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LETTER

# Scenarios of climate adaptation potential on protected working lands from management of soils

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## Abstract

Management of protected lands may enhance ecosystem services that conservation programs were designed to protect. Practices that build soil organic matter on agricultural lands also increase soil water holding capacity, potentially reducing climatic water deficit (CWD), increasing actual evapotranspiration (AET) and increasing groundwater recharge (RCH). We developed nine spatially-explicit land use and conservation scenarios (2001–2100) in the LUCAS land use change model to address two questions for California working lands (cropland and rangeland): How does land use change limit opportunities to manage soils for hydrologic climate adaptation benefits? To what extent and where can soil management practices increase climate adaptation on protected working lands? Hydrologic benefits [$\Sigma(\Delta CWD, \Delta AET, \Delta RCH)$] due to soil management were simulated in the Basin Characterization Model (a state-wide water balance model) for two Representative Concentration Pathway 8.5 climate models. LUCAS simulated land conversion and new conservation easements with potential for maximum hydrologic benefits. Climate drove differences in lost potential for water benefits due to urbanization (33.9–87.6 $m^3 \times 10^6$) in 2050. Conflict between development pressure and potential hydrologic benefits occurred most in Santa Clara County in the San Francisco Bay Area and Shasta County in Northern Sacramento Valley. Hydrologic benefits on easements were similar in magnitude to losses from development. Water savings from management of California Land Conservation (a.k.a. Williamson) Act contract lands were an order of magnitude greater, totaling over 460 $m^3 \times 10^6$ annually in a drier climate by 2050. Few counties provide most benefits because of soil properties, climate and land area protected. The increase in hydrologic benefits varies by agricultural practice and adoption rate, land use type and configuration, and terms of conservation agreements. The effectiveness of programs designed to improve climate adaptation at county to state scales will likely increase by taking this variability into consideration.

## Introduction

According to the recent California Fourth Climate Change Assessment, climate change in California will have multiple consequences including lower and less reliable water supply (Schwarz *et al* 2018) and species range shifts (Keeley *et al* 2018). These climate-driven changes can limit the provision of ecosystem services from working lands, thus reducing the efficiency of land protection programs, including conservation easement programs (Rissman *et al* 2015). Given climate and other ecological stressors, preservation alone may not sustain ecosystem services, and lack of land management can lead to reduced landscape resilience (Stroman and Kreuter 2015, Running *et al* 2017). Since land management can alter ecosystem function, managing protected lands may enhance the ecosystem services that conservation programs were designed to protect (Stroman and Kreuter 2015). While the protection of working lands has been proposed as a strategy for climate change adaptation (California Natural Resources Agency 2019), there has been little research on land management practices to support climate adaptation and resilience.

In recent years management of soils on agricultural lands has been identified as a key climate mitigation and adaptation strategy (Conant *et al* 2011, Zomer *et al* 2017). A U.N. Intergovernmental Panel on Climate Change special report indicates that all emission pathways that limit global warming to 1.5 °C include the use of carbon dioxide removal strategies (including soil carbon sequestration) on the order of 100–1000 $GtCO_2$ annually over the 21st century (Rogelj *et al* 2018). A wide range of agricultural practices have been shown to sequester carbon and improve soil quality or health, defined as the capacity of soil to function, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (USDA Natural Resources Conservation Service 2019b). These practices include mulching/compost application, residue and tillage management, multi-story cropping, plantings of hedgerows and windbreaks, nutrient management, and prescribed grazing, among others (Swan *et al* 2019, USDA Natural Resources Conservation Service and Colorado State University 2019).

Practices that increase soil carbon on agricultural lands can also support climate adaptation and drought resilience by reducing soil erosion, moderating soil temperature and increasing soil water holding capacity (Ryals and Silver 2013, Flint *et al* 2018b). Increases in soil water holding capacity can facilitate reduction in climatic water deficit (CWD, calculated as potential minus actual evapotranspiration (AET), the annual evaporative demand that exceeds available water). It can also facilitate increase in AET, which implies greater soil moisture, less irrigation demand and less landscape stress (Stephenson 1998, Flint *et al* 2013), and an increase in net primary productivity and, potentially, carbon sequestration (Ryals and Silver 2013).

