benefits and tradeoffs from land cover/land use types. Furthermore, they require an understanding of what is already known about the magnitude and direction of benefits/tradeoffs from land covers and where urgent knowledge gaps remain. Ultimately, the goal for Central Valley ecosystem management will be to optimize tradeoffs and leverage synergies to achieve multiple goals for the benefit of all who live and depend on our natural capital.

Objectives and roadmap

The objective of this report was to inform and guide multi-stakeholder conservation planning and policy in the Central Valley by reviewing and synthesizing the recent (2010-2020) scientific literature pertaining to the multiple benefits and tradeoffs associated with agricultural and natural landcovers in California’s Central Valley. In Sections I and II, we present the results of a rapid evidence assessment of published, quantitative estimates for multiple benefits metrics linked to priority Central Valley land covers. We summarize the state of the science, the reliability and extent of information, and the evidence for tradeoffs and synergies among benefits. We also present the results from surveying two expert panels, which scored land covers according to their relative value for avian conservation and their vulnerability to climate change impacts. In Section III, we present a spatial model that uses publicly-available datasets to visualize the distribution of ecosystem benefits and tradeoffs, including carbon storage potential, air and water quality, groundwater recharge, and socio-cultural benefits. Finally, we include appendices for detailed coverage of methods for the rapid evidence assessment, benefit/tradeoff analyses, and index development. **The complete database of reviewed literature, extracted data, and associated code in R script are freely available on the Dryad repository under DOI: https://doi.org/10.25338/B8061X.**

Section I: Land Cover Profiles

The following section provides an in-depth overview of predominant land covers in the Central Valley and the possible benefits and tradeoffs associated with each. Because comparisons across land covers must be restricted to the metrics for which there are comparable data, these land-cover-specific profiles allow for the inclusion of potential additional benefits that could not be included in the benefit/tradeoffs analysis in Section II. Furthermore, not all the land covers that will feature in the cross-land cover comparisons will be reviewed in depth in this section; those for which the availability of information in the recent literature was not sufficient, such as sunflowers and chaparral, are omitted. Section I is roughly organized by management category, with land covers managed for production purposes coming first, followed by land covers that may be managed, but not for production purposes. The exception is grasslands, which for the purposes of this report include both production-oriented land covers such as rangelands and pastures, and non-production-oriented (unmanaged) grasslands.

Alfalfa

+ Carbon sequestration
+ Aquifer recharge potential
+ Some wildlife support

— High consumptive water use
— N_2O emissions

Climate Change Vulnerability: **Med-Low**

2018 harvested area (ha): **251,000**

Alfalfa is a short-lived perennial that plays an important role in the dairy-forage supply chain, such that prior to the growth in importance of high-value fruit and nut tree crops it was California's highest acreage crop [10]. It has a long history in the Central Valley and was the first crop to be grown there under irrigation. Alfalfa is particularly suited to the Mediterranean conditions in the Central Valley and regularly yields twice the national average [11].

Alfalfa's life history and physiology make it unique among California crops, and also an interesting case study for multiple benefits from agricultural land covers (**Figure 2**). Its deep, perennial root systems create opportunities for soil carbon sequestration, while its nitrogen-fixing capabilities mean it has low applied nitrogen requirements. The latter characteristic makes it a potential candidate for managed aquifer recharge (ag-MAR) in some contexts, in alignment with the state's groundwater sustainability goals. More so than other field crops in the Central Valley, it offers support to avian fauna and associated biodiversity – though not to the same extent as rice or rangelands. These benefits are counterbalanced by distinct tradeoffs, principally in the form of high consumptive water use and the potential for relatively high N_2O, NOx, and PM10 emissions, especially in older stands. Furthermore, the small mammals used as prey by avian fauna are also considered pests by alfalfa growers, creating the potential for conflicts between production and biodiversity outcomes.

Healthy environment

One published estimate for NOx flux in alfalfa – 9.6 g NOx-N ha^{-1} day^{-1} according to Horwath and Burger [12] – are higher than estimates for orchard crops and winter cereals, but not as high as corn or tomatoes. However, this was the only recent study (2010-2020) available that measured NOx in alfalfa, reflecting a distinct gap in the literature. Similarly, alfalfa fell into the intermediate range in terms of both PM10 emissions from agricultural dust and pesticide use rates but with little available literature to draw from for these metrics. Land in alfalfa crops was estimated to emit some 4,000 tons PM10 yr^{-1} (compared to 16,000 tons in orchard crops and 290 tons in citrus) primarily from frequent mowing operations [13]. As for pesticide use, the CA Department of Pesticide Regulation reported a rate of 0.1 kg pesticide product per ha^{-1}, or 1.4 million kg across all alfalfa acreage [14]. This rate fell into the 50th percentile of all pesticide use rates reported by the DPR.

Climate regulation

Although it seems likely that, given its leguminous roots and perennial life history, alfalfa would be a good candidate for soil carbon storage, few recent (2010-2020) estimates of carbon storage in soils and above- and belowground biomass exist for alfalfa. One published estimate that used IPCC methods for carbon accounting placed C storage in above- and belowground biomass in alfalfa at 7 Mg C ha^{-1} [15]. A less recent study from Kroodsma and Field [16] calculated Net Primary Productivity of hay, which included alfalfa, Sudan, and wild hay varieties, as 74 Mg C ha^{-1} yr^{-1}, but no assumptions were made as to the proportion of this carbon that could be subsequently stored in soil.

As for alfalfa's contribution to GHG emissions, one study from 2017 measured CH_4 emissions from an alfalfa field in the Delta region at 10 kg CH_4-C ha^{-1} yr^{-1} [17], which was fairly negligible in comparison to high methane emitters such as rice and wetlands. The same study showed that alfalfa was a net sink for CO_2, with two estimates from Delta alfalfa fields ranging from approximately -2,500 to -4,000 kg CO_2-C ha^{-1} yr^{-1}. Additional published measurements were available for N_2O, which reportedly ranged from 0 [15] to 4,100 g N_2O-N ha^{-1} yr^{-1} [18]. The higher of these estimates is of most concern from the perspective of climate tradeoffs associated with alfalfa land covers, as this estimate fell in the 90th percentile of reviewed estimates across all land covers. The lower estimate was based purely on IPCC emissions factors considering N fertilization rates, which are low in alfalfa. But Burger et al. [19] caution that N_2O flux in alfalfa is variable across the lifespan of the crop and can be more than twice as high in older stands (4-5 years old) compared to younger stands (1-2 years old).

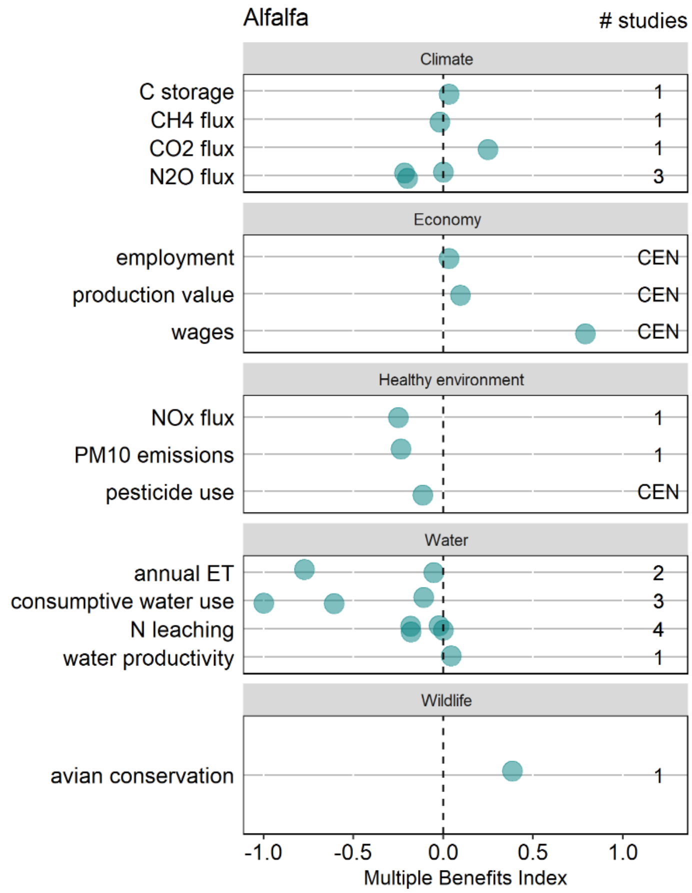

Figure 2. Comparative analysis of benefits and tradeoffs from alfalfa in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: C storage in Mg ha-1, CH_4 flux in kg CH_4-C ha^{-1} yr^{-1}, CO_2 flux in Mg CO_2-C ha^{-1} yr^{-1}, N_2O flux in g N_2O-N ha^{-1} yr^{-1}, employment in number of workers 1000 ha^{-1}, production value in $USD ha^{-1}, wages in average $USD $week^{-1}$, NOx flux in g NOx-N ha^{-1} day^{-1}, PM10 emissions in Mg yr^{-1}, pesticide use in kg ha^{-1}, annual ET in mm yr^{-1}, consumptive water use in m^3 ha^{-1}, N leaching in kg N ha^{-1} yr^{-1}, and water productivity in kg m^{-3}.

Economy

Alfalfa falls in the intermediate range in terms of livelihood value. The CA Employment Development Department reported average employment rates for alfalfa and similar hay/forage operations at 12 workers per 1,000 hectares [20], 5th out of the 8 land covers for which the metric was reported. Average weekly wages and 2017 production value per unit area were similarly intermediate, at $759 USD wk^{-1} for the former and $3,460 ha^{-1} production value. Total production value for all harvested alfalfa acreage in 2017-2018 was approximately $869M USD, which placed alfalfa as 5th out of the 10 land covers for which the metric was available. However, similarly to corn silage production, the farm gate value (i.e., the market value minus the selling costs) of alfalfa does not reflect its indirect value to the dairy industry, which at approximately $22 billion USD in 2018 is California's top agricultural commodity.

Water

Alfalfa is most notable for its high consumptive water use relative to other agricultural land covers, with the highest estimated consumption across land covers at 12,222 m^3 ha^{-1} [21]. This value, obtained via the InVEST modeling approach, superseded even rice and orchard crops in terms of per-unit-area water use. However, other estimates in alfalfa gave much lower values for consumptive water use, e.g., 1,756 m^3 ha^{-1} using the pan evaporation/crop coefficient method [22] and 7,620 m^3 ha^{-1} using Landsat-derived evapotranspiration [23]. Estimates of annual ET were similarly high, with one study reporting an average of 902 mm yr^{-1} [24]. This estimate fell in the 75th percentile of annual ET estimates across the reviewed land covers.

On the other hand, alfalfa was uniformly considered a low nitrate leaching hazard due to the combination of its deep rooting systems and low N fertilizer requirements [25]. Published estimates for N leaching or N load from alfalfa in 4 independent studies ranged from 0 [15] to 30 [26] kg N ha^{-1} yr^{-1}, the highest of which was in the 50th percentile for N leaching estimates across land covers. This characteristic has led to discussion of alfalfa as a potential candidate for agricultural Managed Aquifer Recharge. Dahlke et al. [27] reported that off-season managed flooding resulted in high percolation rates and minimal loss of yield in two established alfalfa stands, and that 95-98% of applied flood water left the root zone as deep percolation. This resulted in total annual deep percolation rates ranging from 20 to 310 inches, depending on the amount and timing of water applications. Similarly, Bachand et al. [28] estimated that winter alfalfa, wine grape, and tomato fields could support flood water infiltration of up to 2.5 inches per day. At this rate, the authors projected that approximately 12,000 ha of agricultural recharge could capture 80% of flood flows and potentially even offset groundwater overdraft in the Kings Basin.

Avian Conservation Score

Alfalfa was given an intermediate score of 0.46 on a 0-1 scale for its value to avian conservation. Alfalfa was considered as providing greater habitat value than annual field crops such as tomato and cotton, and other perennials such as fruit and nut trees. However, rice, rangelands/pastures, wetlands, and riparian areas provided much greater habitat value overall. Alfalfa is used relatively infrequently by a number of avian groups, including non-breeding and breeding season waterfowl and waterbirds, and as secondary habitat by non-breeding season shorebirds. It provides foraging benefits for some of the species considered under these groups, as well as to raptors by providing habitat for small prey mammals. However, its overall value to avian conservation is limited by the frequent mowing that must take place, which diminishes its utility for nesting and other behaviors.

Climate Change Vulnerability Index

Alfalfa was rated by the panel of 12 domain experts as relatively robust to impacts from climate change, with intermediate to low levels of vulnerability compared to the other land covers considered. According to the panel, the most important factor contributing to alfalfa's climate vulnerability was drought sensitivity, given the high rates of applied water required for the crop. On the other hand, sensitivity to flooding and temperature extremes was rated as low, and management flexibility (e.g. ease of fallowing, migration, crop changes in the event of adverse conditions) was relatively high. Furthermore, alfalfa was not considered very exposed to research & development capacity gaps, market volatility, or pest and disease risks, although stem nematode was recently reported in Yolo County [7]. The changes in climate expected for the Central Valley to 2090 may even be favorable to alfalfa, and projections have shown increases in alfalfa yields under some scenarios [7].

Knowledge gaps

- Carbon storage potential
- Tradeoffs from environmental pollution, e.g., NOx flux, PM10/PM2.2 flux, and pesticide use
- Benefits and drawbacks from ag-MAR on alfalfa fields

Citrus

+ Production and livelihood value	– Heavy pesticide use – High consumptive water use	Climate Change Vulnerability: **High** 2018 harvested area (ha): **104,000**

The Central Valley, and in particular Kern, Fresno, and Tulare counties are home to 75% of California's citrus acreage. The principal citrus crops in these counties are oranges and mandarins, while lemons and grapefruits are produced primarily in southern California and the coastal region. While the benefits associated with citrus production are clear in terms of their high production value and employment rates, the tradeoffs in environmental quality and water and pollution and consumption are equally evident.

Specifically, citrus crops had one of the highest pesticide use rates among land covers as well as one of the highest estimates for consumptive water use after alfalfa, rice, and orchard crops (**Figure 3**). N leaching from citrus crops is also a concern, given their preference for well-drained soils and relatively high N application rates. However, there are still many unknowns about potential multiple benefits and tradeoffs from this crop including their contribution to air quality metrics, GHG emissions, and carbon storage.

Healthy environment

Estimates for NOx emissions from citrus crops were not available in the literature from the reviewed period. However, two studies examined the contribution of citrus crops to biogenic gas or Volatile Organic Compound (VOC) emissions, which contribute to ground-level ozone. These studies found that citrus can be both a source and a sink of VOCs and ozone depending on the time of year, with emissions of biogenic gases being highest during flowering [29]. Gentner et al. [29] argued that the total mass of these emission from agricultural crops during the growing season, and the resulting ozone and aerosol formation, is on approximately the same order as emissions from vehicles, making them important to consider in air quality models and pollution control planning . On the other hand, ozone deposition in citrus tree canopies, combined with reactions between ozone, VOCs, and NO, can make citrus orchards a major sink for ozone, particularly during the fall months [30]. Unfortunately, we found no direct measurements for biogenic gas contribution to air pollution in any other agricultural land covers in the Central Valley for comparison.

Pesticide use in citrus was reported as 0.6 kg product per ha^{-1}, or a total of 3 million kg of pesticide products applied across all citrus acreage in 2017. This rate was the highest among the Central Valley land covers considered other than tomato, which also had a pesticide use rate of 0.6 kg ha^{-1} on average [14].

Climate regulation

Surprisingly, we found very little information on GHG emissions or reductions from citrus orchards in the Citrus Valley. Using a spatial simulation model, one study found that N_2O emissions from citrus orchards were negligible [18]. No estimates for emissions of other GHGs were available from the literature in the reviewed period. The similar lack of information on carbon storage and sequestration dynamics in citrus represents a significant knowledge gap, as carbon cycling functions are likely to be quite different in subtropical, evergreen plants such as oranges and mandarins than in other deciduous orchard crops.

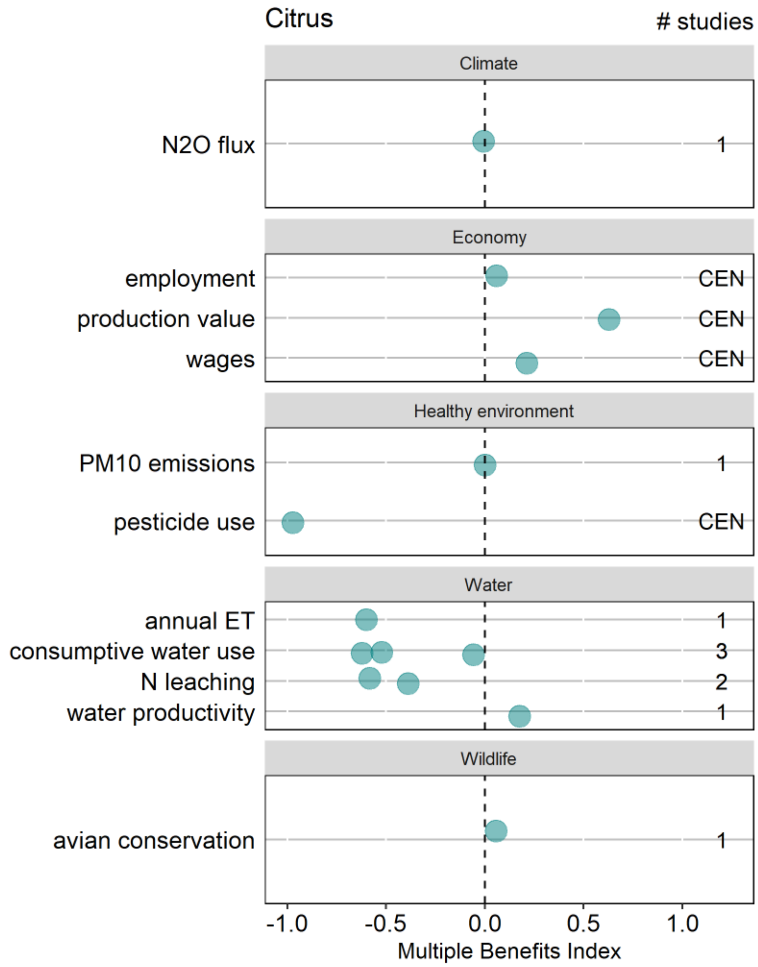

Figure 3. Comparative analysis of benefits and tradeoffs from citrus in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: N_2O flux in g N_2O-N ha^{-1} yr^{-1}, employment in number of workers 1000 ha^{-1}, production value in \$USD ha^{-1}, wages in average \$USD $week^{-1}$, PM10 emissions in Mg yr^{-1}, pesticide use in kg ha^{-1}, annual ET in mm yr^{-1}, consumptive water use in m^3 ha^{-1}, N leaching in kg N ha^{-1} yr^{-1}, and water productivity in kg m^{-3}.

Economy

Citrus had one of the highest crop production values of the land covers considered here. The CDFA's 2017 crop report estimated the value of citrus at more than $22,000 USD per hectare annually, or approximately $2.3 billion USD across all citrus acreage in the state [31]. Furthermore, harvest operations in citrus are not uniformly suitable for mechanization, meaning they generate seasonal labor opportunities far exceeding annual row crops such as winter cereals and corn. The Employment Development Department reports that employment by citrus operations averaged 20 workers per 1,000 hectares from 2012-2016, compared to 2 workers per 1,000 hectares for winter cereals or corn [20]. Wages were low, however, at approximately $647 per week on average, which was only slightly better than orchard crops and vineyards at $605 and $632 per week, respectively [20].

Water

Most of the information that was available on citrus crops revolved around issues of water quality and supply. Nitrate leaching risk from citrus crops was high due to their location on permeable soils (citrus cannot tolerate saturation), their relatively high fertilization rates, and the shallow groundwater table in citrus-growing areas of the San Joaquin Valley, even though many citrus orchards have converted from furrow to microsprinkler irrigation systems in the past 10 years [25]. Recommended fertilizer rates for citrus are on the order of 100 lbs of N per acre per year, compared to 250 lbs for almonds on the highest end or 15-30 pounds for wine grapes on the lower end [32]. One published estimate of N leaching rate for citrus was an average of 97 kg N ha^{-1} yr^{-1}, which was in the 80th percentile of published estimates across the land covers reviewed here [33]. Similarly, Ransom et al. [34] estimated potential N loading from citrus at 65 kg N ha^{-1} yr^{-1} using a Bayesian regression approach [34].

In terms of consumptive water use, citrus had high water use but also high water productivity. Consumptive water use estimates for citrus ranged from 1,158 m^3 ha^{-1} [22] to 7,778 m^3 ha^{-1} [21] from pan-evapotranspiration/crop coefficient and process-based model approaches, respectively. The highest of these estimates was in the 80th percentile of estimates for all Central Valley land covers. A measurement of water use in citrus in terms of annual ET fell in the intermediate regions of all measured ET estimates, at approximately 756 mm yr^{-1} [35]. On the other hand, water productivity, or the weight of harvestable product per unit of water applied, was also high in citrus at 4.2 kg m^{-3}, which was in the 90th percentile of all water productivity estimates across land covers. This water productivity estimate translates to returns to water of approximately $2 USD per cubic meter of applied water, the highest return to water of any Central Valley land cover other than orchard crops (peaches) [21].

Avian Conservation Score

The value of citrus orchards for avian conservation was scored as 0.17 on a 0-1 scale, the second lowest among land covers and on par with deciduous orchard crops and vineyards. As with these other perennial crops, citrus was considered as low importance, i.e., used under relatively rare or infrequent circumstances, for only two of the avian groups considered: oak savannah landbirds and riparian landbirds. For the remainder of avian groups considered, citrus orchards were rated as having little to no importance for nesting, foraging, or roosting, among other behaviors.

Climate Change Vulnerability Index

Citrus was ranked by the panel of 12 domain experts as the most vulnerable to the impacts of climate change among the Central Valley land covers examined in this review. Factors that the panel considered as contributing to citrus's vulnerability were similar to the factors influencing vulnerability in orchard crops, including management rigidity (inability to easily fallow, switch crops, migrate crop in the event of adverse climate or loss of climatic suitability range) and heavy dependence on applied water inputs. Furthermore, expected increases in the frequency of heavy flooding events to 2099 in citrus growing regions is expected to cause delays in citrus harvest [7] and could cause considerable damage to citrus tree themselves, which have little to no tolerance for standing water [32]. Citrus has a narrow range of temperature suitability and is therefore extremely sensitive to extreme heat as well as freezing, especially after fruit set. Beyond these physiological sensitivity factors, citrus was rated as highly exposed to negative impacts from pests and diseases, most notable citrus greening disease. Citrus greening has destroyed millions of acres of citrus crops in Florida and Texas and represents a severe continuing threat to the California citrus industry.

Knowledge gaps

- Climate impact – emissions of greenhouse gases and carbon storage potential.
- Emissions of biogenic gases and VOCs relative to other land covers, and impact on overall air quality models.

Corn

Sweet, grain, and silage corn varieties are all grown in the Central Valley, but silage corn acreage typically outpaces grain corn acreage due to many growers' strong association with the Central Valley dairy industry. Management of corn crops differs greatly depending on the region. In much of the San Joaquin and Sacramento Valley growing regions, for instance, corn is grown conventionally and irrigated using furrow or flood irrigation. In the Delta region, corn fields are often flooded after harvest to create temporary wetlands, which become important habitats for birds and other wildlife in the winter. In other regions, post-harvest flooding on annual corn land can also be used as a strategy for managed aquifer recharge.

Photo: T Reynolds

+ Robust to climate change
+ Avian conservation value when flooded

− N_2O and NOx flux
− Consumptive water use

Climate Change Vulnerability: Low

2018 harvested area (ha): 188,000

In other respects, the tradeoffs that come along with corn land covers can be considerable (**Figure 4**). Research in corn has generated some of the highest estimates of NOx flux of any of the land covers considered here, and N_2O fluxes can be significant as well depending on the timing and placement of fertilizer, water, and measurement equipment. Although market prices for corn vary considerably, the relative production value of corn compared to other Central Valley agricultural crops is low, despite the fact that it is a critical input for the dairy industry. On the other hand, corn was scored as the Central Valley land cover with the least vulnerability to climate change, suggesting that both physiological and socio-economic factors will enable it to persist and potentially thrive even under adverse climate scenarios.

Healthy environment

NOx flux values reported for corn were some of the highest estimates of any Central Valley landcover, ranging from 31-38 g NOx-N ha^{-1} day^{-1} [12]. These estimates came only from one study, however. On the other hand, corn fields had relatively low contributions to PM10 emissions (3,000 tons yr^{-1}) and relatively low pesticide use rates (0.09 kg ha^{-1} or 553,000 kg of product applied to all acres) compared to other land covers.

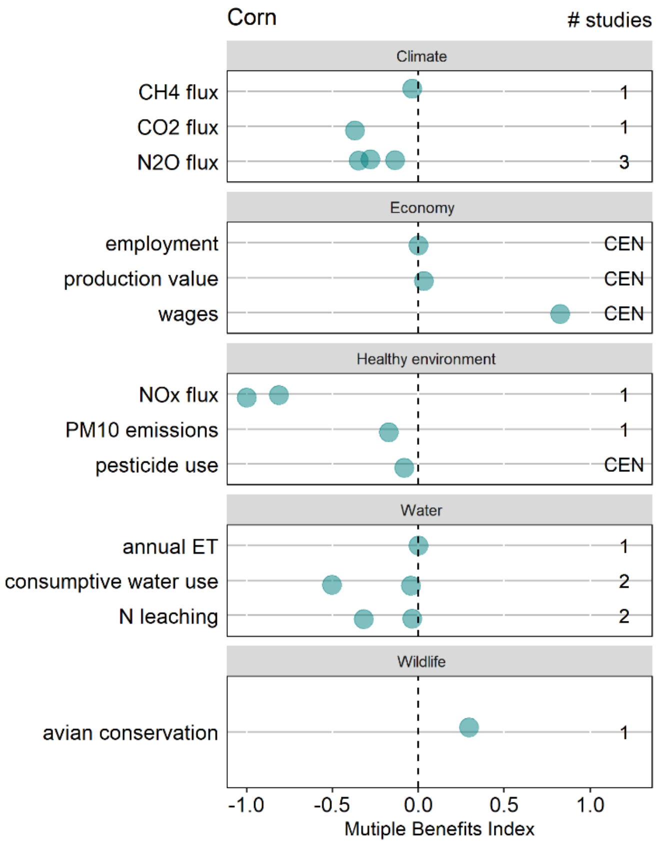

Figure 4. Comparative analysis of benefits and tradeoffs from corn in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: CH_4 flux in kg CH_4-C ha^{-1} yr^{-1}, CO_2 flux in Mg CO_2-C ha^{-1} yr^{-1}, N_2O flux in g N_2O-N ha^{-1} yr^{-1}, employment in number of workers 1000 ha^{-1}, production value in \$USD ha^{-1}, wages in average \$USD $week^{-1}$, NOx flux in g NOx-N ha^{-1} day^{-1}, PM10 emissions in Mg yr^{-1}, pesticide use in kg ha^{-1}, annual ET in mm yr^{-1}, consumptive water use in m^3 ha^{-1}, and N leaching in kg N ha^{-1} yr^{-1}.

Climate regulation

Estimates of N_2O flux in corn varied greatly among studies, from 2,600-6,625 g N_2O-N ha^{-1} yr^{-1} [36,37]. However, all reported N_2O estimates were in at least the 70th percentile of N_2O measurements across land covers, and the highest was in the 94th percentile. In addition, the authors of the study with the lowest estimate (DAYCENT model estimate) indicated that fertilization rates at the study site were atypically low [36]. Horwath and Burger [12] estimated N_2O emissions from corn at 6.8 g N_2O-N ha^{-1} hr^{-1}, but they did not provide an estimate of cumulative seasonal or annual emissions. Few published estimates for emissions of other greenhouse gases were available in the reviewed period, but one study estimated CO_2 flux from a corn field at 5.6 Mg ha^{-1} yr^{-1} [17], in the 80th percentile of CO_2 flux measurements across land covers. The same study estimated CH_4 flux at 20 kg CH_4-C ha^{-1} yr^{-1}, which was relatively low (in the 30th percentile) compared to measurements from other land covers such as rice and wetlands. These measurements were taken from a field in the Delta region, suggesting not only that soils were highly organic and had a much higher average water content than corn fields elsewhere in the Central Valley, but that these fields were sites of ongoing carbon loss.

Economy

As with other commodity row crops, corn had a low production value of approximately $1,200 USD ha^{-1}, higher only than cotton and winter cereal crops. Employment numbers were similarly low, at approximately 2 workers employed on corn operations per 1,000 hectares or an average of 334 total workers across all Central Valley acreage. Conversely, average wages were the third highest among agricultural land covers at $766 per week.

Water

Corn presents several tradeoffs in the areas of water supply and quality. Although as a C4 plant its water use is extremely efficient – an estimate of annual ET for corn in the Central Valley was 247 mm yr^{-1} [35], the lowest among land covers in this review – consumptive water use is high in proportion with the amount of water applied as irrigation. Published estimates for consumptive water use in corn ranged from 963 to 6,400 m^3 ha^{-1} [22,23], the higher of which was in the 60th percentile of all estimates. N leaching associated with corn is also a concern, although estimates vary widely. The highest reported value for N leaching to groundwater from corn was 53 g N ha^{-1} yr^{-1} [33], which again fell in the 60^{th} percentile of N leaching estimates across land covers.

Avian Conservation Score

Corn was considered as having low to intermediate value for avian conservation, with an Avian Conservation Score of 0.38 on a 0-1 scale. Corn had little-to-no value as bird habitat when managed conventionally, but when flooded post-harvest as in the Delta region then its conservation value increased. When flooded, Delta corn fields were considered primary habitat for non-breeding season waterfowl, shorebirds, and waterbirds, including the threatened Sandhill Crane (*Antigone canadensis*). Even when left unflooded, Delta corn has been noted to provide significant habitat value for this group, providing extensive foraging opportunities in the form of residual grains (when residue is left standing) and terrestrial invertebrates. Corn, whether flooded or unflooded, had minimal/no value for birds in any of the other bird groups considered.

Climate Change Vulnerability Index

Corn was scored by the panel of 12 domain experts as one of the least vulnerable land covers to the impacts of climate change. This relative robustness was attributed to a variety of factors, the most important being corn's low sensitivity to temperature extremes. Furthermore, land use/land cover change was rated as a minimal threat to corn crops as they are highly flexible from a managerial standpoint. The latter also means that unpredictability in yearly weather conditions is not likely to affect corn system functions, as they can be easily redirected for another purpose (cut for silage instead of grain when grain markets are poor, for example), fallowed, or migrated to a more suitable region, among other adaptation measures. Investment in research and development for corn and corn adaptation to climate change was rated as highly robust relative to the other Central Valley land covers considered.

Knowledge gaps

- Potential carbon storage
- CH_4 and CO_2 flux
- Water and environmental quality metrics

Cotton

Photo: alasam

+ Low pesticide use rates	− Low production value	Climate Change Vulnerability: **Low**
− Air quality, PM10 emissions	− N_2O emissions	2018 harvested area (ha): **105,000**

California cotton is grown primarily in the San Joaquin Valley, though a small amount of acreage is growing in the Sacramento Valley. Of the two dominant varieties, Acala and Pima, the extra-long staple Pima has gained dominance in California in the past 10 years and now represents 90% of total U.S. Pima cotton production. However, overall cotton acreage in the San Joaquin Valley has declined rapidly due to competition from higher-value crops such as almonds and grapes.

From a multiple benefits perspective, cotton falls more or less in the middle of the pack with neither high potential for multiple benefits nor extreme tradeoffs (**Figure 5**). It is among the higher-risk crops for N leaching to groundwater given that it has high N requirements and is typically grown on well-drained soils. It also is among the group of crops with highest consumptive water use, though it is not as thirsty as other big consumers in the Central Valley such as alfalfa, rice, and orchard crops. The increasing frequency of drought and water scarcity expected in the near future has the potential to lead to loss of cotton acreage in the Central Valley due its dependence on irrigation, unlike the dryland cotton grown in the U.S. Cotton Belt. Competition for water resources under scarcity is also likely to lead to conversion from cotton acreage to higher value crops that have higher profit margin potential per unit of water.

Healthy environment

Cotton had the third highest PM10 emission rate after orchard crops and rice, emitting over 6,400 tons yr^{-1} of large particulate matter during land preparation, management, and harvest operations [13]. Some authors speculate that cotton may also contribute to PM2.5 formation through biogenic gas emissions, as during flowering it had the highest emissions rate of oxygenated monoterpenes after citrus [29]. However, cropland contributions to ozone formation and air quality issues from emission of these volatile organic compounds are still poorly understood.

Climate regulation

Two studies reported on N_2O emissions from cotton. A direct measurement approach estimated N_2O emissions at 15400 g N_2O-N ha^{-1} yr^{-1} [18], while a modeled estimate using DAYCENT was considerably lower at 3600 g N_2O-N ha^{-1} yr^{-1} [36]. The direct estimate was in the 97th percentile for N_2O flux across land covers. There were few recent estimates of N_2O flux in cotton, but Li et al (cited in [38]) put cotton among the top 3 N_2O emitters in the state, along with corn and vineyards.

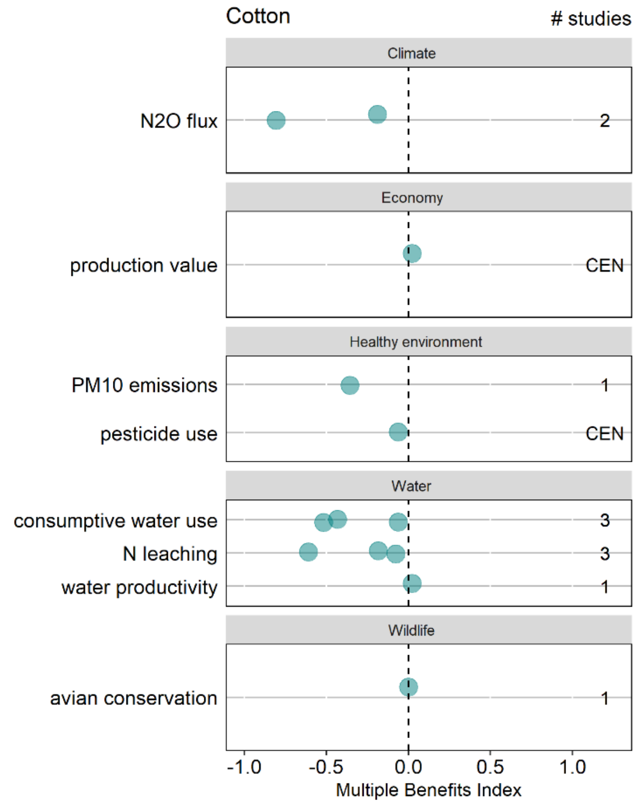

Figure 5. Comparative analysis of benefits and tradeoffs from cotton in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: N_2O flux in g N_2O-N ha^{-1} yr^{-1}, production value in \$USD ha^{-1}, PM10 emissions in Mg yr^{-1}, pesticide use in kg ha^{-1}, consumptive water use in m^3 ha^{-1}, N leaching in kg N ha^{-1} yr^{-1}, and water productivity in kg m^{-3}.

Economy

Cotton ranks 8th out of 9 land covers for which crop production value information was available, at roughly \$89 million USD yr^{-1} or \$850 USD ha^{-1} yr^{-1}. Of the crop-based agricultural land covers considered here, only winter cereal crops had a lower per-area production value. No information on employment and wages for cotton operations was available from the CA Employment Development Department, but the California Cotton Ginners and Growers Association estimates over 25,000 jobs are directly linked to the cotton industry, including farm operations, gins, warehouses, oil mills, and textile operations.

Water

Cotton does not appear to be among the most significant contributors to groundwater N leaching given its relatively limited acreage, but it is considered an intermediate-risk crop due to the permeability of the soils on which it is typically grown, relatively high N inputs, and the prevalence of surface irrigation and sprinkler irrigation. One study, which grouped cotton with field crops such as flax and safflower, found negligible nitrate levels in Tulare, Kings, Merced, and Stanislaus county groundwater wells when field crops were the dominant land use [39]. Median nitrate levels in wells were much higher when the dominant land use surrounding the well was in citrus (11.4 mg NO_3-N L^{-1}) or deciduous fruit and nut trees (9.3 mg NO_3-N L^{-1}). On the other hand, a recent estimate of N leaching to well water surrounded by primarily cotton fields was 101 kg NO_3-N ha^{-1} yr^{-1} [26], which was in the 85th percentile for N leaching across all land covers in this review.

The highest estimate for consumptive water use by cotton crops, 6,500 m^3 ha^{-1}, was in the 65th percentile of water use estimates across land covers. Water use estimates in cotton ranged from 1,200-6,500 m^3 ha^{-1} [22] and were typically lower than land covers such as alfalfa, citrus, vineyard, and orchard crops.

Avian Conservation Score

Cotton was ranked the lowest for avian conservation value alongside tomato, scoring 0.13 on a 0-1 scale. In general, field and horticultural crops were considered of low value for biodiversity support because of frequent field operations, few foraging resources or vegetative cover, and high pesticide application rates.

