A scenario-planning system to optimize cover cropping practices for maximum infiltration and soil health in California

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INTRODUCTION

California's Sustainable Groundwater Management Act (SGMA) has brought focus to approaches for groundwater replenishment and reduction in groundwater demand, particularly in the Central Valley where agricultural irrigation has the potential to impact groundwater storage and result in subsidence, reduced groundwater quality, and negative impacts to groundwater-dependent ecosystems, industries, and communities.

Distributed changes in agricultural management practices can be an essential part of the solution for achieving groundwater sustainability. Reducing groundwater demand through increased irrigation efficiency will be an important strategy in the Central Valley, but this only benefits groundwater reserves if producers irrigate using groundwater sources. If using surface water for irrigation, efficiency improvements can actually reduce important infiltration that occurs in conveyance systems or on fields when water is not used by plants or evaporated. Furthermore, this strategy cannot be implemented where high-efficiency irrigation systems already exist. Winter flooding of agricultural fields using excess surface waters, known as managed aquifer recharge (MAR), will also be an important tool for groundwater recharge, but it can only be implemented where infrastructure is present to divert surface waters to fields, and in years where excess surface water is available in the winter. Additionally, water rights issues and perceived risk to crops currently complicate implementation of MAR. Irrigation efficiency upgrades and MAR also have minimal benefits beyond reducing demand or increasing supply of groundwater, respectively, such as improving surface water quality, pollinator habitat, and soil health.

Beyond irrigation efficiency upgrades and MAR, there is another management practice to consider. Cover cropping, if adopted at scale, may contribute to achieving groundwater sustainability through the capture of on-field winter precipitation and stormwater. Cover crop roots and plant tissue potentially reduce surface and subsurface flows of water off fields and alter soil structure to facilitate water percolation and storage. Moreover, relative to irrigation efficiency improvements and MAR, cover cropping has lower perceived risk to the primary crop, lower costs, and/or low regulatory burden. Cover cropping can also result in additional groundwater benefits even if a farm operation is already irrigating efficiently and/or implementing MAR.

The potential of cover cropping to improve groundwater conditions to the same degree as the other strategies mentioned may be lower, but it taps into storing a different water source (winter rain that falls directly on fields) than irrigation efficiency (groundwater) or MAR (snowmelt and off-site stormwater); therefore, it may be considered as part of a comprehensive strategy for groundwater sustainability through agricultural management. If groundwater benefits of cover cropping can be quantified, it would increase flexibility in how a producer chooses to meet potential future groundwater regulatory demands. For example, cover cropping would provide an orchardist irrigating with groundwater an opportunity to contribute to watershed groundwater sustainability goals, even if they are already using a high-efficiency irrigation system and are not able to implement MAR due to economic or infrastructure constraints.

Finally, cover cropping has multiple co-benefits, including: the reduction of nutrient and sediment runoff, improvement of soil health and pollinator habitat, and sequestration of atmospheric carbon. The field-specific quantification of the multiple benefits of cover cropping would provide farmers, Groundwater Sustainability Agencies, and basin-wide managers with the ability to understand how the implementation of cover crops contributes to meeting SGMA goals, as well the goals of other regulatory frameworks and environmental initiatives, such as the Irrigated Lands Regulatory Program.

Little data exists to quantify the field-specific groundwater benefits and economic costs of winter cover cropping in California. These data are needed to understand the potential costs and groundwater benefits of widespread cover crop adoption at the basin-scale, and, therefore, allow consideration of large-scale cover cropping programs in Groundwater Sustainability Plans in agriculture-dominated basins. Moreover, an understanding in the *variability* of cost and benefits among fields will better facilitate strategic implementation, funding, and incentivization to achieve basin goals along the fastest, most cost-effective trajectory. In this documentation, using existing methodologies and models in a unique way, The Freshwater Trust (TFT) demonstrates a methodology for (1) the quantification of site-specific costs and benefits of using cover crops and (2) basin-wide analysis and prioritization of cover crop implementation.

With its local USDA Natural Resources Conservation Service (NRCS) and Resource Conservation District (RCD) partners, TFT has expanded its basin-scale assessment and prioritization system to include cover cropping in orchards and vineyards in Solano County. Solano County sits within the Sacramento Valley, and a significant portion of its agronomic acreage includes groundwater irrigated orchards and vineyards. The system developed by TFT is applicable to other basins and geographies throughout the Central Valley to assess the potential for cover cropping in orchards and vineyards to be included in a strategy to achieve groundwater sustainability.

METHODS

OVERVIEW

TFT expanded its existing basin-scale assessment and prioritization tool to build a transferable, scenario-planning system for the optimized implementation of cover cropping in orchards and vineyards in Solano County. The automated workflow steps are outlined below and described in greater detail throughout this methods section, as well as in the Technical Appendices.

1. *Field identification and farm management classification.*

   Using both publicly available spatial data and analysis of aerial imagery, TFT detected all orchards and vineyards in Solano County and identified their individual field boundaries, field sizes, crop types, irrigation methods, soil types, and slopes. These data are stored in a relational database designed by TFT to facilitate cost-benefit modeling and storage of output data.

2. *Site-specific modeling of costs and benefits.*

   These data, in addition to site-specific meteorological data, served as inputs to a suite of models that are used to estimate field-specific annual irrigation volume, shallow infiltration volume, runoff volume, and edge-of-field nitrogen, phosphorus, and sediment losses. Each of these values were modeled under two scenarios for each orchard or vineyard:

   - *without* the use of an annually-seeded winter cover crops (or ‘no cover crop’ scenario: NO), and
   - *with* the use of an annually-seeded winter cover crops (‘with cover crop’ scenario: CC).

   TFT also modeled the field-specific economic costs and benefits of implementing cover crops each year for 20 years.

3. *Basin-wide assessment and prioritization.*

   Field-specific costs, irrigation, infiltration, and runoff values for each scenario, and the differences in these values between scenarios, were used to assess the basin-wide potential for environmental benefit given various spatial distributions of cover crop implementation. Site-specific implementation costs were further used to identify priority sites to achieve the greatest environmental gains at the lowest cost.

   TFT then used the field-specific, modeled outputs to identify optimized, basin-wide scenarios where various environmental and/or cost objectives and constraints are met. For example, what basin-wide scenario of cover crop implementation results in the maximization of annual shallow infiltration, given a 20-year implementation budget of $5 million dollars?

TFT has created a larger, integrated agricultural management scenario-planning system with broader applicability than cover cropping in orchards and vineyards. Although it is not described here, the broader scenario-planning system creates optimized implementation plans for additional crop types and considers additional management actions. Only data, scenarios, and models required for cover crop analyses are discussed in this document. Furthermore, all methods are under continued development and improvement; draft methods are documented here and reflect TFT’s scenario-planning system as of December 2019.

DATA SOURCES, AGGREGATION, AND PROCESSING

The data described in this section are those that are associated in TFT's database with each individual Solano County agricultural field. Other data are associated with a certain crop type, irrigation type, or other field attribute and are stored as lookup tables in TFT's database. These data are discussed in the individual model descriptions where they are applicable.

AGRICULTURAL FIELD BOUNDARIES AND ACREAGE

Each unique agricultural field within Solano County was delineated via a convolutional neural network and stored as a polygon for use in ArcGIS. This method is commonly used for feature identification via image analysis. Field boundaries were delineated by the model using a year (approximately the 2017 calendar year) of multispectral data from the Sentinel-2 satellite. Areas that appeared to have non-agronomic land uses are excluded from field polygons. Selected fields typically contain a single crop type and are not intersected by, or inclusive of, any other features, such as houses, irrigation and fertilization structures, barns, roads, canals, etc. Each field's acreage was then calculated using ArcGIS.