The State of California has identified Carbon Sequestration in the Land Base (natural and working lands) as one of the key strategy pillars for meeting 2030 Greenhouse Gas (GHG) Reduction Goals (https://arb.ca.gov/c.c./natandworkinglands/natandworkinglands.htm). Management of soils on working lands (croplands and rangelands), which comprise a significant portion of the land base in California, has the potential to play a large role in meeting these goals while increasing landscape resilience to climate change. With increased risk of drought and reduction in water supply due to climate change (AghaKouchak *et al* 2014, Mann and Gleick 2015), there is an interest in determining how management activities teamed with conservation investments can increase long-term agricultural sustainability.

The USGS Basin Characterization Model (BCM) is a California state-wide gridded (270 m) process-based water balance model validated to measured streamflow (figure S1 is available online at stacks.iop.org/ERL/14/104001/mmedia) (Flint *et al* 2013, Flint *et al* 2018a). BCM modeling exercises have shown that increases in total soil organic matter (SOM) of 3% increased the soil water holding capacity by up to 5.8 billion cubic meters (4.7 million acre-feet) across all working lands in California (Flint *et al* 2013, Flint *et al* 2018a). However, uncertainties exist on how to implement soil management practices at a scale needed to meet GHG reduction goals and related climate adaptation benefits. Two barriers to implementing practices on working lands are (1) the socioeconomic challenges and (2) related land use pressures converting rangeland and cropland to urban or suburban development or more intensive agriculture. Approximately 2746 $km^2$ of the state's farmland were converted to development between 2002 and 2012 alone (California Department of Conservation Farmland Mapping and Monitoring Program 2004–2015). The high proportion of rangelands in private ownership (e.g. 80% of hardwood woodland (California Department of Forestry and Fire Protection 2018)), and tendency for lower profits on rangelands compared to other land types, also make rangelands subject to conversion. Between 1984 and 2008, over 1950 $km^2$ of rangeland in the California Central Valley and Coast Range were converted to residential development, more intensive agriculture, or lands for mineral extraction (Cameron *et al* 2014).

Various forms of private land conservation can play a key role in meeting environmental targets (Drescher and Brenner 2018). As part of California's Fourth Climate Change Assessment, the primary question driving this study was: what is the potential for land protection programs to provide climate adaptation benefits and enhanced ecosystem services derived from soil management? To answer this question, we developed spatially-explicit future land use and conservation scenarios based on historical land change data, population projections, and incremental levels of conservation investment representative of current conservation programs.

One State of California program that incentivizes farmland conservation is the Department of Conservation's (DOC) Land Conservation (a.k.a. Williamson) Act of 1965. The Williamson Act enables local governments to enter into 10-year renewable contracts with private landowners that restrict land to agricultural or related open space use in return for lower property tax assessments. While subvention payments from the state to counties for the program have stopped, more than 72,843 $km^2$ (18 million acres) are still under contracts that restrict development, although conversions to other agricultural land uses

**Table 1.** Scenario definitions, PopMed = moderate population projection, BAU = business-as-usual population projection, and WA = Williamson Act. EH = high easement scenario, EM = medium easement scenario, and EL = low easement scenario.

| | |
|---|---|
| PopMed_EH | PopMed; Easements 240 km (~60 k acres)/year for 30 years, WA lands present |
| PopMed_EM | PopMed; Easements 120 km (~30 k acres)/year for 30 years, WA lands present |
| PopMed_EL | PopMed; Easements 120 km (~30 k acres)/year for 15 years, WA lands present |
| PopMed | PopMed; no easements. WA lands present |
| BAU_EH | BAU; Easements 240 km (~60k acres)/year for 30 years, WA lands present |
| BAU_EM | BAU; Easements 120 km (~30k acres)/year for 30 years, WA lands present |
| BAU_EL | BAU; Easements 120 km (~30k acres)/year for 15 years, WA lands present |
| BAU | BAU; no new easements. WA lands present |
| BAU_noWA | BAU; no new easements; no WA lands after 2020 |

are allowed (California Department of Conservation Division of Land Resource Protection 2017). DOC and other agencies and land trusts also implement conservation easement programs, designed to incentivize farmland conservation. A common tool for private land conservation, a conservation easement is a voluntary, legal agreement between a landowner and land trust or government agency that permanently limits conversion of the land in order to protect its conservation values, while allowing owners to retain many property rights and potentially receive tax benefits (NCED 2017).