Climate Change Vulnerability Index

Cotton was rated as having low vulnerability to the impacts of climate change by the panel of 12 domain experts. The panel considered cotton’s relative tolerance for extreme temperatures and flexibility in management options (e.g., the possibility of fallowing or switching crops during drought years) as important factors influencing the crop’s low vulnerability. Cotton was also rated as having low exposure to market volatility and land use/land cover change, which can exacerbate climate change impacts. Nevertheless, decline in cotton acreage is to be expected with recurring drought events and water shortages, as water is likely to be diverted to higher-value crops such as fruits and nuts.

Knowledge Gaps

- Potential contribution to air quality issues from VOC emissions
- Environmental quality metrics such as NOx emissions
- Greenhouse gas emissions
- Potential livelihood benefits

Orchard Crops


Photo: M LaBar

+ Production value	− Air quality	Climate Change Vulnerability: **High**
+ Employment rate	− N leaching risk	2018 harvested area (ha): **722,000**
	− Consumptive water use	

Agricultural area dedicated to orchard crops has expanded rapidly in the last 5-7 years. This profile covers deciduous fruit and nut trees (i.e., excluding olives and citrus) with emphasis on the most prominent orchard crops in the Central Valley: almond, walnut, pistachio, peach, and prune. Orchard crops present unique challenges and opportunities from a multiple benefits perspective (**Figure 6**). Their perennial life cycle creates opportunities for carbon storage belowground and in woody biomass. Furthermore, the tolerance of some species for brief dormant-season submersion makes them candidates for managed aquifer recharge, although nitrate leaching is a barrier to this activity. They are the second most valuable crops per hectare in California after vineyard crops. The state accounts for approximately 80% of the global supply of almonds and 100% of U.S. commercial supply, along with 25% of the global supply of pistachios and 98% of U.S. commercial supply.

Along with these benefits come tradeoffs in the form of poor rural air quality due to PM10 emissions, heavy pesticide and consumptive water use, and nitrate leaching risk. Though almonds and other deciduous orchard crops benefit greatly from the wild pollination services supported by adjacent wildlands, particularly grasslands, orchards themselves are poor pollinator habitat and provide little support for other forms of biodiversity. Orchard crops are also extremely vulnerable to the impacts of climate change given their heavy dependence on external irrigation inputs, inflexible management, exposure to pest and disease risks, and physiological susceptibility to temperature conditions.

Healthy environment

Orchard crops ranked 1st among Central Valley land covers for PM10 emissions, with more than 16,000 tons of large particulate matter emitted per year from almonds alone [13]. The southern counties of the Central Valley, where orchard crop production is concentrated, have some of the poorest air quality ratings in the state due to a combination of agricultural pollution, pollution from industrial activities such as oil extraction, and to atmospheric conditions that allow ground-level ozone and diesel PM from automobile traffic from coastal and southern urban areas to settle over the area. Agricultural dust created from almond production is related somewhat to land preparation activities but especially to harvest activities, which in the case of almonds involve multiple equipment passes to shake, sweep, and pick up the product during the hottest and driest time of year.

Orchard crops were also associated with intermediate levels of pesticide use, ranking 5^{th} out of 11 land covers with 0.27 kg product applied per hectare or 24.8 million kg of total product applied to orchard crop acreage in 2017 [14].

Climate regulation

A study from 2006 estimated the C sequestration potential of orchard crops at up to 26 g C m^{-2} yr^{-1} including both woody materials and soil C [16]. This estimate was higher than the estimate for vineyards, but these were the only two agricultural land cover types for which this metric was reported in the Central Valley. No more recent estimates (2010-present) were found for C sequestration potential in Central Valley orchard crops. Existing C storage was in the 65^{th} percentile across land covers, after riparian areas and rangelands. Estimates for C storage in orchard crops ranged from 4-45 Mg C ha^{-1} in soil and above- and belowground biomass [15,40].

N_2O flux from orchards was one of the most extensively researched metrics encountered among land covers. Flux varied considerably within orchard crop-related studies but was negligible in comparison to the much larger fluxes observed for land covers such as corn, alfalfa, and cotton. Day-to-day flux rates differed depending on nitrogen fertilization rate, timing and location of measurement, timing of irrigation events, and type of irrigation system. Cumulative annual flux rate estimates ranged from 500 to 1,571 g N_2O-N ha^{-1} yr^{-1} [18,41], the highest of which was in the 50th percentile of N_2O emissions estimates across land covers. Only one study was available in the reviewed period that estimated CH_4 flux from orchards, which was minimal at 0.1 kg CH_4-C ha^{-1} yr^{-1} [42].

Economy

Orchard crops, which included deciduous orchards of almonds, walnuts, pistachios, prunes, and peaches, had the 2^{nd} highest production value in the Central Valley after grape vineyards at over $13,000 USD ha^{-1} and $9.5 billion USD overall in 2018. Orchard operations also employed the 2^{nd} highest number of agricultural workers after tomato operations, at 131 workers 1,000 ha^{-1}, but with the lowest average weekly wage rate per employee ($605 USD) [20].

Water

Water supply and quality issues are where a number of tradeoffs occur for orchard crop land covers. The highest estimates for consumptive water use observed in orchard crops fell in the 93^{rd} percentile of all observations across land covers, at 10,000 m^3 ha^{-1} [21]. Only rice and alfalfa had higher estimates for consumptive water use. Estimates were lower for consumptive water use (1,200-1,300 m^3 ha^{-1}) when measured using the pan evaporation/crop coefficient method, e.g., [22]. These figures for water use are further contextualized by estimates of water productivity, which are high for orchard crops. Orchard crops rank 3^{rd} for water productivity after tomatoes and citrus with one estimate at 3.2 kg harvestable product per m^3 applied water [21]. Economic returns to applied water were equally high, at $1.45 m^{-3} for almonds, $3.35 m^{-3} for peaches, and $1.49 m^{-3} for pistachios [21]. The growing use of micro-sprinkler irrigation systems likely contributes to high water productivity in orchard crops, similar to other drip irrigated crops such as tomatoes.

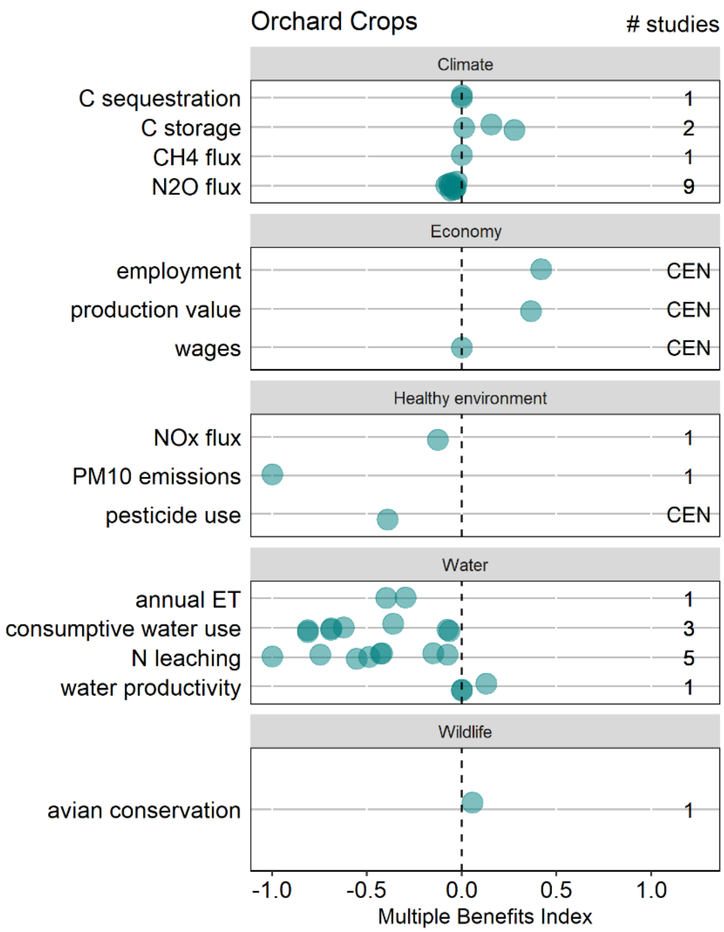

Figure 6. Comparative analysis of benefits and tradeoffs from orchard crops in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: C sequestration in kg C ha^{-1} yr^{-1}, C storage in Mg ha^{-1}, CH_4 flux in kg CH_4-C ha^{-1} yr^{-1}, N_2O flux in g N_2O-N ha^{-1} yr^{-1}, employment in number of workers 1000 ha^{-1}, production value in $USD ha^{-1}, wages in average $USD week^{-1}, NOx flux in g NOx-N ha^{-1} day^{-1}, PM10 emissions in Mg yr^{-1}, pesticide use in kg ha^{-1}, annual ET in mm yr^{-1}, consumptive water use in m^3 ha^{-1}, N leaching in kg N ha^{-1} yr^{-1}, and water productivity in kg m^{-3}.

Orchard crops also ranked 1st in terms of nitrate leaching risk, with the highest reported estimate among land covers at 166 kg N ha^{-1} yr^{-1} [33]. Viers et al. [33] also cited a value of 285 kg N ha^{-1} yr^{-1} from a heavily fertilized peach orchard. Even the lowest recorded N leaching value of 70 kg N ha^{-1} yr^{-1} [15], calculated using the IPCC emissions factor method for carbon and nitrogen accounting, was in the 64th percentile of N leaching estimates from all land cover types. Given that orchard crops have perennial life histories with deep root systems, and furthermore are increasingly irrigated with lower-risk micro-sprinkler systems instead of the conventional furrow irrigation systems, it is reasonable to expect that N leaching risk from orchard crops may lessen with further changes in management practices.

Dzurella et al. [25] argue that the high leaching hazard of orchard crop land is due more so to the high-risk soils (deep, well-drained, low organic matter content, high permeability, lacking restrictive layers) on which almost 90% of orchard crops are grown, along with the large proportion of land area that they occupy. Thus, although 70% of almond orchards were microirrigated in 2015, the remaining 30% of furrow irrigated trees occupied such a large land area that they made a significant contribution to overall nitrate leaching risk for the crop. These estimates of leaching risk agree with groundwater well data, which report N leaching from tree fruits and nuts at 92 and 81 kg N ha^{-1} yr^{-1}, respectively, the third highest estimate from land covers examined in the study after vegetables/berries and cotton crops [26].

Avian Conservation Score

Orchard crops were scored as having the 2nd lowest value for avian conservation, tied with citrus and vineyard land covers. Only tomato and cotton had lower conservation values. Deciduous orchard crops were considered as infrequently or rarely used by some oak savannah landbirds and riparian landbirds, and of minimal or no value to all other avian groups considered. Because birds consume both marketable product and potential insect pests, they are considered both pests and agents of pest control in almonds [43]. Although nut crops reportedly support the persistence of species such as Southern Grey Shrikes (*Lanius meridionalis*), Great Bustards, and Woodchat Shrikes (*Lanius senator*) in other Mediterranean regions, similar results have not been reported for California tree crops, and there is little overlap between orchard crops and designated Important Bird Areas in the Central Valley [43].

Climate Change Vulnerability Index

Orchard crops were rated by the panel of 12 domain experts as highly vulnerable to impacts from climate change relative to other Central Valley land covers. The panel attributed the vulnerability of orchard crops partly to management rigidity – high upfront costs for establishment, perennial life cycle, heavy dependence on external water inputs even during years of scarcity – that precludes adaptive measures such as fallowing during drought years, migration, or transitioning to alternative crops. Furthermore, orchard crops were rated as highly sensitive to temperature stress and can experience yield declines both from loss of winter chilling hours (e.g., in walnuts) and from heat extremes during flowering in nut and fruit crops. While irrigation-dependent orchards can experience extreme yield losses during drought years, they are also sensitive to negative impacts from flooding during heavy spring irrigation events. While plums/prunes, pears, and walnuts can tolerate up to several weeks of saturated soil condition prior to budbreak, cherries and peaches are much more susceptible to heavy tree death with even short periods of saturation [32]. The panel also considered orchard crops among the most sensitive to impacts from pests and diseases, such as navel orangeworm (*Amyelois transitella*) in almonds and pistachios. Compounding these impacts, orchard crops were rated as being exposed to volatility in commodity markets and boom-bust supply cycles due to the alternate-bearing nature of many nut trees, an attribute that is expected to interact with the physiological impacts of climate change to increase vulnerability.

Knowledge gaps

- Carbon storage/sequestration potential
- Air quality metrics, particularly PM10 emissions

Rice

Photo: B Barnett

- \+ Biodiversity value
- \+ C storage potential
- \+ High average wages
- — CH_4 emissions
- — Consumptive water use and water quality

Climate Change Vulnerability: **Med-Low**

2018 harvested area (ha): **205,000**

Rice presents an interesting case study from a multiple benefits perspective, with a profile of characteristics unlike any of the other agricultural land covers examined here (**Figure 7**). The flood and drain dynamics of a typical Sacramento Valley or Delta rice field emulate the hydrological and nutrient cycling functions of a native wetland while producing a useful and profitable grain. Converting drained agricultural fields in the Delta to rice can contribute to reversing subsidence by allowing for the accretion of several centimeters of sediment per year. Flooding rice fields post-harvest to decompose residual stubble, as is the current practice in the region, creates an opportunity for rice fields to be further useful in the off-season, whether by providing important habitat for migrating birds along the Pacific flyway or by offering flood water storage after heavy rainfall events. To enable the required flooded seeding environment, rice soils are typically heavy clays underlain by a hardpan or similar impermeable layer. This makes rice areas unlikely to be top candidates for managed aquifer recharge, but also means they are a low N-leaching hazard.

Of course, these benefits are not without tradeoffs. In rice, these tradeoffs come in the form of substantial methane fluxes due to the anaerobic soil environment, potential for mercury, phosphate, and nitrogen contamination of surface waters, and a high level of consumptive water use from both evaporation and plant transpiration.

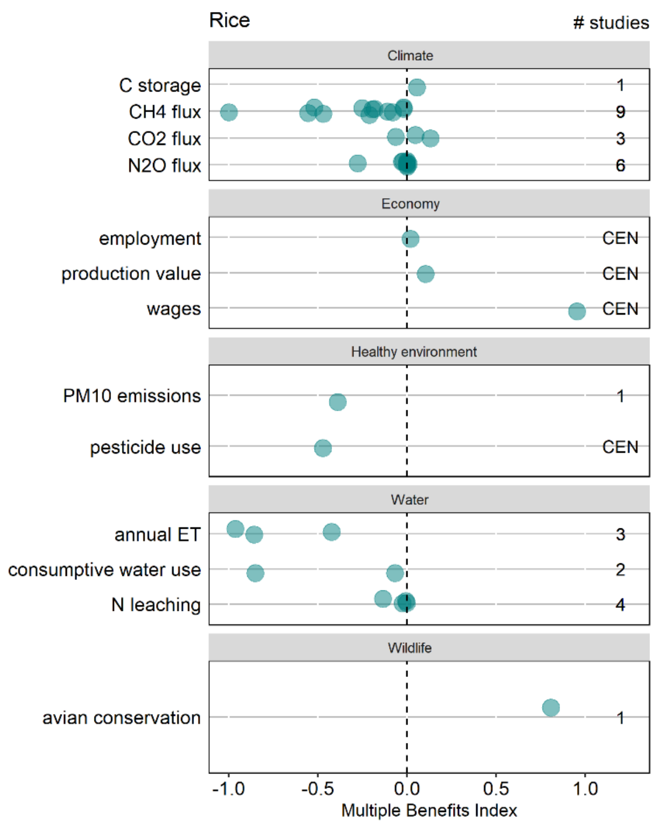

Figure 7. Comparative analysis of benefits and tradeoffs from rice in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: C storage in Mg ha^{-1}, CH_4 flux in kg CH_4-C ha^{-1} yr^{-1}, CO_2 flux in Mg CO_2-C ha^{-1} yr^{-1}, N_2O flux in g N_2O-N ha^{-1} yr^{-1}, employment in number of workers 1000 ha^{-1}, production value in $USD ha^{-1}, wages in average $USD week^{-1}, PM10 emissions in Mg yr^{-1}, pesticide use in kg ha^{-1}, annual ET in mm yr^{-1}, consumptive water use in m^3 ha^{-1}, and N leaching in kg N ha^{-1} yr^{-1}.

Healthy environment

Because of the substantial land preparation required to form the dikes and water flow control systems in rice fields, rice was considered a significant source of PM10 emissions during land prep [13]. Rice contribution to PM10 emissions were negligible during the remainder of the year, however. Total pesticide use in rice systems was relatively high at 0.3 kg ha^{-1} or approximately 2 million kg of product applied across all rice acreage [14]. This amount fell in the 70th percentile for pesticide use, after orchard crops, vineyards, tomato, and citrus. An often under-reported aspect of flooded rice fields is that they can be habitat for mosquito larvae, particularly during the warmer months, creating tradeoffs for environmental health in the form of mosquito-borne illnesses.

Climate regulation

The greatest concern over tradeoffs from rice covers stems from methane emissions, with reported estimates as high as 564 kg CH_4-C ha^{-1} yr^{-1} [44]. This was the highest reported value for the literature sources reviewed here and came from flux chamber measurements in rewetted agricultural peatlands (i.e., recently converted from row crop to flooded rice agriculture to mitigate subsidence) in the Delta region. As with other trace gas fluxes, estimates for CH_4 flux varied widely, from this maximum to a minimum of 10.7 kg CH_4-C ha^{-1} yr^{-1} [45]. Daily flux rates can change considerably depending on air and soil temperature, time of year, timing of flooding events, and timing of measurement, and these cumulative flux estimates were derived from integrated average daily flux rates across seasons.

Estimates of N_2O flux from rice fields ranged from -150 (net sink; [46]) to 5,300 g N_2O-N ha^{-1} yr^{-1} [44], the latter of which was in the 90th percentile of N_2O flux measurements across land covers but was lower than measurements in pasture, cotton, and corn experimental sites. In a review, Verhoeven et al [41] noted that many studies use generic IPCC emissions factors to calculate N_2O emissions, rather than direct measurements accounting for management effects and correcting for background emissions. Many of the observations for N_2O flux in rice fields were negligible or even negative, as would be expected given that the redox environment under flooded conditions is favorable for methanogenesis but not denitrification. Therefore, continuously flooded fields are not a major source of N_2O, despite a large degree of variability and some instances of high cumulative annual flux rates due to large flux events after drainage. Intermittent flooding or alternate wetting and drying has been suggested as an alternative management approach for rice systems because it can result in reduced water consumption, methane emissions, and heavy metal accumulation [47]. However, a study from Indian rice systems noted that N_2O flux from intermittently flooded fields were as much as 30-45 times higher than under continuous flooding [48], suggesting the need to account for variation in management when assessing the greenhouse gas contribution of rice agriculture in California.

Carbon dioxide emissions were also relatively low in rice systems, but this depended to a large extent on the time of year that measurements were taken. During flooded periods CO_2 flux can be negligible or even negative [49,50], but the periodic draining necessary for management operations creates ideal conditions for soil respiration and loss of carbon. This flood/drain dynamic means that rice fields can be either carbon sinks or sources depending on the time of year [17]. The only estimate of carbon storage found for rice systems was 10 Mg C ha^{-1} [15], and potentially more given that the study did not include C stored in rice soils. As with wetlands and in contrast to the rest of the Central Valley landscape, these soils are highly organic and anaerobic conditions make for slow decomposition rates. Conversely, the high existing C storage in rice soils means that there may not be much potential for additional C storage and sequestration as rice soils could be approaching saturation points (see Section III).

Economy

Rice had an intermediate production value of \$3,710 USD ha^{-1}, which was 5th highest out of the 8 agricultural land covers for which information was available from USDA census data. Although average weekly wages paid were 2nd highest after winter cereal crops, again due to the skilled labor required to operate heavy harvest and land prep machinery, the employment rate was proportionately lower. Wages average \$791 USD $week^{-1}$ for rice operations, while employment rates were only 8 workers per 1,000 hectares, 3rd lowest among agricultural land covers before corn and winter cereal crops.

Water

A California Rice Commission report [51] found no nitrates in excess of the maximum allowable contaminant level in USGS rice wells, and an estimate using nutrient input-nutrient loss accounting estimated N leaching rates of 23 kg N ha^{-1} yr^{-1} in rice, but no direct estimates were available on nitrogen-related water quality benefits or tradeoffs from rice systems for the reviewed period. It may be that rice is a relatively low N leaching hazard due to the poorly-drained soils on which it is usually located, but nitrate and other agricultural nutrient contamination of surface waters is still highly likely. Furthermore, heavy metal accumulation and contamination of surface waters in rice systems is a cause of concern, particularly in the case of mercury. Studies in Central Valley rice systems have documented net ecosystem production and accumulation of mercury species in water and sediment, MeHg load, and bioaccumulation of toxic metals in aquatic invertebrates [52–56]. Dissolved organic carbon, total suspended solid, nitrogen, and phosphorus loads were assessed in rice systems [57–59], but these metrics were not included in the overall benefit/tradeoff analysis due in part to their specificity to land covers with an aquatic component.

Annual ET values in rice included the highest relative values across land covers, ranging from 607-1,065 mm yr^{-1} [35,60]. The high ET values were associated mainly with evaporation during the flooded stage and before vegetative cover has been established. Similarly, consumptive water use estimates for rice were also high at 10,490 m^3 ha^{-1} yr^{-1} according to one study using Landsat derive ET estimates [23].

Avian Conservation Score

Rice fields are typically flooded for a large portion of the growing season, but also during the fall, winter, and spring off-season depending on management. Offseason flooding – done in the winter on about 50% of California ricelands – may be done both to encourage decomposition of rice stubble and to intentionally create wildlife habitat, and the resulting temporary wetlands are important foraging grounds and resting places for millions of migratory ducks and geese, among other species. During the 2014-15 fall/spring migration season, flooded rice fields were the site of some of the highest shorebird densities ever recorded on California agricultural land [61]. As with corn in the Delta region, unflooded rice fields may also provide important habitat, especially for foraging geese, cranes, and other species. For this reason, rice was scored as 0.83 on a 0-1 scale for its value to avian conservation, on par with grassland/pasture/rangeland systems and the only other managed agricultural system to approach the importance of natural areas such as wetlands and riparian zones. Rice was considered primary habitat 6 out of the 9 focal bird groups, including non-breeding and breeding season waterfowl, shorebirds, and waterbirds. It was also noted to provide for occasional or infrequent use by riparian landbirds such as Common Yellowthroats (*Geothlypis trichas*) and Song Sparrows (*Melospiza melodai*).

Climate Change Vulnerability Index

Rice was rated by the panel of 12 domain experts as relatively robust to the impacts of climate change, with medium-to-low levels of vulnerability. The panel considered drought sensitivity to be an issue for rice as it is a heavily water-dependent crop, and 5-inch water depth at establishment is an inflexible management requirement. More frequent water shortages due to drought and changes in precipitation regimes could lead to loss of rice acreage, and drought combined with temperature extremes would likely have large negative impacts on yield. Furthermore, rice is a heat-sensitive crop that can experience yield reductions of up to 10% for each 1°C increase in nighttime temperatures [62].

Knowledge gaps

- Carbon storage potential
- Air quality metrics, particularly NOx emissions

Tomato

The dry, converted floodplains in the Central Valley and especially the Sacramento Valley are ideal for tomato crops, which elsewhere are vulnerable to fungal and viral diseases. Because of widespread conversion to micro sprinkler and subsurface drip irrigation in many processing tomato operations, tomatoes have the highest water productivities of any agricultural land cover in the Central Valley (**Figure 8**). The crop is the fourth most valuable crop in the state and the most valuable annual crop, worth about \$11,000 USD ha^{-1}, and it uses remarkably less water than other crops to achieve those benefits. To add to their economic dominance, tomatoes also employ the second most agricultural laborers after orchard crops and the most per unit planted area, at 309 workers per 1,000 ha^{-1}. Tomatoes require hand labor at various times during the growing season including for transplanting and harvest. Tradeoffs from land planted in tomatoes include a high rate of pesticide application, CO_2 flux, and flux of the NOx gases that negatively affect air quality in tomato-growing regions.

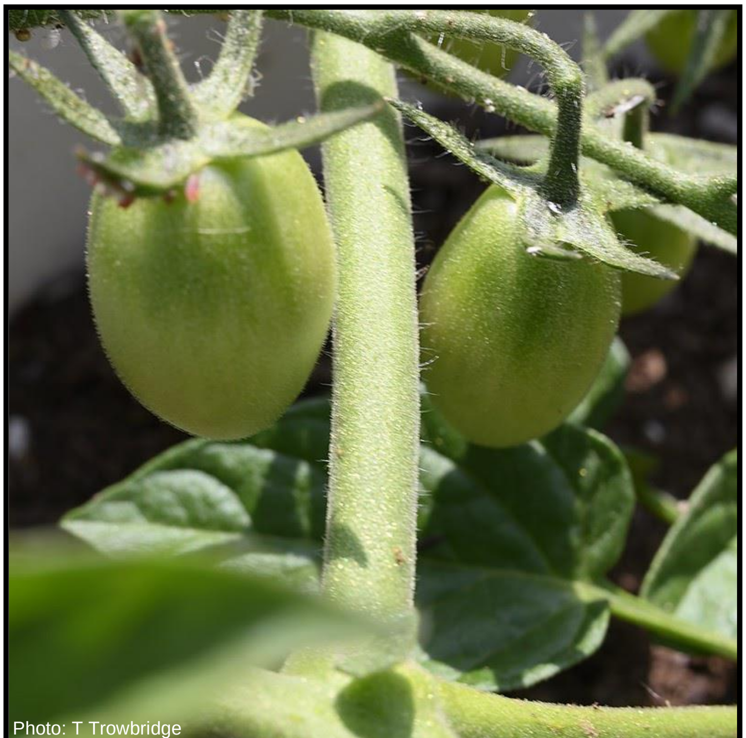

Photo: T Trowbridge

+ High employment, production value	– Heavy pesticide use	Climate Change Vulnerability: **Med-High**
+ Water productivity	– CO_2 and NOx flux	2018 harvested area (ha): **106,000**
	– Poor for biodiversity	

Healthy environment

Tomatoes had the highest pesticide use rate per hectare among the land covers considered here: 0.62 kg of product ha^{-1}, or almost 5 million total kilograms of pesticide product applied across all tomato acreage [14]. Tomatoes also had the second highest NOx flux observed in the reviewed literature, estimated at 14 g NOx-N ha^{-1} day^{-1} in soil under tomato in a tomato-corn rotation. In their review of NOx emissions from California cropping systems, Horwath and Burger [12] observed higher NOx fluxes in furrow irrigated tomato than in subsurface drip irrigated tomato. High N-input systems were likely to have high NOx flux events with unpredictable timing. The factors influencing NOx flux events included N input rates, time since fertilizer application, temperature, and soil moisture, among others – all management-related factors that are expected to vary within the land cover.

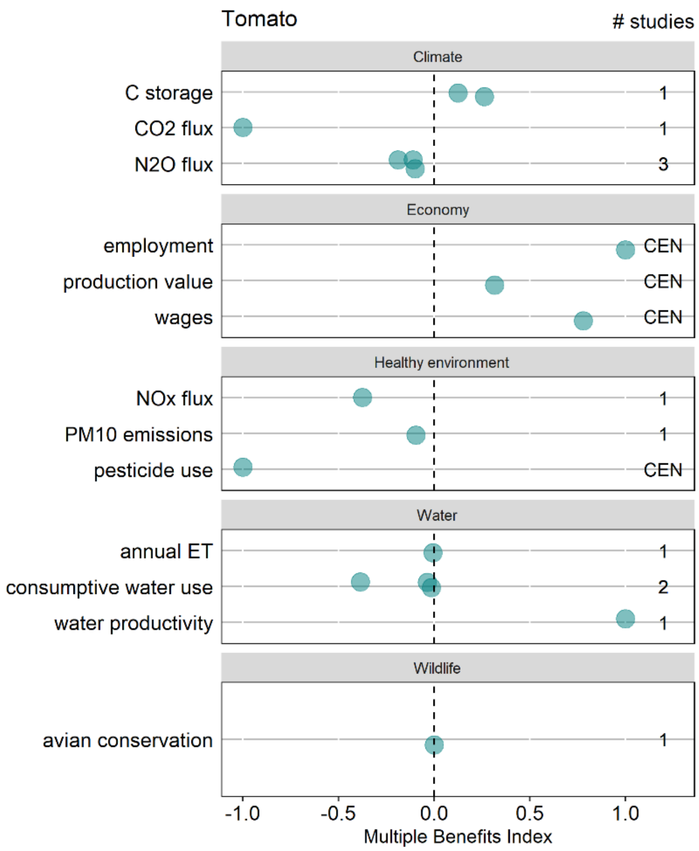

Figure 8. Comparative analysis of benefits and tradeoffs from tomatoes in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: C storage in Mg ha^{-1}, CO_2 flux in Mg CO_2-C ha^{-1} yr^{-1}, N_2O flux in g N_2O-N ha^{-1} yr^{-1}, employment in number of workers 1000 ha^{-1}, production value in $USD ha^{-1}, wages in average $USD week^{-1}, NOx flux in g NOx-N ha^{-1} day^{-1}, PM10 emissions in Mg yr^{-1}, pesticide use in kg ha^{-1}, annual ET in mm yr^{-1}, consumptive water use in m^3 ha^{-1}, and water productivity in kg m^{-3}.

Climate regulation

Relatively high values for daily/hourly N_2O emissions were observed in tomato systems. One observation using the chamber flux method reported average flux of 24.8 g N_2O-N ha^{-1} day^{-1} during the growing season, with peaks in flux after irrigation events [63]. Although this estimate fell into the 90th percentile of all N_2O flux observations across land covers in this review, it was an order of magnitude lower than the highest observations from riparian areas and corn crops. The lowest daily N_2O flux estimate was 1.7 g N_2O-N ha^{-1} day^{-1}, also using the chamber flux method [64]. Cumulative annual flux rates ranged from 1,900 to 3,600 g N_2O-N ha^{-1} yr^{-1}, the highest of which was in the 80th percentile for N_2O flux measurements across land covers.

Five different studies measured CO_2 flux from tomato soils in the Central Valley, but only one of these studies included an estimate of integrated annual CO_2 flux across an entire growing season [37]. The latter study reported CO_2 flux of approximately 15 Mg CO_2-C ha^{-1} yr^{-1} from a tomato field, which was the highest flux estimate across land covers. Most studies reporting daily or hourly flux rates used a similar static chamber efflux method for direct measurement of CO_2 flux from tomato soils over short time periods. Estimates ranged from 30 kg CO_2-C ha^{-1} day^{-1} [63] to 13 kg CO_2-C ha^{-1} day^{-1} [65] and included a variety of cover cropping and irrigation treatments. The annual 15 Mg estimate was the highest annual CO_2 flux measurement reported for any land cover in the reviewed literature, although this was the only study that reported annual CO_2 flux for tomatoes. Kallenbach et al. [65] showed that CO_2 flux in tomatoes was negatively correlated with soil moisture and positively correlated with soil temperature, with the latter appearing to have the dominant effect on CO_2 flux due to increased root respiration rates. Large CO_2 pulses also occurred following precipitation events during the off-season.

The only estimate of carbon storage available for tomatoes from the reviewed period was from Smukler et al. [64] and ranged from 21-43 Mg C ha^{-1} in two different fields. This estimate accounted for soil C stocks only.

Economy

The most salient benefit from land in tomatoes was economic, due to the high production and livelihood value associated with the crop. Tomatoes had the highest per-unit-area employment rate with 309 workers employed per 1,000 hectares, and a 5-year average of 32,600 workers employed across all tomato acreage [20]. However, in agreement with the general trend for operations that employ more workers to pay lower wages, tomato operations paid the 4th lowest average weekly wages out of the 8 land covers for which the information was available, and the lowest wages among annual row crops, at $757 USD week^{-1}.

Water

Tomatoes had the highest water productivity of any of the reviewed land covers, with approximaty 22.5 kg of product per m^3 of water applied [21]. This estimate was an order of magnitude higher than the next most productive crop, citrus, with a water productivity of 4.2 kg m^{-3}. It should be noted that this metric reflects the average weight of harvestable yield per unit of water, while the average value per unit of water was higher for orchard crops such as peach and stone fruits. Average consumptive water use was in the 50th percentile for one estimate (5,000 m^3 ha^{-1}; [21]), but was more moderate than any perennial land cover (e.g., alfalfa, orchard crops, citrus) and generally lower than other annual row crops such as rice and cotton.

Avian Conservation Score

Tomato crop land was tied with cotton for the lowest value to avian conservation, scoring only 0.13 on a 0-1 scale. Non-breeding season waterfowl, shorebirds, and waterbirds were noted as occasionally using tomato land, typically only during the offseason when tomato lands are fallow and under the relatively infrequent occasions when they are flooded. Pre-season irrigation of tomato and other annual crop fields has been noted to generate favorable responses from shorebirds, highlighting the importance of considering seasonal differences in habitat value for annual crops. During the growing season annual crops such as tomatoes and cotton may have little value for wildlife, but management during the offseason – including flooding, cover cropping, or fallowing – can have a disproportionately large impact on provisioning of benefits to wildlife. This is also an important difference between annual crops and perennials such as nut and fruit trees, where potential damage to the crop must be considered when implementing offseason flooding. On annual croplands, potential benefits from offseason management practices such as flooding must be weighed with tradeoffs such as risk of nitrate leaching.

Climate Change Vulnerability Index

The panel of 12 domain experts rated tomato crops as having medium-to-high vulnerability to climate change, due in equal amounts to sensitivity and exposure factors. Tomatoes were considered to be physiologically sensitive to both temperature and precipitation extremes, including drought or flood events occurring during the growing season and high temperatures during sensitive growth stages. They were also considered highly exposed to risks from pests and diseases, including fungal and viral foliar, soilborne, and seedborne diseases (e.g., Fusarium wilt, mosaic viruses). Market volatility was also seen as a threat to tomato systems given their high perishability and specialized supply chain.

Knowledge gaps

- Nitrate leaching hazard
- Air and environmental quality metrics
- CH_4 emissions

Vineyards

Photo: K Lund

+ Highest production value
+ C sequestration and storage potential

− Heavy pesticide use
− High consumptive water use

Climate Change Vulnerability:
Med-High

2018 harvested area (ha):
349,000

Vineyards are one of the most recognizable images of the Central Valley landscape, from boutique wineries in San Joaquin County to the expanses of raisin and table grapes quilting the valley floor around Fresno and Bakersfield. From a multiple benefits perspective, vineyards bring the highest agricultural production value of any of the land covers considered, along with potential for carbon storage and sequestration in soil and woody biomass, contribution to agricultural livelihoods and wages, and suitability for managed aquifer recharge (**Figure 9**). These benefits come with tradeoffs in the form of heavy pesticide and consumptive water use. CO_2 flux measurements included some of the highest recorded in the reviewed period. Furthermore, vineyards do not have much value for avian conservation due to the relative lack of vegetative cover, nesting, and foraging sites, though some studies have reported support for invertebrate biodiversity. Finally, vineyards were rated among the most vulnerable to the effects of climate change of the land covers reviewed due to a combination of sensitivity and exposure factors.

Healthy environment

Vineyards ranked 3rd out of 11 land covers in terms of total pesticide applications after tomato and citrus, according to the CA Department of Pesticide Regulations 2017 Pesticide Use Report [14]. A total of more than 20 million kg of pesticide product were applied to vineyards in 2017, or 0.5 kg ha^{-1}.

Air quality metrics were favorable towards vineyards. PM10 emissions were low relative to other land covers, with one study estimating PM10 at 548 Mg emitted per year compared to 16,000 Mg in orchard crops [13]. No information on NOx emissions from Central Valley vineyards was recovered for the reviewed period.

Climate regulation

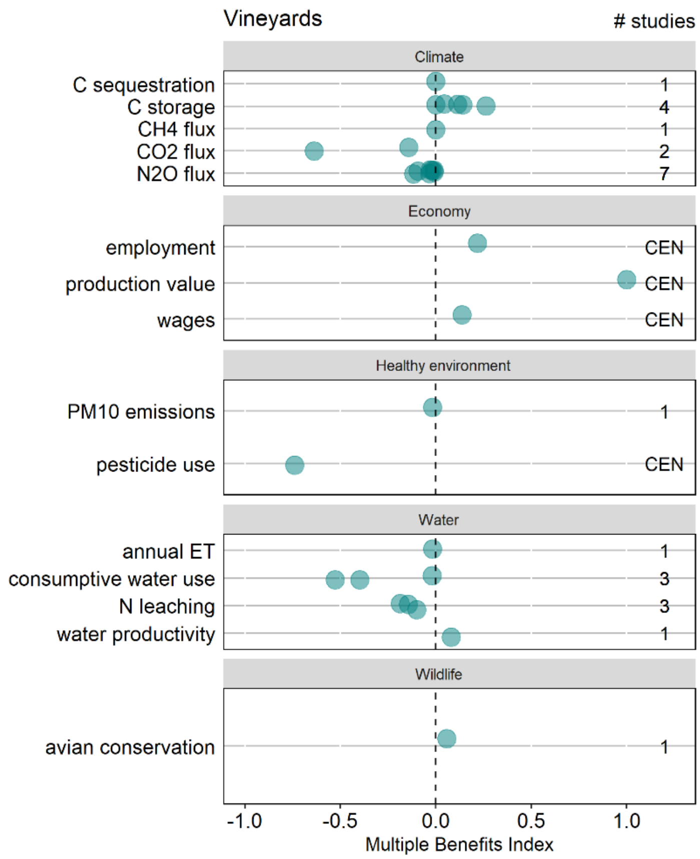

Figure 9. Comparative analysis of benefits and tradeoffs from vineyards in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: C storage in Mg ha^{-1}, C sequestration in kg C ha^{-1} yr^{-1}, CH_4 flux in kg CH_4-C ha^{-1} yr^{-1}, CO_2 flux in Mg CO_2-C ha^{-1} yr^{-1}, N_2O flux in g N_2O-N ha^{-1} yr^{-1}, employment in number of workers 1000 ha^{-1}, production value in \$USD ha^{-1}, wages in average \$USD $week^{-1}$, PM10 emissions in Mg yr^{-1}, pesticide use in kg ha^{-1}, annual ET in mm yr^{-1}, consumptive water use in m^3 ha^{-1}, N leaching in kg N ha^{-1} yr^{-1}, and water productivity in kg m^{-3}.

