**Supplementary Information: Limited economic-ecological trade-offs in a shifting agricultural landscape: a case study from Kern county, California**

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SI Table 1. Crop classification for 121 distinct crop species produced in Kern County between 2002 - 2018

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| **Crop Cover Classification** | **Kern County Original Crop Classes** |
| Alfalfa | Alfalfa |
| Almond | Almond |
| Apple | Apple |
| Carrot | Carrot |
| Citrus | Citrus; Grapefruit; Kumquat; Lemon; Orange; Tangelo; Tangerine |
| Cotton | Cotton |
| Fallow | Fallow land |
| Garlic | Garlic |
| Grape | Grape |
| Onion | Onion; Green onion |
| Other field crops | Artichoke; Arugula; Asparagus; Barley; Bean ; Beet; Bermuda grass; Blackberry; Blueberry; Bok-choy; Broccoli; Cabbage; Cantaloupe; Cauliflower; Celery; Chinese Green; Chive; Cilantro; Collard; Corn; Cucumber; Daikon; Dandelion green; Dill; Eggplant; Fennel; Berries; Gai-choy; Gai-lon; Garbanzo; Gourd; Grain; Hemp/Cannabis; Herb/spice; Honeydew melon; Jojoba bean; Kale; Kohlrabi; Leek; Lettuce; Melon; Musk melon; Mustard; Mustard greens; Napa cabbage; Oat; Ornamentals (Flowering Plants, Flowers, Vines); Okra; Parsley; Parsnip; Peas; Peppers; Pepper spice; Pumpkin; Radish; Rape; Rutabaga; Rye; Safflower; Sorghum; Soybean; Spinach; Squash; Strawberry; Sugarbeet; Sweet basil; Sweet potato; Swiss chard; Triticale; Turf/sod; Turnip; Vegetable; Vegetable leaf; Watermelon; Yam, Zucchini |
| Other trees | Apricot; Avocado; Cherry; Chestnut; Fig; Jujube; Kiwi; Nectarine; Olive; Ornamentals (Christmas Trees); Pear; Pecan; Persimmon; Plum/Prune; Pomegranate; Stone fruit; Walnut |
| Pasture/Forage | Forage hay/silage; Lovegrass; Pasture; Pastureland; Rangeland; Ryegrass; Sudangrass; Vetch |
| Peach | Peach |
| Pistachios | Pistachio |
| Potato | Potato |
| Tomato | Tomato |
| Wheat | Wheat |

SI Table 2. Dataset description

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| Variable | Input Data | Input Source | Input Dataset Description | Methodology Details | Output Dataset Description |
| Land Cover  | * Kern County annual crop boundaries
* Farmland Mapping and Monitoring Program
 | * County of Kern Agriculture and Measurement Standards
* California Department of Conservation, Division of Land Resource Protection, Farmland Mapping and Monitoring Program
 | * Shapefile; parcel specific commodity type and location per year, data used in building the land cover dataset
* Shapefile; classified land cover type for the study area (bi-annually) into 11 broad categories, used to build the land cover dataset
 | The Kern County crop data spatial data described polygon boundaries of the different crop types cultivated. These boundaries were based on the yearly permitted crop boundaries at the parcel or sub-parcel level based on the type of permits that local growers applied for each year. The number of individual crop commodities varied each year ranging from 127 (in 2002) to 172 in 2018. However, this dataset did have gaps in areas where no crop data was recorded. In the attempt to complement the crop dataset and document the land cover type present in non-agricultural areas, or in agricultural areas where no permit was granted for the year studied, we incorporated data from the California Farmland Mapping and Monitoring Program (FMMP) (see Moanga 2020). This dataset contains a county-wide inventory of agricultural resources recorded every two years and classifying the landscape into 11 distinct land cover categories which we further used in developing the land use and land cover dataset used in our analysis. We created our land cover layers for the years studied by merging the two datasets in ArcPro 2.4 software (ESRI 2019. ArcPro Desktop: Release 2.4, Redlands, CA: Environmental Systems Research Institute), and projected in NAD\_ 1983\_ StatePlane\_ California\_V\_FIPS\_0405\_Feet (Moanga, 2020). In areas where there was overlap between the Kern County crop layer and the FMMP layer, priority was given to the Kern County crop layer since this layer was considered much more detailed (providing information at the parcel level). Within our study region rangeland areas and areas covered with natural vegetation were mostly covered by the FMMP dataset.  | Shapefile; annual crop boundary polygons (parcel-scale) for 120+ crop types for 2002 & 2018. This shapefile represents a continuous land cover layer for our study area for the years analyzed. The land cover layers were further incorporated into our modelling framework. |
| Soil Erosion | * Digital Elevation Model
* Rainfall erosivity (R-factor)
* Soil erodibility