Historically, approximately 129.5 km$^2$ (32,000 acres) of conservation easements have been placed on California working lands annually since 1988 (NCED 2017). One relatively new program, the Sustainable Agricultural Lands Conservation Program (SALC) administered by DOC and the Strategic Growth Council, funds conservation easements and strategic plans for agricultural lands; in 2017 SALC awarded grants to permanently protect over 186 km$^2$ (46 000 acres) of land (California Strategic Growth Council 2019).

This analysis for California working lands addresses two main questions: (1) How does land use change limit opportunity for climate adaptation benefits, in particular hydrologic benefits, derived from managing soils on working lands? (2) To what extent and where can teaming soil management practices with conservation programs maximize climate adaptation on protected working lands? BCM simulation of soil management and associated increase in SOM and water holding capacity provided estimated spatially-explicit hydrologic benefits. Benefits were defined as increase in groundwater recharge, reduction in CWD, and increase in AET (cubic meters of water) relative to no management activity (Flint *et al* 2018a, 2019). Land use change scenarios were modified from two growth scenarios developed for the California Fourth Climate Change Assessment and modeled spatially (270 m) using the LUCAS state and transition simulation model (LUCAS model) (Sleeter *et al* 2017a). Given state population growth scenarios, we conducted a sensitivity analysis of hydrologic benefits associated with incremental areal and spatial allocation of land for conservation and management (Byrd *et al* 2015a).

## Study area

The land use change modeling was conducted for the entire land area of the State of California, totaling 423 812 km$^2$. Hydrologic modeling was conducted for all California working lands suitable for soil management, identified as grasslands (annual grasslands, perennial grasslands, pasture), oak woodlands (blue oak-foothill pine, blue oak woodland, coastal oak woodland, valley oak woodland), shrublands (coastal scrub), and croplands (cropland, dryland grain crops, deciduous orchard, evergreen orchard, irrigated grain crops, irrigated row and field crops, irrigated hayfield, vineyard) in the Wildlife Habitat Response (WHR) class of the vegetation type map (California Department of Forestry and Fire Protection 2015). Areas identified as non-suitable for soil management included urbanized areas or low rainfall deserts (Flint *et al* 2018a, 2019). In all, the total area of working lands selected for analysis represent 28% of the total area of California, or 118 667 km$^2$.

## Methods: scenario development and analysis

Land use change scenarios were developed to simulate in the LUCAS model current and projected levels of growth in typical state-wide private lands conservation programs (table 1). The LUCAS model is a gridded form of a state-and-transition simulation model where empirically-defined transitions stochastically move each cell between a defined set of states (figure S1) (Sleeter *et al* 2017a). The model is validated against historical distributions for each transition type (Sleeter *et al* 2017a, 2017b). We developed nine land use/conservation scenarios from 2001 to 2100 representing variable levels of conservation land acquisition, at a spatial resolution of 270 m. For each scenario, we ran 10 Monte Carlo iterations to develop uncertainty estimates for the area of land cover conversion. Baseline model land use/land cover was derived from the USGS National Landcover Dataset, with classes for development, annual agriculture (cropland), perennial agriculture (orchards/vineyards), wetland, shrubland, grassland, and forest (i.e. conifer and hardwood woodland) (Wilson *et al* 2016). The model restricted land use change on currently protected land as indicated by the USGS Protected Areas Database (US Geological Survey Gap Analysis Program GAP 2016).