CROP TYPE

TFT used the crop type according to the United States Department of Agriculture's 2019 Cropland data layer[1] (USDA CropScape). The majority crop type for each field polygon is used when this dataset shows multiple crops within a field polygon. See 'Data Quality Control' below for a description of how accuracy in crop type is verified.

IRRIGATION METHOD

Irrigation type for each unique field was estimated using a convolutional neural network, trained with 2015 ground-truthed irrigation type data from the California Department of Water Resources. Field-level irrigation was classified as one of four methods: (1) non-irrigated, (2) unpressurized (i.e., flood or furrow), (3) pressurized (i.e., sprinkler), or (4) high-efficiency (i.e., drip or micro). This model used multispectral data from the Landsat 8 satellite throughout 2017. See 'Data Quality Control' below for a description of how accuracy in irrigation method is verified.

Data Quality Control

Remotely sensed crop and irrigation data from the sources described above went through a Quality Assurance/Quality Control (QA/QC) procedure and ground-truthing process. First, TFT checked a random subset of these datasets against 2019 satellite imagery and Google Earth "street view" images to look for inconsistencies (i.e., orchards or vineyards identified as row or field crops, evidence of misclassified irrigation systems based on visible infrastructure, summer-time green fields identified as non-irrigated, etc.). Second, TFT performed 'reasonableness' checks within the TFT database between the crop and irrigation types identified on each field to identify unlikely combinations (e.g., "alfalfa" irrigated with drip, non-irrigated orchards, etc.). Finally, TFT's NRCS and RCD project partners checked correctness in crop and irrigation type for a random subset of Solano County fields based on their own knowledge and

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[1] USDA National Agricultural Statistics Service Cropland Data Layer. Published crop-specific data layer. Available at https://nassgeodata.gmu.edu/CropScape/ USDA-NASS, Washington, DC.

available farm reports. The project partner input, aerial imagery analysis, and Google Earth "street view" imagery were used to rectify data issues identified through the above procedures.

SOILS AND FIELD SLOPE

Individual agricultural field topography and soil type are characterized using publicly available data. The majority slope within each field polygon is calculated in ArcGIS using the U.S. Geological Survey 10-meter digital elevation model (DEM)[2], and the majority soil type within each field polygon is determined using the NRCS SSURGO Database[3].

CIMIS WEATHER DATA

The California Irrigation Management Information System (CIMIS)[4] is a program within the California DWR. CIMIS is an integrated network of over 145 automated weather stations throughout California. Hourly precipitation (in inches) is provided for each weather station location. TFT interpolates rainfall for each agricultural field using an inverse distance weighted average of data from the three nearest reporting stations to each field for the total precipitation each day. The spatial centroid of each field is used to determine the three nearest stations and the distance to them. Using an inverse weighted average is a well-accepted approach that avoids extreme values that may otherwise be observed by simply taking data from a single nearby station, yet preserves the influence of distance-from-measure overall. The equation is as follows:

$$\hat{P} = \sum \frac{\frac{1}{d_i}}{\sum 1/d_i} * p_i$$

P-hat is the estimated precipitation at the location.
d_i is the distance from the location to reporting station ***i***.
p_i is the observed precipitation at station ***i***.

ET_O is the rate of evapotranspiration from a reference surface, usually a hypothetical grass, that is used to calculate estimated crop evapotranspiration (ET_C) as a function of the growth-stage specific crop coefficient (K_C). Daily ET_O (in mm) is provided through Spatial CIMIS, a raster grid of two-kilometer resolution for which ET_O is calculated through interpolation of temperature, humidity, and other data from nearby CIMIS stations using the American Society of Civil Engineers' version of the Penman-Monteith equation (ASCE-PM). Solar radiation data required for the ASCE-PM is acquired by CIMIS through NOAA's Heliosat-II model. The two-kilometer raster that an agricultural field's centroid falls within is the raster used for ET_O for a given field.

DATABASE DESIGN

TFT's modeling database supports the organization of data used as model inputs and the collection of model results. The field-specific data described above are associated with and stored as JSON files, which are used to populate several tables within the database. Other assemblies in the database

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[2] https://www.usgs.gov/core-science-systems/national-geospatial-program/national-map
[3] https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627
[4] https://cimis.water.ca.gov

(referred to as lookup tables) contain information specific to crop type, irrigation types, and management practices; these hold economic information and other data used to support modeling and analysis (and are described with each model description below and in the Technical Appendices). The contents of the database tables are broadly grouped into five categories: geophysical data, land management practices, economic data, model results, and tables used for administrative purposes.

The “Scenario” table is a key table in this schema because it is used to delineate the current management practices on each field from the potential changes to management practices that can be modeled on that field (for this analysis, the change is the adoption of winter cover cropping). The “Impact” table is another key element in the schema that brings together all necessary information to quantify the costs and benefits of various improvement scenarios on each field. The modeling inputs, model run identifiers, and model outputs are recorded in the “ModelResults” table, so that a full audit trail is maintained for the scenario-planning process.

Some models also draw on information not contained in this database. Specifically, there is too much statewide daily CIMIS meteorological data to store in TFT’s primary database; therefore, when used in irrigation and infiltration modeling, CIMIS data is called upon from TFT’s alternative data storage sources.

COVER CROPPING SCENARIO DEVELOPMENT AND MODEL SELECTION

In general, the CC (or ‘with cover crop’) scenario represents the following management practices in addition to typical management of the primary orchard or vineyard crop:

- annually seeding a legume-dominant cover crop mix between rows each fall after harvest,
- irrigating once upon sowing and then subsequently irrigating enough to keep the plants alive (based on weather data, implies irrigation system can water between rows)
- spring mowing to maintain the crop is performed three times, followed by chemical termination approximately one month prior to leaf out
- plow down of the cover crop is assumed to occur in the first five years of orchard development to build the soil nutrient levels.

The NO scenario implies no fall seeding, winter irrigation, or other activities to maintain or terminate cover crops. The specifics of modeling scenarios were developed through consultation with TFT’s NRCS and RCD project partners, as well as through interviews with seven Solano County orchard managers who use winter cover crops. The participants and results of these interviews are detailed in the final Conservation Innovation Grant report submitted December 2019.

While simulations of the NO and CC scenarios always reflected the general scenario descriptions above, they differed among each model used by TFT, based on each model’s specific methods and parameters. NO and CC simulations in each model are detailed below and summarized in Table 1.

While winter cover cropping has been adopted in Solano County on some orchards and vineyards, it is rare, and TFT is not currently able to remotely detect whether cover cropping is used on specific farms. Therefore, for this analysis, TFT assumed cover cropping does not presently occur on any farm. As a result, both the NO and CC scenarios were simulated on all fields to determine potential environmental benefits of from using cover crops.

The criteria for model selection by TFT included the model's ability to: (1) estimate irrigation, infiltration, or runoff at the individual agricultural field level (rather than a coarser spatial unit) and (2) simulate differences in management scenarios on each field, particularly the presence or absence of winter cover crops.

Table 1. Summary of model specifications and outputs for simulation of NO and CC scenarios.