Overall, CH_4 and N_2O fluxes from vineyards were negligible in the reviewed literature. Two studies reported annual N_2O flux rates in the 60th percentile [41,66], but the majority of studies reported annual flux rates of 600 g N_2O-N ha^{-1} yr^{-1} or less. On the other hand, two studies reported high annual CO_2 flux rates, ranging from 2.4 Mg CO_2-C ha^{-1} yr^{-1} [67] to over 9 Mg CO_2-C ha^{-1} yr^{-1} [68]. The latter was a measurement of soil microbial respiration using an in-situ IR gas analyzer in the cover cropped alley of a Napa County vineyard, while the former was estimated using a soil incubation technique (microbial respiration CO_2 emitted in headspace) for a vineyard in Monterey County, also from a cover cropped alley. The authors of both studies reported that higher CO_2 emissions were attributable to greater microbial activity under live vegetation in the alleys, but they argued that these emissions were counterbalanced by improved soil C accumulation. These examples demonstrated how CO_2 fluxes from soils should be contextualized by background C levels and total soil C turnover. In other words, CO_2 emission may not necessarily be clearly categorized as a "tradeoff" when it is indicative of improved microbial function in an agronomic context.

Economy

Vineyards stood out among Central Valley land covers for having the highest production value, at \$35,800 USD ha^{-1} across wine, table, and raisin grapes and \$12.5 billion across all vineyard acreage. Vineyards also had the 3rd highest employment rate per hectare with an average of over 24,000 laborers employed yearly (5-year average), or approximately 69 workers per 1,000 hectares. However, weekly wages averaged \$632 USD, the second lowest among land covers before orchard crops [20].

Water

One of the main tradeoffs accompanying the high production value for vineyards is their similarly high consumptive water use. The highest value observed for consumptive water use in vineyards was estimated at about 6,700 m^3 ha^{-1}. This estimate came from a modeling approach using the InVEST platform and was in the 70th percentile of all consumptive water use measurements across land covers [21]. Schauer and Senay [23] estimated a slightly lower consumptive water use of 5,100 m^3 ha^{-1} using a Landsat-derived evapotranspiration approach. The CA Department of Water Resources had the lowest estimate for vineyard water use of only 700 m^3 ha^{-1} using a pan evaporation and crop coefficient calculation method.

On the positive side, vineyards were associated with low risk for N leaching due primarily to the low nitrogen inputs required for grapevine crops. Mayzelle et al. [26] reported that vineyards, along with alfalfa, make suitable agricultural buffer zones to reduce groundwater nitrate levels in rural areas. Estimated N in leachate in a 1,000 m buffer zone around rural, disadvantaged communities was 31 kg N ha^{-1} yr^{-1}, compared to the highest rate of 400 kg N ha^{-1} yr^{-1} for cropland fertilized with dairy manure, 183 kg N ha^{-1} yr^{-1} for dairy facilities themselves, and 115 kg N ha^{-1} yr^{-1} for vegetables and berries.

Along with the low nitrogen inputs noted above, the well-drained soils and winter flooding tolerance of dormant grapevines makes vineyards suitable for agricultural managed aquifer recharge (ag-MAR). Bachand et al. [52] found an average potential recharge rate of 10.7 cm day^{-1} across alfalfa, vineyard, and fallow winter tomato fields in an area of the Kings River basin, although they did not distinguish between land cover types when reporting overall recharge potential.

Using the InVEST model, Matios and Burney [21] estimated a water productivity of 2.1 kg m^3, falling approximately in the middle of water productivity estimates across Central Valley land covers. Returns to water, on the other hand were \$2.37 m^{-3}, the second highest returns to water after peaches.

Avian Conservation Score

Vineyards were assigned a score of 0.17 on a 0-1 scale, the second-lowest score across Central Valley land covers alongside other deciduous and subtropical perennial crops. This relatively low value for avian conservation reflects the lack of nesting, foraging, and roosting sites available in vineyards and may also be related to high pesticide use rates and physical protection measures employed specifically to prevent crop damage from birds. Only oak savannah landbirds and riparian landbirds were noted as using vineyard habitats to any extent, and then only under rare or infrequent conditions such as when native habitat is present nearby.

Climate Change Vulnerability Index

The panel of 12 domain experts rated vineyards as having medium-to-high levels of climate change vulnerability, placing it among the most vulnerable of Central Valley land covers. Vineyards were considered highly sensitive to temperature extremes as well as drought, reflecting both physiological limits and high demand for external water inputs which are likely to become unreliable under drought conditions. Similarly to the other perennial land covers examined in this review, vineyards are subject to rigid management strategies. Their long time to establishment and perennial life history mean they cannot be fallowed should water conditions become limiting, are not easily swapped for better-adapted crops, and are not easily migrated to more climatically suitable locales. In the case of wine grapes, exposure to market volatility was also rated as high because wine is a substitutable luxury item.

Knowledge gaps

- Air and environmental quality metrics

Winter Cereals

+ Water productivity

+ Negligible climate and ag pollution impact

— Low livelihood value (employment)

Climate Change Vulnerability: Low

2018 harvested area (ha): 243,000

Central Valley winter cereal production includes approximately 390,000 ha of winter wheat, 30,000 ha of spring durum wheat, 60,000 ha of barley, and 75,000 ha of oats, among other cereals grown for feed, hay, or haylage. Although they are low-value crops considering the price of water and labor in the Central Valley, they present growers with the opportunity to produce a second, offseason crop from annual croplands, and the Valley's Mediterranean climate means irrigation applications are relatively low in most years. For this reason, despite the low prices they command, winter cereal crops occupy the 4th largest extent of the agricultural land covers considered in this review.

However, research on winter cereals from a multiple benefits perspective is somewhat lacking relative to higher-value crops and natural land covers (**Figure 10**), as they are associated with benefits mainly from an agricultural management perspective: they allow producers to make more efficient use of land during the off-season, their water consumption is minor, they can be used for multiple purposes from grain to hay to forage for grazing livestock, and they provide ground cover and soil protection from potentially heavy or flashy winter and spring precipitation events. Winter cereal crop benefits for environmental health, climate regulation, and biodiversity benefits, if any, are poorly understood in comparison.

Healthy environment

Relatively little information was available on winter cereal crop contribution to air pollution factors, and one study reported that NOx flux from soils under winter cereals was largely negligible [12]. Similarly, the pesticide use rate reported for winter cereals was the lowest among Central Valley agricultural land covers, at 0.05 kg of product applied per hectare in 2017 [14].

Climate regulation

Winter cereal crops are not associated with major drawbacks from a climate regulation perspective, though little targeted research in the Central Valley in recent years has been done on the issue other than for N_2O flux. Five independent studies were recovered measuring N_2O flux from winter cereal fields from 2010-2020, one of which only provided flux rates on an hourly basis and therefore was not included in Multiple Benefits Index calculation. Estimates of cumulative annual N_2O flux ranged from 700 g N_2O-N ha^{-1} yr^{-1} [18] to 1,783 g N_2O-N ha^{-1} yr^{-1} [15]. The latter measurement was in the 60th percentile of all reported N_2O flux values across land covers and was derived from IPCC emissions factors and assumed fertilization rates for winter cereals.

One study estimated the C storage benefit from lands in winter cereals at 7.1 Mg C ha^{-1} for aboveground C only [15], using the IPCC carbon accounting approach. This estimate fell in the 15th percentile of C storage estimates across all Central Valley land covers. The IPCC approach used in this study calculates the aboveground carbon content of non-woody crop vegetation by assuming that 45% of crop biomass is carbon, and crop biomass is equal to crop yield divided by harvest index (proportion of biomass harvested). No direct or modeled estimates for soil carbon stocks were available in the literature from the reviewed period.

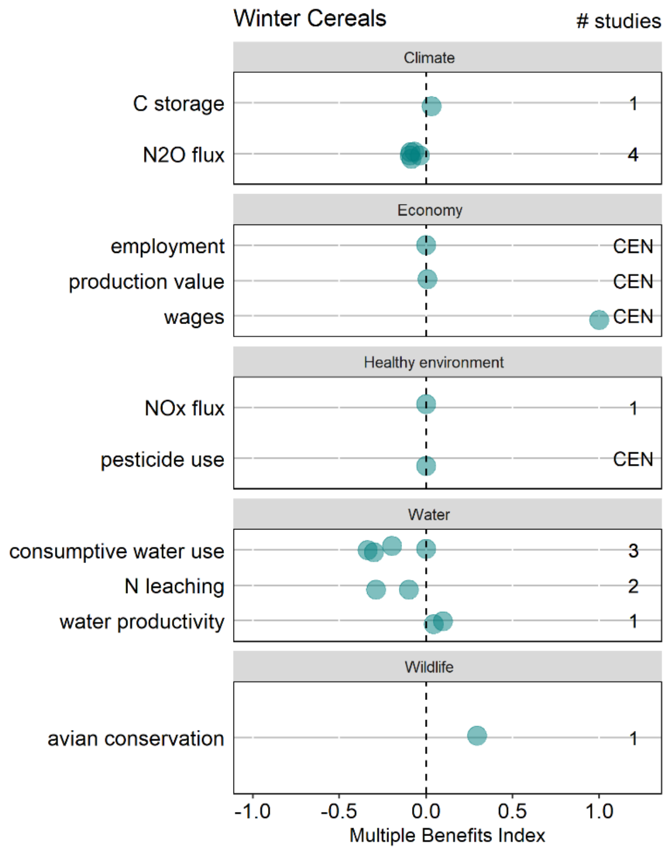

Figure 10. Comparative analysis of benefits and tradeoffs from winter cereals in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: C storage in Mg ha^{-1}, N_2O flux in g N_2O-N ha^{-1} yr^{-1}, employment in number of workers 1000 ha^{-1}, production value in \$USD ha^{-1}, wages in average \$USD $week^{-1}$, NOx flux in g NOx-N ha^{-1} day^{-1}, pesticide use in kg ha^{-1}, consumptive water use in m^3 ha^{-1}, N leaching in kg N ha^{-1} yr^{-1}, and water productivity in kg m^{-3}.

Economy

As fully mechanized commodity crops, winter cereals ranked the lowest among agricultural land covers for their livelihood (employment) and production value. Employment by winter cereal crop operations averages 2 workers 1,000 ha^{-1} according to the CA Employment Development Department, compared to more than 300 workers 1,000 ha^{-1} for tomatoes [20]. Production value was also the lowest among agricultural land covers at slightly more than $300 USD ha^{-1} in 2018 [31]. The mechanized nature of winter cereal crops means that while few workers can perform management operations for thousands of hectares, those workers tend to be more skilled and paid a slightly higher wage to operate heavy machinery. Wages for workers on winter cereal crop operations were the highest among agricultural land covers at an average of $800 USD $week^{-1}$, although agricultural wages varied by no more and $200 $week^{-1}$ across all crop types [20].

Water

For the Mediterranean climate in the Central Valley, winter rains mean that water requirements for winter cereals are typically low. For this reason, the estimate for water productivity of wheat reported in [21] was the highest among Central Valley land covers, at 2.5 kg m^{-3}. Off-season production schedules mean that water use is largely from effective rainfall rather than applied water. However, returns from water are low, at $0.41 m^{-3} applied water. Only alfalfa had lower returns to water among the land covers considered

Two studies reported on potential N leaching from winter cereals, with estimates ranging from 17-48 kg N ha^{-1} yr^{-1} [15,33]. The higher of these estimates fell in the 30th percentile of N leaching estimates across land covers. The relatively low nitrate leaching hazard for grain crops may stem from lower rates of fertigation along with lower N fertilizer rates and irrigation rates overall.

Avian Conservation Score

Winter cereal crops were scored as a 0.38 on a 0-1 scale for importance for avian conservation. Use of winter cereal crops as a primary habitat was assumed to be applicable only for breeding season waterfowl, while non-breeding season waterfowl occasionally use winter cereal crops as secondary habitat. The Avian Conservation Score for cereals assumes conservation value based on winter cereals raised for grain rather than hay, as cereal crops that are periodically mown offer significantly less habitat value for birds (e.g., the endangered Tricolored Blackbird, *Agelaius tricolor*) than standing grain crops. As with Delta-grown corn, winter cereal management can be adjusted to allow for off-season flooding. For example, short-season triticale grown in the Delta can be managed for early harvest in July and subsequently flooded for use by migrating bird groups. Thus, winter crops and winter cereals in particular offer a good example for how crop rotation strategies and creative land use plans can be adopted for the benefit of multiple land use objectives (e.g., agricultural productivity and wildlife habitat).

Climate Change Vulnerability Index

Winter cereals were rated by the panel of 12 domain experts as falling into the category of lowest climate change vulnerability among land covers. The panel considered the most significant contributor to climate change vulnerability for winter cereals to be sensitivity to flood risks, as temporary submersion from large precipitation events in the winter is expected to be highly detrimental to cereal crop development and ultimate yields. On the other hand, winter cereals were considered “nimble” crops that can easily be migrated or fallowed as variable conditions demand, can be grown for either grain or forage depending on the favorability of the season, and have an offseason production schedule that lessens exposure to drought and extreme temperatures. Furthermore, cereals were rated as having low exposure to pest and disease risks, along with a robust research and development sector to facilitate adaptive capacity.

Knowledge gaps

- Carbon storage potential
- Greenhouse gas emissions, particularly CO_2 and CH_4.
- Air and environmental quality metrics

Grasslands


Photo: J Meissen

+ High carbon storage potential
+ Biodiversity value
+ Soil health, sediment retention
− CO_2 and CH_4 flux

Climate Change Vulnerability:
Med-Low

Area in CV (ha):
1.7 million

Land cover classification for grasslands

Grasslands are among the most iconic natural land covers in California's Central Valley. However, compiling the literature on multiple benefits from grassland ecosystems can be a challenge because of the different ways in which grasslands can be classified: annual, native, managed, unmanaged, grazed, ungrazed, pasture, or rangeland, among others. In many land cover classification schemes, rangelands are not distinguished from grasslands, or grasslands are split into open grasslands, oak savannas, and oak woodlands depending on the percent cover of woody biomass. The matrix surrounding vernal pools can be classified as vernal pool or as grassland, and both could be rangeland. Any of the above could be considered a rangeland, in fact, if they are managed for livestock production purposes. And any grassland could be assessed for its forage production potential with the understanding that it could convert into a managed grassland in the future.

For the purposes of this report, we take a flexible approach to classifying grasslands. Where enough information existed to treat "managed grasslands" such as pastures (irrigated and dryland) and rangelands as separate from unmanaged grasslands we did so, but where information was not specific to subcategories of grassland we presented information for the broader classification that included all grass-based land covers. Croplands dedicated entirely to the production of hay were lumped with pasture where appropriate, while winter grains such as wheat, oat, and barley were treated only as grain crops, and not as potential sources of baling for hay, even though the habitat value of a winter grain that is cut for hay is much lower than the value of a standing crop harvested for grain. This is a limitation both in our approach to the rapid evidence assessment and in the availability of the literature, where a standardized definition of grasslands has not been agreed upon and experimental studies often do not report the residue management aspects of grain crops that are relevant for multiple benefits assessment.

High potential for multiple benefits, but little integration into assessment frameworks

As a flagship native California ecosystem, grasslands are well documented in the literature. However, the metrics that are used to assess benefits from grasslands often do not translate to other land cover types (**Figure 11**). Pollination services provided by native grasslands are one example - there are few if any studies examining this metric in other natural land cover types for the period reviewed, and agricultural land cover types are the beneficiaries of pollination rather than the providers. For another, the carbon storage and sequestration potential of grasslands has been receiving renewed and growing interest from conservation planners and policy makers, but like benefits from agricultural land covers, these benefits are highly dependent on management and intervention scenarios. An overgrazed grassland could be a net source of carbon to the atmosphere, while a moderately grazed, well-managed grassland could be a greater sink for carbon than a pristine, unmanaged grassland. Grasslands that receive compost inputs are likely to store more carbon than un-amended grasslands [69], but with potential tradeoffs in emissions of other greenhouse gases such as N_2O [41]. Similarly, when grasslands are grazed, studies have shown that they support more native plant and songbird diversity than ungrazed grasslands, e.g., [70].

The rapid evidence assessment returned 13 unique metrics used for assessing multiple benefits in California's grasslands, and 25 unique metrics when managed grasslands (pastures and rangeland) were included. Overall, the managed grasslands had better documentation of metrics that were comparable across land cover types, including GHG fluxes, pesticide use rates, and water supply/quality indicators. Metrics used in unmanaged grasslands, such as native species cover, richness, and diversity, belowground net primary productivity, decomposition rates, and C and N mineralization, though informative in their own right, were less conducive to cross-land cover comparisons. The search criteria returned relatively few studies dealing with rangelands and grasslands, with 21 independent studies (of the 107 studies reviewed) covering only 8 unique metrics that could be included in the analysis of benefits and tradeoffs. Therefore, there is still a high level of uncertainty regarding the contribution of grasslands and rangelands to relative benefits and/or tradeoffs.

Healthy environment

No information was recovered from the reviewed period for any association between unmanaged or managed grasslands and environmental health metrics such as air pollution. However, managed grasslands, whether irrigated or non-irrigated, were reported by the CA Department of Pesticide Regulation as receiving approximately 0.09 kg of product ha^{-1} in 2017, with rangelands ranking 7/11 and pastures ranking 9/11 for volume of pesticide applications [14].

Climate regulation

The majority of information available on climate regulation benefits associated with unmanaged grasslands relates to carbon storage, particularly soil carbon, which is expected to be the largest carbon pool in grasslands. Grasslands are receiving considerable attention in the literature for their expected potential to contribute to carbon drawdown, especially with interventions such as compost application. However, tradeoffs in the form of changes in ecosystem integrity and/or function as well as altered emissions of other trace GHGs as a result of these interventions need to be examined more fully. In terms of absolute magnitude of carbon storage, estimates for soil carbon stocks from the reviewed period range from 11 to 246 Mg C ha^{-1} depending on the site, the presence or not of woody vegetation, and depth in the soil profile [71]. An additional 3.5 Mg C ha^{-1} is estimated to be stored in above- and belowground biomass [15]. Similarly, estimates for C storage in managed pastures and rangelands from various sources ranged from 3.5-140 Mg C ha^{-1}, primarily in belowground pools

[69,71,72]. Techniques for assessing C storage included both direct measurement of soil C stocks in grasslands with and without interventions such as compost amendments, spatial modeling of SOC using USGS and USDA-SSURGO soil assessment datasets [8], and calculation of C storage in aboveground biomass using IPCC carbon accounting methods and published harvest indices [15].

Information on fluxes of GHGs was limited to managed grasslands such as pastures and forage systems, as these metrics are highly dependent on the impact of management strategies for nutrients, water, and animal grazing. For pastures, cumulative annual N_2O flux estimates ranged widely from 127 g N_2O-N ha^{-1} yr^{-1} for an unimproved pasture, one of the lowest reported across land covers [15], to more than 19,000 g N_2O-N ha-1 yr-1 [41] for a dairy forage pasture fertilized with solid manure. The latter was the highest N_2O flux rate among land covers reviewed here, demonstrating the large impact of management and system type on overall GHG estimates. More studies would be needed to provide the range of possible estimates of N_2O flux within each grassland/rangeland system type and management system.

Estimates of CH_4 and CO_2 emissions from the reviewed period were found in only one study, which compared the relative climate benefits of restoring degraded agricultural peatlands to wetlands. The pasture site on the Sacramento-San Joaquin Delta was on a drained peatland and produced negligible fluxes of CH_4 relative to a restored wetland (90 kg CH_4-C ha^{-1} yr^{-1} compared to 433 kg CH_4-C ha^{-1} yr^{-1} for the wetland), and significantly less CO_2 flux than corn (3 vs. 6 Mg CO_2-C ha^{-1} yr^{-1} in corn) [17]. However, this estimate for annual CO_2 flux in pasture was in the 70th percentile of CO_2 flux measurements across the land covers reviewed here.

Economy

In general, the potential production value of grasslands, both managed and unmanaged, is related to annual net primary productivity (ANPP), i.e., forage production. ANPP can be used to derive potential livestock live weight gain from grazing, or agricultural use value, among other approaches. The latter approach takes into account average lease rates for grazing land, recommended dry matter allowances to ensure continued productivity of grazed grasslands, and the resulting livestock carrying capacity in terms of animal unit months per hectare [73]. Thus, although agricultural use value for managed and unmanaged grasslands can be reported using the same units as production value of croplands, it is a derived metric rather than direct report of market value. Therefore, although we calculated relative benefits to economic value across all land covers, the metrics for valuation of grasslands should not be considered equivalent to metrics for valuation of croplands. Using this approach, unmanaged grasslands were valued at an average of $120 USD ha^{-1}, ranking lower than any agricultural land covers. This approach to estimating production value of grasslands relies largely on spot measurements of forage production available from the recent literature, but these would likely vary considerably among sites.

For Central Coast grasslands, a spatial modeling approach estimated NPP of between 300-450 kg m^{-2}, which converts to breakeven-only agricultural use value assuming a lease rate of $12 ha^{-1} [74]. These authors noted that grazing tended to increase NPP through June, thus increasing the use value of grasslands without considering the contribution of livestock weight gains to overall profitability of a grazing enterprise. Becchetti et al. [75] estimated mean annual production in long-term rangeland monitoring sites across the Central Valley to range in value from $8.70-$66.43 USD ha^{-1} when converted to agricultural use value.

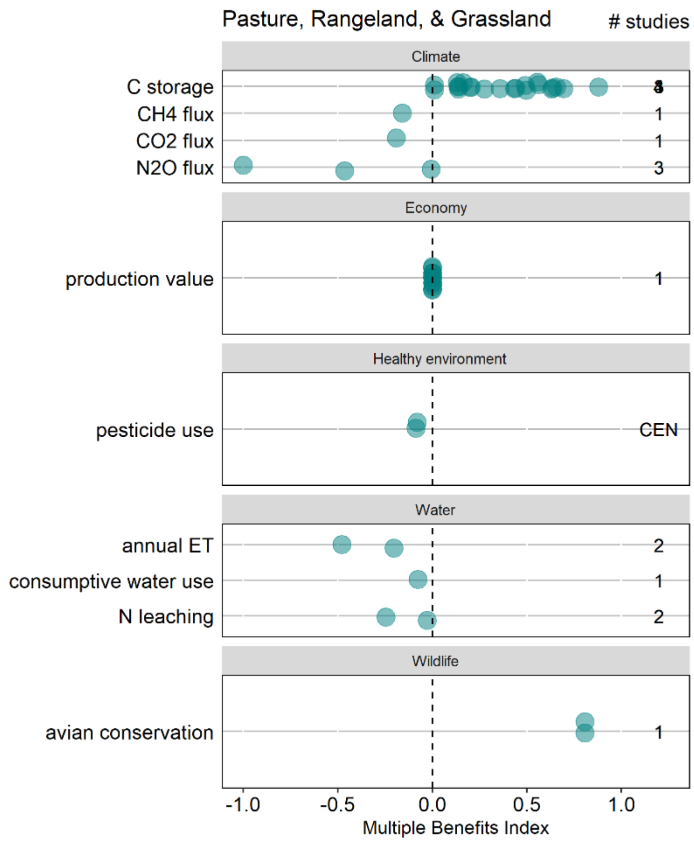

Figure 11. Comparative analysis of benefits and tradeoffs from pastures (including irrigated and non-irrigated), rangelands, and grasslands in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: C storage in Mg ha^{-1}, C sequestration in kg C ha^{-1} yr^{-1}, CH_4 flux in kg CH_4-C ha^{-1} yr^{-1}, CO_2 flux in Mg CO_2-C ha^{-1} yr^{-1}, N_2O flux in g N_2O-N ha^{-1} yr^{-1}, production value in USD ha^{-1}, pesticide use in kg ha^{-1}, annual ET in mm yr^{-1}, consumptive water use in m^3 ha^{-1}, and N leaching in kg N ha^{-1} yr^{-1}.

Water

The information available on water quality and supply benefits/tradeoffs for unmanaged grasslands was limited primarily to estimates of annual ET. As noted for the other non-agricultural land covers considered in this review, ET by natural vegetation is not fully conducive to analysis from a multiple benefits/tradeoffs perspective because it is necessary for the baseline maintenance of vegetation in the ecosystem and because the system does not receive external water inputs, e.g., from irrigation. Some authors report that because unmanaged grasslands intercept less water than trees and shrubs they allow for more infiltration and thus more plant available water and potential groundwater recharge [76]. However, direct estimates of these potential benefits are lacking in the recent literature pertaining to the Central Valley. For managed grasslands, one study reported blue water use, i.e., drinking water and irrigation water used for forage production, was between 3,700-9,100 L of water per kilogram of live weight cow/calf production [76]. The majority of the water footprint of cow-calf operations was instead associated with green water use, or water sourced for precipitation and used only for plant growth (31,000 L of water per kg live weight).

Other benefits

Grasslands, whether unmanaged or managed for livestock production purpose, were considered to provide valuable support to pollination services for agriculture, both from wild and managed pollinators. Habitats including grasslands, meadows, shrublands, and savannah provide nesting and foraging resources for diverse bee communities. Chaplin-Kramer et al. [77] estimated that these habitats provide on the order of $2.6-6.3 billion USD per year in pollination services for California crops. Counties with the highest pollination services from grasslands/rangelands included Fresno, Kern, and Stanislaus, primarily due to their large crop acreages and prevalence of pollination-dependent, high-value crops such as almonds and stone fruit.

Avian Conservation Score

Grasslands were scored 0.83 on a 0-1 scale for their importance to avian conservation, ranking 2/13 across land covers alongside rice. The relative importance of grasslands, including pastures and rangelands of varying management status, stems from their heavy use as primary habitat by breeding season waterfowl and grassland-associated landbirds, as well as their use as secondary habitat by oak savannah landbirds. Recent declines in grassland-dwelling birds, particularly aerial insectivores, are cause for concern in grassland habitats, and further research is urgently needed to understand the potential drivers of these declines.

Climate Change Vulnerability Index

Unmanaged grasslands and managed pastures were both rated by the panel of 12 domain experts as having medium-to-low vulnerability to climate change. For both land covers, vulnerability to climate change was considered as more attributable to exposure to risks such as pollution impacts rather than from intrinsic physiological sensitivity to climatic changes. This suggests that grasslands and pastures are robust to extreme environments and to environmental variability, but are at risk from extrinsic factors such as lack of research into adaptation/mitigation options, lack of protections from environmental pollution (e.g., nitrogen deposition) or land use conversion, among others. Nevertheless, grassland habitats are projected to decline in area by 1-20% by 2070 due to hotter, drier conditions in the Sacramento Valley [7].

Knowledge gaps

- Economic valuation, e.g. production potential or value of ecosystem services
- Greenhouse gas emissions, particularly CO_2 and CH_4.
- Air and environmental quality metrics
- Hydrology, water cycling and water use

Riparian Areas

+ High carbon storage potential
+ Agricultural pollutant removal
+ Biodiversity value
− N_2O flux

Climate Change Vulnerability:
Med-High

Area in CV (ha):
3,051

Riparian areas bordering surface waters, and even those bordering agricultural ditches and irrigation supply canals, supply benefits with an impact disproportionate to their small land area footprint (**Figure 12**). While buffer areas consume a portion of surface water to maintain woody and vegetative biomass, they also regulate surface water quality and flow volume, filtering out contaminants from adjacent agricultural or urban areas and mitigating flashy flow events. The latter helps prevent stream bank erosion and thus feeds back into water quality regulation by lowering total suspended solid concentrations. Riparian areas also create opportunities for substantial carbon storage benefits in woody biomass and provide critical habitat for a high density and rich species assemblage of birds [78] and invertebrates [79].

It remains a challenge to integrate riparian areas into landscape-wide analyses of multiple benefits, as the metrics used to quantify these benefits often do not translate across land cover types or are measured exclusively in riparian areas. Their proximity to surface waters and the relative contribution of large woody species to riparian vegetation communities relative to other land covers in the Central Valley are some of the characteristics that uniquely apply to this land cover. Conversely, metrics used to quantify multiple benefits in agricultural land covers are often not measured in adjacent riparian areas to enable comparative analysis. Furthermore, information is lacking on benefits that have long been assumed to accrue to riparian areas, such as reduction in stream bank erosion as well as flood mitigation potential. Few if any recent publications provide information on these metrics within the Central Valley.

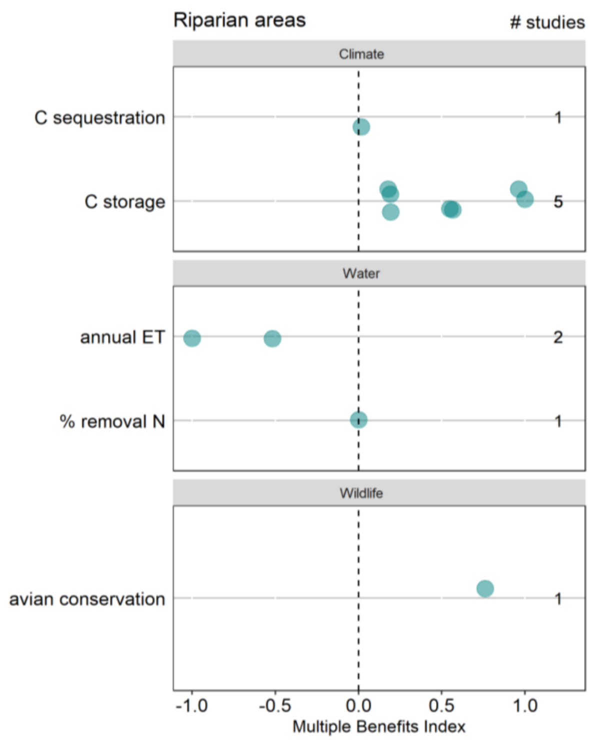

Figure 12. Comparative analysis of benefits and tradeoffs from riparian areas in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination, or observations derived from census/survey instruments (CEN). Original units for each metric were as follows: C sequestration in kg C ha^{-1} yr^{-1}, C storage in Mg ha^{-1}, and annual ET in mm yr^{-1}.

Climate regulation

A single study from 2010-2010 estimated carbon sequestration rates in riparian areas at 3,100 kg C ha^{-1} yr^{-1} using a net ecosystem exchange approach [80]. Carbon storage estimates for riparian areas ranged from 30 Mg C ha^{-1} for soil only [64], to 159 Mg C ha^{-1} when accounting for both above- and belowground carbon [64,72]. Riparian areas were ranked first for carbon storage among all Central Valley land covers considered in the review. Estimates of carbon storage, both existing and potential, in riparian areas is limited by their small areal footprint, making remote sensing and spatial techniques challenging. Furthermore, carbon storage benefits and particularly soil carbon stocks vary with the structure and quality of the riparian area, including stand age and species composition of forest cover, which complicates aggregated estimates of total storage [81].

Two studies reported hourly N_2O flux rates from riparian areas in Yolo and Stanislaus counties at 1.7 mg N_2O-N m^{-2} hr^{-1} and at 0.005 mg N_2O-N m^{-2} hr^{-1}, respectively. Because these measurements were taken sporadically over short time periods, the authors did not provide an assessment of integrated cumulative emissions over the course of the active season or year. Therefore, it is difficult to know how riparian areas compare directly to other land covers for which seasonal/annual estimates of emissions are available. Further research with greater spatial and temporal sampling intensity is needed in riparian areas to understand, for example, GHG tradeoffs involved in land cover changes, and also to begin to understand the sources of N_2O emissions in riparian areas, as pulse events may originate from N entering the area by runoff from adjacent land covers.

Economy

While the metrics used to estimate the contribution of agricultural land covers to economic interests typically do not apply to riparian areas and other non-commercial land covers, a 2006 study found that riparian restoration that targets both social and ecological benefit metrics has the potential to optimize improvements in both. Such an approach created benefits for ecosystem health as well as socioeconomic services such as reduction in losses from damage to floodplain infrastructure and increased access to recreational resources along the Sacramento River [82]. In terms of economic tradeoffs, some studies report concern from agricultural producers that weed seed banks from riparian areas might affect crop yields in adjacent production areas. However, evidence to support this possibility is weak and shows that weed penetration into agricultural areas adjacent to riparian habitat is limited both in space and time [83].

Water

Riparian zones, whether adjacent to canals, drains, or managed and unmanaged surface waters, can mitigate pollution from non-point sources, but much depends on the quality of the riparian area. For example, improvement in ditch bank vegetation may not be as effective as fully functioning riparian forests or wetlands in terms of filtering pollutants. A directly sampled estimate of percent removal of N contamination for zones of varying riparian function ranged from -47% to 29%, but only one estimate was available from the recent literature [84]. This study also examined removal efficiency for other contaminants, including total suspended solids (-56% to 60% removal) and soluble reactive phosphate (1% to 65% removal) [84]. As for water supply, riparian areas had the highest reported annual ET (1,095 mm yr^{-1}) from one study, given the presence of mature woody biomass in many riparian zones and their proximity to surface water sources [35]. However, a 2018 report to the Nature Conservancy found that over the long-term, ET of riparian zones was less than orchard crops in the Sacramento River Basin, with a 32-year average of 799 mm yr^{-1} for orchards and 759 mm yr^{-1} for riparian zones [85]. This difference was attributed to the adaptability of consumptive water use in riparian vegetation, which tends to respond to the availability of water in a given year, whereas orchard crops transpire at relatively constant rates even in low precipitation years as long as they continue to receive irrigation water.

Another benefit from riparian areas that does not necessarily translate across land covers includes their flood mitigation potential, which one estimate places at up to $4{,}159 \times 10^6$ m^3 of potential flood storage capacity for major Central Valley watersheds [86]. The value of this benefit could prove considerable in terms of reduced infrastructure damage and improved water storage in a region experiencing increasingly flashy spring precipitation events and increased frequency of extreme storms [87].

Avian Conservation Score

Several studies reported on the biodiversity benefits of riparian areas, both restored and remnant [78,88]. Riparian zones offer important support to wildlife by providing thermal refugia and migration corridors, along with relatively rich and diverse vegetation cover and thus habitat availability relative to the rest of the semi-arid Central Valley.

In general, riparian areas were noted as being critically important for many bird species across all seasons. Riparian areas were scored at 0.79 on a 0-1 scale for their benefits to avian conservation, ranking at 3/13 land covers (grasslands, pastures, and rice were tied for 2nd). In particular, riparian areas were rated as important for riparian landbirds and oak savannah landbirds, given that riparian areas are likely the closest approximation available in the Central Valley to oak savannah or woodlands. Some breeding and non-breeding season waterfowl and waterbirds also occasionally use riparian areas.

Climate Change Vulnerability Index

Riparian areas were rated by the panel of 12 domain experts as having medium-to-high vulnerability to climate change among the Central Valley land covers considered in the review. The main sources of vulnerability for riparian areas were attributed to exposure to losses from land use/land cover change, capacity gaps for adaptation and management, and specificity in geophysical range. Studies note that riparian areas are sensitive to changes in climate and weather, as well as constrained in their adaptive capacity due to other stressors [89]. However, they also note opportunities for human-assisted adaptation in riparian areas due to the abundance of win-win intervention options with the potential to provide social, economic, and ecological benefits. It is also important to consider that vulnerability in riparian areas is likely influenced by the specific hydrology of the area, i.e., whether that region is expected to see streamflow reductions, and so the generality of this vulnerability score for all riparian areas across California cannot be assumed.

Knowledge gaps

- Economic valuation of multiple benefits
- Greenhouse gas emissions, particularly N_2O to enable the creation of land use scenarios
- Air and environmental quality metrics
- Hydrology, water cycling and water use
- Surface/groundwater pollutant mitigation
- Cultural benefits from recreational activities such as birdwatching, hiking, hunting, fishing, and boating are poorly quantified.