Scenarios represented permutations of one business as usual (BAU) population/development projection (Wilson *et al* 2016) and one moderate population projection (PopMed) (Sleeter *et al* 2017a). The moderate population growth scenario is based on county-level population projections from the California Department of Finance. The BAU scenario represents a higher growth rate based on historical data from the California Farmland Mapping and Monitoring Program (Wilson *et al* 2016). Rates of agricultural expansion and contraction in each case were based on historical trends from 1992 to 2012 for each scenario. Both BAU and PopMed scenarios assumed implementation of the Williamson Act in which all renewal contract lands in the DOC Williamson Act geodatabase (California Department of Conservation Division of Land Resource Protection 2017) are maintained from 2020 to 2100. For both population projections, we implemented a simulated easement program based on historical and future acquisition rates starting in 2020 with scenarios for zero, low (120 $km^2 yr^{-1}$ for 15 years), medium (120 $km^2 yr^{-1}$ for 30 years) and high (240 $km^2 yr^{-1}$ for 30 years) acquisition rates. In addition, we included a scenario with no Williamson Act lands after 2020 and no new easements to compare outcomes.

The LUCAS model preferentially targeted conservation easements on working lands that provide current maximum hydrologic benefits from soil management (figure S1). These benefits were measured by the Hydrologic Benefits Index that sums water savings from increased evapotranspiration (AET), reduced CWD, and increased groundwater recharge (RCH) from soil management, relative to no management activity, calculated in the BCM. On all working lands, BCM model runs assumed adoption of one or more soil management practices that increase SOM by 3% from baseline USDA SSURGO mapped SOM (Flint *et al* 2018). This assumption is based on studies showing that standard soil conservation practices such as reduced tillage, cover cropping, and adding livestock manures and compost, can lead to significant increases in SOM concentration and mass over time, particularly when applied together in a comprehensive conservation agriculture scenario (Lal 2015, Chambers *et al* 2016, Paustian *et al* 2016).

Easements were allocated annually based on the rates provided above. Easement sizes ranged from 20 to 1500 ha, which represents a typical size distribution of California easements in the National Conservation Easement Database (NCED 2017). As a result of this and the fact that easements were preferentially located in areas with high hydrologic benefits, the easement scenarios represent a 'best case' for hydrologic benefits for each level of conservation land acquisition. Easements could also occur on Williamson Act lands. While conversions between grassland, annual and perennial agriculture were allowed on Williamson Act lands, no land change was permitted on easements after they were established in the model.

In addition to a simulated current climate, the BCM was also run annually to 2100 using climate projections from two Representative Concentration Pathway (RCP) 8.5 climate models: relatively wet CanESM2 and relatively dry HadGEM2-ES (mean downscaled projections for 2070–2099 relative to 1951–2005: CanESM2: +33.7% ppt (std 18.2%) and +5.5 °C (std 0.45 °C); HadGEM2-ES: +1.9% ppt (std 8.9%) and +5.5 °C (std 5.0 °C)) (Pierce *et al* 2014, Pierce *et al* 2016, Flint *et al* 2018a). These climate models represent a subset of the priority models for California's Fourth Climate Change Assessment that exemplify the specific conditions of California historical climate such as atmospheric rivers and droughts (Lynn *et al* 2015). The RCP 8.5 scenarios were selected to represent business-as-usual GHG emission rates. The simulated hydrologic benefits from these model runs were summarized and reported for each land use, management and conservation scenario.

In particular, for each scenario we calculated by county: (1) area of development on working lands and lost potential for hydrologic benefits [$\Sigma(\Delta CWD, \Delta AET, \Delta RCH)$] from soil management due to development; (2) total area of conservation lands by land cover class and opportunities for hydrologic benefits on conservation lands resulting from soil management (figure 1). Benefits of soil management on conservation lands were also summarized for: (1) Williamson Act lands, (2) easements, and given likely overlaps in land area, (3) all Williamson Act and easement lands combined. Mean annual hydrologic benefits were calculated from 10 Monte Carlo iterations of land use change, specifically from new development and easement spatial allocation. We report results for both RCP 8.5 climate models: CanESM2 and HadGEM2-ES for years 2050 (based on the 2040–2070 climate average) and 2100 (based on the 2070–2100 climate average) (Flint *et al* 2018a).