(K-factor)* Crop management

(C-factor)* Support practice

(P-factor) | * United States Geological Survey
* US EPA Web Archives
* SSURGO database
* Various sources
* Wischmeier & Smith (1978)
 | * Shapefile; 10m resolution digital elevation model; metric units
* Shapefile
* 4 Shapefiles covering the study area
* Tabular data (see SI Table 3)

 * P-factor set to 1.0 across all land-cover classes.
 | We followed the InVEST protocol for the Sediment Retention Ratio model to access and prepare all data layers.* **R-factor**: values were converted to metric units ( MJ\*mm \* (ha\*h\*yr)-1), then converted to a 30m resolution raster.
* **K-factor**: shapefiles were matched to our study area in ArcGIS using the *Merge* and *Clip* tools. Value were converted to metric units (tons\*ha\*h \* (ha\*MJ\*mm)-1) converted to a 30m resolution raster.
* **C-factor**: Values for individual land-cover classes were determined based on existing literature and agricultural extension database values
* **P**-**factor:** Given the lack of consistent data regarding erosion control practices (e.g. contouring, buffer strips, etc.) available across all parcels and land-use classes represented in this study, we made the assumption of no erosion control practices to get conservative model outcomes.

We ran the model for 2002 and 2018 and downloaded the *usle* output with predicted soil loss per pixel. | Raster; 10.27m resolution |
| Actual evapotranspiration | * Actual Evapotranspiration
 | * Schauer & Sennay (2018), supplementary information
 | * Rasters; 30m resolution; the datasets contain actual evapotranspiration values, obtained through processing of available Landsat satellite imagery through the Operational Simplified Surface Energy Balance (SSEBop) model.
 | Datasets for 2002 and 2018 were downloaded and clipped to the study area.  | Raster; 30m resolution |
| Caloric contents | * Calories per crop class
 | * USDA Food and Nutrient Database for Dietary Studies
 | * Reports; detailing calorie contents for individual crop-derived products.
 | Values for individual land-cover classes were determined based on available estimates; values for the land cover classes *other field crops* and *other trees* were aggregated based on the nutritional contents of the five individual crops with highest acreage in each class and were calculated separately for 2002 and 2018. | Tabular data |
| Profits | * Crop-specific total revenue for 2002 and 2018
* Crop-specific total cost value.
 | * Kern County Crop Reports
* California Annual Statistical Reviews
* UC Davis Agricultural Extension Program Cost Study Files
 | * Reports; detailing revenues for individual crop commodities in the county.
* Reports; detailing total area and revenue for individual crop commodities in the state.
* Reports; detailing cost estimates for individual crop commodities in the county. Cost values include production operating costs (e.g. irrigation, fertilization, pest management, labor, harvest, transport, equipment, etc.) as well as cash and non-cash overhead expenses (e.g. property taxes, insurance, investments in tools, irrigation and infrastructure, establishment costs amortized over production lifespan, etc.).
 | Values for the land-cover classes "other field crops" and "other trees" were based on summed revenues, as reported in Kern County’s crop reports, from all individual crops contained within each class. For missing values (*carrots* and *peach*) we supplemented the data reported in Kern County crop reports with data obtained from California’s Annual Statistical Reviews for the years 2002 and 2018.For each crop group we prioritized regional and temporal matches. Where possible, distinct values were computed for 2002 and 2018. We note that, due to data limitations, production cost estimates for the *other field crops* and *other trees* classes were based on the top 5 individual crops with greatest cultivation area contained within each class in each study year. | Tabular data |
| Pesticide use | * Total pesticide application per parcel
* Toxicity levels
 | * Kern County pesticide application database
* US EPA Pesticide Product database; individual product labels & material safety data sheets
 | * Tabular data; entries detail total applied pesticide amount by parcel and by product name
* Tabular data; entries detail toxicity levels (low – medium – high – and very high) for >1000 products in 2002, and >1500 products in 2018. Toxicity levels were based on LD50 (oral toxicity for rats, in mg/kg), US EPA guideline online databases and individual material safety data sheets. Pesticide products were classified according to the following pesticide toxicity levels: very high (0-49 mg/kg); high (50-499 mg/kg); medium (500-4999 mg/kg); low (>5000 mg/kg). For products with no available LD50 values we used those of products with similar active ingredient concentrations, if available, or derived the value based on products with the same active ingredient and different concentrations. If no value at all was available or there was no detail on active ingredients (e.g. for some biological products) toxicity level was assigned based on the toxicity of similar products.
 | Based on original data on farmer-reported pesticide application per permitted farm and per pesticide product, we derived total amount of pesticide applied per location for 2002 and 2018; all value converted to metric units. We note that some locations had several entries in the original dataset.To account for varying toxicity of different products and active ingredients, we assigned toxicity levels to all pesticide products for which use was reported in the study area in 2002 and 2018. We then computed “toxicity-adjusted pesticide application”, determined per parcel and pesticide product, according to the formula given in our main text. Parcel-level farmer-reported pesticide application rates were available for 33% of all agricultural area; in the absence of other crop-specific datasets, we applied these values to extrapolate average pesticide application intensity rates for each of our land-cover classes. We note that for all crop classes *except* pasture/forage and fallow land, reported pesticide application rates were available for 40% to 82% or more of all farmed area.  | Tabular data |
| Annual Carbon sequestration | * Soil and litter C sequestration (tC ha-1 yr-1)
 | * Various sources
 | * Tabular data (see SI Table 4)
 | We used carbon sequestration values for soil and litter components reported in published literature as a proxy for annual carbon sequestration across our land-cover classes. Where several values were available, we either a) took the more conservative value if the calculations were model-based or covered a range of systems; or b) calculated an average if the calculations were based on limited field-based data. | Tabular data |