	Irrigation	Infiltration	Runoff	Economics
No cover cropping (NO)	Irrigation volume modeled for primary crop only (tree or vine crop)	"Hydrologic Condition" for selection of runoff curve reflects field-specific data (e.g., field slope, land cover) and can range from "poor" to "good". Winter cover crop water demand is not reflected in the water balance, and there is no winter irrigation for cover crops.	Runoff estimated using NTT for typical orchard/vineyard operations with no cover crop seeding, irrigation, or other fall/winter management simulated.	Assumed to be zero; only the economic costs and benefits of implementing cover crops in addition to standard operating costs are estimated.
With cover cropping (CC)	Irrigation volume modeled for primary and secondary crop (tree or vine crop + winter cover crop)	"Hydrologic Condition" for selection of runoff curve is "good". Winter cover crop water demand and irrigation is reflected in the water balance.	NNT orchard/vineyard management simulation included clover used as surrogate cover crop at fall seeding rate of 1,224 seeds/m^2, plus changes to irrigation, fertilizer, and other inputs as specified in Table 2.	Cost and revenue changes related to cover cropping are estimated (in relation to non-cover cropped orchard or vineyard). Cost/revenue changes considered include: cover crop seeding, termination, fertilizer inputs, etc. (Table 3)
Meteorological Data Source & Time Step	Daily precipitation and ET_o data from CIMIS from the most recent of each of the five CA water year types, as defined by the DWR Water Year Hydrologic Classification Indices (November 1 prior year through October 31 of the listed year): wet (2017), above normal (2005), below normal (2016), dry (2013), and critical (2015)		Daily PRISM meteorological data from previous 35 years	No meteorological data required
Field-specific Model Results	Average annual water used for irrigation with and without cover crops	Average annual shallow infiltration with and without cover crops	Average annual sediment, nitrogen, and phosphorus runoff with and without cover crops	Annual and total costs of cover cropping over 20 years

FIELD-SPECIFIC COST-BENEFIT MODELS

The below modeling methods are used to estimate agricultural field-specific costs and benefits of winter cover cropping. Both environmental and economic costs and benefits are determined by simulating the NO and CC scenarios on each field, using this suite of modeling methods. Each model uses data in TFT's modeling database, and in some cases, the outputs of one model serve as the inputs of another. All modeling is written in either Python or R scripts that interact with the modeling database and facilitate easy revisions to these methodologies upon expert review and/or new data or information.

IRRIGATION MODEL

TFT has implemented a limited version of the Consumptive Use Program Plus (CUP+ version 6.1), developed by DWR.[5, 6] The original CUP+ model was developed as a Microsoft Excel workbook to "help growers and water agencies determine reference evapotranspiration (ET_O), crop coefficient (Kc) values, and evapotranspiration of applied water (ET_{aw}), which provides an estimate of the net irrigation water needed to produce a crop." TFT's scripted version automates the batch modeling of site-specific, daily water use on many fields across a landscape under multiple scenarios, while the Excel version is used on a field-by-field, single-scenario basis. Furthermore, the timeframe for ET_c and ET_{aw} estimations in TFT's irrigation model are user-defined, pulling location-specific ET_O and weather data from any range of dates for which CIMIS data is available. Irrigation efficiency values are also applied to ET_{aw} values, based on the existing irrigation system on each field, to estimate the total water used for irrigation during the timeframes specified for modeling.

TFT modeled water use for irrigation for each orchard and vineyard in Solano County across each of the five California water year types, as defined by the DWR *Water Year Hydrologic Classification Indices*.[7] Daily precipitation and ET_O data from CIMIS were used for the most recent representative years (November 1 prior year to October 31 of the listed year): wet (2017), above normal (2005), below normal (2016), dry (2013), and critical (2015). The resulting modeled values are field-specific, total annual irrigation volumes, averaged across these five years. More detailed methods of irrigation modeling are provided in Appendix A.

TFT's scripted irrigation model has also expanded upon the CUP+ functionality by allowing the modeling of ET_c and ET_{aw} of both a primary and secondary crop. The two cover cropping scenarios were simulated in TFT's irrigation model by modeling only the primary orchard crop for the NO scenario and modeling the primary orchard crop and a secondary fall-planted cover crop for the CC scenario. NO simulations assume potential for ET_c and ET_{aw} only exists between the leaf out and harvest dates of the orchard crop, while the CC simulation results in year-round ET_c and ET_{aw} values as a result of the winter cover crop. The model assumed irrigation of the cover crop was required when crop demand (ET_C) was not met through precipitation volume. TFT used a general legume surrogate for the simulated cover crop, which has a comparable Kc growth curve to other cover crops commonly used in this geography.

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[5] Orang, M.N, Snyder, R.L., and J.S. Matyac. 2005. CUP (Consumptive Use Program) Model. DWR and UC Davis. California Water Plan Update 2005.

[6] Orang, M.N, Matyac, J.S., and R. L. Snyder. 2011. CUP+ (Daily Soil Water Balance Program). ICID 21st International Congress on Irrigation and Drainage. 15-23 October 2011. Tehran, Iran.

[7] See http://cdec.water.ca.gov/reportapp/javareports?name=WSIHIST

The daily ETc values for each field and scenario are used as part of the water budget in the infiltration model (described below).

INFILTRATION MODEL

TFT's infiltration model applies a water balance (or water budget) equation at the field level to estimate the changes in water distribution given the implementation of cover cropping. The water balance approach is a flexible method that allows various component water sources and sinks to be defined for a unit of analysis, and manipulated to estimate how the presence or absence of cover crops impact the distribution of source water among sinks.

The model uses daily, field-specific volumes of water sources to estimate their daily, field-specific distribution among various sinks. Sources include precipitation and irrigation. Daily precipitation volumes are from CIMIS weather data, and irrigation volumes are outputs of the irrigation model described above. Sinks include crop evapotranspiration, runoff as surface runoff and subsurface flows, and shallow infiltration. TFT's infiltration model assumes that a fraction of the source water that remains after allotment to crop demand and runoff will percolate past the root zone to shallow groundwater stores and potentially deeper aquifers.

Crop water demand is determined by daily ET_c values from TFT's irrigation model. Runoff is determined by the runoff curve number, as described in the National Engineering Handbook (NEH), Part 630 (Hydrology).[8] A runoff curve is a function that defines the volume of water that will runoff an agricultural field given a volume of source water. Runoff curves are selected based on the fields hydrologic soil group, land use (cropping and tillage practices), and "hydrologic condition". Hydrologic condition qualitatively describes the infiltration potential of a field as "good", "fair", or "poor". It is a function of land cover, field slope, crop residue, and grazing intensity. An additional adjustment to the curve number is made based on precipitation or irrigation events in the last five days to account for the increased likelihood of soils either being saturated or dried out. See Appendix B for full details of the infiltration model.

Fields in this study are all orchards and vineyards, which are generally well kept, low sloped, not annually tilled, and efficiently irrigated. The simulation of the NO and CC scenarios differed in two ways, and reflect differences in source water volumes and the distribution among discharges resulting from cover crop use:

(1) The daily crop water demand (ET_c) and resulting irrigation volume outputs from the irrigation model will differ as a result of the presence of cover crops in the CC scenario. The crop water demand is met first through precipitation and remaining demand is met through irrigation. Therefore, irrigation as a source will typically increase in the CC scenarios and evapotranspiration will typically be a greater component of discharge compared to runoff and infiltration.
(2) The runoff curve number will potentially change as a result of the "hydrologic condition" differing between the NO and CC scenarios. For the NO scenario, the hydrological condition of "poor",

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[8] See chapters 7 - 10: https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/hydrology/?cid=stelprdb1043063

"fair", or "good" is generated for each field based its current conditions (e.g., slope and crop type), but for the CC scenario, hydrologic condition is set to "good" regardless of existing determinants.