Wetlands

+ Primary importance for avian conservation	– Tradeoffs between CH_4 flux and carbon storage	Climate Change Vulnerability: **Med-High**
+ Mitigation of surface and groundwater pollutants	– High annual ET, especially open wetlands	Area in CV (ha): **143,000**

It is difficult to overstate the importance of wetland ecosystems, not only for their primary role in the regulation of hydrological function in the Central Valley and particularly the Delta region, but also for the multiple other benefits they provide to the ecology and society of the Central Valley (**Figure 13**). As an avian conservation resource, wetlands are more important than any other Central Valley land cover for their use by a broad range of avian taxa for nesting, foraging, and roosting. For water quality, they act as an extremely effective filter for agricultural and industrial pollutants, removing up to 75% of nitrogen pollution [90], 95% of bacterial contaminants, and 66% of phosphorus [91]. Wetlands are also receiving renewed attention as potential sedimentary carbon sinks, although some researchers note that this comes with a tradeoff in methane gas emissions [92]. It follows that wetland restoration, along with sustainable groundwater management, is also an important intervention for subsidence reversal in the Delta region, an effort to counteract years of drainage for agricultural use.

As with grasslands, riparian areas, and other natural land covers not examined in this review, the challenge in incorporating wetlands into a multiple benefits framework comes from the relative scarcity of metrics that can be reasonably compared across land covers. Many of the diverse water quality metrics reported for wetlands, such as fluxes in total suspended solids, denitrification potential, bioaccumulation/biotransformation of toxins and pesticides, potential flood storage capacity, and % removal of pollutants, are only applicable in wetlands and occasionally rice and riparian areas as well. This is a drawback to be expected of any exercise that attempts to draw comparisons across spatially and functionally distinct systems, but highlights the importance of crosstalk among ecosystems scientists working in agricultural and natural settings. While common metrics may not be relevant or desirable in many cases, a minimum common dataset for benefits assessment could be extremely useful for landscape-wide conservation planning and management.

Climate regulation

Wetlands were highlighted in the literature for their potential to store carbon in sediment, but there were few quantified estimates of this potential. Underwood et al. [15] indirectly calculated aboveground C storage in wetlands at 4.1 Mg ha^{-1}, which falls in the 16th percentile of direct and indirect C storage estimates found across land covers in this review. No estimate was available for combined above and

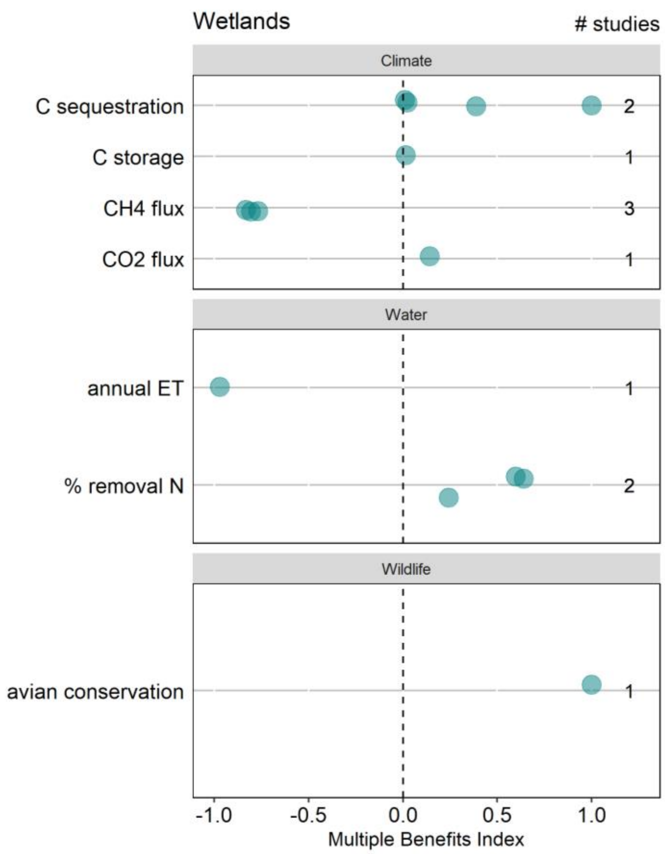

Figure 13. Comparative analysis of benefits and tradeoffs from wetlands in the Central Valley, CA. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index. Negative index values represent a tradeoff, while positive index values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination. Original units for each metric were as follows: CO_2 flux in Mg CO_2-C ha^{-1} yr^{-1}, CH_4 flux in kg CH_4-C ha^{-1} yr^{-1}, C storage in Mg ha^{-1}, C sequestration in kg C ha^{-1} yr^{-1}, and annual ET in mm yr^{-1}.

belowground storage or soil C storage which may be due to the unique sampling difficulties in wetland environments. As for C sequestration, Maynard et al. [93] measured sediment accumulation rates in a seasonal wetland on the San Joaquin River and found that C accumulation was on the order of 100 g C ha^{-1} yr^{-1}, much less than orchards or vineyard crops due to the lack of woody biomass. Despite the relative lack of information found for wetland soils, the spatial analysis of SOC storage in Section III highlights the Delta region and associated wetlands as the highest concentration of carbon storage in the Central Valley. Conversely, the Delta region had the lowest SOC storage *potential*, a potential indicator of C saturation in wetland soils the region.

Furthermore Hemes et al. [92] noted the potential biogeochemical “compromise” between carbon storage and increased methane flux in wetlands, which they estimated to sequester C at rates of 698 g C m^{-2} yr^{-1} but emit CH_4 a rates of 433 kg CH_4-C ha^{-1} yr^{-1}. Given the high global warming potential of methane, the result is that wetlands are often a net GHG source despite peat accretion and C sequestration. Two other estimates of CH4 flux in wetlands were similar, at 455 and 470 kg CH_4-C [92,94], both of which were in the 90th percentile of CH_4 flux estimates across land covers reviewed here.

Potential for subsidence reversal has been noted for restored wetlands replacing drained agricultural lands in the Delta region, which can accrete 3 cm yr^{-1} of new peat [92].

Water

Wetlands were most noted for their pollutant mitigation benefits. Recent studies have shown healthy wetlands to be highly effective for filtering a variety of pollutants ranging from N and P in agricultural runoff, to bacterial contaminants such as *E. Coli*, to suspended solids. Díaz et al. [95] reported a removal efficiency from a constructed wetland of 22-99% for nitrate, and 31-96% for total suspended solids, although results were mixed for other contaminants such as DOC and phosphorus. Similarly, Maynard et al. [93] reported 62% removal of particulate organic carbon and 90% removal of total suspended solids.

Wetlands also provide flood mitigation potential that serves to reduce the “flashiness” of precipitation events and surface water flows. Duffy and Kahara estimated the storage capacity of wetlands at 4,159x10^6 m^3 for palustrine wetlands, 2,182x10^6 m^3 for riparian wetlands, 2,140x10^6 m^3 for vernal pools, and 3,953x10^6 m^3 for Wetland Reserve Program Wetlands [86].

Avian Conservation Score

Wetlands were scored as a 1 on a 0-1 scale for their importance to avian conservation. This was the highest score among land covers and reflects use of wetlands for nesting, foraging, and roosting, among other behaviors, by a wide range of avian taxa, including many species of special concern.

Climate Change Vulnerability Index

Wetlands were rated by the panel of 12 domain experts as having medium-to-high vulnerability to climate change due to a combination of sensitivity and exposure factors. Wetlands were rated as highly sensitive to drought impacts as well as sensitive to climate impacts due to range specificity, meaning they are dependent on a narrow suite of geophysical conditions for continued functioning. Furthermore, wetlands were rated as being highly sensitive to the effects of pollution (e.g., phosphorus and nitrate excesses from agricultural, industrial, and urban runoff), which though not directly related to climate change impacts are expected to interact with them to increase vulnerability. Finally, wetlands were rated as having a major capacity gap, meaning lack of investment in research, conservation, and development to enable adaptation.

Knowledge gaps

- Economic valuation of human health and livelihood benefits
- Greenhouse gas emissions, particularly CH_4
- Air and environmental quality metrics
- Hydrology, water cycling and water use
- Cultural benefits from recreational activities such as birdwatching, hiking, hunting, fishing, and boating are poorly quantified.

Section II: Rapid Evidence Assessment of Multiple Benefit Metrics for Central Valley Land Covers

Much of the information that is available on the potential benefits from agricultural and natural landcover is not centralized. Instead, disparate reports from research activities that vary in geographic location, scope, and timeframe constitute the bulk of the literature. Furthermore, most studies implement a particular suite of metrics to characterize benefits or tradeoffs provided by a land cover depending on the objectives of the study. Therefore, a synthesis of information on multiple benefits that aggregates metrics into a single database with comparable units of measure is an important step towards incorporating multiple benefits research into concerted planning and policy making efforts.

Methods: rapid evidence assessment and benefit/tradeoff analysis

We performed a rapid review of the literature from the last 10 years focusing on benefits from agricultural and natural land covers in the Central Valley. We focused our search on 10 priority agricultural land covers, selected according to harvested acreage as reported by the California County Agricultural Commissioners’ 2018 Crop Report [31], and 3 priority natural (i.e., not for production purposes) land covers based on land area in the Central Valley [96]. See Appendix II for a detailed overview of the search strategy employed, the inclusion criteria, and the data collected from each study in the review. The resulting library of research included reports from peer-review studies as well as publicly available federal or state surveys/censuses and expert source surveys.

In total, we reviewed 107 studies that included approximately 10 agricultural land covers and 3 natural land covers, recording over 77 different metrics for benefits and tradeoffs provisioned by those land covers. See Appendix II **Table A2.3** for a complete list of the metrics reported in the reviewed literature and their representation under different benefit categories. We found heterogeneous representation of land covers in the multiple benefits literature as well as heterogeneous representation of benefit metrics within land covers (**Figure 14**). For example, studies focusing on rice made up about 17% of all studies for agricultural land covers, while agricultural land covers as a whole made up the bulk of the reviewed literature (83%).

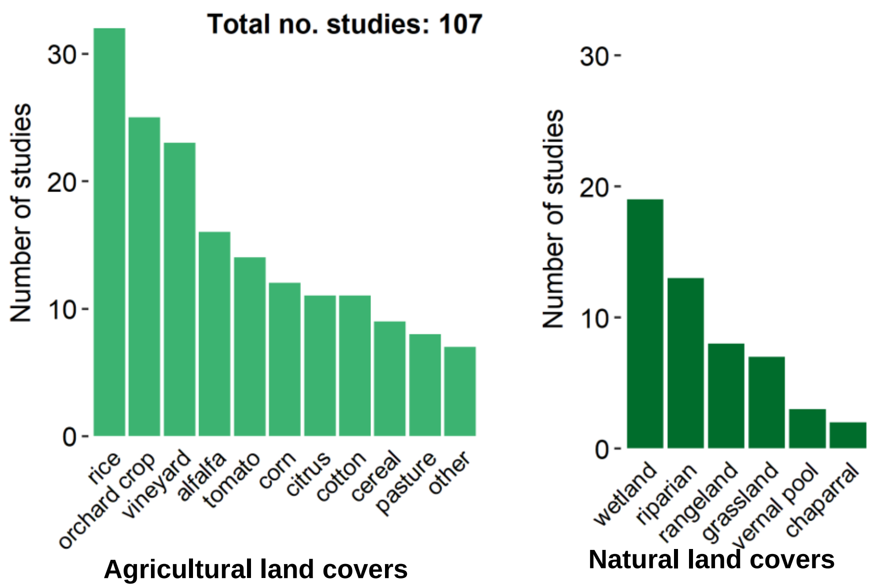

Figure 14. Breakdown of land cover representation in the literature from 2010-2020 pertaining to ecosystem services or benefit and/or tradeoff provisioning metrics in the Central Valley of California.

From the 107 studies we obtained 512 unique observations across land covers and benefit metrics. However, some of these metrics were reported more frequently than others, while others were reported in only one study (**Figure 15**). Not all land covers were represented under each metric, and likewise, not all metrics were reported for every land cover. This uneven representation was related in some cases to the type of land cover. For example, fewer agricultural land covers had published reports of biodiversity metrics, while fewer natural land covers had published reports of air quality metrics. However, **Figure 15** illustrates that a subset of land covers had observations under most of the benefit categories, e.g., tomato and vineyard. Similarly, a few benefit categories were studied across all or most land cover categories, e.g., N_2O flux and annual ET. A detailed breakdown of number of studies and number of observations reported by land cover type, benefit category, and metric is available in Appendix II.

To complement the metrics reported in the peer-reviewed literature, we also included metrics with quality data available in public repositories such as federal and state censuses, technical reports, and databases, along with metrics derived from surveys of domain experts. These metrics were chosen because they provided information to supplement a benefit category with few examples in recent published literature or because they described metrics that are more suitable for survey formats than for the experimental interventions in the studies reviewed above. These additional datasets included:

- Crop production value ($USD ha^{-1}) [31]
- Pesticide use by land cover type (kg applied ha^{-1}) [14]
- Consumptive water use (m^3 ha^{-1}) [22]
- Employment (workers 1,000 ha^{-1}) and average weekly wages earned ($USD $worker^{-1}$ ha^{-1}) in the agricultural sector [20]
- Avian conservation score (expert survey)
- Climate Change Vulnerability Index (expert survey)

The Avian Conservation Score was developed through a survey of domain experts chosen for their involvement in applied avian conservation research in the Central Valley. In an iterative process, the 12 expert sources reached a consensus on scores for each landcover type according to their relative value for nesting, foraging, or roosting different avian taxa during the breeding and non-breeding seasons. Avian taxa considered were those for which the Central Valley Joint Venture has established conservation objectives, including grassland, oak savannah, and riparian landbirds, waterfowl, shorebirds, and other waterbirds [97]. Each land cover type was given a final score on a 0-1 scale representing its relative total value across taxa and seasons. Appendix IV contains further information about the assumptions involved in the scoring process, the focal species for each taxon, and further considerations for at-risk species.

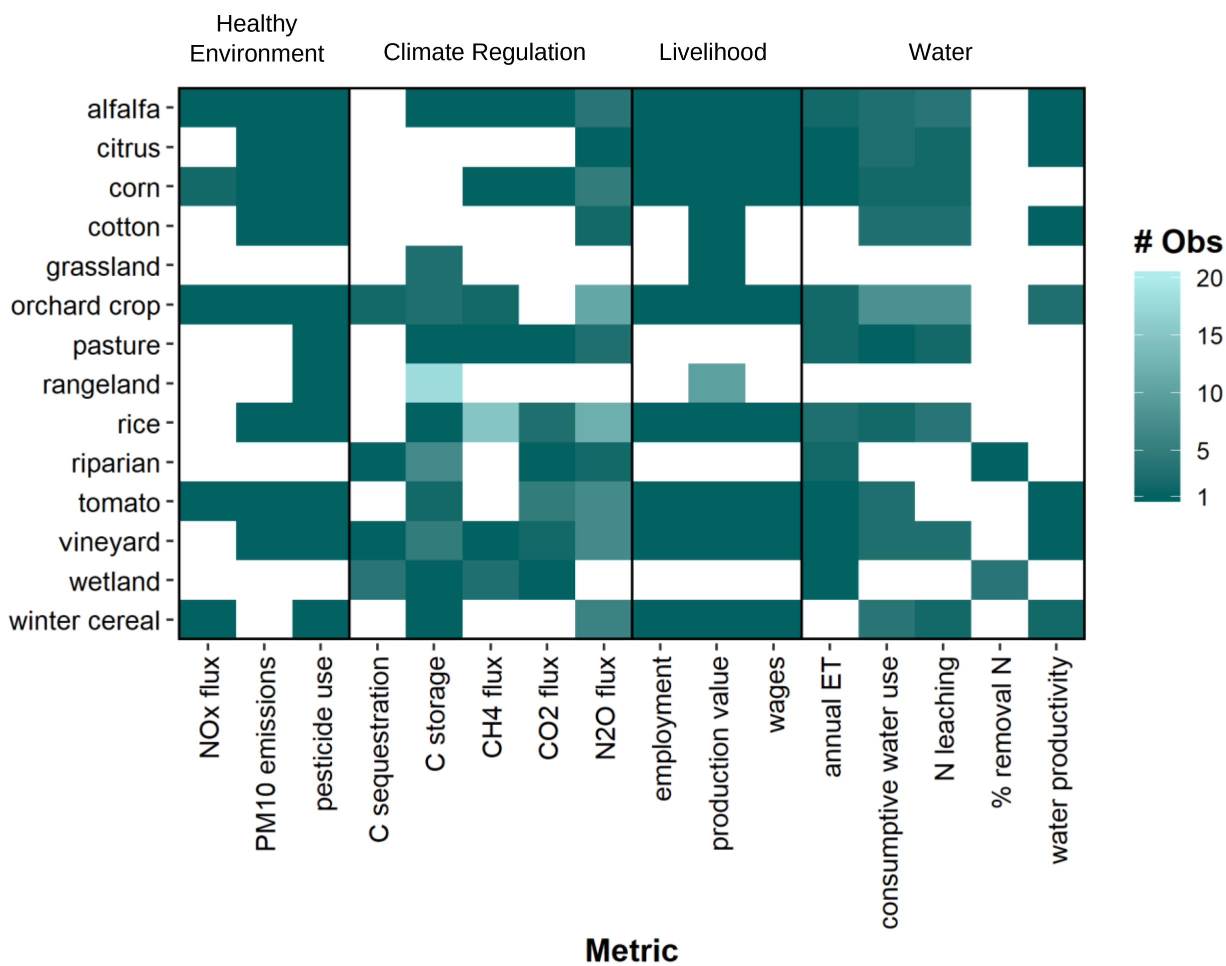

Figure 15. Gap analysis of literature coverage from 2010-2020 for land covers and metrics of multiple benefits and/or tradeoffs associated with each land cover in the Central Valley, California. White cells indicate 0 publications recovered in the literature search.

Although our search strategy reflected *a priori* selection of focal benefit categories and metrics, benefit categories were subsequently adjusted to reflect the actual availability of information on each benefit category and associated metrics. Of the metrics described in the gap analysis above, we chose a subset of metrics with the best representation across land cover types and recategorized them into a suite of benefit categories: 1) environmental health or quality, which included air pollution and pesticide use metrics; 2) economy, which included agricultural (crop and forage) production value and livelihood value metrics; 3) climate, which included greenhouse gas emission and carbon storage/sequestration metrics; 4) water, which included water quality/pollution and water use metrics, and 5) wildlife, which included the Avian Conservation Score (**Table 1**). These categories were subsequently used to calculate a Multiple Benefits Index across land covers (within metrics).

Table 1. Benefit categories and metrics included in the Multiple Benefit Index and benefit/tradeoff analysis.

Sector/Interest	Benefit category	Metrics
Healthy Environment	Air quality	• NOx pollution (g NOx-N ha^{-1} day^{-1}) • PM10 emissions (Mg yr^{-1})
	Pesticide exposure risk	• Pesticide application rates* (kg ha^{-1})
Economy	Production value	• Crop production value* ($USD ha^{-1}) • Forage production value+ ($USD ha^{-1})
	Livelihoods	• Wages earned from agricultural jobs* ($USD wk^{-1}) • Number of employees in ag jobs* (employees 1000 ha^{-1})
Climate	Climate regulation	• N_2O emissions (g N_2O-N ha^{-1} yr^{-1}) • CH_4 emissions (kg CH_4-C ha^{-1} yr^{-1}) • CO_2 emissions (Mg CO_2-C ha^{-1} yr^{-1}) • Carbon sequestration (kg ha^{-1} yr^{-1}, soil, above-, or belowground) • Carbon storage (Mg ha^{-1}, soil, above-, or belowground)
Water	Water supply	• Consumptive water use+ (m^3 ha^{-1}) • Water productivity (kg m^3) • Annual ET (mm)
	Water quality	• Nitrate leaching (kg N ha^{-1} yr^{-1}) • Pollutant mitigation (% removal)
Wildlife	Support for biodiversity	• Avian Conservation Score~

* federal/state databases
+federal/state databases plus published estimates
~expert survey

The Multiple Benefits Index was calculated by normalizing all of the above metrics to a similar scale to enable comparison of multiple benefits and tradeoffs across land cover types. To compare benefit metrics across land covers, reported values were converted to the same unit of measure and then transformed to a 0-1 scale by setting the highest reported value across all land covers to 1 and then calculating the remaining values according to the following formula:

$$MBI = \frac{X_i - \min(|X|)}{\max(|X|) - \min(|X|)}$$

where MBI represents the Multiple Benefits Index, or the normalized value of X, and X_i represents a single value in the vector of values for X. Observations were treated separately when they were taken from multiple, independent experimental sites within the same study. For studies that included multiple observations for different treatments and treatment-years at the same site, we used the average of all treatments to calculate the MBI. The latter approach should be kept in mind when interpreting our results, as it occasionally would have included non-typical treatments and controls that would not ordinarily be practiced in an agronomic setting, such as zero-N fertility or deficit irrigation treatments.

Metrics were then categorized *post hoc* as either “benefits” or “tradeoffs” depending on their perceived value to the above sectors or interests. Benefits were those metrics that related to provisioning of a desirable service such as pollutant removal, while tradeoffs were metrics that related to provisioning of an undesirable service such as greenhouse gas emissions. Metrics considered tradeoffs were assigned a negative value by multiplying the Multiple Benefits Index by -1.

Finally, the benefit/tradeoff analysis was placed into the context of a changing environment through the development of a Climate Change Vulnerability Index (CCVI), similarly to the climate change vulnerability index developed for birds in California [98]. As with the Avian Conservation Score, we developed a survey for a panel of 12 expert sources chosen for their experience working on benefit/ecosystem service quantification in Central Valley agricultural and natural land covers. The panel consisted of members from conservation-oriented research organizations and faculty members at University of California campuses; not all members were the same as the panel that produced the Avian Conservation Scores, though some members overlapped both groups. The 12 members of the CCVI expert panel scored land covers according to their estimated vulnerability to climate change based on a combination of sensitivity (intrinsic, physiological factors that contribute to climate change vulnerability) and exposure (extrinsic, environmental factors that contribute to climate change vulnerability) factors. Sensitivity scores and exposure scores were summed separately within each land cover and then multiplied together to derive the overall vulnerability index (sum of sensitivity*sum of exposure). See appendix IV for more detail on the index calculation methods.

Because it does not represent a specific benefit or tradeoff, but rather a property of individual land covers, the CCVI was not included in the benefit/tradeoff analysis. Instead, it was used as a standalone metric to contextualize benefits and tradeoffs expected from land covers under climate change and the resulting uncertainty surrounding management scenarios.

Limitations of our approach

The results of the MBI for particular land covers were presented in the land cover profiles in Section I, while the results of cross-land cover MBI benefit/tradeoff analysis are presented below. It is important to note that the MBI as we use it here is a *relative* indicator for benefit/tradeoff values based on available data for the Central Valley from the last 10 years. It is therefore a summary of the available scientific literature and reflects the unique experimental conditions of that body of literature; it is not an exhaustive comparison among land covers, nor is it known to what extent this sample of observations is representative of the overall population of observations from a particular land cover. Each observation is influenced by the unique site factors of the experimental year, including management, weather, sampling design, and analytical approach, among others. Therefore, we can only treat these observations as a record of known recorded values. We cannot generalize among all locations or instances of the land cover, nor can we assume that the observations collected from the reviewed literature encompass the full range of possible values. Appendix III provides further details on the rationale behind the selected metrics, along with unit conversions and assumptions made for each metric included in the benefit-tradeoff analysis.

Results: benefit/tradeoff analysis across land covers

We found a high degree of variability in metrics both within and across land covers, likely reflecting similar variability in experimental approaches, measurement techniques, and research objectives. Nevertheless, by examining the available literature for each land cover for a minimum common dataset of benefit and tradeoff metrics we were able to resolve general patterns of multiple benefit provisioning. Furthermore, we detected a number of potential benefits from Central Valley land covers that have not been systematically tested across land cover types, such as Managed Aquifer Recharge on agricultural land (Ag-MAR), soil health metrics such as erosion potential and rate of carbon sequestration, support for pollination and biological control services, and contribution to or mitigation of air pollution.

Climate

Among the sectors or interests standing to gain from land cover-related benefits in the Central Valley, climate and climate regulation services were among the most extensively represented in the literature from the reviewed period. We found 56 studies from 2010-2020 examining at least one metric of climate regulation at a Central Valley site, out of 107 total studies (**Figure 16**). Of the common metrics used to examine climate regulation tradeoffs among land covers, emissions of the greenhouse gases N_2O and CH_4 were the best represented, although in the case of both metrics there were biases towards particular land covers. For example, N_2O flux was most commonly measured in orchard crops, while CH_4 flux was most commonly measured in rice. Of the metrics used to measure climate regulation benefits among land covers, namely below- and aboveground carbon storage and carbon sequestration, carbon storage was much more commonly reported. Publications including measurements of carbon storage were more common for rangelands, grasslands, riparian areas, and vineyards, although even for these land covers most measurements were drawn from only 4-5 independent studies.

Because greenhouse gas flux measurements were considered a “tradeoff,” their normalized Multiple Benefits Index values were negative when represented in **Figure 16**. The negative “tradeoff” representation should not be confused with negative flux values as they would be interpreted in their original units of measure, where negative flux indicates a sink (negative emissions) and positive flux indicates a source (positive emissions) of the given greenhouse gas. Instead, negative MBI values for greenhouse gases represented positive emissions (i.e., a tradeoff), while positive MBI values where they occurred represented removal/sequestration of the gas (i.e., a benefit).

N_2O flux measurements ranged from -150 (net sink; [46]) to 19,000 g N_2O-N ha^{-1} yr^{-1} [41] across land covers, and the largest emissions were recorded in pastures, cotton, corn, and drained rice fields. Conversely, the lowest 25th percentile of N_2O flux measurements were primarily from flooded rice systems, which often acted as N_2O sinks, along with alfalfa, citrus, and vineyards. Authors assessing this metric noted that estimates of N_2O flux are highly spatially and temporally variable. Estimates are likely to be much higher when measurements are taken immediately after an irrigation or fertilization event, for example, just as they are likely to be higher nearer to the irrigation source, e.g., the emitter of a microsprinkler system [99]. Furthermore, interpretation of flux measurements must take into account the context of the measurement site within the surrounding landscape. For example, N_2O emissions from riparian areas could be either intrinsic to the riparian zone or could be traced to extrinsic sources of N inputs such as adjacent land runoff that subsequently increases N_2O emissions. Two studies recorded N_2O flux measurement in riparian areas, one at 0.005 mg N_2O-N m^{-2} hr^{-1} [64] and the other at 2.6 mg N_2O m^{-2} hr^{-1} [100]. Both studies focused on periodic spot measurements of short-term emissions, and therefore did not provide integrated estimates of cumulative annual emissions from the sites. As such, they were not included in this comparative analysis. This lack of high-frequency emissions measurements from Central Valley riparian areas represents a distinct shortcoming in the scientific literature, especially as understanding of seasonal differences in overall N_2O emissions would help us understand the tradeoffs involved in land cover changes and the relative benefits/tradeoffs of riparian restoration projects.

CO_2 flux measurements were similarly variable, ranging from -3.2 Mg CO_2-C ha^{-1} yr^{-1} at an alfalfa site (net sink; [17]) to 14.6 Mg CO_2-C ha^{-1} yr^{-1} in a tomato field [37]. Measurements in the highest 25th percentile were recorded principally in a tomato crop, vineyard, corn field, and pasture. Measurements in the lowest 25th percentile occurred in rice, wetland, and alfalfa land covers. Although pulses of CO_2 emissions have been recorded at certain times of the year in the latter three land covers, measurements integrated up to an annual basis report that they tend to act as a net CO_2 sink. As for CH_4 flux, measurements in the reviewed literature ranged from -0.3 kg CH_4-C ha^{-1} yr^{-1} in a vineyard [101] to more than 450 kg CH_4-C ha^{-1} yr^{-1} in a wetland [92] and a rice field [44]. Measurements of CH_4 flux were only available for 7 out of the 13 land covers considered in the rapid review.

To enable comparisons among different land covers, only flux measurements that were estimated on a cumulative annual or seasonal basis were considered. Cumulative seasonal flux estimates were not converted to annual fluxes; we assumed that fluxes reported on a seasonal basis represented the majority of GHG emissions for that land cover, and that any fluxes during the offseason would be minimal. By considering only flux estimates that were integrated over entire seasons or years, we eliminated some studies from the comparative analysis where only short-term spot measurements of GHG fluxes were made. The danger in including these short-term measurements is that the extreme temporal and spatial heterogeneity of flux measurements means that atypically large flux events could be overemphasized by extrapolating hourly or daily flux rates to an entire year, leading to spurious conclusions about the relative cumulative GHG contributions of each land cover. On the other hand, cumulative annual/seasonal estimates of GHG emissions must also be treated with caution. These are typically calculated by integrating the area under the GHG flux curve generated from average daily emissions and can overestimate flux when uncorrected for background emissions or underestimate flux if large but rapid GHG pulses are missed in the measurement campaign.

With regard to benefits for climate regulation stemming from different land covers, carbon storage metrics (in terms of temporary carbon storage in soils and woody biomass) were more commonly reported than carbon sequestration metrics (in terms of rate of carbon accrual in soils and biomass). Rangelands, grasslands, vineyards, and riparian areas each had between 4-5 independent studies from the reviewed period that recorded a metric of carbon storage, while corn, cotton, and citrus land covers had none. Carbon storage measurements ranged from 1.8 Mg C ha^{-1} (soil C in a vineyard) to 159 Mg C ha^{-1} (above- and belowground biomass in a riparian area). Riparian areas and rangelands, which often included oak savannahs, shrublands, and grasslands, consistently reported the highest levels of carbon storage among land covers when considering all sources: aboveground biomass, belowground biomass, and soil. Although information in the literature was much sparser for *rates* of carbon accumulation, with only 4 unique studies measuring carbon sequestration benefits in only 4 different Central Valley land covers. Of these, the highest C sequestration reports were for wetlands, with measurements ranging from 2,000 to 165,000 kg C ha^{-1} yr^{-1}.

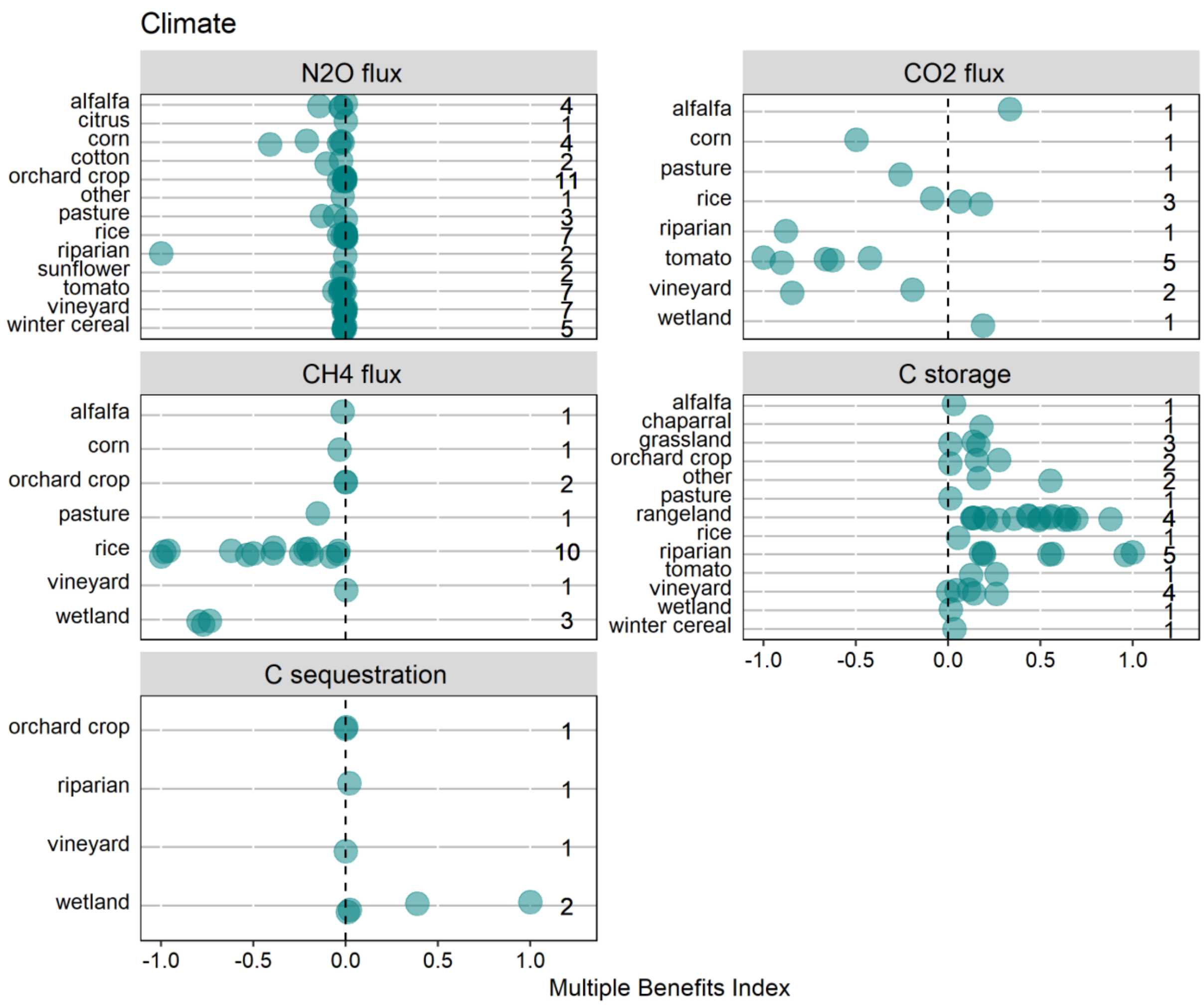

Figure 16. Comparative analysis of climate benefits and tradeoffs among Central Valley land covers. For each metric, published measurements from 2010-2020 were converted to a common unit and represented as a proportion of the highest recorded measurement of that metric across land covers, or the Multiple Benefits Index (MBI). Only land covers for which there was information available are shown. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination. Negative MBI values represent a tradeoff, while positive MBI values represent a benefit. In the case of GHG flux metrics, negative MBI values represent a "tradeoff" in the form of positive emissions. Original units for each metric were as follows: N_2O flux in g N_2O-N ha^{-1} yr^{-1}, CO_2 flux in Mg CO_2-C ha^{-1} yr^{-1}, CH_4 flux in kg CH_4-C ha^{-1} yr^{-1}, C storage in Mg ha^{-1}, and C sequestration in kg C ha^{-1} yr^{-1}.

Economy

Despite its importance for characterizing relative tradeoffs from land use and land cover change, quantification of economic value is in many cases incompatible with the experimental approaches reviewed here. As a result, we used metrics from state census databases to illustrate relative economic value among land covers (**Figure 17**). All values for average weekly wages earned and for employment (number of laborers per 1,000 hectares) for each land cover were acquired from the California Employment Development Department's Quarterly Census of Employment and Wages [20]. The values given here are the average of quarters from 2014-2018. Production values for crop lands were acquired from the California County Ag Commissioner's Annual Report for crop year 2017 [31], and production value for grazing lands/rangelands were acquired from the reviewed literature where available.

In terms of livelihood benefit, average weekly wages did not vary greatly among land covers, ranging from an average of \$600-\$800 per week. The highest wages were paid in rice and winter cereal operations at \$791 and \$800 wk^{-1}, respectively. However, these operations employed far fewer workers, 2-8 workers per 1,000 hectares compared to 100-300 workers per 1,000 hectares in tomato and orchard crops. This difference reflects the relative mechanization possible in tomato and orchard crops, many of which must be harvested and – especially in organic operations – cultivated by hand. Winter cereals and rice, on the other hand, can be mechanically harvested over many hectares with relatively few workers. These workers are typically skilled laborers operating heavy machinery and therefore paid a higher wage than manual laborers.

Orchard crops were also among the three most valuable crops on a per area basis, worth more than \$13,000 per hectare in 2017. Citrus crops and vineyard crops were worth more at \$22,000 and \$36,000 USD ha-1, respectively. Rangelands and grasslands were typically valued the least, at less than \$100 ha-1 from most reports in the literature. It is important to note that metrics for production value were not equivalent between croplands and rangelands. Whereas crop value was assigned according to market value of commodities, value of rangelands and grasslands was a function of forage production and implicit livestock production potential. The values for forage production were converted to agricultural use value, which is derived from annual forage production capacity, livestock carrying capacity given by recommended residual dry matter levels, and rangeland lease values [73]. This metric was adopted because the value of livestock is not derived solely from distinct grazing areas in many cases. Beef cattle, for example, might rotate among pasture across their life spans and be finished on grain in a feedlot. Therefore, live weight gain from rangeland/pasture forage consumption accounts for only a portion of the carcass eventually sold.

An important caveat for this metric is that the gross production values given are not reflective of net profits as they do not take into account production costs. These costs are often higher for the higher-value crops such as nut trees because they are more labor and input intensive. Therefore, production value should not be taken as a substitute for a full economic profile for a land cover, but merely a benchmark metric offering context for the potential gross income that a land cover could offer.