SI Table 3. Crop management (C-factor) value applied to obtain soil erosion values using the Natural Capital Project’s InVEST Sediment Delivery Ratio (SDR) model.

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| **Crop** | **C factor** | **Source / Details** |
| Alfalfa | 0.13 | US EPA Metadata archives – Alfalfa as cover crop in orchard, CA (2000) |
| Almonds | 0.28 | US EPA Metadata archives – Almonds in San Joaquin Valley, CA (2000) |
| Apples | 0.22 | Panagos et al. 2015 – EU data (Table 3, *fruit trees*) |
| Carrots | 0.23 | Panagos et al. 2015 – EU data (Table 3, *annual crops*) |
| Citrus | 0.12 | US EPA Metadata archives – Citrus in CA (2000) |
| Cotton | 0.48 | US EPA Metadata archives – Cotton in Fresno County, CA (2000) |
| Fallow | 0.50 | Panagos et al. 2015 – EU data (Table 1, *fallow*) |
| Garlic | 0.63 | US EPA Metadata archives – Onion/Garlic crops in CA (2000) |
| Grapes | 0.40 | US EPA Metadata archives – Grapes grown on bare ground, CA (2000) |
| Onion | 0.63 | US EPA Metadata archives – Onion/Garlic crops in CA (2000) |
| Other field crops | 0.23 | Panagos et al. 2015 – EU data (Table 3, *annual crops*) |
| Other trees | 0.22 | Panagos et al. 2015 – EU data (Table 3, *fruit trees*) |
| Pasture/Forage | 0.009 | Salls et al. 2018 – CA data (Table 1, *rangeland, medium RDM*) |
| Peach | 0.22 | Panagos et al. 2015 – EU data (Table 3, *fruit trees*) |
| Pistachios | 0.22 | Panagos et al. 2015 – EU data (Table 3, *fruit trees*) |
| Potato | 0.34 | Panagos et al. 2015 – EU data (Table 1, *potatoes*) |
| Tomato | 0.15 | US EPA Metadata archives – Tomato in Fresno County, CA (2000) |
| Wheat | 0.20 | Panagos et al. 2015 – EU data (Table 1, *durum wheat*) |

**Sources :**

* Panagos, Panos, et al. "Estimating the soil erosion cover-management factor at the European scale." Land use policy 48 (2015): 38-50.
* Salls, W., et al. "Modeled soil erosion potential is low across California's annual rangelands." California Agriculture 72.3 (2018): 179-191.
* US EPA MetaData archives - <https://archive.epa.gov>