The first difference between scenarios reflects the potential for cover crops to reduce infiltration through increased crop water demand, especially if winter precipitation is low. Conversely, the second difference between scenarios reflects the widely accepted effect cover crops have to potentially increase infiltration capacity, but it allows this effect to be quantified independently for each field. It also allows the existing infiltration capacity to be high without cover crops if indicated by the current conditions.

As with irrigation, TFT modeled shallow infiltration for each orchard and vineyard across each of the five California water year types, represented by the most recent of each. The resulting modeled values are field-specific, total annual infiltration volumes, averaged across these five years.

NUTRIENT AND SEDIMENT RUNOFF MODEL

TFT's field-specific, edge-of-field nutrient and sediment runoff analyses employ the Nutrient Tracking Tool (NTT). NTT was developed by the Texas Institute for Applied Environmental Research (TIAER) at Tarleton State University with funding and technical support from USDA's Office of Environmental Markets. A proprietary implementation of NTT was developed by TFT, where key inputs to NTT for each individual field in an entire area of interest are aggregated and formatted via scripted procedure, which then generates input files and submits them to a cloud-based server hosting all NTT databases and modeling processes. Once simulations are complete, TFT's procedure retrieves the results for aggregation and analysis. This novel automated process was developed as a scalable alternative to the existing, publicly available NTT simulation process, which requires manually-entered field-specific inputs for each simulation via the tool's web-based user interface. As a result, in the amount of time it might take a user of the publicly available NTT to manually generate a simulation scenario for a single field, TFT's runoff model can assess all current and alternative scenarios for hundreds or thousands of fields across an entire basin.

The scientific basis for NTT is the APEX (Agricultural Policy/Extender; (Gassman et al., 2010)[9] (Version 0806) model, which has been widely used and extensively tested for modeling the environmental impacts of agricultural conservation practices on farmland (Tuppad et al., 2010)[10]. APEX uses mostly physically-based modeling routines, and validation efforts for both APEX and NTT has been conducted across many parts of the United States, including California (Saleh, Gallego, & Osei, 2015)[11].

NTT outputs used in this analysis include average annual edge-of-field total nitrogen, total phosphorus, and sediment losses based on 35 years of simulated weather data (PRISM; (Daly & Bryant, 2013)[12],

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[9] Gassman, P. W., Williams, J. R., Wang, X., Saleh, A., Osei, E., Hauck, L. M., Izaurralde, R. C., Flowers, J. D. (2010). The Agricultural Policy/Environmental eXtender (APEX) model: An emerging tool for landscape and watershed environmental analyses. Transactions of the ASABE.

[10] Tuppad, P., Santhi, C., Wang, X., Williams, J. R., Srinivasan, R., & Gowda, P. H. (2010). Simulation of conservation practices using the apex model. *Applied Engineering in Agriculture*

[11] Saleh, A., Gallego, O., & Osei, E. (2015). Evaluating nutrient tracking tool and simulated conservation practices. *Journal of Soil and Water Conservation*. https://doi.org/10.2489/jswc.70.5.115A

[12] http://www.prism.oregonstate.edu/

which includes 2-km resolution daily rainfall and minimum and maximum temperature through 2018[13]. In addition to nutrient and sediment loss estimates, TFT uses the simulated average annual crop yield from NTT to compare field-specific NO and CC scenarios against one another; the resulting change in crop yield is included as either a cost or benefit in the economic model (described below).

To estimate the difference in the NO and CC scenarios, TFT simulates the annual management for both scenarios in NTT, and report differences in the outputs. For both scenarios, NTT models the representative orchard/vineyard operations with planting occurring in the first year, fertilizer applied annually in spring, irrigation over the summer, and harvest annually in the fall. All orchards/vineyards are assumed to be untilled, and for all NTT scenarios, TFT uses the auto-irrigation practice, which applies water based on crop demand. The simulation uses a clover cover crop. The simulation inputs that differ between the NO and CC scenarios are summarized in Table 2.

Table 2. Acreages of crops and irrigation types considered. Gray shading indicated exclusion from the irrigation demand (in-lieu use) analysis.

Crop	Simulation Input	No Cover Crop (NO)	With Cover Crop (CC)
Almonds	Nitrogen Fertilizer (lbs/ac)	250	218
	Cover crop planting	n/a	Date: Oct. 20 Density: 1224 seeds/m^2
	Cover crop termination*	n/a	Date: Feb. 18
Walnuts	Nitrogen Fertilizer (lbs/ac)	200	168
	Cover crop planting	n/a	Date: Oct. 20 Density: 1224 seeds/m^2
	Cover crop termination*	n/a	Date: Mar. 18
Grapes	Nitrogen Fertilizer (lbs/ac)	30	0
	Cover crop planting	n/a	Date: Oct. 20 Density: 1224 seeds/m^2
	Cover crop termination*	n/a	Date: Apr. 18
Pistachios	Nitrogen Fertilizer (lbs/ac)	160	132
	Cover crop planting	n/a	Date: Oct. 20 Density: 1224 seeds/m^2
	Cover crop termination*	n/a	Date: Mar. 18
Olives	Nitrogen Fertilizer (lbs/ac)	160	132
	Cover crop planting	n/a	Date: Oct. 20 Density: 1224 seeds/m^2
	Cover crop termination*	n/a	Date: Mar. 18

* Termination is used to communicate to NTT when to stop irrigating a crop. The default setting in our modeling is one month prior to the planting month. We generally assume that the biomass of the crop remains in orchard until it breaks down, which provides the erosion and runoff protection without continued water use.

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[13] Weather data used in this portion of the analysis differs from that used in the irrigation and infiltration analysis portions, in that the runoff modeling is based on simulated weather, while the others use measured weather data from the California Irrigation Management Information System (CIMIS).

ECONOMIC MODEL

TFT's economic model applies a cost-benefit analysis framework to winter cover cropping in orchards and vineyards over 20 years. The field-specific model outputs include average annual costs and benefits, as well as the total net present value (NPV), which reflects the sum of annual costs and benefits associated with cover crop implementation over 20 years. All dollar values are presented in 2017 dollars. Furthermore, TFT employs a partial budgeting approach[14] to quantify the *changes* in a producer's costs and revenues given the implementation of cover cropping; therefore, the NO scenario costs and benefits equal $0, while the economic model generates outputs for the CC scenario only.

Components of cost and benefit values fall into three categories:

(1) Those based on specific attributes of each field, such as crop type and irrigation method. Most components of the cost or benefit calculation, such as per-acre fertilizer application costs, are identified based on these field-level attributes.
(2) Those assumed to be consistent across all orchards and vineyards (e.g., per-acre cost of mowing).
(3) Those that are determined through outputs of other models described above (e.g., the cost or benefit resulting in change in crop yield as determined by NTT).

Furthermore, some cost and benefit values vary over the 20-year timeframe (including some cost that apply only to the first year of cover cropping), while others have the same annual value over time.

Organizing, standardizing, and aggregating the data needed to complete the cost-benefit analysis required extensive research among a wide variety of sources. Crop Enterprise Budgets from the University of California Davis provided the basis for many of the values used, but technical reports, peer-reviewed literature, professional opinion, and USDA data were used extensively in developing the final values. All values were transformed into a per acre (variable) or per field (fixed) value. Net present value (NPV) of implementing cover crops over 20 years is also calculated to reflect the long-term cost of cover cropping in today's dollar. It is calculated (i.e., inflated/deflated) using the consumer price index[15] (CPI). Finalized dollar values and documentation of sources are presented in Table 3.