Healthy environment

In many respects, the benefits from production value dovetailed with tradeoffs related to environmental contamination and pollution (**Figure 17**). The three land covers with the highest pesticide use rate per unit area were the same as the three land covers with the highest crop production value: tomato, citrus, and vineyards, with 0.62, 0.61, and 0.47 kg of total pesticide (all products) applied per hectare in 2017, respectively. However, vineyards and citrus, along with orchard crops and alfalfa, also had the highest production value per kilogram of pesticide applied, reflecting the input intensity mentioned above for the higher-value crops. On the other hand, land covers with relatively low pesticide application rates included winter cereals (0.05 kg ha^{-1}), cotton (0.08 kg ha^{-1}), and pasture (0.09 kg ha^{-1}), although the latter was not differentiated into irrigated and non-irrigated pastures. All pesticide use rates were acquired from the California Department of Pesticide Regulation's Pesticide Use Annual Report for 2017 [14].

Orchard crops had opposite patterns for particulate matter (PM10) emissions and NOx flux, both of which contribute to poor air quality. They had the highest reported value for PM10 emissions from land prep and harvest operations [13] but one of the lowest value for NOx flux. Conversely, corn ranked 5th out of 8 land covers for PM10 emissions but had the highest reported NOx flux values for the reviewed literature, ranging from 31-38 g NOx-N ha^{-1} day^{-1} [12]. Assessment of air quality metrics for Central Valley land covers represents a significant knowledge gap. For the period 2010-2020, we encountered only two publications on NOx flux across land covers [12,102] and one publication on particulate matter emissions [13], although some studies returned by our search assessed NOx flux across broader land cover types or the Central Valley as a whole, e.g., [103].

Water

Water-related metrics were highly variable both within and among different land covers (**Figure 18**). They also varied with respect to their coverage in the literature, with benefit-oriented metrics such as water productivity and N pollution mitigation (% removal) less commonly reported than tradeoff-oriented metrics such as N leaching. Percent removal of N contaminants was only applicable to land covers with an aquatic element, but even for these land covers the number of studies assessing % N removal was limited to 1-2 for both riparian areas and wetlands. Although studies returned by our search covered % removal of a wide variety of contaminants, particularly in wetlands, we elected to use only nitrogen-related metrics both to avoid double-counting within a broader metric and because of the importance of nitrogen pollution issues for the Central Valley region. Nitrogen removal from inflow/outflow measurements ranged from 32%-75% for wetlands from 2 different studies [90,95], and 6% in a riparian area from another study [84]. There was also one report of an increase in nitrate concentration at a wetland outflow by 114% [95]. Removal of other contaminants not included in the benefit/tradeoff analysis ranged from -495% and -386% for chlorophyll-a and phaeophytin-a, respectively, to 93%, 90%, and 81% removal of enterococci, total suspended solids, and *E. coli*, respectively [93,95].

Water productivity, or the amount of harvestable product acquired per unit of applied water was particularly high for tomatoes, likely due to the widespread adoption of conservation irrigation techniques such as subsurface drip in many Central Valley processing tomato operations. Water productivity for tomatoes was estimated at 23 kg of harvestable product for every cubic meter of water applied, an order of magnitude higher than citrus, which had an estimated water productivity of 4.2 kg m^{-3}. When not considering tomatoes, the variability in water productivity among land covers was relatively low, ranging from 0.3 kg m^{-3} for orchard crops to 4.2 kg m^{-3} for citrus. All water productivity estimates were drawn from a single study which used a modeling approach to generate overall water yield, water use, and crop productivity for land covers in Fresno County [21]. Also important to note is that water productivity estimates do not necessarily reflect production *value* per unit of applied water, which was highest for orchard crops and particularly peaches. Economic returns to water in this study ranged from \$0.30 per m^3 for alfalfa to \$3.35 per m^3 for peaches. Further detail on economic returns to applied water is given in the land cover profiles for which the metric applies (Section I).

Measured estimates for leaching of nitrogen species, and nitrate in particular, were highest in orchard crops, followed by cotton and citrus. Estimates of N leaching in orchard crops ranged from 166 kg N ha^{-1} yr^{-1} to 70 kg N ha^{-1} yr^{-1} from 4 different studies. Estimates for N leaching from cotton ranged from 31-101 kg N ha^{-1} yr^{-1} and an estimate for citrus was at 97 kg N ha^{-1} yr^{-1} [33]. On the other hand, risk of N leaching was lower on average for alfalfa, pastures, vineyards, and rice crops, with measured estimates for these land covers ranging from 0 to 41 kg N ha^{-1} yr^{-1}. For alfalfa, pastures, and vineyards, N leaching risk is low likely due to correspondingly low nitrogen inputs and the crops' deep root systems, while for rice the low N leaching risk may be due to the largely impermeable layer of heavy clay in most rice fields that allows for flooded seeding conditions. In the case of rice, N contamination of surface waters may be more relevant than N leaching to the vadose zone, but this metrics was not examined here due to the dispersed nature of surface water pollution and thus the difficulty in attributing contamination levels to a particular land cover. Dzurella et al. [25] developed a Nitrate Hazard Index (HI) for California that scores land cover on their potential to contribute to nitrate pollution based on a combination of soil type, crop life history and N requirements, and irrigation system. In agreement with the above results from the literature, the HI was highest for land covers dominated by shallow-rooted annuals, such as cotton and corn, and lowest for deep-rooted perennials such as alfalfa. However, the HI for orchard crops was in the least vulnerable category, in contrast to the published estimates reported here. The authors of these studies noted that N leaching is highly variable across space and time due to water flow and N transport dynamics, therefore leaching estimates will likely depend heavily on when and where in the soil profile measurements were taken [104].

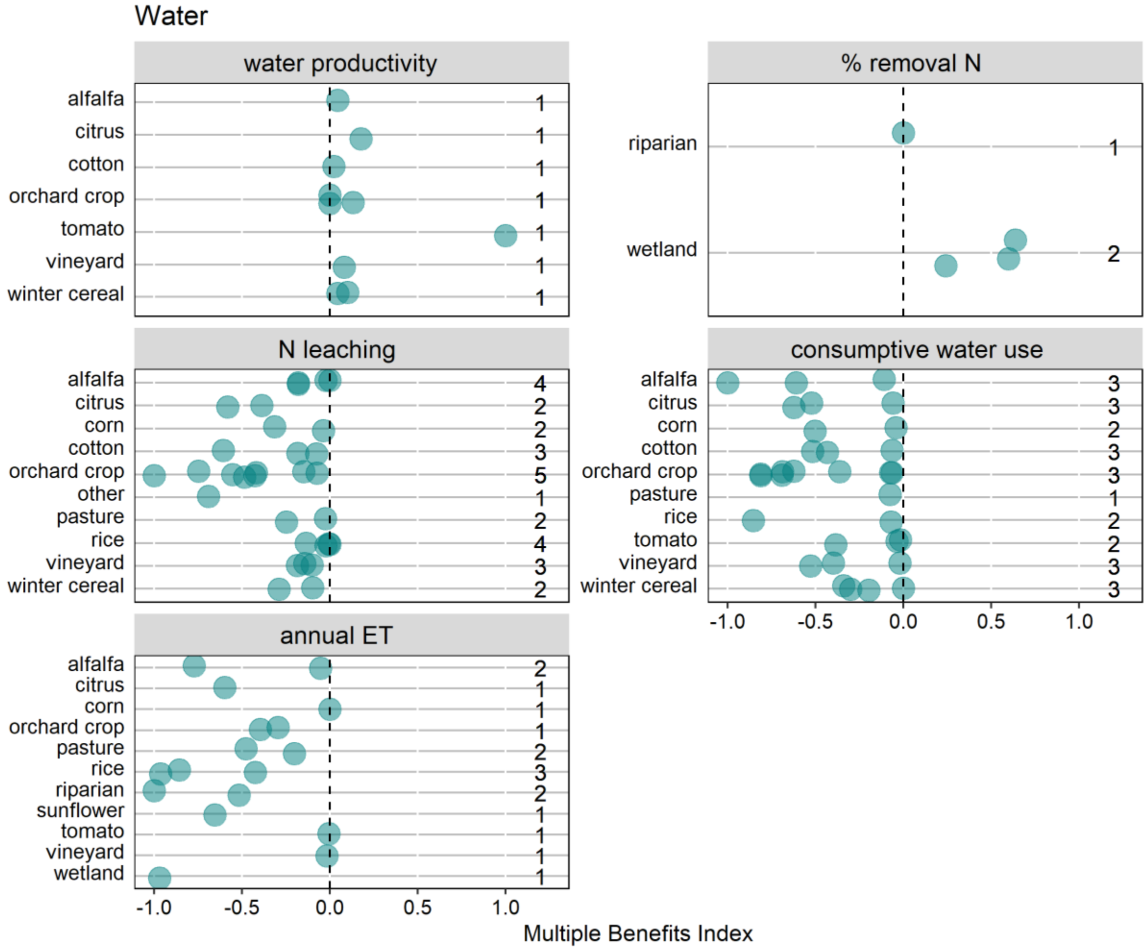

Figure 18. Comparative analysis of water-related benefits and tradeoffs among Central Valley land covers. For each metric, published or census-derived measurements were standardized as a proportion of the highest recorded measurement of that metric across land covers, given as the Multiple Benefits Index (MBI). Only land covers for which there was information available are shown. Negative MBI values represent a tradeoff, while positive MBI values represent a benefit. Numbers in the right-hand column of each panel are the number of unique studies that reported on the metric/land cover combination. Original units for each metric were as follows: water productivity in kg m^{-3}, % removal N as a percent, N leaching in kg N ha^{-1} yr^{-1}, consumptive water use in m^3 ha^{-1}, and annual ET in mm ha^{-1} yr^{-1}.

Both consumptive water use and annual evapotranspiration (ET) measurements were included in the benefit/tradeoff because while the former only applies to land covers where water is applied as irrigation, the latter applies to both irrigated and non-irrigated land covers. However, care should be taken not to interpret these metrics strictly as tradeoffs. In the case of annual ET, for example, it is often difficult to differentiate this metric into transpiration, or water use that directly contributes to net primary productivity, and evaporation, or water use that does not contribute to NPP. Likewise, several different methods were used to estimate consumptive water use among the reviewed studies, from Landsat-derived estimates of ET to pan evaporation to modeling techniques. In most cases the lower-end estimates of consumptive water use were derived from the pan evaporation or reference evapotranspiration method [22].

Among irrigated land covers, alfalfa, rice, and orchard crops all had estimates of consumptive water use in the 90th percentile of reported measurements. Consumptive water use for alfalfa ranged from 1,756 m^3 ha^{-1} [22] to 12,222 m^3 ha^{-1} [21]. For rice, estimates ranged from 1,277-10,490 m^3 ha^{-1}, and for orchard crops from 1,233-10,000 m^3 ha^{-1}. Similarly, rice and alfalfa had some of the highest reports of annual ET in the reviewed studies, approximately 1,000 and 900 mm ha^{-1} yr^{-1}, respectively. However, reports of annual ET for non-irrigated land covers were higher, ranging from 686-1,095 mm ha^{-1} yr^{-1} for riparian areas and 1,070 mm ha^{-1} yr^{-1} for wetlands. These values reflect the large contribution of transpiration from large woody biomass in forested riparian areas and of evaporation from open water components of wetlands to overall values of ET.

Wildlife

Benefits to wildlife – both plant and animal species – attributable to Central Valley land covers were measured by a wide variety of metrics in the reviewed literature, from percent cover of native plant species in grasslands, to bird population densities in riparian areas [78], to invertebrate species richness in vineyards [79] and cropland soils [64]. However, this diversity in metrics and target species complicates comparisons across studies or land cover types. Even regardless of target species, biodiversity-related metrics are often highly context-specific, such that a given level of species diversity in one land cover may be less reflective of its value for conservation and wildlife habitat than the same level of diversity in another land cover.

For these reasons, we elected to focus on birds as the primary taxonomic group for which benefits to wildlife were assessed. Birds are a major focus of conservation efforts in the Central Valley, particularly due to its importance for migratory waterfowl and shorebirds along the Pacific Flyway [97]. The historical conversion of many land cover types to agriculture and urban land covers has resulted in population declines and special conservation status for many Central Valley bird species, yet certain crops and agricultural management practices can also provide valuable habitat for birds. Birds are also frequently identified as excellent indicators of habitat and ecosystem condition due to their diversity of habitat requirements [105,106]. Rather than attempt to compile landcover-specific bird abundance or diversity estimates, we elected to draw on the expertise of local avian conservation biologists who have contributed to the development of Central Valley conservation strategy and objectives for birds [97]. The resulting Avian Conservation Score (**Figure 19**) was based on a separate assessments of the relative value of each land cover type for each taxonomic group in terms of habitat for nesting, foraging, or roosting during the breeding and non-breeding seasons (see Appendix IV for details).

The highest Avian Conservation Score (**Figure 19**) was assigned to wetlands due to their importance across bird species groups, including landbirds, waterfowl, waterbirds, and shorebirds. Rice, pastures, grasslands, and riparian areas had relatively similar scores resulting from their importance to different taxonomic groups: in the case of rice, for its importance to waterfowl, shorebirds, and waterbirds, and in the case of pastures, grasslands, and riparian areas, for their importance to grassland, oak savannah, and riparian landbirds as well as some waterbirds. In contrast, annual summer row crops such as tomato and cotton scored the lowest for avian conservation. Corn, winter cereals, and alfalfa were assigned similar intermediate scores, but only when corn crop management was assumed to be as in the Delta region where fields are often flooded post-harvest.

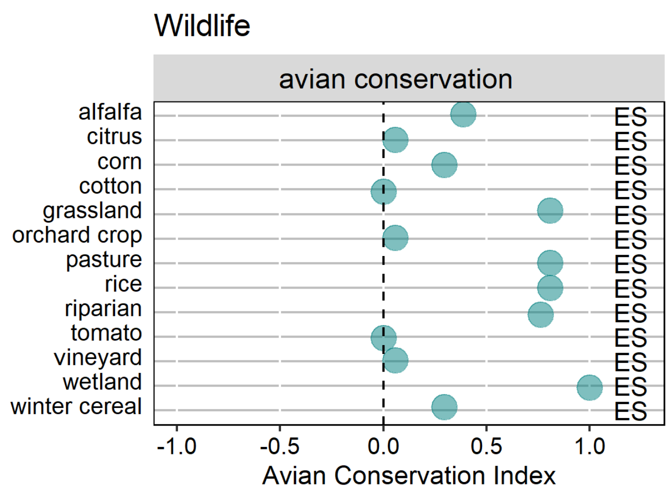

Figure 19. Comparative analysis of wildlife-related benefits among Central Valley land covers. The avian conservation index was developed from a survey of experts (ES) who rated land covers based on their importance for use by different categories of land-, water-, and shorebirds. The index was converted to a 0-1 scale where 1 represents the land cover with the highest avian conservation value, and all other land cover scores were a proportion of the highest score.

Results: Climate Change Vulnerability Index

The panel of 12 subject matter experts rated citrus, orchard crops, and wetlands as most vulnerable to the effects of climate change, while cotton, winter cereals, and corn were rated as the least vulnerable (**Figure 20**). As shown in **Figure 21**, these ratings were the product of combined sensitivity and exposure scores. Typically, sensitivity and exposure contributed roughly equally to the overall CCVI, but for land covers such as orchard crops and citrus high sensitivity contributed more to overall CCVI than exposure. Conversely, for land covers such as grassland and riparian areas, exposure contributed more to overall CCVI than sensitivity.

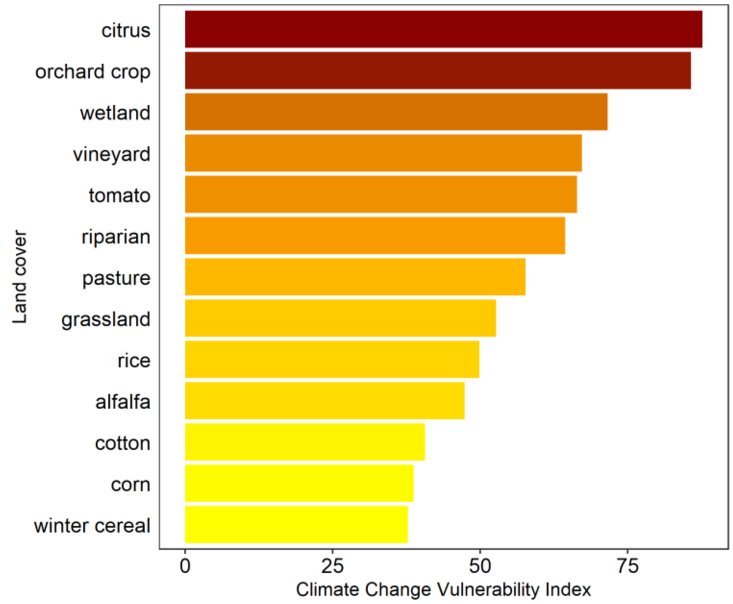

Figure 20. Land cover ranking by Climate Change Vulnerability Index score, or the product of cumulative sensitivity and exposure factors impacting the vulnerability of land cover in California's Central Valley to the effects of climate change as rated by a panel of 12 domain experts. A larger score indicates greater vulnerability of the land cover to climate change.

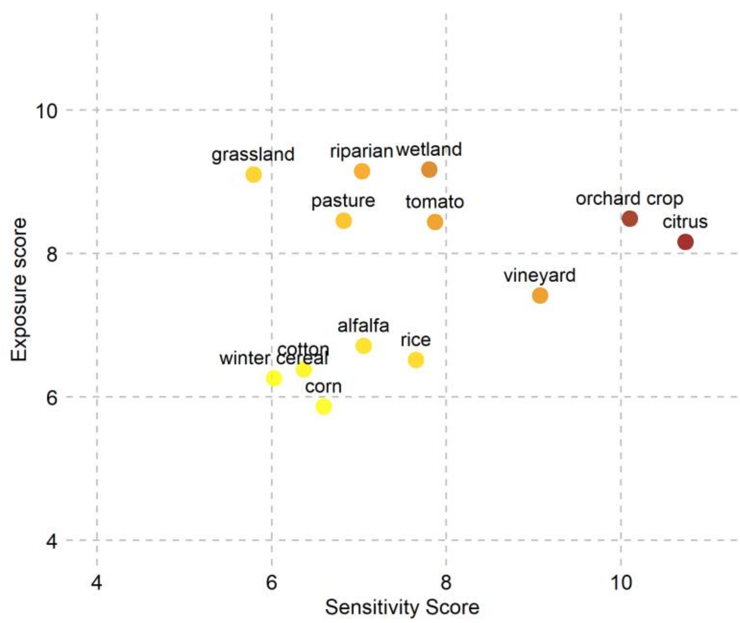

Figure 21. Matrix of sensitivity factors and exposure factors contributing to the overall Climate Change Vulnerability Index for land covers in California's Central Valley as rated by a panel of 12 domain experts. Points represent the CCVI score for each land cover. X and Y axes are the sum of scores for sensitivity factors and exposure factors, respectively.

Citrus was considered as the most vulnerable to climate change of any of the land covers, a rating that the expert panel attributed primarily to its sensitivity to temperature extremes and drought along with its management rigidity. Many citrus varieties are highly susceptible to yield impacts when temperature extremes occur during flowering, maturation, and/or fruit drop. The interacting effects of high temperatures and drought can also increase the salt-sensitivity of citrus trees, in addition to causing heavy fruit drops, delayed color break, and overall yield losses [107]. Citrus was also considered by the panel to be highly exposed to pests and diseases. Citrus greening disease, transmitted by the Asian citrus psyllid *Diaphorina citri* Kuwayama, has at this time been effectively quarantined in California, but the disease has destroyed millions of acres of citrus crops in the United States, particularly in Florida (USDA-APHIS). Despite the quarantine, citrus greening represents a considerable and continuing threat to the California citrus industry.

Similarly, the high CCVI for orchard crops was attributed to their perceived sensitivity to drought and in particular their management rigidity. These two factors are related in that, given their perennial life history, deciduous orchard crops cannot be fallowed in the event of an irrigation water shortage. This means that with the growing likelihood of multiyear droughts of the kind seen from 2012-2014 in the Central Valley, orchard crops that cannot obtain supplemental irrigation water would have to be destroyed. In essence, perennial crops offer less flexibility in management options. For example, an annual crop can simply be fallowed in a year of water shortage, forgoing production revenues for that year but avoiding large losses of sunk capital that would be involved in destroying an established orchard. Orchards were also rated as having high sensitivity to temperature. This factor reflects sensitivity not only to high temperature extremes, but also to loss of chilling hours that impact yields for many deciduous orchard crops. Almonds, for example, only require about 200 chilling hours and are not likely to experience critical loss of chilling hours by the end of the 21st century. But walnuts and many stone fruits require at least 500 chilling hours, meaning that only 78% of the Central Valley will be suitable for production of these crops by 2080-2095 [7].

Orchard crops were also considered as highly exposed to pests and diseases, with navel orangeworm (*Amyelois transitella*) being one of the best-known examples of a serious pest for almonds and pistachios. The ranges of many such pests and diseases are expected to expand with warming temperatures across much of the Central Valley, with a high likelihood of impacting the profitability of deciduous orchard crops in the coming decades [7].

Among the natural (non-agricultural) land covers examined, wetlands were rated as the most vulnerable to climate change. High ratings were given to wetlands for sensitivity to drought and range specificity, along with high ratings for exposure to capacity gaps, pollution, and land use conversion. Range specificity implies that only a narrow suite of geophysical conditions is adequate for the existence and continued functioning of a land cover. Changing climate regimes and environmental conditions, if sufficient to alter any of these requirements, could lead to the eradication of that land cover without continued intervention from managers. Saltwater intrusion into coastal wetlands making up the Sacramento-San Joaquin Delta due to sea level rise is one example of how the effects of climate change can alter the ability of wetlands to continue functioning.

Furthermore, wetlands were considered highly exposed to a lack of funding and investment into research and development to aid in adaptation to the effects of climate change, representing a significant capacity gap. They were also considered exposed to negative impacts from pollution, often from runoff from adjacent agricultural or industrial sources, which interact with the effects of climate change to increase overall vulnerability. Wetlands, along with riparian areas, were also considered particularly exposed to land use change and land use conversion, both directly as when wetlands are drained for development or agricultural use, and indirectly as when expansion of water-intensive perennial crops increases agricultural drawdown of surface waters, threatening the minimum flow requirements needed to ensure continued wetland functioning. As with pollution effects, these factors interact with the effects of climate change to create a moving target and risk of loss of the multiple social and ecological benefits of these land covers.

Section III: Spatial Patterns of Multiple Benefits

In many cases, biophysical and socioeconomic benefits and tradeoffs vary spatially in relation to topography, soil type, local hydrology, distance from urbanized areas, and vegetation communities, among other factors. As a result, a limited number of observations of the climate, water, wildlife, and socioeconomic metrics from land covers such as those summarized in Sections I and II provide only part of the picture. For example, estimating the air quality status of Kern County is not as simple as adding up the emissions associated with the land covers in Kern County, as it will also be strongly affected by point pollution sources (e.g., from oil rigs and refineries) and by atmospheric mixing dynamics that occur beyond county boundaries.

An additional source of information comes from spatial models of the distributions of these metrics, which enable analysis of co-location or stacking of benefits and/or tradeoffs. Although these models do not allow us to draw direct links between the extent of a particular land cover and the status of biophysical and socioeconomic benefit provisioning, we can use land cover distribution as a contextualizing factor to further understand areas of concern or, conversely, to highlight co-occurrence of particular land covers and multiple different benefit metrics.

Understanding the spatial distribution of multiple, stacked benefits across the Central Valley landscape provides a more comprehensive and inclusive knowledge base to inform policy and conservation planning and management efforts. For example, the broader spatial patterns of benefits ranging from climate mitigation potential to access to recreational sites – whether or not these metrics can be directly linked to land cover – can inform prioritization of regions for restoration, environmental mitigation, or strategic land use planning. Combining this understanding with stock-taking of scientific evidence regarding benefits and tradeoffs from land covers allow for nuanced approaches to land use planning that account for potential unexpected consequences or co-benefits from a particular land use or land cover. With the following analysis, our objective was to map the spatial patterns in selected benefits and tradeoffs to determine the location of hotspots and coldspots of benefit provisioning: where do multiple benefits tend to stack together? Conversely, where are we more likely to see multiple tradeoffs that fail to outweigh the benefits from land cover properties and uses?

Benefit metrics and source data

We used publicly available, spatially-explicit datasets to quantify the following benefit metrics in the Central Valley. These benefits were chosen because they complement or expand upon the metrics explored in the previous section.

For climate regulation benefits, temporary carbon storage and potential for carbon accumulation for different land covers was calculated using an extension of the time-adjusted warming potential approach used by Marvinney et al. [108] for orchard crops. Using a semi-informed ranking system for the parameters in Table 1 below, land covers were ordered according to assumed aboveground biomass productivity, with forest representing the highest productivity and developed land the lowest. The same process informed ratings for disturbance frequency, SOC accumulation potential, and mean crop productivity.

Above-ground biomass productivity was obtained from primary data on orchard removals as well as the results of the 2007 and 2013 California Biomass Resource Assessments [109,110]. Biomass productivity informed the soil C accumulation potential ranking under the assumption that below-ground biomass accumulation is proportional to aboveground biomass accumulation. That is, an orchard or forest with high aboveground biomass accumulated over a long period of time is assumed to accumulate belowground biomass at a greater quantity than an annual, low biomass accumulation system. Biomass accumulation was obtained from primary data on orchard removal biomass from previous Life Cycle Assessment analyses [108] as well as work by the CA Biomass Collaborative [109,110] and the SSURGO geospatial data (for forest and rangeland, details below).

Soil C accumulation potential was ranked by land cover type based on the following parameters: soil clay content, soil tillage/disturbance frequency, and land cover non-harvested biomass accumulation. The time adjusted warming potential approach is an alternative to IPCC GWP metrics specifically used to quantify the benefits of temporary carbon storage on timeframes of less than 100 years. Therefore, the ranking process for soil C accumulation potential accounted for the lifespan of the land cover/production system in question. The longer the lifespan, the longer the timeframe between soil disturbance events, and thus, the higher the soil C accumulation ranking. Tillage/disturbance frequency was based on UC Davis ARE Cost and Return Studies (e.g., [111]) where available, and otherwise gap-filled with the authors' best estimates. For example, in the case of developed land, which includes a wide range of uses from open space to apartment buildings, disturbance was assumed to be on average once every 5 years. In other cases, annual tillage (e.g., for corn, cotton, and other annual row crops) was ranked at 1.0, while no disturbance (e.g., forest, open water) was ranked at 0. Perennial systems were ranked based on assumed productive lifespan (given in the above Cost and Return Studies and collected in previous work). This ranking was inverted when combined with soil physical and biomass accumulation ranking such that 1 was "best" and 0 "worst" in agreement with the other ranked categories.

The biggest assumption inherent to the above approach is that the broad results generated here are meaningful in the absence of data on typical frequency of management practices influencing soil C stocks and flux in the Central Valley. The above ranking of potential accumulation represents qualitative estimates based on basic soil physical characteristics, existing C stock, and land cover, and does not make any assumptions about management practices. A more informed ranking would require a full literature review for quantitative data on actual C flux in each land cover type and management systems, which was beyond the scope of the geospatial analysis presented here. Because only a very limited set of factors (disturbance frequency, soil max C – soil initial C, and land cover biomass productivity) were used to generate a qualitative ranking, the values in **Table 2** (below) are not directly comparable to quantitative measurements of soil C flux in any particular study site.

For environment health benefits, we examine both air and water quality metrics. While PM10 and NOx emissions were examined in the previous section's rapid evidence assessment, the spatial air quality metrics examined in this section also include data on ozone, PM2.5, and other pollutants as given in the California Healthy Places Index (HPI) [112]. We also include the HPI's water contamination index to further complement the healthy environment metrics examined in Sections I and II. For water-related benefits, we opted to prioritize a metric that was difficult to characterize using the rapid evidence assessment approach but that is of critical importance for both conservation and agricultural goals in the Central Valley: groundwater sustainability. Similarly, for wildlife-related benefits we supplement the Avian Conservation Score presented in Sections I and II with a spatially explicit habitat quality score based on data from the CA Department of Fish and Wildlife.

Finally, because social and cultural benefits associated with land covers were difficult to quantify using the rapid evidence assessment approach and relatively scarce in the reviewed literature, we provide a simplified assessment of this metric here using park access, overcrowding, and tree canopy cover data to represent an index of socio-cultural benefits across the Central Valley. These data account for only a small portion of the metrics that could potentially be used to represent socio-cultural benefits, but can provide at least a provisional glimpse at access to quality-of-life benefits associated with physical aspects of a landscape such as shade, park access, and the density of physical structures and human population. These metrics, rather than providing a comprehensive assessment of quality of life for Central Valley regions, are instead intended to provide further context on the distribution of benefits across the Central Valley, in particular the location of areas of concern for low quality of life and additional tradeoffs.

Climate regulation source data

1. **Soil organic carbon content.** Soil organic carbon (SOC) content and percent clay particles were obtained from the NRCS SSURGO soil data viewer [113] and aggregated from individual soil horizons by volume up to soil map unit components. They were subsequently aggregated from map unit component by percent total extent to map units. Theoretical maximum carbon storage was calculated based on percent clay as per Hoyle et al. [114] using the following equation:

$$SOC\% = 0.5482\ x \ln(clay\%) + 1.3073$$

2. **Potential soil carbon accumulation.** Calculated by subtracting existing soil carbon stock (SSURGO) from the theoretical maximum described above and applying a weighting factor based on land cover expected biomass productivity and soil disturbance frequency (**Table 2**).

3. **Biomass productivity.** Biomass productivity layers were used to inform the carbon content and storage potential layers 1-2 above. Rangeland and forest biomass productivity were obtained from SSURGO soil data viewer by map unit component and aggregated to map unit by percent total extent. Perennial crop biomass productivity, which were previously used in orchard life cycle assessment modeling [108,115], were obtained for 14 tree crops from a cooperating agri-services firm operating in the San Joaquin Valley region. These data were joined to the Cropland Data Layer 2019 perennial crops layer [116]. Missing biomass values were assigned the average value across tree crops.

Healthy environment source data

4. **Air and water quality.** Data were obtained from the California Healthy Places Index geospatial dataset, from the pollution, ozone, and PM2.5 and water contamination indices [112]. The pollution percentile is the domain percentile ranking of the average of Z-scores for percent of households with access to an automobile and percent that commute to work. The ozone index is the mean daily maximum 8-hour ozone concentration (ppm) during the summer months averaged over three years (2012-2014). The water contamination index is equivalent to the Cal EnviroScreen 3.0 drinking water contaminant index for selected contaminants.

Water source data

5. **Groundwater sustainability.** Groundwater recharge potential was obtained from the UC Davis Soil Agricultural Groundwater Banking Index (SAGBI; [32]) dataset. Groundwater depth data were obtained from the CA Department of Water Resources (DWR) open test well dataset as a five-year average from 2015-2019 [117].

Wildlife source data

6. **Habitat quality.** Data were obtained from the CA Department of Fish and Wildlife Areas of Conservation Emphasis (ACE) dataset, Species Biodiversity layer, habitat rank data [118].

Other benefits source data

7. **Socio-cultural benefits.** Tree canopy cover, overcrowding, and park access indices were obtained from the HPI and transformed into a combined socio-cultural benefits index [112]. Tree canopy cover is the population-weighted percentage of census tract areas with tree canopy. Canopy cover includes tree crops and orchards, but urban and suburban tree cover tends to be emphasized given the weighting by population. Overcrowding is the percentage of households with greater than 1 occupant per room. Park access is the percentage of the population living within a half-mile of a park or open space of greater than 1 acre.

Transformation and aggregation of benefit metrics

For each of the above metrics, a linear transformation was used to convert the range of values in each metric dataset to a scale of 0-1, with 0 being the "worst" or lowest provisioning of the benefit category and 1 being the "best" or highest provisioning. Combined metric indices were generated by averaging the transformed values of the relevant metrics and applying a linear transformation to re-scale the values to 0-1. Metrics were then aggregated to a 5 km hex grid by area-weighted averaging applied across the Central Valley. Ecosystem "coldspots" and "hotspots" were generated by extracting hexagons with re-scaled values below 0.2 and above 0.8, respectively, for the mean of all individual metrics.

Summary of results: multiple benefits mapping for land covers in the Central Valley

The heatmaps in **Figure 22** reveal several broad spatial trends for benefit metrics in the Central Valley. Firstly, the Sacramento and San Joaquin Valley regions exhibit dissimilar trends for a number of metrics, most notably air and water quality, habitat quality, and SOC storage, all of which tend to be higher in the Sacramento Valley region. For SOC, however, this trend is only clear when the high-carbon soils in the Delta region are omitted. Air quality, water quality, and habitat quality all ted to be higher in the Sacramento Valley compared to the San Joaquin Valley. These two regions of the Central Valley similarly diverge in terms of the principal land covers. The Sacramento Valley is dominated by rice production, interspersed with orchard crops such as peach and walnut. The San Joaquin, on the other hand, accounts for the majority of the greater Central Valley's land area in orchard crops, citrus, vineyard crops, and cotton.

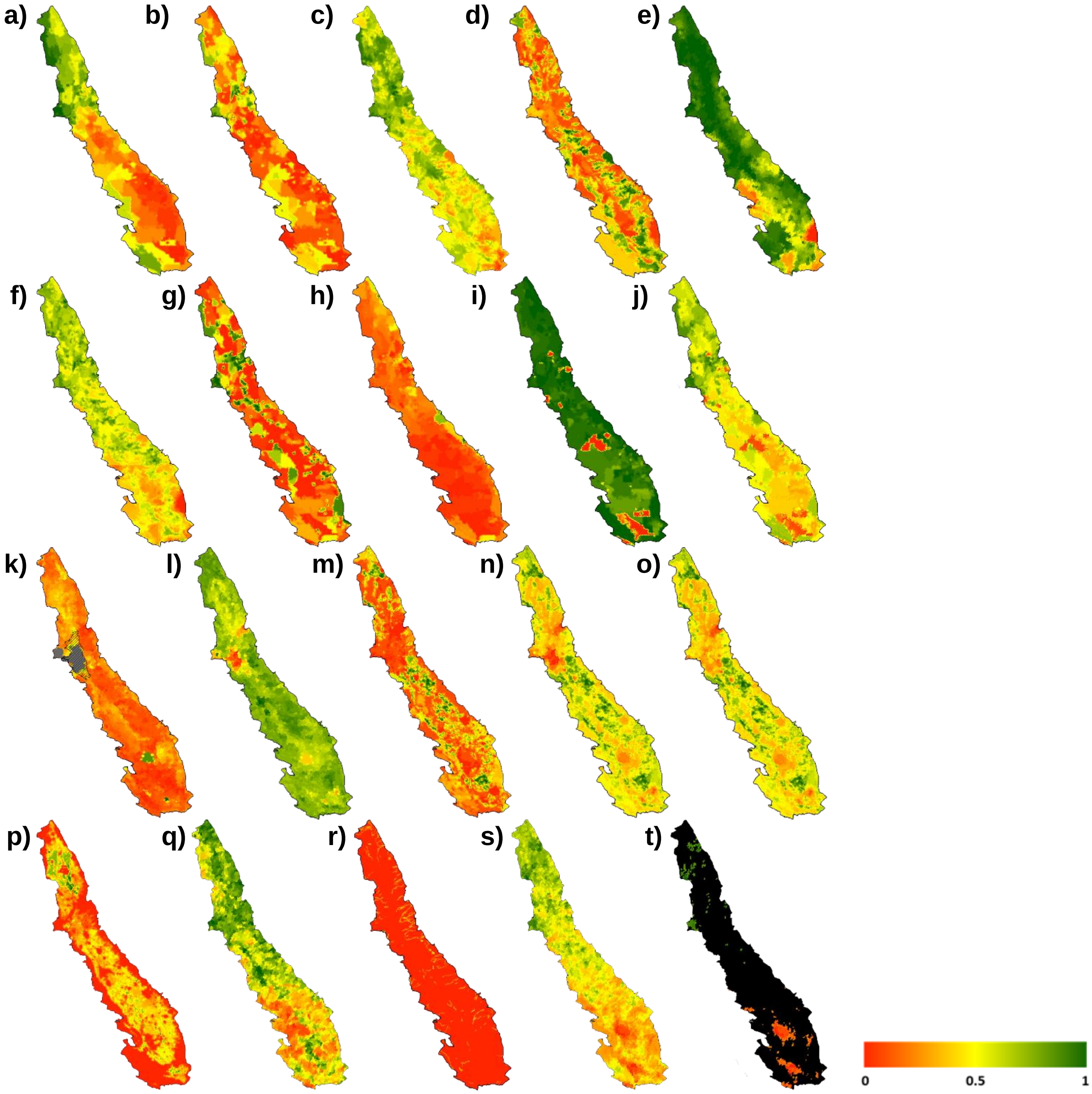

Figure 22. Selected benefit metric heatmaps for the Central Valley of California. All metrics were transformed from their original units to a normalized 0-1 scale, with 0 representing the lowest provisioning of the benefit in question and 1 representing the highest provisioning. The mapped metrics (and their source data) are: a) air quality (HPI); b) water quality (HPI); c) combined air and water quality; d) groundwater recharge potential (SAGBI); e) groundwater depletion (DWR); f) combined groundwater metrics; g) park access (HPI); h) tree canopy cover (HPI); i) overcrowding (HPI); j) combined socio-cultural metrics; k) annual SOC storage excluding the Delta (SSURGO); l) SOC accumulation potential (SSURGO, SPARCS-LCA); m) annual aboveground biomass C accumulation (SSURGO, SPARCS-LCA); n) combined biomass and soil carbon accumulation metrics; o) combined C storage and accumulation metrics; p) crop productivity (CCC, CDL); q) habitat quality (CDFW-ACE); r) percent riparian area (NHD, CDL); s) all individual metrics combined; t) top and bottom 20th percentile “hotspots” and “coldspots.”