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| **Crop** | **Annual C seq****(tC ha-1 yr-1)** | **Source / Details** |
| Alfalfa | 0.33 | Mortenson et al. 2004: WY, 1m, mean – C seq for 36 year stand (rangeland+alfalfa) |
| Almonds | 2.04 | Vicente-Vicente et al. 2016: Mediterranean, mean C seq for different mgmt systems |
| Apples | 0.80 | Zanotelli et al. 2018: Italy, 7-year avg NECB of mature orchard with 3000+ trees/ha (p.17) |
| Carrots | 0.12 | Kroodsma & Field 2006: CA, total C seq for annual crops (non-silage), converted |
| Citrus | 0.26 | Kroodsma & Field 2006: CA, total C seq for orchards (soils + woody material), converted |
| Cotton | 0.34 | Causarano et al. 2006: SE US (review), mean SOC seq – no-tillage, no cover crop |
| Garlic | 0.40 | Chambers et al. 2016: cropland value (mean), *referring to Lal et al. 1998c (not cited in source)* |
| Grapes | 0.590.24 | Vicente-Vicente et al. 2016: Mediterranean, mean soil C seq for different mgmt. systemsKroodsma & Field 2006: CA, total C seq for vineyards (soils + woody material), converted  |
| Onion | 0.12 | Kroodsma & Field 2006: CA, total C seq for annual crops (non-silage), converted |
| Pasture /Forage | 0.130.30 | Chambers et al. 2016: grazing land value (mean), *referring to Follet et al. 2001*Frank et al. 2004: ND, avg peak green biomass and CO2-C flux over 6 years |
| Peaches | 0.76 | Montanaro et al. 2017; EU, 14 yr old peach orchard; mean for conv/sust mgmt. |
| Pistachios | 0.26 | Kroodsma & Field 2006: CA, total C seq for orchards (soils + woody material), converted |
| Potatoes | 0.12 | Kroodsma & Field 2006: CA, total C seq for annual crops (non-silage), converted |
| Tomato | 0.12 | Kroodsma & Field 2006: CA, total C seq for annual crops (non-silage), converted |
| Wheat | 0.12 | Kroodsma & Field 2006: CA, total C seq for annual crops (non-silage), converted |
| Other field crops | 0.12 | Kroodsma & Field 2006: CA, total C seq for annual crops (non-silage), converted |
| Other trees | 0.26 | Kroodsma & Field 2006: CA, total C seq for orchards (soils + woody material), converted |

SI Table 4. Annual C sequestration values, including soil and litter components, for all land-cover classes (in tC ha-1 yr-1).

**Sources :**

* Chambers, Adam, Rattan Lal, and Keith Paustian. "Soil carbon sequestration potential of US croplands and grasslands: Implementing the 4 per Thousand Initiative." Journal of Soil and Water Conservation 71.3 (2016): 68A-74A.Causarano et al. 2006
* Follett, Ronald F., and John M. Kimble, eds. The potential of US grazing lands to sequester carbon and mitigate the greenhouse effect. CRC press, 2000.
* Frank, A. B., et al. "Biomass and carbon partitioning in switchgrass." Crop Science 44.4 (2004): 1391-1396.
* Kroodsma, David A., and Christopher B. Field. "Carbon sequestration in California agriculture, 1980–2000." Ecological Applications 16.5 (2006): 1975-1985.Montanaro et al. 2017
* Mortenson, Matthew C., Gerald E. Schuman, and Lachlan J. Ingram. "Carbon sequestration in rangelands interseeded with yellow-flowering alfalfa (Medicago sativa ssp. falcata)." Environmental Management 33.1 (2004): S475-S481.
* Vicente-Vicente, José Luis, et al. "Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis." Agriculture, Ecosystems & Environment 235 (2016): 204-214.
* Zanotelli, Damiano, et al. "Evapotranspiration and crop coefficient patterns of an apple orchard in a sub-humid environment." Agricultural Water Management 226 (2019): 105756



SI Table 6. 2002 and 2018 measured values, proportion of total value across the study area (%), as well as observed percent change from 2002 to 2018 (Δ%) and contributions to change from land-cover allocation (Δ%A) and land-use efficiency (Δ%E), for yields and agricultural ecosystem service indicators. Since annual C sequestration rates are constant in our models, we note that Δ%E is equivalent to zero across all land-use classes.

SI Table 5. 2002 and 2018 measured values, proportion of total value across the study area (%), as well as observed percent change from 2002 to 2018 (Δ%) and contributions to change from land-cover allocation (Δ%A) and land-use efficiency (Δ%E), for land-cover area and agricultural ecosystem pressure indicators.