Data for crop yield and sediment loss changes with cover cropping are based on the model outputs of the NTT. This provides a more accurate representation of the physical changes associated with conservation action adoption.

Costs:

- *Seed*. Seed costs reflect the average material costs of cover crop seed. Given the innumerable combinations of seeds and ratios, an average cost is representative of the widest range of scenarios. Seeding is assumed to occur annually, therefore this is a reoccurring cost over the defined timeframe.

- *Soil preparation/seeding*. Soil preparation and seeding costs are operations cost which include the machine and labor costs. Seeding is assumed to occur annually, therefore this is a reoccurring cost over the defined timeframe.

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[14] See https://www.extension.iastate.edu/agdm/wholefarm/pdf/c1-50.pdf

[15] https://www.bls.gov/cpi/

- *Irrigation*. Irrigation costs cover the cost to irrigate seeds shortly after planting and then minimally to keep cover crops alive in winter. This estimate includes the acquisition, set-up, and operation of a temporary irrigation system. This is a reoccurring cost over the defined timeframe.
- *Mowing.* Mowing costs are operations costs that include the machine and labor costs for three mowing events per year to keep plant height and biomass controlled. Mowing is assumed to occur annually, therefore this is a reoccurring cost over the defined timeframe.
- *Pest management*. Pest management costs are primarily to address a potential increase in gophers. Estimates are an average cost of a trapping mechanisms and rodent baiting. This cost is assumed to occur over the defined timeframe, but realistically might be higher in some years and lower in others depending on frequency of infestation.
- *Termination.* Termination costs are all-inclusive costs which are assumed to include material, application, and labor. Chemical termination of the cover crop prior to incorporation is assumed to occur annually.
- *Plow-down.* Plow-down costs are operations costs which are assume to include the machine and labor costs. Plow down of the cover crop is assumed to occur in the first five years of orchard development to build the soil nutrient levels.

Benefits:

- *NRCS cost share*. USDA NRCS cost share programs are assumed in all active cover cropping scenarios as benefits that accrue for the first three years of implementation.
- *Fertilizer replacement value.* Fertilizer replacement value accounts for additional nutrients added to the soil by a cover crop, reducing the level of fertilizer application required. This value represents only the material cost savings (not labor), given most crops still require some application.
- *Flood avoidance*. Flood avoidance costs savings are estimated as an annual benefit of reduced flood damage to infrastructure and reduced labor for erosion control. This benefit is assumed to accrue annually over the defined timeframe, but realistically might be higher in some years and lower in others depending frequency and intensity of flooding.
- *Yield impact*. Yield impacts are listed under benefits, because TFT generally expects gains in yields associated with cover cropping. However, this measure has the ability to be a benefit or cost, and may end up being a cost if runoff modeling (NTT) shows decreases in yield. Yield changes are calculated from the average result of a 20-year simulation, and monetized using a per unit crop price.
- *Sediment loss reduction*. Sediment loss reduction is a value calculated from TFT's runoff model outputs (via NTT). This value represents the value to a producer of retaining soil on his or her field, and consists largely of non-flood related erosion control labor savings.

The model calculates the NPV over 20 years based on various combinations of the following components. The specific dollar values of costs and benefits each year and their sources are provided in Tables 3 and 4.

Table 3. Economic measures (costs and benefits) and specific dollar amounts over 20 years

Economic Measure	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
Flood/Storm Control	$0.00	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31	$37.31
Mite Control	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$37.00	$37.00	$37.00	$37.00	$37.00	$37.00	$37.00	$37.00	$37.00	$37.00	$37.00	$37.00	$37.00	$37.00	$37.00
Fertilizer Replacement Value	$0.00	$25.40	$25.40	$25.40	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93	$16.93
Seed	$0.00	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53	-$40.53
NRCS Payment	$0.00	$71.36	$71.36	$71.36	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Irrigation	$0.00	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94	-$99.94
Mowing	$0.00	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96	-$45.96
Pest Management	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00	-$5.00
Plow down	$0.00	-$13.32	-$13.32	-$13.32	-$13.32	-$13.32	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Soil Prep/Seeding	$0.00	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88	-$66.88
Termination	$0.00	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69	-$12.69
*Yield Impact**	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
*Reduced Sedimentation**	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Grand Total	$0.00	-$145.25	-$145.25	-$145.25	-$225.08	-$225.08	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76	-$179.76

* Values for Yield Impact and Reduced Sedimentation are field specific measure that calculated dynamically for each field/scenario.

Table 4. Sources of dollar amounts for economic measures in Table 3.

Economic Measure	Source
Avoided Cost (Flood/Storm Control)	Tourte, L., Buchanan, M., Klonsky, K., & Mountjoy, D. (2003). *Estimated Costs and Potential Benefits for an Annually Planted Cover Crop*.
Avoided Cost (Mite Control)	Rash, W., Gordon, H., Teiken, C. (2018). *Economics of Cover Crops.*
Fertilizer Replacement Value	Sustainable Agriculture Network. (2007). Managing Cover Crops Profitably. (A. Clark, Ed.) (3rd ed.). Beltsville, MD: Sustainable Agriculture Network. Retrieved from http://soilandhealth.org/wp-content/uploads/0302hsted/covercropsbook.pdf; Solution Center for Nutrient Management. (2018). Cover Crop Tables. Retrieved May 7, 2018, from http://ucanr.edu/sites/Nutrient_Management_Solutions/stateofscience/Cover_Crops_287/Cover_crop_tables/#table2; Winger, M., Ogle, D., St. John, L., & Stannard, M. (2012). TN Agronomy No. 56: Cover Crops. Retrieved from https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_045132.pdf; Sullivan, P. (2003). Overview of Cover Crops and Green Manures. Retrieved from https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/e/4211/files/2014/04/Overview-of-Cover-Crops-and-Green-Manures-19wvmad.pdf
Material (Seed)	Grant, J., Anderson, K. K., Prichard, T., Hasey, J., Bugg, R. L., Thomas, F., & Johnson, T. (2006). Cover Crops for Walnut Orchards.; Tourte, L., Buchanan, M., Klonsky, K., & Mountjoy, D. (2003). Estimated Costs and Potential Benefits for an Annually Planted Cover Crop.; Conservation Technology Information Center. (2014). Report of the 2013-2014 Cover Crop Survey Report. Retrieved from https://www.sare.org/Learning-Center/From-the-Field/North-Central-SARE-From-the-Field/2013-14-Cover-Crops-Survey-Analysis; Roth, R. T., Ruffatti, M. D., O'Rourke, P. D., & Armstrong, S. D. (2018). A cost analysis approach to valuing cover crop environmental and nitrogen cycling benefits: A central Illinois on farm case study. Agricultural Systems. https://doi.org/10.1016/j.agsy.2017.10.007
NRCS Payment	NRCS. (2018). Environmental Quality Incentives Program: Fiscal Year 2018. USDA Natural Resources Conservation Service. Retrieved from https://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=nrcseprd1327752&ext=pdf
Operation (Irrigation)	Tourte, L., Buchanan, M., Klonsky, K., & Mountjoy, D. (2003). *Estimated Costs and Potential Benefits for an Annually Planted Cover Crop*.
Operation (Mowing)	Tourte, L., Buchanan, M., Klonsky, K., & Mountjoy, D. (2003). *Estimated Costs and Potential Benefits for an Annually Planted Cover Crop*.
Operation (Pest Management)	Rash, W., Gordon, H., Teiken, C. (2018). *Economics of Cover Crops.*
Operation (Plow down)	Tourte, L., Buchanan, M., Klonsky, K., & Mountjoy, D. (2003). *Estimated Costs and Potential Benefits for an Annually Planted Cover Crop*.
Operation (Soil Prep and Seeding)	Grant, J., Anderson, K. K., Prichard, T., Hasey, J., Bugg, R. L., Thomas, F., & Johnson, T. (2006). Cover Crops for Walnut Orchards.; Tourte, L., Buchanan, M., Klonsky, K., & Mountjoy, D. (2003). Estimated Costs and Potential Benefits for an Annually Planted Cover Crop.; Conservation Technology Information Center. (2014). Report of the 2013-2014 Cover Crop Survey Report. Retrieved from https://www.sare.org/Learning-Center/From-the-Field/North-Central-SARE-From-the-Field/2013-14-Cover-Crops-Survey-Analysis
Operation (Termination)	Schnitkey, G., Coppess, J., & Paulson, N. (2016). Costs and Benefits of Cover Crops: An Example with Cereal Rye. Farmdoc Daily, 6(126). Retrieved from http://farmdocdaily.illinois.edu/2016/07/costs-and-benefits-of-cover-crops-example.html; Lazarus, W., & Keller, A. (2018). Economic Analysis of Cover Crops on Farms Participating in the Southeastern Minnesota Cover Crop and Soil Health Initiative. Retrieved from http://www.bwsr.state.mn.us/soils/LCCMR_Cover_Crop_Final_Report_U_of_M_Applied_Economics.pdf; Roth, R. T., Ruffatti, M. D., O'Rourke, P. D., & Armstrong, S. D. (2018). A cost analysis approach to valuing cover crop environmental and nitrogen cycling benefits: A central Illinois on farm case study. Agricultural Systems. https://doi.org/10.1016/j.agsy.2017.10.007
Reduced Sedimentation	Hansen, L., & Ribaudo, M. (2008). Regional Values for Policy Assessment Economic Measures of Soil Conservation Benefits.