The multiple benefits hotspot/coldspot analysis echoes these trends. The majority of multiple benefit hotspots, or areas where the mean of all metrics exceed 0.8 on the normalized scale, occur in the Sacramento Valley, or the northern 1/3 of the greater Central Valley (**Figure 23**). This area coincides with wetlands adjacent to the Sacramento-San Joaquin Delta, but also includes wetland and riparian areas in Glenn and Colusa counties and areas where orchard and rice land covers predominate. In contrast, areas in the San Joaquin Valley and particularly the southern 1/3 of the greater Central Valley corresponded to the most coldspots, or areas where the mean of all benefits metrics was less than or equal to 0.2 on the normalized scale. These areas tended to coincide with areas of predominantly cotton and field crop production, as well as some areas of perennial crop production and fallow land (or land in use by the oil industry) in Kern county.

While these patterns of benefit and tradeoff distributions may be partially attributable to the distribution of land covers in the same areas, it is also important to consider other factors such as geologic history, crossover of benefit/tradeoff metrics from adjacent regions and land covers, density of urban areas, industrial activities, and regional topography and hydrology when interpreting overall benefit/tradeoff distributions.

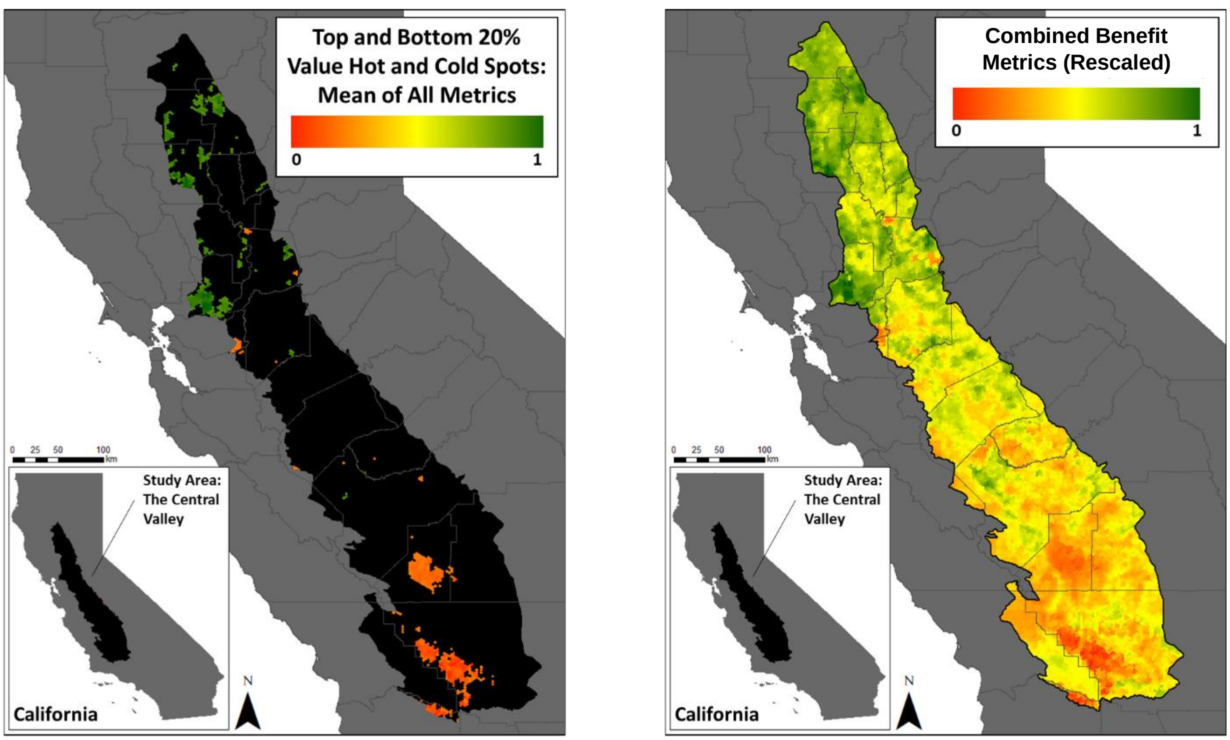

Figure 23. Left: hotspots (mean of metrics >= 0.8) and coldspots (mean of metrics <= 0.2) of multiple benefit provisioning in California's Central Valley, and right: combined and rescaled benefit metrics. The metrics included (and their source data) were: air quality (HPI); water quality (HPI); combined air and water quality; groundwater recharge potential (SAGBI); groundwater depletion (DWR); tree canopy cover (HPI); overcrowding (HPI); annual SOC storage excluding the Delta (SSURGO); SOC accumulation potential (SSURGO, SPARCS-LCA); annual aboveground biomass C accumulation (SSURGO, SPARCS-LCA); crop productivity (CCC, CDL); habitat quality (CDFW-ACE); percent riparian area (NHD, CDL).

Climate regulation and crop productivity

The rangeland/pasture (grassland) category was estimated to have one of the lowest crop productivity ratings, an intermediate biomass productivity at 0.4 on a normalized 0-1 scale, and above-average SOC accumulation potential. Perennial crops were rated the highest among agricultural land covers for biomass productivity and SOC accumulation potential, even though citrus and vineyards had below-average crop productivity ratings. The highest SOC accumulation potentials among agricultural/managed land covers were assumed for orchard crops, citrus, vineyards, rangelands and pastures, and alfalfa, which were assigned ratings of 0.88, 0.88, 0.83, 0.65, and 0.63, respectively.

Table 2. Disturbance frequency, biomass productivity, crop productivity, and estimated soil carbon accumulation potential parameters used to model temporary carbon storage and carbon accumulation potential for Central Valley land covers with the time-adjusted warming potential method.

Land Cover	Extent (ha)	Percent Total Study Area	Disturbance Frequency Rating	Biomass Productivity Rating	SOC Accumul-ation Potential Rating	Central Valley Mean Crop Productivity Rating
Alfalfa	233512	4.02%	0.33	0.6	0.63	0.79
Citrus	106723	1.84%	0.04	0.8	0.88	0.51
Corn	96796	1.67%	1.00	0.6	0.30	0.50
Cotton	122942	2.12%	1.00	0.6	0.30	0.53
Developed	538694	9.27%	0.80	0	0.10	--
Fallow	462231	7.95%	0.50	0.1	0.30	--
Field Crop	102384	1.76%	1.00	0.6	0.30	0.13
Forage	58633	1.01%	1.00	0.6	0.30	0
Forest/Woodland	6229	0.11%	0.00	1.0	1.00	--
Open Water	74880	1.29%	0.00	0.2	0.60	--
Orchard	1036948	17.84%	0.03	0.8	0.88	0.27
Rangeland/ Pasture	1679593	28.90%	0.00	0.3	0.65	--
Rice	213547	3.67%	0.83	0.5	0.33	1.00
Riparian*	3051	0.05%	--	0.6	--	--
Shrubland	153453	2.64%	0.00	0.6	0.80	--
Tomatoes	115764	1.99%	1.00	0.7	0.30	0.29
Vineyard	264231	4.55%	0.03	0.7	0.83	0.02
Wetland	143194	2.46%	0.00	0.6	0.85	--
Winter cereal	369076	6.35%	1.00	0.6	0.30	0.33

*Riparian zones may be Forest, Shrubland, Wetland, or Rangeland within 25m of a river or open water and share the properties of that particular land cover category for purposes of this analysis. In reality, some metrics – particularly disturbance frequency – may differ between riparian areas and the adjacent land cover type.

Current and potential SOC storage/accumulation in the Central Valley was highly heterogeneous. Current SOC storage was orders of magnitude higher in the Sacramento-San Joaquin Delta region than in the rest of the Central Valley, causing the skewed scale apparent in **Figure 24A.** When the Delta region was omitted from the analysis (**Figure 24C**), broader patterns in SOC storage in the rest of the Central Valley were detectable, including several hotspots of SOC storage in the former Tulare Lake basin and Kern Lake. A general pattern of higher SOC storage in the Sacramento Valley rice-growing regions was also evident when Delta SOC storage was omitted. It is important to note that the high SOC storage in the Delta and former Tulare/Kern Lake regions in particular reflects historical biophysical conditions, and that these regions – all of which have undergone extensive conversion to row crop agriculture – are currently areas of net carbon loss. In other words, this model can present a snapshot of existing carbon storage at a given point in time, but is not an indicator of the direction of trends of carbon accumulation or loss.

In contrast to patterns for existing SOC storage, potential SOC accumulation was lowest in the Delta region, suggesting active carbon loss or nearness to SOC saturation thresholds in this region. Areas of relatively high soil + biomass carbon storage potential tended to coincide with areas where perennial crops such as orchards and vineyards predominate, such as Kern, Fresno, and Stanislaus counties.

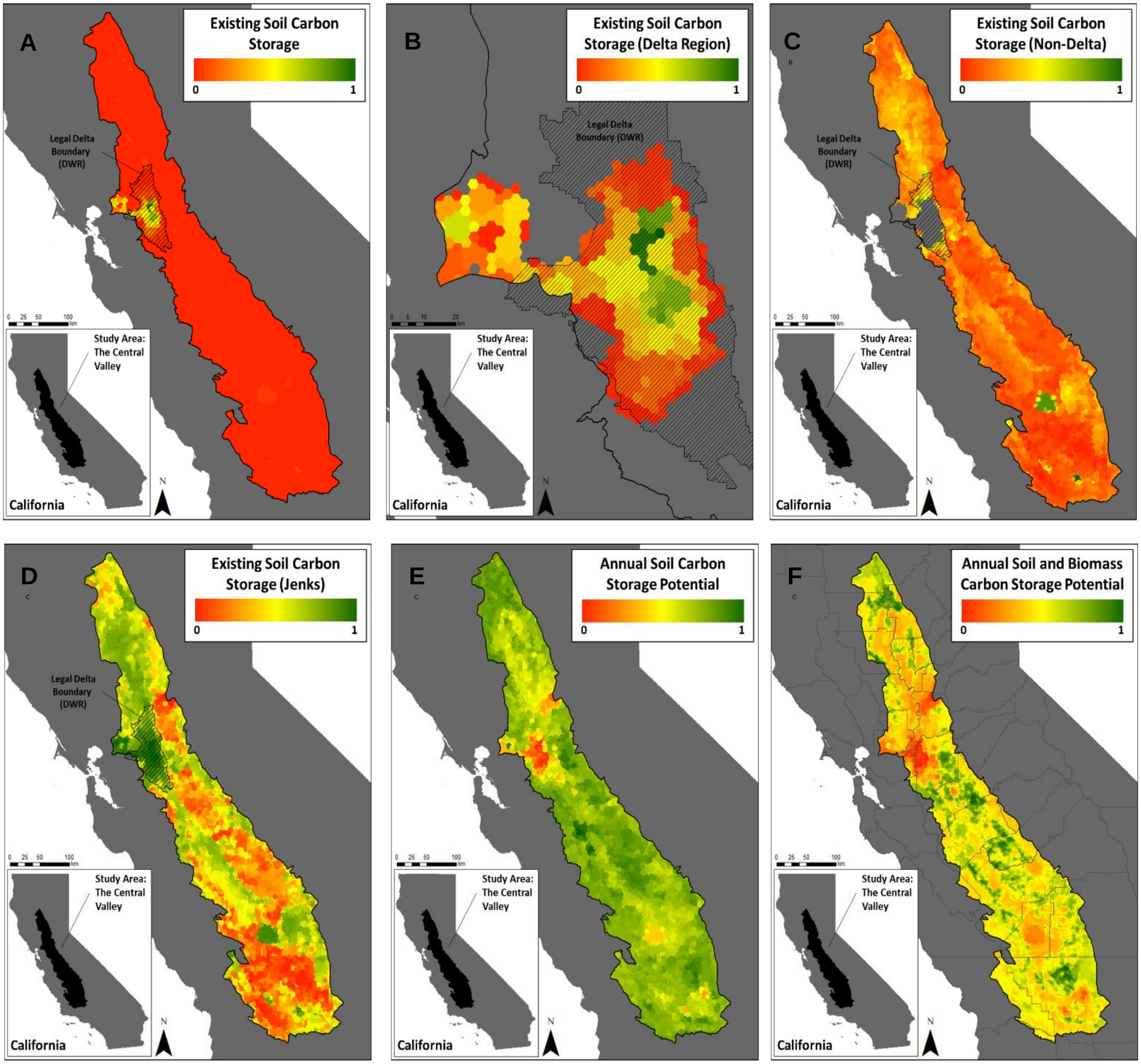

Figure 24. A) Relative soil organic carbon stocks (SSURGO); B) Soil organic carbon stocks within the legal boundaries of the Sacramento-San Joaquin Delta region; C) Relative soil organic carbon stocks with values from the Delta region omitted; D) Soil organic carbon stocks visualized according to a natural breaks scheme (Jenks); E) annual soil carbon accumulation/storage potential (SSURGO/SPARCS-LCA) and F) Combined soil and aboveground biomass carbon storage potential in California's Central Valley.

Healthy environment and wildlife benefits

Air, water, and habitat quality metrics exhibited similar north-south trends, with quality scores higher in the northern, Sacramento Valley than the southern San Joaquin Valley. However, in the case of air quality (**Figure 25A**) in particular, associating the metric with any specific land cover can be problematic as the source of the contaminants may not coincide with their ultimate distribution in space. Land cover can play a role, as with the significant contribution of management operations and harvest in orchard crops, particularly almonds, to particulate matter pollution in the southern Central Valley. Certain land covers can also act as a sink for air contaminants such as ozone and NOx gases by providing surface area for the interception of contaminant molecules (e.g., citrus [30]), though typically only during certain times of year. But spatial distribution of air pollution also depends on atmospheric

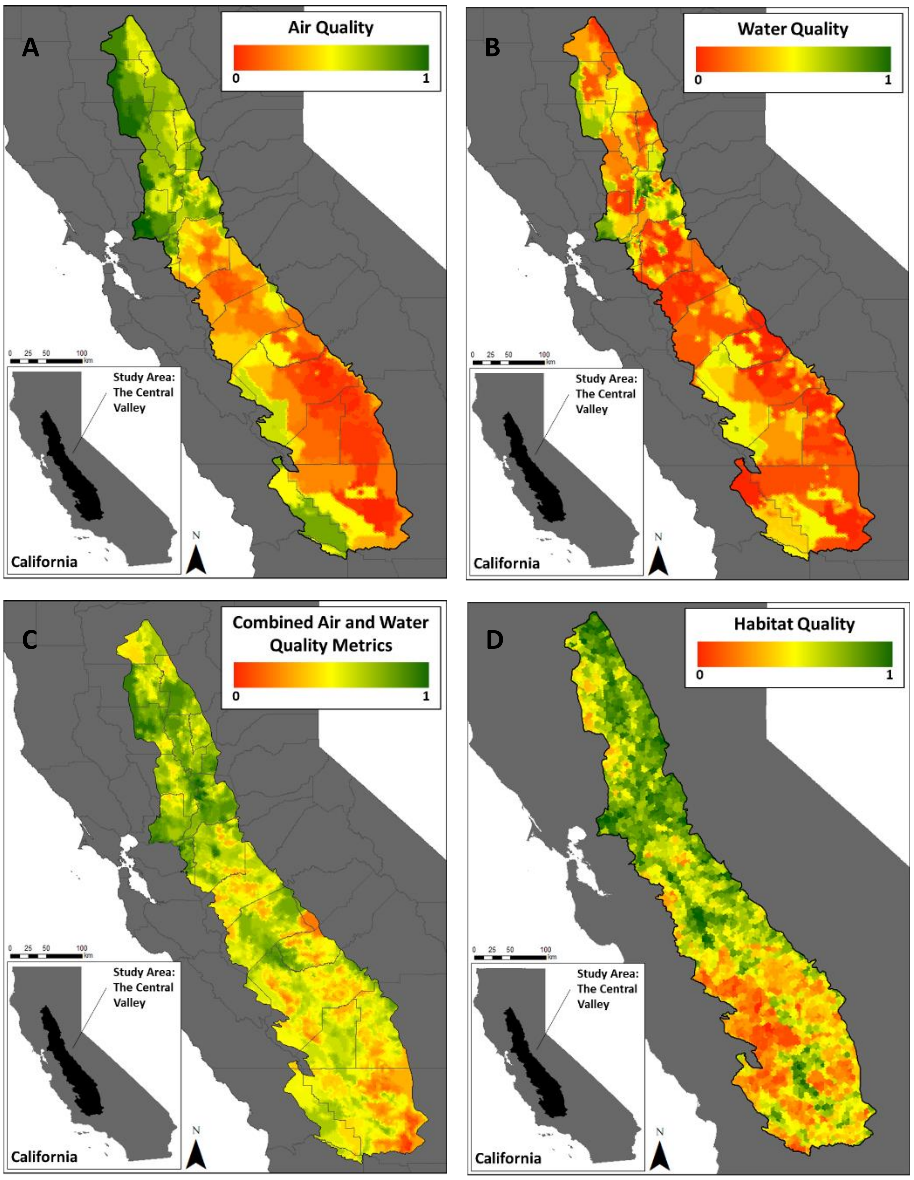

Figure 25. A) Air quality and B) Water quality metrics (HPI); C) Combined air and water quality metrics; and D) Habitat quality (CDFW ACE) in California's Central Valley.

mixing, weather patterns, topography, industrial activity, transportation, and other variables unrelated to land cover or vegetation class.

Water quality metrics are subject to similar limitations in that spatially explicit representations must be interpolated from spot measurements at wells and gauges. These spot measurements can be related to the percent of surrounding land area occupied by a given land cover, but they are necessarily loose associations. Nevertheless, the combination of these metrics can inform general spatial patterns of metrics impacting human health and wellbeing which can coincide with given land covers. A hotspot of concern for both air and water quality, for example, occurs in the southeast corner of the Central Valley in Kern county, an area in which citrus and vineyard crop land cover is particularly abundant (**Figure 25B**).

The habitat quality metric reflects a combination of variables related to biodiversity, connectivity, significant habitats, and climate resilience [118]. Hotspots of concern for low habitat quality include the Kings county region, which also coincides with a large proportion of the San Joaquin Valley's cotton and annual field crop production. These are also the land cover types that tended to have low Avian Conservation Scores, as described in Sections I and II. Conversely, areas of the Central Valley coinciding with wetlands and riparian areas, such as the Delta, San Joaquin River, and the San Joaquin and San Luis National Wildlife Refuges, are hotspots of high habitat quality according to these spatial layers, again in agreement with the results of the Avian Conservation Score.

Water benefits: groundwater sustainability

The Soil Agricultural Groundwater Banking Index generates a spatially-explicit model of suitability for managed groundwater recharge on agricultural land [32]. The index combines five major factors to determine an overall suitability rating: deep percolation, which is derived from the soil horizon with the lowest saturated hydraulic conductivity, root zone residence time, which accounts for the need for good drainage to avoid damaging crops, chemical limitations such as electrical conductivity (salinity), topographic limitations such slope, and surface condition, or the potential for soil crusting or erosion. The index is more specifically geared towards perennial crops, as these are expected to have roots in the ground in the offseason when flooding might occur, whereas suitability for offseason flooding in annual crops is less dependent on crop type. For the Central Valley, highly suitable areas for groundwater recharge include the southern tip of the Valley within Kern County, a large hotspot on the eastern edge of the Valley outside of Merced, CA, and numerous hotspots along the Hwy 99 corridor intersecting with the Merced, Tuolumne, and Stanislaus Rivers (**Figure 26A**).

Hotspots of groundwater depletion, an indicator of aquifer overdraft, occurred in the area east of Bakersfield, CA in Kern County and along the western edge of Fresno County (**Figure 26B**). Both of these areas are notable for their hilly topography, which stands in contrast to most of the rest of the Valley floor.

Figure 26C shows that in some instances, areas of low suitability for groundwater recharge often intersect with areas of high groundwater depletion (closer to 0 on the benefits scale). This pattern is evident in north-central Kern County, western Fresno County, and Madera County near Madera, CA. By highlighting areas of particular concern for groundwater sustainability, the combination of these metrics could provide useful insights for sustainable groundwater management as mandated by the CA Sustainable Groundwater Act (SGMA, 2014). The spatial distribution of groundwater benefits and tradeoffs is somewhat tied to land cover, as mentioned above for perennial vs. annual croplands, but like the other metrics examined here the overall distribution also depends on layers of landscape elements both above and below land cover type. For example, recharge potential may be higher on fallow lands than lands planted in perennial fruit trees, but this potential also depends on whether the topography of the land is hilly or flat and on the underlying hydrology and subbasin characteristics of the region.

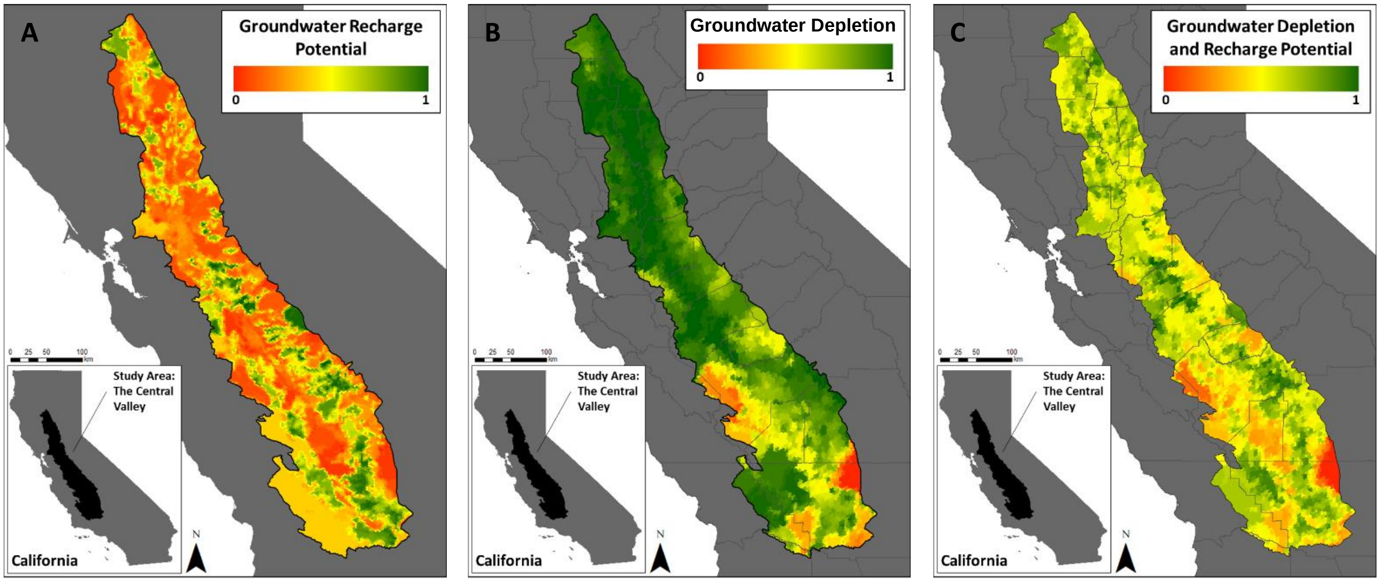

Figure 26. A) groundwater recharge potential (SAGBI); B) groundwater depletion (CA-DWR); and C) combined (mean) recharge potential and depletion highlighting areas of concern both for groundwater depletion and low recharge potential in California's Central Valley. On the 0-1 scale, 0 represents the lowest provisioning of the benefit and 1 represents the highest. In the case of groundwater depletion (B), 1 represents the least depletion, i.e., the highest water table.

Socio-cultural benefits

Tree canopy cover, overcrowding, and park access metrics from the California Healthy Places Index [112] were combined to generate an overall socio-cultural benefits index (**Figure 27**). Similarly to the air and water quality metrics, these metrics cannot be directly associated with particular land covers but rather contribute to the overall picture of benefits and tradeoffs in a spatially explicit manner. In other words, they allow us to understand how spatial distribution of quality-of-life-related benefits may coincide with spatial distribution of other benefits/tradeoffs, potentially indicating regions of concern for multiple tradeoffs. For one, the combined index illustrates "coldspots" of concern for low socio-cultural benefits in western Kern county and Madera county near the large urban centers of Bakersfield and Fresno (**Figure 27D**). These areas also correspond to large areas of citrus and orchard crop production, and in the case of Madera county, vineyard crop production. Tree canopy cover is scarce in the vast majority of the San Joaquin Valley. Although orchards and fruit/nut trees are included in the tree canopy indicator, population-based weighting system means that they contribute relatively little to the overall index. Given that orchard crop are typically located on private land and not accessible to the public for recreation purposes, this aspect of the tree canopy index would be consistent with the park access indicator in terms of representing the availability of recreation resources and microclimate benefits provided by urban/suburban shade trees.

The three metrics considered here are not intended to represent a comprehensive assessment of socio-cultural benefits. Furthermore, they are among the metrics with the most disconnect between actual land cover distributions because they largely reflect urban/suburban landscape elements. However, they do represent physical aspects of the landscape tied with human wellbeing, and understanding their spatial distribution can help further contextualize patterns of high or low overall provisioning of benefits/tradeoffs associated with land cover types. They also provide a complement to economic indicators of underserved or disadvantaged communities, which are typically based on median household incomes, by highlighting infrastructural and land-use oriented elements that also contribute to quality of life.

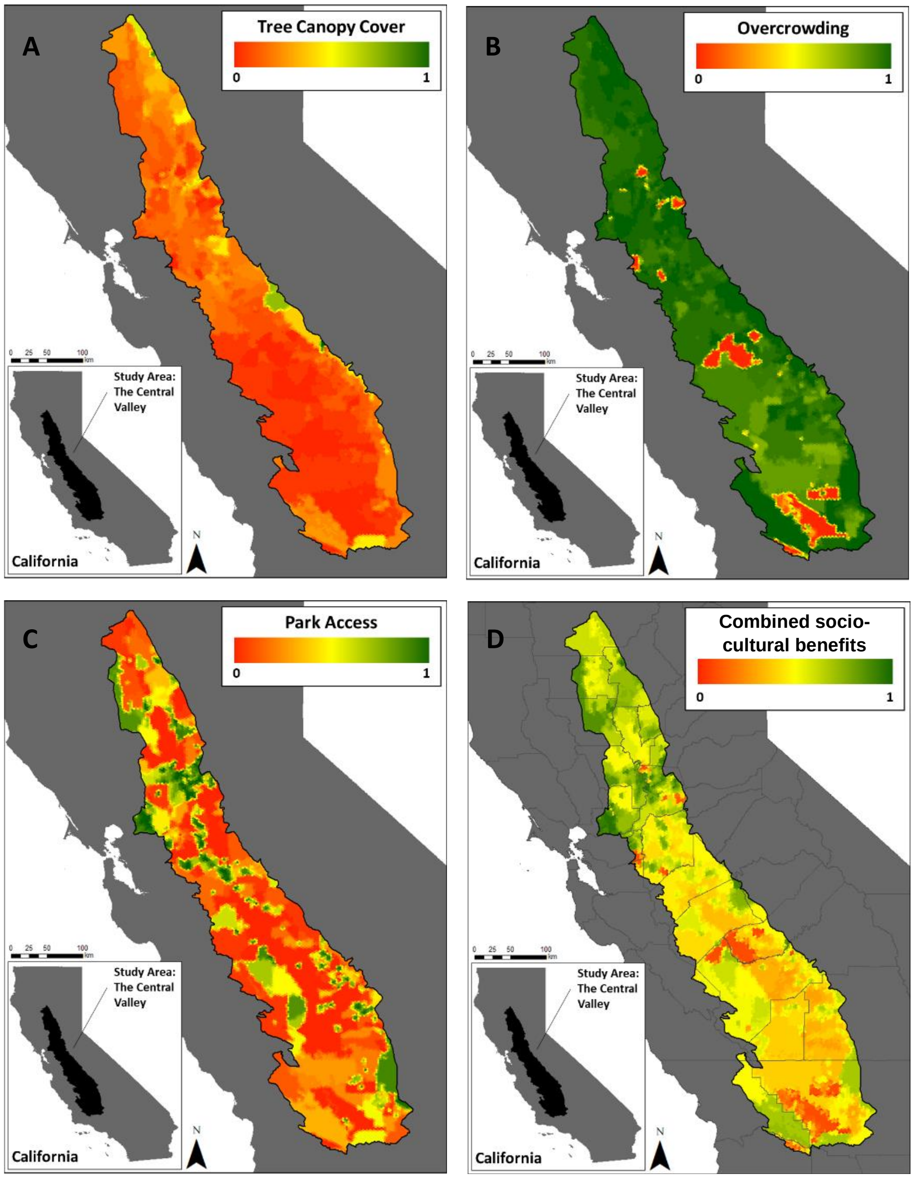

Figure 27. Socio-cultural benefit metrics (HPI): A) tree canopy cover; B) overcrowding; C) park access; and D) all socio-cultural benefit metrics combined for California's Central Valley. For the overcrowding metric, 0=more overcrowding and 1=less overcrowding. For the remaining metrics, 1 represents the highest level of provisioning of the benefit.

Section IV: Knowledge Gaps and Limitations

Summary of findings

This report was intended to provide an overview of the state of knowledge on the socioeconomic and ecological tradeoffs and benefits associated with land covers in California's Central Valley. Using rapid evidence assessment techniques, we reviewed the recent (2010-2020) published evidence on metrics of environmental health (air quality and pollution), climate regulation (GHG emissions, carbon storage), economy (production value, employment, wages), water (consumptive water use, pollution mitigation, water productivity/returns to water), and wildlife (avian conservation score), as well as in index of climate change vulnerability, for 13 priority land covers in the Central Valley. We also used spatial modeling techniques to map the distribution of selected benefit and/or tradeoff metrics across the Central Valley, providing further regional context around otherwise localized experimental data. Our objective was to collect information on the range of possibilities for each of these metrics to ultimately inform understanding of the complex, multi-dimensional impacts of land management decisions and land conversion decisions. We found that, while literature on benefits associated with particular land covers was fairly abundant, only a small subsection of this literature documented common metrics that could be used for cross-land cover comparisons. Those that did were limited in number, geographic scope, and agronomic context, and so are problematic for making larger-scale comparisons or constructing scenario analyses.

The information presented here is not intended to be an exhaustive comparative analysis among land covers. However, it can be used to begin characterizing Central Valley land covers within the context of site-specific land management systems and environmental contexts, and to serve as a guide for future research by highlighting the gaps in our knowledge base.

Knowledge gaps

Because experimental studies often focus on one or few land covers using a suite of tailored metrics, fully assessing the landscape-wide multiple benefits associated with land covers in the Central Valley will require more research that adopts a cross-land cover approach along with a set of common metrics that apply to both natural and agricultural land covers. Taking a multiple benefits approach will facilitate the creation of a minimum common dataset of metrics within benefit categories that are relevant across multiple land covers. Furthermore, there is a need for standardization of land cover categorizations to facilitate a multiple benefits approach. Rangelands provide a good example of a land cover that overlaps many other distinct categories: grasslands, oak woodlands, vernal pools, and shrublands can all be considered rangelands if they are managed for forage and/or livestock production. Often studies fail to clearly delineate the conceptual boundaries around their experimental system, meaning that the resulting datasets are not interoperable in the context of knowledge synthesis, and information on associated benefits and tradeoffs remains siloed in land-cover- and metric- specific domains.

Some land covers and benefit categories in particular constituted large gaps in our dataset and would benefit from more research focus. Given regional specificity of our search strategy and the composition of California's agricultural landscape – i.e., the importance of high-value, perennial crops over a large proportion of Central Valley land area – little recent information on benefits/tradeoffs was available for annual, commodity row crops such as wheat and corn. Because these land covers are likely to present a distinct combination of benefits and tradeoffs compared to high-value perennial crops such as almonds and fruit trees, it is worth explicitly including them in research plans for cross-land cover assessments.

Several benefit categories, despite generating interest from policy makers and conservation practitioners, are under-studied from a multiple benefits perspective. In particular, air quality metrics associated with individual land covers were lacking, apart from a single study from 2003 that relied on a static model of agricultural dust creation (PM10 emissions) but made no direct measurement of particulate matter emissions from different land preparation operations in agricultural land covers. Similarly, our search strategy returned few studies examining the relative pesticide load associated with different land covers, although this may be in part due to the difficulties inherent in establishing point sources of pesticide contamination, lapses in reporting, and insufficient understanding of hydrologic flows, ecotoxicology, and permanence of the multitude of products available on the market today.

Excitement revolving around soil carbon sequestration as a natural climate solution, is perhaps surprisingly, not met with commensurate availability of research and direct measurements of soil carbon under differing land uses. While extensive soil carbon research was available for rangelands and grasslands, the same was not true for crop production lands, wetlands, or riparian areas. Studies that addressed a combination of soil carbon storage/sequestration along with above- and below-ground biomass pools of carbon were also relatively rare. The set of spatial models presented in Section III therefore provide valuable insight into trends and patterns of existing carbon storage, as well as potential for storage of further carbon in soil, above-, and belowground pools.

We found that net ecosystem carbon balance, with particular reference to measures of soil respiration, were not given adequate treatment from the multiple benefits perspective. For example, the addition of cover crops to the alleys in a vineyard may increase CO_2 emissions from microbial respiration, but allow for more soil C accumulation overall, resulting in a net ecosystem benefit. For this reason, representing CO_2 flux as a standalone metric (and a tradeoff) in the Multiple Benefits Index could be misleading, and is better represented as part of overall ecosystem carbon balance. However, we found that few studies reported greenhouse gas emissions using this approach and therefore did not include carbon balance in the benefit/tradeoff analyses. Similarly, while studies examining an individual metric of greenhouse gas emissions were plentiful, few compared multiple GHGs simultaneously such that a common Global Warming Potential or Sustained Global Warming Potential could be calculated using carbon dioxide equivalents.

Similarly, while a number of studies reported hourly or daily flux rates of various GHGs to address variability in flux rates stemming from management systems, irrigation, cover cropping strategy, and fertilization rates, among others, not all of these measurements were conducted with sufficient spatiotemporal intensity to enable accurate integration to annual flux rates. Cumulative annual (or seasonal, if off-season emissions are negligible) flux rates are more relevant for planning purposes in multifunctional landscapes and for examining tradeoffs in GHG emissions among land covers, and they are less influenced by anomalously large pulse events that may happen with soil wetting/drying cycles or after fertilization. However, precisely because GHG fluxes are so difficult to capture given their dramatic spatial and temporal heterogeneity, there is not enough information on cumulative annual fluxes available in the literature to provide confident assessments of overall GHG impact associated with different land covers in the Central Valley.

Challenges and limitations

Our approach for assessing benefits and tradeoffs from agricultural and natural land covers was limited by several factors. Most importantly, the rapid evidence assessment and derived Multiple Benefits Index it is limited to the geographic extent and management contexts of the studies included within the search criteria. For example, the sum of information provided by these studies on relative benefits/tradeoffs from different land covers may be spatially biased, given that research sites are often preferentially located near land grant universities and long-term experiment networks. Therefore, drawing comparisons across land covers from a limited set of observations can be problematic without further context, and we cannot draw broad conclusions about comparative benefits/tradeoffs among the entire extent of each land cover in the Central Valley. Rather, we can use this information to better understand the state of the science on this set of metrics pertaining to the management systems and geographic locations involved, and to examine relative values among these metrics, but we cannot assume that they are representative of the entire population of observations for these metrics within a land cover.

Similarly, our rapid evidence assessment approach did not allow for understanding the spatial and temporal variability inherent in many of the metrics examined, from the local to the landscape scale. We attempted to address this deficiency using the spatial models presented in Section III, but this still does not allow for direct relationships to be drawn between the extent of a land cover and the relative distribution of benefits and tradeoffs. The co-occurrence of land covers with a given spatial distribution of benefit/tradeoff does not allow us to draw conclusions as to the causation of the benefit/tradeoff distribution, but it does provide further context for analyzing landscape-level patterns in benefit provisioning, accounting for exogenous factors such as climate, topography, and proximity to urban areas, among others.

Furthermore, although we made cross-metric comparisons possible by ensuring consistency in units and normalizing metric values to a common 0-1 scale, this approach does not account for the differing impacts of benefit tradeoff metrics. For example, a CO_2 flux index of -0.32 and CH_4 flux index of -0.24 may capture the relative magnitude of each emission source, but not the differential impact of CH_4 as a more potent greenhouse gas. Another example is annual ET, which may reflect consumptive use of applied water in the irrigated agriculture setting but also reflects necessary ecosystem maintenance in natural land covers such as grasslands. For this metric, the index may be comparable mathematically but not comparable in interpretation unless the potential impacts of land use conversion are under consideration.