SI Table 7. Index-transformed mean per-hectare indicator values for ecosystem service and pressure indicators, calculated at the land-cover class level. Transformations were based on absolute minimum and maximum values for 2002 and 2018 for each indicator. Values closer to 0 represent non-desirable outcomes, whereas values closer to 1 represent desirable outcomes.

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|   | **2002** | **2018** |
| **Land-Cover Class** | **Water** | **Erosion** | **Pesticide** | **Profit** | **Calorie** | **AnnualC** | **Water** | **Erosion** | **Pesticide** | **Profit** | **Calorie** | **AnnualC** |
| **Alfalfa** | 0.16 | 0.94 | 0.97 | 0.14 | 0.14 | 0.25 | 0.34 | 0.94 | 0.96 | 0.15 | 0.12 | 0.25 |
| **Almond** | 0.25 | 0.81 | 0.93 | 0.22 | 0.35 | 1.00 | 0.23 | 0.82 | 0.92 | 0.26 | 0.20 | 1.00 |
| **Apple** | 0.10 | 0.90 | 0.82 | 0.49 | 0.41 | 0.45 | 0.79 | 0.15 | 0.97 | 0.17 | 0.23 | 0.45 |
| **Carrot** | 0.54 | 0.89 | 0.87 | 0.54 | 0.32 | 0.15 | 0.58 | 0.82 | 0.79 | 0.45 | 0.19 | 0.15 |
| **Citrus** | 0.31 | 0.57 | 0.88 | 0.46 | 0.38 | 0.21 | 0.41 | 0.25 | 0.87 | 1.00 | 0.22 | 0.21 |
| **Cotton** | 0.54 | 0.77 | 0.96 | 0.17 | 0.10 | 0.25 | 0.51 | 0.83 | 0.98 | 0.20 | 0.10 | 0.25 |
| **Garlic** | 0.58 | 0.84 | 0.97 | 0.29 | 0.44 | 0.28 | 0.64 | 0.72 | 0.87 | 0.57 | 0.24 | 0.28 |
| **Grape** | 0.53 | 0.69 | 0.70 | 0.33 | 0.35 | 0.29 | 0.46 | 0.57 | 0.73 | 0.56 | 0.20 | 0.29 |
| **Onion** | 0.57 | 0.92 | 0.88 | 0.31 | 0.48 | 0.15 | 0.62 | 0.81 | 0.86 | 0.31 | 0.26 | 0.15 |
| **Peach** | 0.55 | 1.00 | 0.84 | 0.59 | 0.24 | 0.44 | 0.46 | 0.81 | 0.10 | 0.35 | 0.16 | 0.44 |
| **Pistachios** | 0.60 | 0.65 | 0.87 | 0.26 | 0.50 | 0.21 | 0.62 | 0.68 | 0.94 | 0.38 | 0.26 | 0.21 |
| **Potato** | 0.52 | 0.80 | 0.84 | 0.33 | 0.82 | 0.15 | 0.60 | 0.73 | 0.84 | 0.31 | 0.40 | 0.15 |
| **Tomato** | 0.51 | 0.97 | 0.92 | 0.22 | 0.22 | 0.15 | 0.61 | 0.91 | 1.00 | 0.40 | 0.15 | 0.15 |
| **Wheat** | 0.52 | 0.88 | 0.99 | 0.12 | 0.41 | 0.15 | 0.46 | 0.84 | 0.95 | 0.12 | 0.23 | 0.15 |
| **Other field crops** | 0.48 | 0.90 | 0.82 | 0.18 | 1.00 | 0.15 | 0.53 | 0.85 | 0.94 | 0.37 | 0.47 | 0.15 |
| **Other trees** | 0.51 | 0.81 | 0.79 | 0.34 | 0.39 | 0.21 | 0.60 | 0.57 | 0.93 | 0.49 | 0.22 | 0.21 |
| **Pasture/Forage** | 1.00 | 0.79 | 0.93 | 0.10 | 0.22 | 0.20 | 0.94 | 0.97 | 0.95 | 0.10 | 0.15 | 0.20 |
| **Fallow** | 0.81 | 0.61 | 0.91 | 0.10 | 0.00 | 0.10 | 0.82 | 0.10 | 0.87 | 0.10 | 0.10 | 0.10 |