RESULTS & CONCLUSION

Field-specific results are included in an interactive webmap provided to TFT's project partners and stakeholders. The costs and benefits of implementing cover cropping on each Solano County orchard and vineyard are provided when a field is selected on the map, along with the crop, slope, soil type and other "current conditions" data used in modeling costs and benefits. Approximately 550 orchard and vineyard fields were identified, covering approximately 25,000 acres. The mean field size was 44 acres, with fields ranging from below 1 acre to more than 500 acres. Walnuts, almonds, and vineyards comprised 58%, 35%, and 7% of fields, respectively, with olives and pistachios making up the remaining crop types (less than 1%). Drip and sprinkler systems each comprised about 50% of irrigation types on fields, with only three total fields likely using flood or unpressurized irrigation systems.

The average annual estimated costs of cover cropping on an orchard or vineyard was approximately $29,000 (or $667 per acre, not considering returns on investment), and the average net present value was $303,412 (or $6,885 per acre) for cover cropping a field over 20 years (in 2017 dollars, accounting for returns on investment). The net present value of cover cropping all 25,000 acres for 20 years is $171.7 million.

Overall, cover cropping typically resulted in decreased, rather than increased, modeled infiltration compared to the 'no cover cropping' scenario. Average infiltration on a field was 1.1 inches less per acre with cover cropping. Per-acre change in infiltration resulting from using cover crops ranged from an increase in infiltration of 1.3 inches, to a reduction in infiltration of almost 3 inches. Cover cropping on every field would result in an annual average reduction in infiltration by more than 2,000 acre-feet.

While this result did not support the assumptions made at the beginning of this analysis, interviews with producers and discussions with researchers and practitioners indicated that these results do potentially reflect on-the-ground realities of the effects of cover cropping. While some growers anecdotally saw less runoff with cover crops, none cited infiltration as their primary motivation for using them, nor did any augment their spring irrigation because of the increases in soil storage of winter water. Researchers and practitioners also had inconclusive evidence of cover cropping's impacts on infiltration and soil water-holding capacity (although most research projects are still in the data gathering phase), and some believe cover crops can have a negative effect on the field-specific water budget. Indeed, TFT's results indicate that cover cropping more often counteracts increases in infiltration because of the increased water demand by the cover crop itself. Additionally, TFT's analysis indicated that the orchards and vineyards identified in Solano County have very low slopes and relatively well-drained soils, resulting in minimal potential for cover cropping to reduce water runoff and increase infiltration.

Nevertheless, the results of this analysis show the importance of the basin-scale assessment and prioritization system developed here, because they highlight the annual and site-specific variability in infiltration that needs to be identified to strategically fund or incentivize cover cropping for groundwater improvements. For example, when results from all five water year types used in modeling are averaged, 85 of the 550 fields show an increase in infiltration with the adoption of cover crops, resulting in an average of 127 acre-feet of additional infiltration per year, if cover crops were only implemented on these specific fields (covering 4,245 acres). Cover cropping on only these fields has a net present value of approximately $350,000 over 20 years. While consideration of the water year type is difficult for cover cropping because preparations and seeding are done in the fall prior to winter rains that largely determine the water year type, it is notable that if only “wet” year (2017) data is considered, 273 fields show an increase in infiltration with cover crop implementation, for an estimated total of 2,190 acre-feet of additional infiltration across these 13,892 acres. If climate change results in a higher frequency of wet winters, the importance of cover crops for groundwater management will increase.

The low number of fields that showed increased infiltration with cover cropping left little ability for basin-wide scenario development and optimization, because the 85 fields that show average annual increases in infiltration will be prioritized in all scenarios. However, TFT’s site-specific modeling demonstrated widespread benefits of cover cropping in terms of reductions in water, sediment, and nutrient runoffs. If all 550 fields adopted cover cropping, sediment runoff would decrease by 610 tons annually, phosphorus runoff would decrease by 750 pounds annually, and water runoff would decrease by 2,800 acre-feet annually. Therefore, the results of this analysis and the scenario-planning system developed provide the stakeholders with an important tool for prioritizing cover crops for fields that cost-effectively result in the greatest improvements in surface water quality and reductions in flood risk.

NEXT STEPS

TFT will continue to work with stakeholders to use, improve, and expand the basin-scale assessment and prioritization system developed here. TFT is currently working with the Solano County NRCS and RCD project partners to expand the system to incorporate all crop types, and to include the consideration of MAR and irrigation efficiency improvements as projects along with cover cropping to develop integrated, basin-wide customized implementation plans to achieve specific runoff, irrigation demand, and infiltration goals. The modeled reductions in water and sediment reductions found here indicate that cover cropping is an important strategy for groundwater recharge when used with on-field retention or catchment basins, as they will reduce the water and sediment loads that lower percolation and trigger frequent maintenance of these systems. There is inherent uncertainty in the models used by TFT to estimate field-level infiltration resulting from cover cropping; TFT will continue to quantify the uncertainty in the models and reduce potential for error throughout the workflow, including input data, best management practice (BMP) simulation, and model integration.