Finally, the most important limitation of our approach is that it cannot account for the impacts of management on relative provisioning of benefits or tradeoffs. In agricultural settings, management strategies can have dramatic impacts on the magnitude of particular metrics. For example, fertilization rates and timing can change the quantity of nitrous oxide emissions from croplands by orders of magnitude. A grassland that is left ungrazed will have entirely distinct vegetation communities, nutrient cycling dynamics, and carbon accumulation trajectories from a grassland that is managed for moderate grazing. And the relative environmental health and biodiversity benefits/tradeoffs from and agricultural land cover may depend on whether it is under conventional or organic fertility management. The benefit/tradeoff analysis conducted here did not account for differing management treatments, instead using the mean of all treatment values where relevant to calculate the normalized Multiple Benefits Index. While thorough treatment of land management effects on the relative provisioning of benefits and/or tradeoffs from land covers was beyond the scope of this report, there have been recent efforts to synthesize the available evidence to better inform multiple benefits research (see [119]). Research that can simultaneously examine multiple land covers with a set of common metrics, account for management effects, and account for differential impact among benefit metrics will be a critical step forward for multiple benefits research and a valuable contribution to natural resource management, policy, and planning.

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Appendices

Appendix I: Glossary of key terms

Benefit: services or goods obtained by humans from ecosystems; synonymous in this report with "ecosystem services."

Carbon dioxide: atmospheric gas notable for its contribution to the greenhouse effect through radiation trapping. CO_2 accounts for approximately 81% of total greenhouse gas emissions, primarily from the transportation, electricity, and industrial sectors.

Carbon sequestration: the process of drawing down atmospheric carbon into a non-atmospheric reservoir such as oceans, soils, and biomass over time; related to carbon storage.

Carbon storage: retention of carbon in non-atmospheric pools that is considered relatively permanent, i.e. unlikely to return to atmospheric pools in the next 25-50 years.

Climate regulation: an ecosystem service or benefit related to relative reduction in atmospheric concentrations of gases that enhance global warming, such as carbon dioxide and methane, or other processes such as the albedo effect that provide negative feedback to global warming.

Consumptive water use: reduction in quantity or quality of a water resource such that it is no longer available for other uses. Typically refers to the uptake and use of applied irrigation water resources by a crop plant that is not recycled into the water source, e.g., that is instead either stored in plant tissue and subsequently exported from the system with harvest, or is transpired as part of photosynthetic processes.

Ecosystem disservice: functional outputs or results of ecosystem processes that are contrary to human interests, often associated with (but not exclusive to) human-managed ecosystems such as agriculture, e.g., excess nutrient runoff or the proliferation of disease; synonymous in this report with "tradeoff."

Ecosystem process: an intrinsic property of an ecosystem that upholds its basic functionality and identity, and that is often facilitated by various actors/components within an ecosystem, such as decomposition or nutrient cycling.

Ecosystem service: benefits obtained by humans from ecosystems, including provisioning services such as food production and water supply, regulating services such as flood and climate control, cultural services such as recreational or spiritual uses, and supporting services such as nutrient and water cycling that maintain the conditions necessary and suitable for life; synonymous in this report with "benefits."

Evapotranspiration: net exchange of water to the atmosphere through the processes of evaporation (e.g., from plant and soil surfaces) and transpiration through plant tissue.

Exposure factor: the extent to which an entity is subjected to an extrinsic, environmental stressor that increases its vulnerability to adverse conditions; in this report, refers specifically to the extent to which land covers are subjected to the stresses of climate change and interacting phenomena.

Global Warming Potential: a measure of radiative energy than can be absorbed by one ton of a greenhouse gas over a given period of times, relative to the emission of 1 ton of carbon dioxide and expressed as equivalent carbon dioxide emissions.

Land cover: a delimited class of regional physical attributes bounded by soil type and/or vegetation community and related to human use, including agricultural production, residential, or undeveloped areas.

Leaching: loss of an applied crop fertility product, particularly nitrogen and nitrogen species, beyond the plant-accessible zone and into the vadose zone of the soil profile, where it can create concern for pollution of surface and groundwater resources.

Managed Aquifer Recharge (Ag-MAR): the practice of leveraging farmland to capture and recharge legally and hydrologically available flood waters to increase regional capacity for recharge to replenish aquifers (Waterhouse 2020).

Methane: a trace gas with a potent greenhouse effect. CH_4 accounts for approximately 10% of total greenhouse gas emissions, with 25x the radiation trapping potential of carbon dioxide and a mean residence time of 100 years (EPA 2018). Major sources include enteric fermentation in livestock, natural gas and petroleum industries, landfills, and manure management, among others.

Metric: a unit for assessment of relative and/or absolute magnitudes of benefit and/or tradeoff provisioning; can be either quantitative or qualitative.

Multifunctionality: a characteristic that describes the ability or capacity of an ecosystem or landscape to perform one or more processes, functions, or services, both for its intrinsic benefit and for the benefit of human interests.

Net Ecosystem Carbon Balance: the net rate of organic C accumulation in, or loss from, and ecosystem at a given spatial or temporal scale (UCAR 2008).

Net equivalent emissions: Net emission of greenhouse gases, accounting for both direct and indirect sources of greenhouse gas emission and sequestration and represented in a common unit of carbon dioxide global warming equivalents.

Nitrogen oxides (NOx): compounds of nitric oxide (NO), nitrogen dioxide (NO_2), and other oxides of nitrogen typically produced during combustion processes. NOx compounds are major contributors to smog formation and acid deposition, along with being a listed air pollutant that can result in adverse health effects (CA-ARB 2010).

Nitrous oxide: a trace gas with an extremely potent greenhouse effect. N_2O is often emitted as a byproduct of the denitrification process in agricultural soils as well as industrial processes. Accounts for about 7% of total greenhouse gas emissions (EPA 2018), with 300x the radiation trapping potential of carbon dioxide and a mean residence time of 114 years.

Particulate matter: airborne particles with an aerodynamic diameter of 10 microns or smaller (PM10) or 2.5 microns or smaller (PM2.5), which can induce respiratory illnesses and early death in vulnerable populations. Composed of a mixture of compounds such as carbon and metals, along with diesel exhaust and soil. Can be emitted directly into the atmosphere or indirectly emitted through transformation of existing gases in the atmosphere (CA-ARB 2010).

Sensitivity factor: an intrinsic, often physiological characteristic that increases the vulnerability of an entity to the adverse impacts of environmental stressors; in this report, refers specifically to the sensitivity of land covers to the impacts of climate change.

Tradeoff: a characteristic output or process that is related or associated with a land cover that detracts from human objectives or is contrary to human interests; synonymous in this report with "ecosystem disservice."

Vulnerability: the likelihood that a subject, in this case a land cover, will lose functionality, suitability range, or the ability to provide needed goods and services in the event of widespread impacts from climate change.

Water productivity: the mass of harvestable crop product obtained per unit volume of applied water, including both precipitation and irrigation water; an estimate of the efficiency of water use in agriculture.

Appendix II: Methods for the rapid evidence assessment

Defining the scope

Prior to conducting the literature search, the scope of the review was defined by designating priority agricultural (managed for production purposes) and natural (not managed for production purposes) land covers. Priority agricultural land covers were determined on the basis of harvested acreage given in the CA Agricultural Commissioners' 2017-2018 Crop Report [31]. The top 9 reported cropland acreages are given in **Table A2.1**. Area for rangelands and pastures are not shown in this table due to disparities in classification and reporting criteria, although they were included in the subsequent analysis. Priority natural land covers were determined on the basis of land area within the Central Valley. Land area was calculated in ESRI ArcMap using zonal analysis of the USDA NASS Cropland Data Layer (CDL) [116]. The priority natural land covers chosen for review and their corresponding classifications in the CDL are given in **Table A2.2**. Chaparral and vernal pool land covers were originally included in the literature review, but were omitted from the subsequent analysis due to: 1) insufficient information available for multiple metrics for both chaparral and vernal pools, and 2) uncertainty as to classification definitions for vernal pools, i.e., whether their area included the grassland matrix surrounding the pools or only the pool area itself. The final set of natural land covers to include in the analysis was based on the above considerations as well as particular priorities of the MBCP for conservation and research purposes.

Table A2.1. Harvested cropland area (hectares) for California, 2018 (USDA-NASS).

Crop Group	Crop		Harvested Area (ha)
orchard crop	almond		441,117
	walnut		141,643
	pistachio		106,435
	prune		17,807
	peach		14,569
		TOTAL orchard crops	**721,570**
vineyard	grapes		**349,251**
alfalfa	alfalfa		**250,911**
winter cereals	wheat		171,995
	oat		44,516
	barley		26,305
		TOTAL w. cereals	**242,817**
rice	rice		**204,775**
corn	corn		174,019
	sweet corn		13,760
		TOTAL corn	**187,778**
tomato	tomato		**105,463**
cotton	cotton		**104,816**
citrus	oranges		59,490
	tangerine		25,091
	lemon		19,021
		TOTAL: citrus	**103,602**

Table A2.2 Area of land cover classes in the Central Valley, CA, from USDA NASS Cropland Data Layer.

Land Cover	Extent (ha)
Grassland/ Rangeland/Pasture	1679593
Wetland	143194
Shrubland	153453
Forest/Woodland	6229
Riparian*	3051

The sectors or interests to include in the search were determined based on MBCP priorities along with the authors' evaluation of pressing challenges in policy, planning, and land management relevant to the Central Valley. The benefit categories falling within each sector were not determined *a priori*, but rather populated organically based on the availability and consistency of information in the literature. The same was true for metrics within each benefit category.

Search strategy

We followed a protocol for rapid evidence assessment similar to that given in Varker et al. [120] and customized to accommodate the extent of the literature being reviewed and timeframe constraints. Search efforts were restricted to the Google Scholar search engine and did not include multiple academic databases. Search results were limited to English-language, full-text, peer-reviewed journal articles from 2010-present. In general, no theses/dissertations, technical reports, or grey literature were included, with some exceptions where the information did not exist with the same comprehensive coverage in any other source (e.g., the UC Davis Nitrate Report [33]). Due to the volume of results typically returned by the Google Scholar engine, only the first 50 results from each search were scanned to determine their eligibility for inclusion in the initial screening.

We performed an iterative search where the same pattern of search terms was used for every combination of land cover and benefit category, for example: California AND [land cover] AND [benefit category]. For each iteration, [land cover] was replaced with agricultur*, (orchard* OR vineyard* OR crop* OR perennial), rice, alfalfa, cotton, (corn OR tomato OR sunflower OR wheat), (rangeland* OR graz*), wetland*, (vernal OR "vernal pool" OR "vernal pools"), riparian, or chaparral, and [benefit category] was replaced with ("ecosystem services" OR "ecosystem service"), ("water quality" OR "water pollution"), (phosphorus OR "nutrient loading" OR "phosphorus loading"), (nitrate OR "nutrient loading" OR "nitrogen loading"), (sediment* or "sediment load"), ("soil health" OR "soil quality" OR "soil carbon" OR "carbon sequestration" OR "carbon storage"), ("air pollution" OR "air quality"), or (PM* OR "particulate matter").

Screening

To be included in the subsequent review and analysis, a study had to meet the following criteria:

1. Study area fell within the Central Valley, including Sacramento and San Joaquin Valleys and the Sacramento-San Joaquin Delta;

2. Land cover categories specified exact crops or ecosystems, not broadly “agricultural land” or “natural ecosystems”;
3. Metrics were examined from multiple benefits perspective (i.e. not an intrinsic value perspective);
4. Study included quantitative measurements of benefit metrics for land cover categories;
5. Benefit metrics were based on direct experimentation or modeled estimates. Surveys, literature reviews, and expert panels were not included in the rapid review phase. Meta-analyses were only included where relevant regions and landcovers were made explicit in subgroupings.

The initial screening process involved manual scanning of the title and abstract for obvious disqualifications, such as wrong geography or wrong topic. Subsequent screening involved more detailed evaluation of each study to determine whether it met the above inclusion criteria.

Data extraction

The following information was extracted from each study meeting the inclusion criteria:

1. Relevant metadata (study authors, citation, year, location/county);
2. Land cover and benefit category being examined;
3. Sample size, min, max, mean, standard deviation, units of measure (metric);
4. Experimental treatments if any;
5. Other notes needed to provide context.

Where studies involved crossed treatment designs or multiple observation years, the mean of all treatments and years was used. For studies that measured the same benefit category in multiple, independent locations, the measurements were treated as independent observations.

Tables A2.3-2.5 show the complete list of metrics that were recorded in the reviewed literature from the period from 2010-2020, the number of observations and unique studies associated with each, and the final subset of metrics used in the subsequent benefit/tradeoff analysis. As described in Appendix III, metric selection was based largely on availability in the literature across land cover types as well as importance for social-environmental concerns in the Central Valley region.

Table A2.3 Metrics reported for each benefit category in the reviewed literature for California’s Central Valley from the period 2010-2020. The number of studies reporting each metric is indicated in parentheses.

Benefit/tradeoff category	**Metrics reported**	
Healthy environment (air quality)	• Ozone formation (2) • NOx flux (1)	• PM10 emissions (1)
Wildlife (biodiversity)	• Species richness (native, weed, invasive) (7) • Species diversity (bird, plant) (6)	• Abundance (bird, soil fauna, soil microbe) (4) • % cover (native, weed) (4)
Climate regulation	• N2O flux (34) • CO2 flux (10) • CH4 flux (16) • C storage	• Net Equivalent Emissions (1) • Net Ecosystem Balance (1) • Net Ecosystem Exchange (1) • (Sustained) Global Warming Potential (4)

Table A2.3 continued…

Benefit/tradeoff category	Metrics reported	
Economy (food production)	• Pollination (2) • Forage production (3)	• Annual value (crop products) • Annual value (livestock products)
Soil	• C storage (14) • Subsidence reversal (2) • Microbial biomass C/N (2) • Microbial community comp./diversity (1) • Microbial activity – respiration (1) • Belowground NPP (1)	• Decomposition (1) • C/N mineralization (4) • Erosion control (1) • N stock (1) • Aggregation (1)
Water quality	• N-NO3-NH4 leaching (6) • N-NO3-NH4 load/flux (6) • Groundwater nitrate concentration (2) • Dissolved organic carbon load/flux (4) • Total dissolved/suspended solids (4) • P-PO4 load/flux (5)	• Pollutant removal (5) • Denitrification potential (3) • Net Ecosystem Production/Accumulation (2) • MeHg load/flux (2) • Bioaccumulation (2) • Pesticide application (1)
Water supply	• Water use (2) • Water productivity (1) • Groundwater recharge (2) • Annual ET (4) • Infiltration (2)	• Blue/Green water use/productivity (1) • Basin recharge (1) • Runoff to basin (1) • Potential flood storage capacity (1)

Table A2.4 Detailed breakdown of number of studies, number of total observations, and metrics reported by land cover type and benefit category for the literature from 2010-2020 for California's Central Valley. A regrouped subset of these metrics and land cover types was utilized in the benefit/tradeoff analysis described in Appendix III.

	Air quality			Biodiversity			Climate regulation			Soil quality			Water quality			Water supply		
Land cover	Studies	Observations	Metrics	Studies	Observations	Metrics	Studies	Observations	Metrics	Studies	Observations	Metrics	Studies	Observations	Metrics	Studies	Observations	Metrics
Alfalfa	2	2	NOx flux, PM10 emissions	0	0		5	10	N2O flux, CO2 flux, CH4 flux, Net Ecosystem Carbon Balance, Global Warming Potential, Sustained Global Warming Potential, C storage	1	1	C storage	5	5	N leaching, N load, Nitrate Hazard Index	5	7	water use, water productivity, groundwater recharge, annual ET
Citrus	3	3	ozone formation potential, PM10 emissions	0	0		1	1	N2O flux	0	0		3	3	N load, groundwater nitrate, N leaching	3	4	water use, water productivity, annual ET
Corn	2	3	NOx flux, PM10 emissions	0	0		5	10	N2O flux, CO2 flux, CH4 flux, Net Ecosystem Carbon Balance, Global Warming Potential, Sustained Global Warming Potential	0	0		4	5	N leaching, Nitrate Hazard Index, MeHg load	2	2	water use, annual ET
Cotton	1	1	PM10 emissions	1	4	Microbial community composition, Microbial community diversity	2	2	N2O flux	1	1	Microbial biomass	4	4	N load, N leaching	2	3	water use, water productivity
Orchard crops	2	2	NOx flux, PM10 emissions	0	0		13	18	N2O flux, CH4 flux, C storage	3	5	C storage	7	13	N load, N leaching, groundwater nitrate, Nitrate Hazard Index	3	11	water use, water productivity, annual ET

Table A2.4 continued…

	Air quality			Biodiversity			Climate regulation			Soil quality			Water quality			Water supply		
Pasture	0	0		0	0		4	9	N2O flux, CO2 flux, CH4 flux, Net Ecosystem Carbon Balance, Global Warming Potential, Sustained Global Warming Potential, C storage	1	1	C storage	3	3	N leaching, groundwater nitrate	2	2	annual ET
Rice	1	1	PM10 emissions	0	0		13	35	N2O flux, CO2 flux, CH4 flux, Net Ecosystem Carbon Balance, Global Warming Potential, Sustained Global Warming Potential, C storage	2	2	C storage, subsidence reversal	14	40	N load/flux, N leaching, DOC load/flux, TDS load/flux, groundwater nitrate, P load/flux, DON load	4	4	water use, annual ET
Sunfl-ower	0	0		0	0		2	2	N2O flux	0	0		0	0		1	1	annual ET
Tomato	2	2	NOx flux, PM10 emissions	1	11	species diversity, species richness, native plant % cover, species abundance	9	14	N2O flux, CO2 flux, C storage	1	6	C storage, aggregation, mineralizable N, Microbial biomass C, infiltration	3	4	N leaching, MeHg load, DOC	3	4	water use, water productivity, annual ET, infiltration
Vineyard	1	1	PM10 emissions	1	2	species richness, species abundance	12	16	N2O flux, CO2 flux, CH4 flux, C storage	4	5	C storage	5	5	N leaching, N load, groundwater nitrate, Nitrate Hazard Index	4	6	water use, water productivity, annual ET, groundwater recharge
Wint. Cereals	1	1	NOx flux	0	0		5	7	N2O flux, C storage	1	1	C storage	3	4	N leaching, Nitrate Hazard Index	2	5	water use, water productivity
Chap-arral	1	1	NOx flux	0	0		1	1	C storage	1	1	C storage	0	0		0	0	

Table A2.4 continued…

Grassland	0	0		2	7	species richness, species diversity, native species richness, native species % cover	4	4	C storage	6	14	C storage, microbial activity, belowground NPP, decomposition, C mineralization, N mineralization, infiltration	0	0		2	2	infiltration, groundwater recharge
Rangeland	0	0		1	2	species richness, weed % cover	3	13	C storage	5	20	C storage, erosion control	0	0		2	10	blue water use, blue water productivity, green water consumption, green water productivity, basin recharge, runoff to basin
Riparian	0	0		4	24	bird density index, species diversity, species richness, native species % cover, weed species % cover, species abundance	7	11	N2O flux, CO2 flux, C storage, Net Ecosystem Exchange	5	12	C storage, N stock, N mineralization, aggregation, microbial biomass C, infiltration	3	6	% pollutant removal, N leaching, DOC, denitrification potential	4	4	annual ET, flood storage capacity, infiltration
Vernal Pool	0	0		2	4	native species richness, species abundance, species richness	0	0		0	0		0	0		1	1	flood storage capacity
Wetland	0	0		1	2	species abundance, species richness	6	15	CH4 flux, Net Equivalent Emissions, Global Warming Potential, CO2 flux, Net Ecosystem Carbon Balance, C storage	2	2	C storage, subsidence reversal	11	34	% pollutant removal, denitrification potential, total P, MeHg load/flux, Net Ecosystem Accumulation, bioaccumulation, TSS flux	2	2	flood storage capacity, annual ET

Table A2.5 Number of unique observations for all benefit and tradeoff metrics recorded in the reviewed literature, 2010-2020 for the Central Valley of California.

Benefit Category	Metric	# observations
air quality	PM10 emissions	8
	NOx flux	7
	ozone formation	2
biodiversity	species richness	22
	species diversity	18
	species abundance	12
	native species % cover	6
	microbial community composition	3
	native species richness	3
	weed species % cover	3
	change in native spp richness	2
	bird density index	1
	microbial community diversity	1
climate regulation	N2O flux	63
	C storage	50
	CH4 flux	26
	CO2 flux	15
	Sustained Global Warming Potential	7
	Global Warming Potential	5
	Net Ecosystem Carbon Balance	5
	Net Ecosystem Exchange	1
	Net Equivalent Emissions	1
crop production	pollination	6
human health	pesticide application	6
livestock production	forage production	15
soil quality	C storage	50
	infiltration	5
	microbial biomass C	3
	microbial community composition	3
	N mineralization	3
	aggregation	2
	belowground net primary productivity	2
	C mineralization	2
	decomposition	2
	erosion control	2
	Potentially Mineralizable N	2
	subsidence reversal	2
	microbial activity	1
	microbial community diversity	1
	soil N stock	1
water quality	N leaching	31
	% pollutant removal	22
	N load	11
	groundwater nitrate	8
	Nitrate Hazard Index	7
	[DOC]	6
	MeHg load	5
	Net Ecosystem Accumulation	5
	pollutant accumulation in sediment	4
	Net Ecosystem Production	4
	[TDS]	4
	C storage	3
	denitrification potential	3
	P load	3
	bioaccumulation	2
	total P	2
	TSS flux	2
	DOC flux/load	1
	DON load	1
	Hg flux	1
	N flux	1
	P flux	1

Table A2.5 continued…

Benefit Category	Metric	# observations
water quality	[TSS]	1
water supply	water use	20
	annual ET	17
	water productivity	10
	groundwater recharge	7
	infiltration	5
	blue water productivity	3
	potential flood storage capacity	3
	blue water use	2
	green water consumption	2
	basin recharge	1
	green water productivity	1
	runoff to basin	1
	Total # observations:	**570**

Appendix III: Methods for the benefit-tradeoff analysis

All analyses were performed in R version 3.5.2 [121]. The database of multiple benefits metrics was first merged with information acquired from public databases and censuses (e.g., crop production values, pesticide usage reports, wages and employment, and water use), and with the Avian Conservation Scores. This merged database was used for all subsequent steps of the analysis.

Because of the large diversity of metrics considered in the literature for different land covers and benefits categories, and the accompanying diversity of units for each metric that were often particular to individual studies, a series of conversions was required to obtain a minimum common dataset for comparison of metrics within and across land covers. No conversions were required for the wildlife benefit category as only one metric (the Avian Conservation Score) was included.

Unit conversions for healthy environment metrics

The healthy environment benefit group included air quality and pesticide use metrics. Metrics for NOx flux were converted to g NOx-N ha^{-1} day^{-1} as given in **Table A3.1** below:

Table A3.1 Unit conversions for NOx flux measurements. Conversions listed here are not exhaustive, but rather reflect the actual units encountered in the literature for each metric.

Original unit	Conversion factor to g NOx-N ha^{-1} day^{-1}
x g NOx-N ha^{-1} hr^{-1}	x*24
x kg NO-N ha^{-1} yr^{-1}	x*1000/365

No unit conversions were required for PM10 emissions or pesticide use rates as these were all derived from a single source and given in Metric tons yr^{-1} and kg ha^{-1}, respectively.

Unit conversions for climate regulation metrics

The climate regulation benefit group included carbon storage/sequestration and CO_2, CH_4, and N_2O flux metrics, which were each converted to a common unit of C or N flux ha^{-1} yr^{-1} as given in **Table A3.2**. Where gas species were reported as total molecular weights rather than proportion C or N weight, we used the appropriate species conversion factors as given by the IPCC Methodologies for Greenhouse Gas Inventories [122].

Carbon-related metrics were reported in the literature variously as carbon storage in Mg C ha^{-1}, net equivalent emissions, net ecosystem carbon balance (NECB), net ecosystem exchange (NEE), or Global Warming Potential, among others. Measurements of net equivalent emissions and NEE were categorized under carbon sequestration and converted to a common rate unit of kg C ha^{-1} yr^{-1}. NECB was omitted from the analysis both to avoid double-counting, as it is the sum of net ecosystem exchange of CH_4 and CO_2 metrics that were already included in the analysis, and because it was reported in only 1 study. Where negative flux values indicated that the land cover was a net sink rather than a source of the greenhouse gas (e.g., net ecosystem exchange of C in wetlands), these were categorized as C sequestration benefits rather than GHG flux tradeoffs in the comparative analysis.

Table A3.2 Unit conversions for climate regulation metrics. Conversions listed here are not exhaustive, but rather reflect the actual units encountered in the literature for each metric.

Original unit of CH_4-C flux	**Conversion factor to kg CH_4-C ha^{-1} yr^{-1}**
x kg CH_4 ha^{-1} yr^{-1}	x/1.33
x g CH_4-C m^{-2} yr^{-1}	x*10
x Mg CH_4 yr^{-1}	x*1000/[area]/1.33†

Original unit of C or CO_2eq sequestration	**Conversion factor to kg ha^{-1} yr^{-1}**
x g m^{-2} yr^{-1}	x*10
x kg m^{-2} yr^{-1}	x*10000

†converted to per-area basis using area of the land cover in question in the Central Valley

Original unit of CO_2-C, flux	**Conversion factor to Mg CO_2-C ha^{-1} yr^{-1}**
x g CO_2-C m^{-2} yr^{-1}	x/100

Original unit of N_2O-N flux	**Conversion factor to g N_2O-N ha^{-1} yr^{-1}**
x Mg N_2O-N ha^{-1} yr^{-1}	x*1e^6
x kg N_2O-N ha^{-1} yr^{-1}	x*1000
x kg N_2O ha^{-1} yr^{-1}	x/1.57*1000
x lb N_2O-N $acre^{-1}$ yr^{-1}	x*454*2.471

Unit conversions for economy metrics

The economy benefit group included average weekly wages, employment, and production value metrics. No unit conversions were required for wage and employment metrics as these were derived from a single source. Crop production values were converted from total $USD to $USD ha^{-1} using reported harvested acreages (USDA-NASS, **Table A2.1**). Forage production units were first converted to kg ha^{-1} yr^{-1} of annual net primary productivity, then to agricultural use value as described in Eastburn et al. [73]. The assumptions for converting to agricultural use value are as follows:

- $USD ag use value = animal unit months * (average lease rate USD/AUM)
- AUM = (net annual forage production – residual dry matter recommended)/354
- 1 AUM = one mature 454 kg cow grazing for 30 days
- Recommended residual dry matter is 672 kg for grasslands
- 354 kg dry matter is required to support 1 AUM
- Average pastureland lease rate is $12 $acre^{-1}$ or $29.7 ha^{-1} for 2017 [123]

Unit conversions for water metrics

The water benefit group included nitrate leaching, consumptive water use, annual evapotranspiration (ET), water productivity, and N pollution mitigation metrics where available. Other metrics were reported as shown in the gap analysis in Section II, but these metrics had the best representation in the literature and were typically reported in more than one source. In general nitrate leaching was reported in kg N ha^{-1} yr^{-1}. Pollution mitigation (e.g., in wetlands and riparian areas) was typically reported as percent removal from inflow/outflow samples. Although metrics were available for % removal P, MeHg, TSS, and many other contaminants, we chose to restrict the analysis to the most widely available metric which was % removal N.

Metric standardization and comparison

The Multiple Benefits Index was calculated by normalizing all of the above metrics to a similar scale to enable comparison of multiple benefits and tradeoffs across land cover types. To compare benefit metrics across land covers, reported values were converted to the same unit of measure and then transformed to a 0-1 scale by setting the highest reported value across all land covers to 1 and then calculating the remaining values according to the following formula:

$$MBI = \frac{X_i - \min(|X|)}{\max(|X|) - \min(|X|)}$$

where MBI represents the Multiple Benefits Index, or the normalized value of X, and X_i represents a single value in the vector of values for X. Observations were treated separately when they were taken from multiple, independent experimental sites within the same study. For studies that included multiple observations for different treatments and treatment-years at the same site, we used the average of all treatments to calculate the MBI. The latter approach should be kept in mind when interpreting our results, as it occasionally would have included non-typical treatments and controls that would not ordinarily be practiced in an agronomic setting, such as zero-N fertility or deficit irrigation treatments.

Metrics were then categorized *post hoc* as either “benefits” or “tradeoffs” depending on their perceived value to the above sectors or interests. Benefits were those metrics that related to provisioning of a desirable service such as pollutant removal, while tradeoffs were metrics that related to provisioning of an undesirable service such as greenhouse gas emissions. Metrics considered tradeoffs were assigned a negative value by multiplying the Multiple Benefits Index by -1.

The results of within-land cover benefit/tradeoff analyses were presented in the individual land cover profiles in Section I, while the results of cross-land cover benefit/tradeoff analysis are presented below.

Appendix IV: Methods for index development through expert survey

In addition to the data extracted from peer-reviewed literature described in Appendix III, we developed two independent indices based on expert sources from universities – ecology and agriculture faculty at the University of California Davis and UC Berkeley – and conservation organizations, principally members of the Migratory Bird Conservation Partnership science committee. The Avian Conservation Score was included in the benefit-tradeoff analysis as an indicator of benefits to wildlife or support for biodiversity. The Climate Change Vulnerability Index was intended as a standalone score to provide context around the changing management targets and conservation goals that may be required given uncertainty around climate change impacts.

Avian Conservation Score

The Avian Conservation Score (ACS) rates Central Valley land covers according to their value for providing habitat for use by select avian taxa. Use in this context refers to nesting, roosting, or foraging. Land cover types were scored assuming average management practices for the Central Valley, with the exception of corn which was assumed to be grown for grain and flooded post-harvest as practiced in the Delta region. Grain corn that is flooded post harvest provides more value to various taxa than corn for feed or silage that is not flooded, which is typical of the rest of the Central Valley, and the ACS reflects this additional value from corn as managed in the Delta. Scoring reflected the probable change in habitat value of a given land cover after hypothetical conversion to another land cover. A land cover conversion resulting in an increase in score for a species group is intended to reflect a net benefit to that group, whereas a decrease in score from a land cover conversion reflected a net loss. The scoring scale ranged from 3-0, with 3 = high (primary habitat), 2 = medium (secondary habitat), 1 = low (used by only a few species in the group or under relatively rare/infrequent management conditions), and 0 = minimal/no value.

For each land cover type, scores for all species groups were summed and then transformed to a 1-0 scale, with 1 being the highest habitat value across avian groups and 0 being the lowest value habitat. Separate scores were assigned for breeding and non-breeding seasons for waterfowl, shorebirds, and waterbirds because of their distinct habitat requirements and species compositions. A single score was assigned for riparian, oak woodland, and grassland landbirds to represent habitat value year-round. However, scores for landbirds were given double weight in the overall Avian Conservation Score so that each avian species group contributed equally to the standardized result.

The bird species considered in the scoring were grouped into categories originally developed for the Central Valley Joint Venture planning objectives [97]. The species groups and focal species included in each group are listed in **Table A4.1**. The focal species included in each group were not intended to be exhaustive, nor were focal species limited to the ones listed here, but rather they served as a mental guide to the scorers for the kind of species to consider when scoring each land cover type.

Table A4.1 Avian species groups and focal species considered for scoring Central Valley land cover types according to value for habitat (Avian Conservation Score) by a panel of 12 domain experts.

Group	Focal species
Grassland landbirds	Burrowing Owl, Grasshopper Sparrow, Horned Lark, Northern Harrier, Western Meadowlark
Oak savannah landbirds	Acorn Woodpecker, American Kestrel, Lark Sparrow, Loggerhead Shrike, Western Bluebird, Western Kingbird, Yellow-Billed Magpie
Riparian landbirds	Least Bell's Vireo, Yellow-Billed Cuckoo, Bank Swallow, Yellow-Breasted Chat, Lazuli Bunting, Yellow Warbler, Common Yellowthroat, Black-Headed Grosbeak, Nuttall's Woodpecker, Ash-Throated Flycatcher, Song Sparrow, Spotted Towhee
Non-breeding season waterfowl	Northern Pintail, Tule Greater White-Fronted Goose, Aleutian Canada Goose
Non-breeding season shorebirds	Black-Necked Stilt, American Avocet, Black-Bellied Plover, Snowy Plover, Semipalmated Plover, Killdeer, Greater Yellowlegs, Whimbrel, Long-Billed Curlew, Marbled Godwit, Dunlin, Least Sandpiper
Non-breeding season waterbirds	Eared Grebe, Western Grebe, Black Rail, Sandhill Crane, American White Pelican, Forster's Tern, Snowy Egret, White-Faced Ibis
Breeding season waterfowl	Mallard, Gadwall, Cinnamon Teal, Northern Pintail, Northern Shoveler, Wood Duck, Ruddy Duck, Hooded Merganser, Common Merganser, Redhead
Breeding season shorebirds	Black-Necked Stilt, American Avocet, Killdeer, Snowy Plover, Spotted Sandpiper, Wilson's Snipe, Wilson's Phalarope
Breeding season waterbirds	Eared Grebe, Western Grebe, Black Rail, Clack Tern, Least Bittern, Forster's Tern, Snowy Egret, White-Faced Ibis

Only the final, rescaled score was used in the benefit-tradeoff analysis. The full scoring for each land cover type and avian species group is given in **Table A4.2**.

Table A4.2 Full scoring of land cover types, with scores for individual species groups highlighted in green and final Avian Conservation Score highlighted in yellow. Individual species group scores are on a 0-3 scale, with 3 representing the highest habitat value (primary habitat) and 0 representing minimal or no value for a given species group. The final Avian Conservation Score is on a 0-1 scale with 1 representing the highest habitat value and 0 the lowest. Scores for landbirds were assigned double weight to account for the lack of distinct breeding/non-breeding season categories.

Land cover	Grassland landbirds	Oak savannah landbirds	Riparian landbirds	Non-breeding season waterfowl	Non-breeding season shorebirds	Non-breeding season waterbirds	Breeding season waterfowl	Breeding season shorebirds	Breeding season waterbirds	Total score	Rescaled total score
wetland	1	0	2	3	3	3	3	3	3	24	1.00
riparian	0	3	3	2	0	1	1	1	2	19	0.79
deciduous orchard crops (fruits and nuts)	0	1	1	0	0	0	0	0	0	4	0.17
evergreen orchard crops (citrus, subtropical fruit)	0	1	1	0	0	0	0	0	0	4	0.17
vineyard (table and wine grapes)	0	1	1	0	0	0	0	0	0	4	0.17
grassland/pasture/rangeland/hay (not alfalfa)	3	2	1	1	1	1	3	1	1	20	0.83
alfalfa	1	1	0	1	2	1	1	1	1	11	0.46
rice	0	0	1	3	3	3	3	3	3	20	0.83
corn (as managed in the Delta - grown for grain and flooded postharvest)	0	0	0	3	3	3	0	0	0	9	0.38
cereals (winter wheat, oat, barley, etc.)	1	0	0	2	1	1	3	0	0	9	0.38
tomato	0	0	0	1	1	1	0	0	0	3	0.13
cotton	0	0	0	1	1	1	0	0	0	3	0.13

Climate Change Vulnerability Index

As with the Avian Conservation Score, we surveyed a panel of subject matter experts to gain a qualitative understanding of the dynamics of managing for multiple benefits under climate change in the form of a Climate Change Vulnerability Index (CCVI). The scoring mechanism and index calculation were implemented similarly to the climate change vulnerability analysis for California's at-risk birds developed by Gardali et al. [98]. Each of the panel of 12 subject-matter experts scored Central Valley landcovers on a series of sensitivity and exposure factors given in **Table A4.3**. Sensitivity factors refer to intrinsic, physiological characteristics that make a land cover more vulnerable to the impacts of climate change. Exposure factors refer to extrinsic, environmental factors that make a land cover more vulnerable to climate change. Some sensitivity/exposure factors were not considered for agricultural or natural land covers where they were not applicable. These cases are noted in **Table A4.3**.

Table A4.3 Sensitivity and exposure factors considered for calculating the Climate Change Vulnerability Index for land covers in California's Central Valley. Land covers were scored for their relative sensitivity or exposure to each factor by a panel of 12 domain experts.

Sensitivity factors	
Management rigidity*	Land cover is sensitive to climate change due to management rigidity, i.e., it is difficult to fallow, migrate, or swap for another land cover.
Specificity+	Land cover is sensitive to climate change due to reliance on a narrow suite of geophysical conditions, e.g., soil type, elevation, temperature/precipitation regime. More sensitive land covers have low geophysical diversity within their current ranges.
Drought	Land covers that are sensitive to drought have negative productivity or functionality impacts from dry spells, have high consumptive water use, lack of conservation irrigation options such as subsurface drip, or heavy dependence on groundwater/surface water.
Flood	Land covers that are sensitive to flooding have negative physiological impacts from temporary submersion that can affect ecosystem functioning.
Temperature	Land covers that are sensitive to temperature have negative physiological impacts from temperature extremes that can affect ecosystem functioning, e.g., yield reduction due to too few chilling hours or to heat spells during anthesis.
Exposure factors	
Pests, diseases, or invasion	Exposure is higher for land covers that are subject to impacts from pests, diseases, or invasive species leading to loss of functionality, productivity, or suitability range, among others. E.g., citrus greening for subtropical orchards, navel orangeworm for almonds, or medusahead for grasslands.
Markets*	Exposure is higher for land covers affected by commodity market volatility, e.g., crops that are highly perishable, easily substitutable, or have large upfront or sunk management costs.
Pollution+	Exposure is higher for land covers that are negatively impacted by environmental pollution or contamination, e.g., nitrogen deposition, ozone toxicity, salinization, among others. These factors may be independent of climate change impacts but are expected to interact with them.
Land use/land cover change	Exposure is higher for land covers likely to experience range restrictions from lost climatic or environmental suitability or land use conversions.
Capacity gaps	Exposure is higher for land covers with a knowledge and capacity gap, e.g., those that lack a strong commodity board or cooperative, or lack investment in research and development to enable adaptive measures.