APPENDIX A: IRRIGATION MODEL

The order of operations for TFT's implementation of the CUP+ is as follows:

1. A crop coefficient (K_C) curve is constructed for each field to determine the daily K_C. Functions defining the default curves for each crop type or crop series were sourced from DWR's CUP+. The daily CIMIS ET_O value is determined by a lookup table, which associates field centroids with the correct spatial grid. Multiplying the daily CIMIS ET_O by the daily K_C value provides a daily estimate of the crop demand for water (ET_c). All default leaf out and harvest dates from the CUP+ model were used, with the exception of almonds which was changed to a planting date of March 20 and a harvest date of August 31 after input from growers in the region.
2. ET_{aw} (evaporation of applied water) is the net amount of applied irrigation water that contributes to ET_C throughout a growing season. ET_{aw} is calculated using a moderating "bare soil" K_C curve to take into account the effective seepage, bare soil evapotranspiration, and rainfall contributions to ET_C. The bare soil K_C curve provides a floor value for overall crop-related evapotranspiration that primarily affects estimated ET_{aw} during the period when annual crops are in early growth stages (germination included). TFT used daily precipitation data to estimate daily bare soil K_C according to the methods specified by Orang et al. (2011) and through consultation with Dr. Orang (DWR). This adjustment reflects reduced demand for additional irrigation immediately following significant rain events. The effects of bare soil K_C become less impactful as the crop grows and ET_C increases over the course of the irrigation season. ET_{aw} is calculated by subtracting the amount of estimated rainfall from the daily biological crop demand for water (ET_C).

Orang *et al.* (2011) detail multiple methods for estimating the gross effects of rainfall and/or seepage on the final ET_{aw} value depending in part on what data is available. In communications between TFT and Dr. Orang, he has advised that in cases where actual rainfall data is available, CIMIS precipitation data should be used in preference to other approaches.

TFT's implementation follows the CUP+ model as described in the paper presented at the ICID 21st Congress, in Tehran Iran in October 2011. The major difference between the TFT implementation and the original CUP+ Excel-based model is based in a lack of soil moisture data. Since TFT does not have any soil moisture data available, it is not currently incorporated into water use modeling. It is assumed that farmers will not either apply so much or so little water to their fields that plant growth is adversely affected. TFT also assumes that on or about the crop planting date (or alternatively the crop growing season for tree and vine crops), farmers will initiate irrigation if necessary for crop germination or "leaf out."

Irrigation application efficiency (IAE) factors were applied to field-specific ET_{aw} based on the identified irrigation systems used on each field; these account for the total sum of water use for irrigation. Irrigation application efficiency estimates vary greatly between fields, irrigation systems, management decisions, and many other factors. Here, IAE are based solely on the identified class of irrigation system.

Systems were classified as flood/furrow[16], sprinkler, and drip/micro. The ranges of the specific efficiencies for the systems within these classes are well-documented[17], and are used along with local expertise to make general assumptions of application efficiency based on the classification of a field's irrigation system. For this analysis, TFT assumed IAEs for flood/furrow, sprinkler, and drip/micro irrigation as 65%, 75%, and 90%, respectively. The following equation is used to estimate the total applied water for a given field.

$$TAW_i = \frac{(ET_{aw})_j}{\theta_k} * Acres_i$$

Where
TAW_i represent the total applied water to field *i*
$(ET_{aw})_j$ is the crop water demand, met through irrigation for crop *j*
θ_k is the estimated irrigation application efficiency of irrigation system *k*
$Acres_i$ is the size of field *i*, in acres

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[16] Flood/furrow systems are also commonly referred to as surface irrigation, however because we classify field based on water source (surface or ground), flood/furrow prevents us from having two classifications of surface.

[17] Evans, R. G. (n.d.). Irrigation Technologies. Sidney, MT. Retrieved from https://www.ars.usda.gov/ARSUserFiles/30320500/IrrigationInfo/general irrigation systems-mondak.pdf
Martin, D. L., & Gilley, J. R. (1993). Irrigation Water Requirements. Part 623 National Engineering Handbook, (September 1993).
Neibling, H. (1994). Irrigation Systems for Idaho Agriculture. University of Idaho, College of Agriculture.
Rogers, D. H., Lamm, F. R., Alam, M., Trooien, T. P., Clark, G. A., Barnes, P. L., & Mankin, K. (1997). Efficiencies and Water Losses of Irrigation Systems. Retrieved from https://www.bookstore.ksre.ksu.edu/pubs/MF2243.pdf

APPENDIX B: INFILTRATION MODEL

The model development begins with defining the various components of the water balance that will be quantified. The employed water balance can be defined using:

$$P_{tj} + Q_{tj}^{in} - (Et)_{tj} - Q_{tj}^{ro} - S_{tj}^{gw} + S_{tj}^{other} = 0$$

Where:

P_{tj} = total precipitation in time *t*, field *j*
Q_{tj}^{in} = total water volume applied in time *t*, field *j*
$(Et)_{tj}$ = total crop evapotranspiration time *t*, field *j*
Q_{tj}^{ro} = total water volume of surface runoff time *t*, field *j*
S_{tj}^{gw} = weighted volume of ground water storage
S_{tj}^{other} = remaining volume of water storage

Each of these components are defined at the field level, on a daily basis using a mix of estimated and observed data. Daily precipitation depth (P_{tj}) is retrieved from the California Irrigation Management Information System (CIMIS)[18] database, using the lat/long centroid of field *j* to identify the closest CIMIS weather station. Crop evapotranspiration represents the volume of water that a crop uses for growth and cooling.

The total amount of water applied to field *j* (Q_{tj}^{in}) is defined as:

$$Q_{tj}^{in} = \sum_i (q_{tji}^{in})$$

Where:

q_{tji}^{in} = total volume of water applied to field *j*, in time *t*, for operation *i*

Irrigation is assumed to be applied in situations where crop demand exceeds precipitation; this excessive demand is also referred to as Et_{aw}. To meet Et_{aw}, it is assumed that producers apply this volume, plus an amount equal to the inefficiencies of a given irrigation system. TFT assumes efficiencies of 65%, 75%, and 90% for flood, sprinkler, and drip irrigation respectively. The total volume applied is calculated as:

$$V_{ti} = \frac{Et_{(aw)ti}}{e_s}$$

Where:

V_{ti} = volume of water applied to crop *i*, in time *t*
$Et_{(aw)ti}$ = evapotranspiration demand to be met by irrigation of crop *i*, in time *t*
e_s = efficiency of irrigation system *s*

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[18] CIMIS available at https://cimis.water.ca.gov/

The quantity of water leaving the field as runoff is estimated using the runoff curve method as described in the National Engineering Handbook (NEH), Part 630 (Hydrology).[19] Runoff curves estimating the quantity of direct runoff (surface, channel, and subsurface flow) are defined for various curve numbers (CN), which are a function by a hydrologic soil group (Chapter 7), land use class (Chapter 8), and the hydrologic condition (Chapter 9). Hydrologic soil group describes the types of soil underlying an area of interest by assigning a letter identifier ranging from A-D retrieved from the NRCS web-soil survey, where A soils have the lowest runoff potential, and D soils have the highest.[20] Soil types are calculated for a given field based on the majority soil type of that field. Land use class describes the type of use occurring on a given field in terms of the general crop class (row, grass, orchard, etc.) and the treatment (practices like conservation tillage, no-till, contour farming, etc.) occurring on that field which affect runoff. Hydrologic condition qualitatively (good, fair, or poor) describes the infiltration potential of a field as a function of land cover (both density and frequency), field slope, crop residue, and grazing intensity. An additional adjustment is made to the initial assignment of CN to account for five-day antecedent precipitation and irrigation. This adjustment, called the antecedent runoff condition (ARC) is made to account for the increased likelihood of soils either being saturated or dried out. The adjustment is made using both the summed five-day antecedent (q_{tji}^{in}), and the time of the year.[21]

Following the preceding calculations and assignments, the quantity of runoff can be calculated as a function of Q_{tj}^{in} and P_{tj}.[22] As defined in NEH Chapter 10, runoff is estimated as:

$$Q_{tj}^{ro} = \frac{\left(\left(Q_{tj}^{in}+P_{tj}\right) - I_a\right)^2}{\left(\left(Q_{tj}^{in}+P_{tj}\right) - I_a\right) + S} \text{ for } \left(Q_{tj}^{in} + P_{tj}\right) > I_a$$

$$Q_{tj}^{ro} = 0 \text{ for } \left(Q_{tj}^{in} + P_{tj}\right) \le I_a$$

Where:

$Q_{tj}^{ro}, Q_{tj}^{in}, P_{tj}$ = as previously defined

I_a = initial abstraction which consists of interception, initial infiltration, and surface depression storage is assumed in NEH Part 630 to be $(0.2S)$.