*only applies to agricultural land covers
+only applies to natural land covers

For each sensitivity/exposure factor, land covers were rated on a scale of 1-3, where 1 is low sensitivity/low exposure and 3 is high sensitivity/high exposure. To calculate the overall CCVI, sensitivity scores and exposure scores were summed individually for each land cover and then multiplied together as in the following equation:

$$CCVI = \Sigma(\text{sensitivity scores}) * \Sigma(\text{exposure scores})$$

Land covers were then ranked from highest to lowest climate change vulnerability and mapped on a two-dimensional matrix to illustrate the relative contribution of sensitivity or exposure factors to their CCVI score.

The full scoring for each land cover and exposure/sensitivity factor is presented in **Table A4.4** below.

Table A4.4 Full scoring results for the Climate Change Vulnerability Index applied to land covers in California's Central Valley. Within each land cover type, the sensitivity or exposure factor mean was calculated across scores given by 12 domain experts. The means for each factor type (sensitivity or exposure) within a land cover were then multiplied to obtain the final CCVI. Blank cells indicate no response.

			Scorer														
Land Cover	Factor Type	Factor	A	B	C	D	E	F	G	H	I	J	K	L	Factor mean	Factor type mean	CCVI (sensitivity x exposure)
Alfalfa	sensitivity	Management rigidity		1	2	2	2	2		2	1	1	2	2	1.7	1.8	3.0
		Drought		2	2	2	3	2		3	2	2	2	3	2.3		
		Flood		1	2	1		2			1	2	2	2	1.6		
		Temperature		1	2			1			1	2	1	2	1.4		
	exposure	Pests & diseases		1				2		2	1	2		2	1.7	1.7	
		Market volatility		1				3		2	1		2	1	1.7		
		Land use/land cover change		1				3		2	1	3	1	1	1.7		
		Capacity gap		2				2			1	2	2	1	1.7		
Citrus	sensitivity	Management rigidity		2	3	3	3	3		3	3	3	3	3	2.9	2.7	5.4
		Drought		2	3	3	3	3			3		1	3	2.6		
		Flood		3	2	3		2			2	3	2	3	2.5		
		Temperature		3	3			3		2	3		3	2	2.7		
	exposure	Pests & diseases		2				3		3	2			3	2.6	2.0	
		Market volatility		2						2	3		2	3	2.4		
		Land use/land cover change		2				2		1	2		1	2	1.7		
		Capacity gap		2				2			2	1	1	1	1.5		
Corn	sensitivity	Management rigidity		1	1	1	1	1		1	1	1	1	1	1.0	1.6	2.4
		Drought		2	1	1	3	2		2	1	2	3	2	1.9		
		Flood		2	3	2		1			1	3	3	2	2.1		
		Temperature		1	2			1			1	1	2	3	1.6		
	exposure	Pests & diseases		1				1		1	1			2	1.2	1.5	
		Market volatility		1				3		2	1		1	2	1.7		
		Land use/land cover change		1				2		1	1		3	1	1.5		
		Capacity gap		1				1			1	2	3	1	1.5		
Cotton	sensitivity	Management rigidity		1	1	1	1	1		2	1	1	1	1	1.1	1.6	2.6
		Drought		2	1	1	3	2		3	2	2	2	2	2.0		
		Flood		2	3	2		1			2	3	2	2	2.1		
		Temperature		1	2			1			1	1	2	3	1.4		
	exposure	Pests & diseases		2				2		3	3			1	2.2	1.6	
		Market volatility		1				2			1		2	1	1.4		
		Land use/land cover change		1				2		1	1		3	1	1.3		
		Capacity gap		1				2			1	2	2	1	1.5		

Table A4.4 continued…

Land Cover	Factor Type	Factor	A	B	C	D	E	F	G	H	I	J	K	L	Factor mean	Factor type mean	CCVI (sensitivity x exposure)
Grassland	sensitivity	Specificity	2	2	1	1		3	3	2	2	2	1	2	1.9	1.5	3.3
		Drought	2	1	1	1	2	2	1	3	1	1	2	1	1.5		
		Flood	2	1	1	1		1	1	1	1	2	1	1	1.2		
		Temperature	1	1	1			3	1	1	1	1	1	1	1.2		
	exposure	Pests & diseases	2	1				2	3	3		2		3	2.3	2.2	
		Pollution	3	1		2		3	1	1	1	1	1	2	1.6		
		Land use/land cover change	3	3		1		3	3	3	3	2	1	3	2.5		
		Capacity gap	3	3				2			3	3	2	3	2.7		
Orchard crops		Management rigidity		1	3	3	3	3		3	3	3	3	3	2.8	2.5	5.2
	sensitivity	Drought		3	3	3	3	3		3	3	3	1	3	2.8		
		Flood		1	2	3		2		2	2	2	2	2	2.0		
		Temperature		2	3			2		3	3	1	3	3	2.5		
	exposure	Pests & diseases		2				3			3			3	2.8	2.0	
		Market volatility		2				3		3	3		3	2	2.7		
		Land use/land cover change		2				1		1	3	1	1	2	1.6		
		Capacity gap		1				2			3	1	1	1	1.5		
Pasture/ Rangeland	sensitivity	Management rigidity	1	2	3	2	2	3		3	1	2	2	2	2.1	1.7	3.7
		Drought	2	1	1	1	3	1	2	3	2	2	2	2	1.8		
		Flood	2	1	1			3	2	1	2	2	1	1	1.6		
		Temperature	1	1	1			3	2	1	1	1	1	1	1.3		
	exposure	Pests & diseases	2	1				2	3	3	1	1		3	2.0	2.2	
		Market volatility		1				2	2	1	1		2	1	1.4		
		Land use/land cover change	3	3		1		3	2	3	3	2	3	3	2.6		
		Capacity gap	2	2				2			3	3	2	3	2.4		
Rice	sensitivity	Management rigidity		2	3	3	1	3		3	2	1	2	2	2.2	1.9	3.2
		Drought		3	2	3	3	3		3	2	2	3	3	2.7		
		Flood		1	1	1		1		1	1	1	1	1	1.0		
		Temperature		1	2			1		2	3	2	2	1	1.8		
	exposure	Pests & diseases		2				2		1	1			2	1.6	1.6	
		Market volatility		2				2		2	2		2	1	1.8		
		Land use/land cover change		2		1		2		1	2	2	2	2	1.8		
		Capacity gap		1				2			2	1	1	1	1.3		
Riparian	sensitivity	Specificity	3	3	2	3		3	2	3	2	3	2	1	2.5	1.8	4.1
		Drought	2	2	2	2	2	2	3	2	2	2	1	2	2.0		
		Flood	2	1	1	1		1	2	1	1	1	1	1	1.2		

Table A4.4 continued…

Land Cover	Factor Type	Factor	A	B	C	D	E	F	G	H	I	J	K	L	Factor mean	Factor type mean	CCVI (sensitivity x exposure)
Riparian		Temperature	2	1	1			2	3	1	1	1	1	1	1.4		
	exposure	Pests & diseases	3	2				1	3	1	1	2		1	1.8	2.3	
		Pollution	2	2		2		3	3	3	1	2	2	2	2.2		
		Land use/land cover change	3	3		1		3	3	3	3	3	2	3	2.7		
		Capacity gap	3	2							3	3	2	2	2.5		
Tomato	sensitivity	Management rigidity		1	1	1	1	1		2	3	1	1	1	1.3	1.9	4.1
		Drought		1	1	1	3	2			3	2	3	3	2.1		
		Flood		2	3	2		1		3	2	3	3	2	2.3		
		Temperature		2	2			3		2	3	2	2	1	2.1		
	exposure	Pests & diseases		1				3			2			3	2.3	2.1	
		Market volatility		2				3		3	3		1	3	2.5		
		Land use/land cover change		1				3		1	2	2	3	1	1.9		
		Capacity gap		1				2			2	2	3	1	1.8		
Vineyard	sensitivity	Management rigidity		2	3	3	3	2		3	3	3	3	3	2.8	2.3	4.2
		Drought		2	1	3	3	1			3	3	1	2	2.1		
		Flood		1	1	3		2			3	2	2	1	1.9		
		Temperature		3	1			1			3	2	3	3	2.3		
	exposure	Pests & diseases		2				1			2			3	2.0	1.8	
		Market volatility		2				1		3	3		2	2	2.2		
		Land use/land cover change		3		2		1		1	2	1	1	3	1.8		
		Capacity gap		1				2			3	1	1	1	1.5		
Wetland	sensitivity	Specificity	3	2	3	2		3	3	3	2	2	3	3	2.6	2.0	4.5
		Drought	2	3	3	3	2	3	3	3	2	3	2	3	2.7		
		Flood	1	1	1	1		1	1	1	1	1	1	1	1.0		
		Temperature	2	1	1			3	2	2	1	1	1	1	1.5		
	exposure	Pests & diseases	2	3				1	2	2	1	2		2	1.9	2.3	
		Pollution	2	3		1		3	3	3	1	3	3	3	2.5		
		Land use/land cover change	3	3		1		1	3	3	3	1	2	3	2.3		
		Capacity gap	3	2							3	3	2	2	2.5		
Winter Cereals	sensitivity	Management rigidity		1	1	1	1	1		1	1	1	1	1	1.0	1.5	2.3
		Drought		1	1	1	2	1		1	2	1	3	1	1.4		
		Flood		1	3	2		2			2	3	3	2	2.3		
		Temperature		1	2			1		1	1	1	1	3	1.4		
	exposure	Pests & diseases		1				2		1	1	1		2	1.3	1.6	
		Market volatility		1				3		1	1		3	1	1.7		
		Land use/land cover change		1				1		2	1	2	2	1	1.4		
		Capacity gap		1				2			1	3	2	2	1.8		

Appendix V: Annotated bibliography

1. Smart, D. R., Alsina, M. M., Wolff, M. W., Matiasek, M. G., Schellenberg, D. L., Edstrom, J. P., et al. (2011). **N2O emissions and water management in California perennial crops.** ACS Symp. Ser. 1072, 227–255. doi:10.1021/bk-2011-1072.ch013.
Land cover(s): orchard – almond
Ecosystem Service(s): climate regulation
Metric(s): N2O flux
Location: Colusa county
Study description: Field experiment documenting the extreme spatial and temporal variability in denitrifying activity associated with nitrous oxide emissions in almond, an N-intensive crop. N2O accounts for just over half of all emissions from agriculture in California, which original mostly from N fertilization, followed by manure management and residue burning. However, capturing N2O flux is challenging because it is sensitive to many factors, including soil texture, moisture content, carbon content, topography, and irrigation water application method (e.g. drip or sprinkler). N2O emissions are highest just after a precipitation or irrigation event.

2. Halvorson, A. D., Steenwerth, K. L., Suddick, E. C., Liebig, M. A., Smith, J. L., Bronson, K. F., et al. (2012). **Management to reduce greenhouse gas emissions in western U.S. Croplands.** Elsevier Inc doi:10.1016/B978-0-12-386897-8.00010-3.
Land cover(s): various
Ecosystem service(s): climate regulation
Metric(s): greenhouse gas flux
Location: Western U.S., with case studies in Yolo, Colusa, Napa, and Monterey counties
Study description: Review of the effects of agricultural management on emissions of N2O, CH4, and CO2 in Western U.S. production systems. The authors describe the major sources of fluxes in both irrigated and dryland contexts as well as the management practices that impact them, drawing from experimental field studies since 2005. CO2 flux is primarily related to root respiration and microbial decomposition of soil organic carbon, and is influenced by tillage, cropping intensity, and crop type. CH4 fluxes in agricultural lands are typically small and associated with manure management and flooded rice production, and dryland systems are even considered a net CH4 sink. N2O is by far the most impactful GHG with a global warming potential almost 300 times greater than CO2, and agriculture accounts for over 60% of U.S. emissions of N2O. In irrigated systems, N2O emissions are linearly associated with N fertilization rates, with tillage and crop type also having some influence. Gaps in GHG mitigation knowledge are addressed.

3. Cayuela, M. L., Aguilera, E., Sanz-Cobena, A., Adams, D. C., Abalos, D., Barton, L., et al. (2017). **Direct nitrous oxide emissions in Mediterranean climate cropping systems: Emission factors based on a meta-analysis of available measurement data.** *Agric. Ecosyst. Environ.* 238, 25–35. doi:10.1016/j.agee.2016.10.006.
Land cover(s): corn, perennial, winter cereal, rice
Ecosystem service: climate regulation
Metric(s): N2O flux, emission factor (%)
Location: Mediterranean climate regions, including California
Study description: Meta-analysis of nitrous oxide emissions for various cropping systems in Mediterranean climate regions, including 14 studies in California. In addition to compiling annual net N2O emissions, the authors calculated the emissions factor (EF). EF is defined as the difference between N2O emissions from a fertilized treatment and the non-fertilized (control) treatment, divided by the N fertilizer application rate (kg N ha-1). Both annual N2O flux and EF was highest in corn and horticultural crops, although crop types were not significantly different from one another. EFs ranged from 0.8% in corn to 0.2% in rice. The effects of water and fertilizer management are also discussed.

4. Hatala, J. A., Detto, M., Sonnentag, O., Deverel, S. J., Verfaillie, J., and Baldocchi, D. D. (2012). **Greenhouse gas (CO2, CH4, H2O) fluxes from drained and flooded agricultural peatlands in the Sacramento-San Joaquin Delta.** *Agric. Ecosyst. Environ.* 150, 1–18. doi:10.1016/j.agee.2012.01.009.
Land cover(s): rice
Ecosystem service: climate regulation, land subsidence mitigation
Metric(s): CO2 flux, CH4 flux, evaporation, net ecosystem exchange, approximate soil subsidence (due to SOC oxidation)
Location: Sacramento-San Joaquin Delta
Study description: Field experiment derived from eddy covariance flux tower measurements at a conventional drained/grazed and a restored, flooded rice paddy in the San Joaquin Delta, Twitchell Island area. Peat oxidation due to wetland drainage for agriculture has caused extreme rates of land subsidence in the delta. Rice agriculture is a proposed alternative, with flooded conditions that mitigate SOC oxidation and better approximate the original wetland functions. The grazed degraded peatland was a net source of CO2 while the flooded rice paddy was a net sink of CO2. The rice paddy emitted more CH4 and lost more water to evaporation than the degraded peatland, but showed reduced rates of land subsidence.

5. Underwood, E. C., Hutchinson, R. A., Viers, J. H., Kelsey, T. R., Distler, T., and Marty, J. (2017). **Quantifying trade-offs among ecosystem services, biodiversity, and agricultural returns in an agriculturally dominated landscape under future land-management scenarios.** San Fr.

Estuary Watershed Sci. 15. doi:10.15447/sfews.2017v15iss2art4.
Land cover(s): grassland, oak woodland, alfalfa, winter cereals, orchard, rice, vineyard, pasture
Ecosystem service(s): climate regulation, biodiversity, thriving economy
Metric(s): carbon storage, N leaching, N2O emissions, Swainson's Hawk presence/absence, landscape suitability scores, annual revenue per hectare
Location: Cosumnes River area
Study description: Quantifies baseline ecosystem service values for three land-use types (agricultural, natural, and urban) and analyzes tradeoffs for these services under different scenarios of development in the next 50 years (restoration to natural habitat, increasing urbanization, or wildlife-friendly agriculture). The authors estimated spatially explicit values for carbon storage, bird habitat suitability, N leaching, and N2O emissions for the various land cover types using available data and literature. For example, aboveground carbon storage (Mg ha-1) in annual crops was estimated as the yield divided by the harvest index of each crop, multiplied by 0.45 with the assumption that this represents the proportion of the plant that is carbon. Landscape suitability for Swainson's Hawk and associated bird species was assessed by creating presence/absence maps from field surveys and randomly generated pseudo-absence points. These maps were then fit to baseline land cover data using Boosted Regression Trees. Nitrous oxide emissions were calculated using standard IPCC guidelines for emissions from average nitrogen fertilizer application rates for different crops. Nitrate leaching was calculated as the difference between nutrient inputs and nutrient losses. The authors found that the restoration scenario benefited carbon storage, bird habitat, and decreased N2O emission and N leaching, at the expense of agricultural returns. The urbanization scenario negatively impacted carbon storage, bird habitat, and agricultural returns. The enhanced agriculture scenario benefited carbon storage and bird habitat at the expense of increase N2O emissions and N leaching.

6. Almaraz, M., Bai, E., Wang, C., Trousdell, J., Conley, S., Faloona, I., et al. (2018). **Agriculture is a major source of NOx pollution in California.** Sci. Adv. 4, 1–9. doi:10.1126/sciadv.aao3477.
Land cover(s): croplands, natural ecosystems
Ecosystem service(s): NOx pollution (disservice)
Metric(s): kg NOx-N ha-1 yr-1
Location(s): Central Valley
Study description: Large-scale quantification of NOx emissions for the entire Central Valley region. The authors used complementary "bottom-up" spatial modeling approaches with "top-down" airborne NO measurements to map the contributors to NOx pollution in the state. Results showed that cropland accounted for 79% of the Central Valley's total NOx emissions from soil, and 20-32% of total NOx emissions from all sources. Simulated NOx emissions using the IMAGE model were primarily determined by N fertilization rates and climate, whereas soil carbon had little influence on model outcomes. Climate changes in California such as heat waves and drought have the potential to exacerbate air pollution from NOx emissions and increase N deposition in natural ecosystems. The authors suggest N efficiency-enhancing products, precision agriculture, and alternative N sources and timings as approaches to reduce soil NOx emissions from fertilized cropland.

7. Matios, E., and Burney, J. (2017). **Ecosystem Services Mapping for Sustainable Agricultural Water Management in California's Central Valley.** Environ. Sci. Technol. 51, 2593–2601. doi:10.1021/acs.est.6b05426.
Land cover(s): various crops
Ecosystem service(s): groundwater recharge, watershed function
Metric(s): water yield, water consumption (km3 yr-1)
Location(s): Fresno county
Study description: InVEST ecosystem service mapping model was used to estimate water yield and water consumption as functions of land use. Water demand and inferred groundwater use were disaggregated to individual crops. Water yield in the InVEST model is represented as the difference between precipitation and actual evapotranspiration, the latter of which consists of reference ET, root-restricting layer depth, plant available water content, and land use. InVEST outputs the water resupply, which is the different between water yield and water consumption, at the watershed scale. Inputs to the model included high-resolution annual temperature and precipitation data from PRISM, annual reference ET maps, Fresno County's cropland data layers from USDA NASS, and a water-demand table with water-use requirements for various land use types. Results showed that 96% of Fresno county's total water consumption came from croplands, with an increasing disconnect between annual water yields and consumption. Crop water needs are increasingly met with surface water from outside the county and by private groundwater pumping, and adaptability in the face of hydrologic stress is restricted by the expansion of perennial orchard crops.

8. Wolff, M. W., Alsina, M. M., Stockert, C. M., Khalsa, S. D. S., and Smart, D. R. (2018). **Minimum tillage of a cover crop lowers net GWP and sequesters soil carbon in a California vineyard.** Soil Tillage Res. 175, 244–254. doi:10.1016/j.still.2017.06.003.
Land cover(s): vineyard
Ecosystem service(s): climate regulation
Metric(s): Global Warming Potential (GWP), SOC sequestration, NPP, N2O and CH4 emissions, fossil fuel consumption

Location(s): Napa county
Study description: Field experiment demonstrating the effect of minimum-till management with a barley cover crop on Global Warming Potential of a Napa Valley vineyard. Net GWP describes exchanges of CO2, CH4, and N2O and in this study was calculated as CO2 equivalents from soil carbon sequestration, net primary productivity (above- and belowground), N2O emission, soil CH4 flux, fossil fuel consumption from tractor operations, and CO2 emission from soil respiration. The authors performed direct measurements for each of the above variables over 7 years. The minimum-till system resulted in lower yields and lower aboveground net primary productivity, but negative net GWP of approx. -873 kg CO2-eq ha-1 yr-1 due to soil carbon accumulation. Conventional-till alleys had positive net GWP, mostly driven by fuel combustion and soil carbon loss. Methane fluxes were negative for both systems.

9. Suddick, E. C., Ngugi, M. K., Paustian, K., and Six, J. (2013). **Monitoring soil carbon will prepare growers for a carbon trading system.** Calif. Agric. 67, 162–171. doi:10.3733/ca.v067n03p162.
Land cover(s): orchard, vineyard, oak woodland, grassland
Ecosystem service(s): climate regulation
Metric(s): soil carbon sequestration
Location(s): Colusa, Amador, Solano, Napa counties
Study description: Describes a pilot soil carbon monitoring system established in natural and perennial cropping systems along with baseline soil carbon stocks for each land use type. Conventional and conservation (no-till, organic) management practices were compared for each land use. Perennial crops are underrepresented in most carbon stock surveys, and long-term monitoring is required to ensure these systems are accurately represented in future land-use change scenarios and have the data required for ecosystem model validation and calibration. The authors' estimates show that California wine grape acreage stores over 20 million tons of carbon in soil, compared to 5 million tons for almonds and 6 million tons for walnuts under current management practices. Carbon stocks in orchards and vineyards were generally higher in the mid to deep (up to 1 m) soil layers due to cover crop incorporation and tillage practices upon establishment, while in the unmanaged sites more carbon and organic matter was found in the upper 0-10 in. of soil.

10. Horwath, W. R., and Burger, M. (2013). **Assessment of NOx Emissions from Soil in California Cropping Systems.** California Air Resources Board: Sacramento, CA.
Land cover(s): almond, alfalfa, tomato, wheat, corn
Ecosystem service(s): air quality, climate regulation
Metric(s): NOx pollution, N2O flux
Location(s): Colusa, Yolo, Stanislaus, Sacramento counties
Study description: NOx emissions were measured in various cropping systems during the summer for use in regional models of O_3 in the San Joaquin Valley. Emissions varied widely over time depending on soil moisture (e.g., irrigation events), temperature, and time since the last N fertilization event. NOx fluxes were highest at intermediate soil water contents (30-60%), and increased 2.5-fold with each increase of 10 degrees C in soil temperature and 3.5-fold from 1 to 5 cm depth. NOx fluxes typically range from 0.02-2.5 g NO-N ha-1 h-1, but in systems such as corn receiving high N inputs emissions can reach peak hourly fluxes of 40 g NO-N ha-1 h-1 over several days.

11. Dahlke, H. E., Brown, A. G., Orloff, S., Putnam, D., and O'Geen, T. (2017). **Managed winter flooding of alfalfa recharges groundwater with minimal crop damage.** Calif. Agric. 72, 65–76.
Land cover(s): alfalfa
Ecosystem service(s): groundwater recharge
Metric(s): in yr-1 of deep percolation, % deep percolation of applied water
Location(s): Yolo County
Study description: Exploration of intentional winter flooding of agricultural land for the purposes of on-farm winter groundwater recharge. Field experiments on two established alfalfa stands in well-drained soils found high percolation rates, with most applied water reaching the groundwater table. Saturated root-zone conditions were short-lived and did not greatly affect subsequent alfalfa yields. Alfalfa has potential as a land use that promotes groundwater recharge because it is a short-lived perennial, widely grown in California, and is not prone to nitrate leaching due to low N input levels. Furthermore, alfalfa generates substantially lower revenues per acre than other perennial crops in the Central Valley, making risk offsets for winter flooding relatively affordable.

12. Dzurella, K. N., Pettygrove, G. S., Fryjoff-Hung, A., Hollander, A., and Harter, T. (2015**). Potential to assess nitrate leaching vulnerability of irrigated cropland.** J. Soil Water Conserv. 70, 63–72. doi:10.2489/jswc.70.1.63.
Land cover(s): alfalfa, vineyard, grain, corn, strawberry, cotton, tomato, almond, fruit, walnut
Ecosystem service(s): water quality, watershed function
Metric(s): nitrate leaching (hectares vulnerable to NO3 loss), Nitrate Hazard Index
Location(s): Central Valley
Study description: Groundwater nitrate pollution in the Central Valley originates primarily from irrigated cropland. This study uses the Nitrate Groundwater Pollution Hazard Index tool to assess risk of nitrate leaching below rootzone in various cropland types in the Central Valley. The Hazard Index is based on soil properties, crop characteristics, and irrigation system. High risk crops include shallow-rooted annuals with high N requirements just before harvest, such as lettuce. Low risk crops include

deep-rooted perennials with low N inputs, such as alfalfa. Thirty-one percent of the Central Valley was shown to be at high risk for nitrate loss via leaching. This risk would be reduced to 20% of irrigated acreage if micro-sprinkler or drip irrigation were adopted on all orchards, vineyards, and vegetable crops.

13. Gaffney, P., and Yu, H. (2003). **Computing agricultural PM10 fugitive dust emissions using process specific emission rates and GIS.** In: US EPA Annual Emission Inventory Conference (San Diego, CA), 1–10.
Land cover(s): corn, alfalfa, rice, tomato, vineyard, cotton, citrus, almond
Ecosystem service(s): air quality
Metric(s): PM10 emissions (tons yr-1)
Location(s): San Joaquin Valley
Study description: Field test program measuring geologic particulate matter (PM10) originating from agricultural land preparation activities. Land prep activities included discing, ripping, planing, weeding, and harvesting of cotton, almonds, and wheat. PM10 emissions estimates for various crops were allocated temporally based on crop calendars and allocated spatially using digital land cover maps. Field sampling measured PM10 concentrations during agricultural operations, and emissions factors were assigned to land prep activities. Emissions from land preparation were estimated at 13,000 tons PM10 annually, while emissions from harvest were estimated at 13,300 tons PM10 annually. The majority of land prep emissions occurred during the months of October-December, with major contributions from cotton, wheat, and alfalfa crops. The majority of emissions from harvest occurred during September-October with almonds being the principal contributor.

14. Anderson, M., Gao, F., Knipper, K., Hain, C., Dulaney, W., Baldocchi, D., et al. (2018). **Field-scale assessment of land and water use change over the California delta using remote sensing.** Remote Sens. 10. doi:10.3390/rs10060889.
Land cover(s): tomato, citrus, vineyard, sunflower, corn, alfalfa, almond, rice, riparian, nut, pasture
Ecosystem service(s): watershed function
Metric(s): water use, annual and monthly evapotranspiration (mm yr-1)
Location(s): Sacramento-San Joaquin Delta region
Study description: Use of a remote sensing data fusion approach for high spatio-temporal resolution maps of evapotranspiration that can be associated with changes in land use. Daily ET estimates at 30 m resolution were related to detailed land use maps and validated with flux tower measurements. Modeled annual ET was highest for riparian areas, rice, pears, and almonds, whereas ET was lowest for pistachios, tomatoes, citrus, and vineyards. Total annual water use, or ET multiplied by land area occupied by the land use type, was highest for corn and alfalfa, and lowest for citrus, sunflower, and pistachio. The largest reductions in annual ET from 2015-2016 came when almonds were converted to fallow land, while the largest increases in ET came when tomatoes were converted to alfalfa.

15. Eastburn, D. J., O'Geen, A. T., Tate, K. W., and Roche, L. M. (2017). **Multiple ecosystem services in a working landscape.** PLoS One 12, e0166595. doi:10.1371/journal.pone.0166595.
Land cover(s): oak savanna, oak woodland, grassland
Ecosystem service(s): agricultural production, biodiversity, soil quality
Metric(s): forage production, species diversity, species richness, total C/N, bulk density, infiltration
Location(s): Yuba County
Study description: A state-and-transition model framework was used to describe tradeoffs and synergies among ecosystem services in alternative vegetation states. The metric for agricultural production was agricultural use value in USD, calculated as a function of forage production and grazing capacity. Species richness, diversity, and percent cover were catalogued for both native and invasive plant species. Soil health indicators were measure using standard lab and field techniques, and the potential value of soil carbon stores was calculated in terms of offset values. The authors showed that transitions among the more heavily wooded oak woodland sites, treeless grassland sites, and intermediate savanna sites, were accompanied by tradeoffs in the ecosystem services measured. Grassland sites had the most agricultural production value but the least biodiversity and soil health services. On the other hand, savanna and woodland sites exhibited synergies among larger soil nutrient pools, native plant diversity and richness, and fewer invasive species.

16. Díaz, F. J., O'Geen, A. T., and Dahlgren, R. A. (2010). **Efficacy of constructed wetlands for removal of bacterial contamination from agricultural return flows.** Agric. Water Manag. 97, 1813–1821. doi:10.1016/j.agwat.2010.06.015.
Land cover(s): wetland (constructed and restored)
Ecosystem service(s): water quality
Metric(s): percent removal N, P, DOC, TSS, Chlorophyll-a, turbidity, Enterococci, and E. coli
Location(s): San Joaquin Valley, San Joaquin River
Study description: Experimental approach documenting the effectiveness of constructed and restored wetlands for contaminant removal from surface water. Input-output sampling showed that 66-94% of bacterial pathogens from agricultural return flows were retained in wetlands, significantly reducing contaminant load prior to discharge into surface waterways. Total nitrogen and nitrate levels were higher than 5 mg L^{-1} at all input sites, but decreased significantly after passage through wetlands – by up to a factor of 13 for nitrate.

Bacterial pathogen removal efficiency was most influenced by hydraulic residence times, although even very short residence times of less than a day could significantly decrease bacteria indicators by approximately 70%.

17. Butsic, V., Shapero, M., Moanga, D., and Larson, S. (2017). **Using InVEST to assess ecosystem services on conserved properties in Sonoma County, CA.** Calif. Agric. 71, 81–89. doi:10.3733/ca.2017a0008.
Land cover(s): various agricultural and urban/residential
Ecosystem service(s): carbon storage, water quality, water supply
Metric(s): above- and belowground carbon pools, sediment retention, nutrient retention, water yield
Location(s): Sonoma County
Study description: Model-based study using the InVEST toolset to estimate spatially-explicit ecosystem service values for Sonoma County landscapes. Lands were categorized into areas owned by the Sonoma County Agricultural Preservation and Open Space District (protected ag and natural lands), areas directly adjacent to District lands, and lands recently converted from rangeland/woodland to urban or residential development. Using publicly available spatial datasets including LANDFIRE digital vegetation map, SCAPOSD digital elevation model, and NRCS soil viewer, the authors modeled above- and belowground carbon storage, sediment delivery ratio, nutrient retention, and water yield (difference between precipitation and evaporation) ecosystem services. They found that District lands had higher service values for carbon storage, sediment retention, and water yield than adjacent or developed properties, and that correlations among services were driven by topography, soil type, and land use. The authors noted the difficulty in validating modeled estimates as a limitation of the InVEST method.

18. Chaplin-Kramer, R., Tuxen-bettman, K., and Kremen, C. (2011). **Value of Wildland Habitat for Supplying Pollination Services to Californian Agriculture.** Soc. Range Manag., 33–41. doi:10.2111/1551-501X-33.3.33.
Land cover(s): rangeland
Ecosystem service(s): agricultural production
Metric(s): pollination
Location(s): Central Valley, California-wide
Study description: Used results from a field study establishing the relationship between natural habitat availability and pollination services to extrapolate and map the value of pollination services for all Californian agricultural landscapes. County-level crop values were multiplied by their pollination dependence to obtain the value for pollination services for each crop in each county. The LANDFIRE Existing Vegetation Type dataset was used to map the landcover types falling within a 2.4 km radius of agricultural parcels and classify landcovers according to their importance to pollinators. The authors estimated that the total value of pollination services (wild + managed pollinators) in California is $2.7-6.3 billion per year, or 23-54% of the total value of pollinator-dependent crops. Rangelands (including grasslands, shrublands, and savannas) comprised most of the vegetation promoting services from wild pollinators. The authors noted that in addition to their value for pollinator habitat, rangelands have the capacity to provide multiple other ecosystem services including forage production and carbon sequestration.

19. Byrd, K. B., Flint, L. E., Alvarez, P., Casey, C. F., Sleeter, B. M., Soulard, C. E., et al. (2015). **Integrated climate and land use change scenarios for California rangeland ecosystem services: wildlife habitat, soil carbon, and water supply.** Landsc. Ecol. 30, 729–750. doi:10.1007/s10980-015-0159-7.
Land cover(s): rangeland, grassland
Ecosystem service(s): carbon storage, water supply
Metric(s): soil organic carbon stocks, basin recharge, runoff to basin
Location(s): Central Valley
Study description: Using calculated and modeled values, the authors quantified baseline ecosystem service values for six watersheds in the Central Valley along with scenarios for changes in ecosystem service provisioning under various scenarios of climate change and land use-land cover change. Baseline soil organic carbon stocks were calculated by using the USDA-SSURGO database to generate a map of surface (0-20 cm) SOC. Water supply, which was defined as the combination of recharge and runoff to a watershed, was estimated using the Basin Characterization Model developed for California and calibrated using stream gage data to match modeled streamflow. Grassland conversion under future land use-land cover change scenarios was projected to result in the loss of up to 39 Tg of SOC in the top 20 cm of soil by 2100, as well as the reduction in recharge opportunities due to drought and reduced precipitation value.

20. Hemes, K. S., Chamberlain, S. D., Eichelmann, E., Knox, S. H., and Baldocchi, D. D. (2018). **A Biogeochemical Compromise: The High Methane Cost of Sequestering Carbon in Restored Wetlands.** Geophys. Res. Lett. 45, 6081–6091. doi:10.1029/2018GL077747.
Land cover(s): wetland (restored)
Ecosystem service(s): climate regulation
Metric(s): methane flux, net equivalent emissions, Sustained Global Warming Potential
Location(s): Sacramento-San Joaquin Delta
Study description: Draining peatlands is known to result in significant soil carbon loss and CO_2

emissions, but restoring degraded peatlands comes at the cost of increased emissions of methane, a far more potent greenhouse gas. The authors used eddy covariance techniques to measure concentrations of CO_2 and CH_4 every half hour for drained and recently restored peatlands. GHG budgets were calculated using Neubauer and Megonigal's (2015) 100-year Sustained Global Warming Potential, which captures sustained emissions such as those expected over a wetland ecosystem. They found that restored wetlands accumulated significant amounts of sediment and supported net carbon sequestration, these gains were counterbalanced by CH_4 emissions. When accounting for methane flux, wetlands became a net GHG source in most cases.

21. Eichelmann, E., Hemes, K. S., Knox, S. H., Oikawa, P. Y., Chamberlain, S. D., Sturtevant, C., et al. (2018). **The effect of land cover type and structure on evapotranspiration from agricultural and wetland sites in the Sacramento–San Joaquin River Delta, California.** Agric. For. Meteorol. 256–257, 179–195. doi:10.1016/j.agrformet.2018.03.007.
Land cover(s): wetland (restored), rice, alfalfa, pasture
Ecosystem service(s): water supply
Metric(s): water use as annual evapotranspiration
Location(s): Sacramento-San Joaquin Delta
Study description: Used eddy covariance methods to determine the effect of wetland restoration on water cycling in the Delta. Restored wetlands with difference structures and times since restoration were compared to a rice, alfalfa, and grazed pasture areas for water use in the form of annual evapotranspiration. Drained agricultural areas had significantly lower annual ET than open wetlands, while the rice paddy and the highly vegetated (closed) wetland were no different from the alfalfa field. Both plant transpiration and evaporation contributed heavily to ET in the open wetlands, whereas plant transpiration dominated in the closed wetland and drained sites.

22. Young-Mathews, A., Culman, S. W., Sánchez-Moreno, S., O'Geen, A. T., Ferris, H., Hollander, A. D., et al. (2010). **Plant-soil biodiversity relationships and nutrient retention in agricultural riparian zones of the Sacramento Valley, California.** Agrofor. Syst. 80, 41–60. doi:10.1007/s10457-010-9332-9.
Land cover(s): riparian, cropland, rangeland
Ecosystem service(s): biodiversity, carbon storage
Metric(s): diversity and richness of plants, nematodes, earthworms, and PLFA biomarkers; % vegetation cover
Location(s): Yolo County
Study description: Examination of plant communities, nutrient retention (particularly carbon), and belowground faunal diversity in riparian areas adjacent to agricultural land uses. Transects were surveyed along 20 sites in an agricultural landscape of Yolo County. Each site was either cropland – principally walnut orchards, corn, tomatoes, and winter grain rotations – or rangeland consisting of upland grasslands and oak savanna, and all were within 50 m of a waterway. Biodiversity surveys and estimates of woody carbon sequestration were undertaken at each agricultural site and their paired waterway. Riparian zones were found to support greater plant diversity and 2x as much carbon in woody biomass per hectare than adjacent agricultural lands, but had lower soil microbial and faunal diversity and abundance. Belowground diversity had a stronger relationship to overall plant cover than plant diversity or species richness. Higher visual riparian health scores were associated with greater species richness, microbial biomass, and carbon storage, and lower nitrate and phosphorus loading in soil.