S = potential maximum retention calculated as:

$$S = (1000/(CN)) - 10$$

Where:

CN = the curve number as assigned using the hydrologic soil group, land use class, hydrologic condition, and five-day antecedent rainfall.

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[19] See chapters 7 - 10: https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/hydrology/?cid=stelprdb1043063

[20] See. https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

[21] See slide 15: http://njscdea.ncdea.org/CurveNumbers.pdf

[22] $Q_{tj}^{in} + P_{tj}$ is used in place of precipitation alone here because we are treating a daily irrigation event as a precipitation event.

Given the mass balance requirement of water in the hydrologic cycle, the remaining volume of water is assumed to be storage in the atmosphere, soil, and groundwater. These components are defined using S_{tj}^{gw} and S_{tj}^{other} in the balance equation. Given the inclusion of the antecedent rainfall in the runoff equation, TFT is confident that we are accounting for a significant portion of soil storage. Following the definition of runoff using the CN method, a portion of runoff represents subsurface flow. Therefore, we assign the remaining balance to the atmosphere and groundwater, with 85% of the storage value to groundwater, and 15% to remaining storage.

APPENDIX C: ECONOMIC MODEL

The model development starts with identifying the net benefits associated with any given conservation action on an annual basis. TFT employs a partial budgeting approach[23] to describe/quantify the changes in a producer's costs and revenues, given the implementation of a conservation action; this results in a baseline cost of $0. For implemented practices, the annual net revenue is presented as:

$$\pi_{itj} = \Sigma_i \Sigma_{\mathrm{t}} \Sigma_j \left(p_n \Delta\gamma_{ij_n} x_{itj_n}\right) - \Sigma_i \Sigma_{\mathrm{t}} \Sigma_j \left(\Delta c_{itj_n} x_{itj_n}\right) - \Sigma_i \Sigma_{\mathrm{t}} \Sigma_j (I_{it}) \ldots$$

Where:

π_{itj} = net benefits associated with BMP *i,* time period *t,* on farm *j*
p_n = price of crop *n*
γ_n = change in crop yield under BMP *i*, on farm *j,* growing crop *n*
Δc_{itj_n} = change in per unit production costs associated with BMP *i*, time period *t*, on farm *j,* growing crop *n*; this value can appear as a positive (increase) or a negative (decrease) in costs
x_{itj_n} = unit (acres, linear feet) implementation of BMP *i*, time period *t,* on farm *j,* growing crop *n*
I_{itj_n} = investment cost of BMP *i*, time period *t*, on farm *j,* growing crop *n*

Given the importance of the environmental outputs[24] associated with the conservation actions, TFT also includes non-production related cost/benefit in the equation. The economic value of the various environmental outputs (positive and negative) of interest are derived from literature, and are a mix of non-market and market values.

$$\beta_{itk} = \Sigma_i \Sigma_t \Sigma_k \left(\phi_{kt} \Delta\omega_{itk}\right) \ldots$$

Where:

ϕ_{kt} = economic value of environmental output *k*, in time period *t*
ω_{itk} = change in unit (load/volume/amount) of environmental output *k*, associated with BMP *i*, in time period *t*

TFT presents the total net benefits as:

$$\Theta_{it} = \Sigma_i \Sigma_t \left(\pi_{itj}\right) + \Sigma_i \Sigma_t (\beta_{\mathrm{itk}}) + \ldots$$

Where:

π_{itj} = net benefits associated with BMP *i,* time period *t,* on farm *j*
β_{itk} = net benefits associated with BMP *i,* time period *t*, output *k*

The basic NPV (also referred to as net present benefits) model is presented below over time *t*:

$$NPV = \Sigma_i \Sigma_t \frac{(\Theta_{it})}{(1+r)^t}$$

Where:

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[23] See https://www.extension.iastate.edu/agdm/wholefarm/pdf/c1-50.pdf

[24] Includes values for modeled outputs such as shade, nitrogen, phosphorous, sediment, groundwater, etc.

NPV = Net present value
Θ_{it} = total net benefits of BMP *i*, time period *t*
r = discount rate
t = time period

The indices used in the above equations take the following values for this application:

i = BMPs: MAR, Cover Crop, Irrigation Efficiency Improvement, Conveyance Efficiency improvement
j = Farms (tax lots with same owner?)
n = crops (corn, alfalfa, hay, pasture, almonds, walnuts, citrus, tomatoes, beans, etc.)
k = environmental outputs (water, sediment, nutrients, habitat, etc.)

The internal rate of return is defined as *r* where:

$$NPV = \Sigma_i \Sigma_t \frac{(\Theta_{it})}{(1+r)^t} = 0$$

Both of these metrics are commonly used in investment decision making, and provide valuable insights for making conservation investment decisions.

Method Advancements

The approach taken represents a modest improvement in on-farm planning for conservation actions. Existing tools for analyzing on-farm conservation actions generally fall into one of the following categories; too general (difficult to apply to a given field), too specific (limited in application and data intensive), or limited to single conservation actions. This tool attempts to find a balance between generalizability and field specificity, and expand the set of estimable conservation actions in a single tool by using delineated fields as the unit of analysis. This provides a unique perspective on which fields are profitable for conservation actions, which fields are prohibitively expensive, and which fields provide a ripe opportunity for improve environmental conditions. It allows for field-specific physical responses to conservation actions from the NTT tool; which for variables like crop yield, can drive the profitability of adoption. Having field-specific outcomes allows us to identify the most efficient set of conservation practices for a given field, and can inform conservation program design.

The classification/incorporation of off-farm environmental costs/benefits allows for a comprehensive analysis for conservation planners and policymakers where these components are quantified, and can be accounted for in the development of watershed planning initiatives and incentive programs.

Limitations

While this model represents a step forward in the realm of conservation planning, it is not without limitations. Creating a flexible tool means incorporating some simplifying assumptions into the model. Some significant simplifications in this model include:

- Ownership costs of equipment are assumed the same for all producers (e.g., assumes equal financing/insurance/taxes for all producers)
- Equipment/labor needs of each practices are same for all producers (e.g., All fields get the same labor savings/per acre, and assumed all hired labor)
- All fields realize the same crop-specific fertilizer application

- Irrigation is assumed to occur in an optimal setting where when a crop need water it gets the amount it needs
- Fields are not able to be combined: Multiple small fields which seem inefficient could potentially be combined into a very efficient project in reality
- Costs/benefits are assumed to occur on a defined timeline
    - Reality of equipment life, land-use change potential are simplified
- Environmental output values include a great deal of uncertainty: Given the non-market nature of these outputs, estimates are used to avoid assigning no value to a major output of conservation adoption. Location specific values often do not exist, so methods like benefit transfer are employed.