## Results

### Limitations for climate adaptation from land use change

The BAU and PopMed growth projections were similar for year 2050, with approximately 8094 $km^2$ (2 million acres) subject to development in both cases. By 2100, loss of California working lands to development was approximately 17,400 $km^2$ (4.3 million acres) in the BAU projection and approximately 11,169 $km^2$ (2.76 million acres) in the PopMed projection. Also by 2100, the development projection was more influential than the conservation acquisition rate in controlling lost hydrologic benefits. Total lost potential for water savings from soil management on these lands due to urbanization ranges from 33.9 million cubic meters ($m^3 \times 10^6$) to over 87.6 $m^3 \times 10^6$ in 2050 and from 61.6 $m^3 \times 10^6$ to over 218.3 $m^3 \times 10^6$ by 2100 (figure 2, table S1).

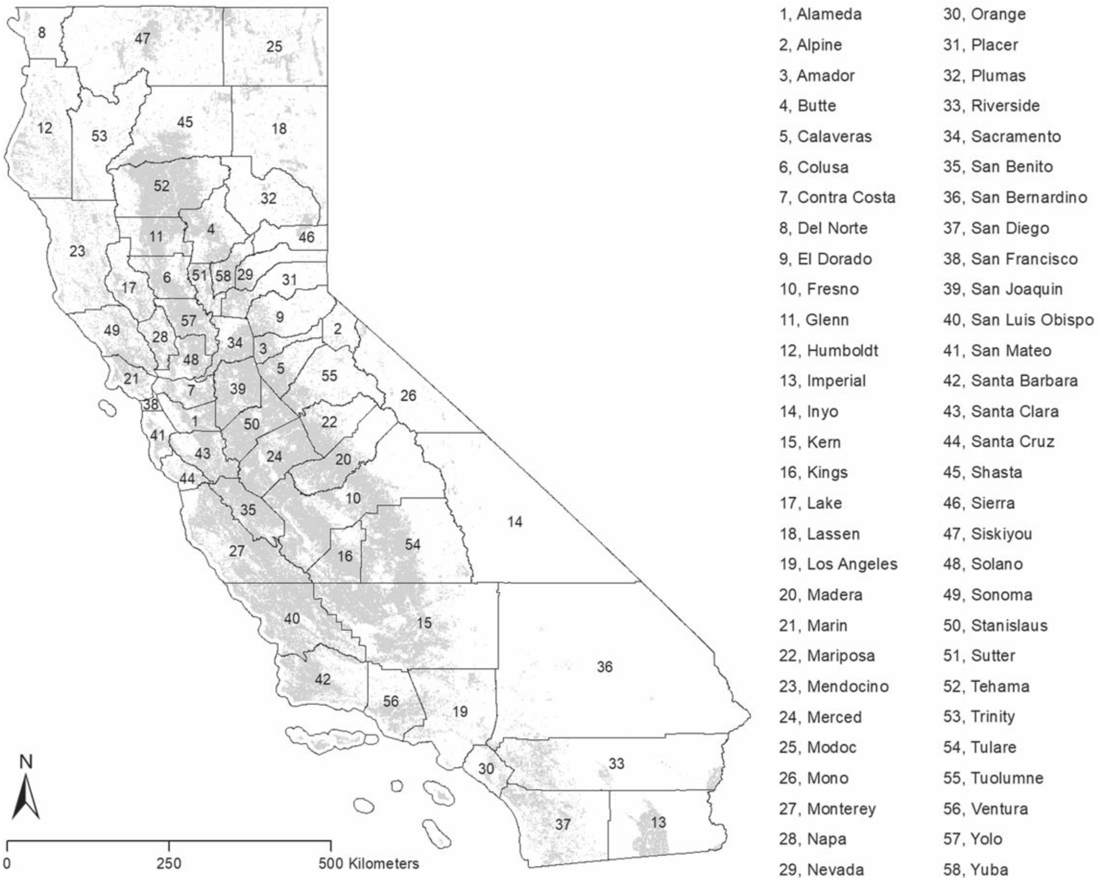


**Figure 1.** Map of Counties for the State of California. Shaded area represents working lands analyzed in this study.

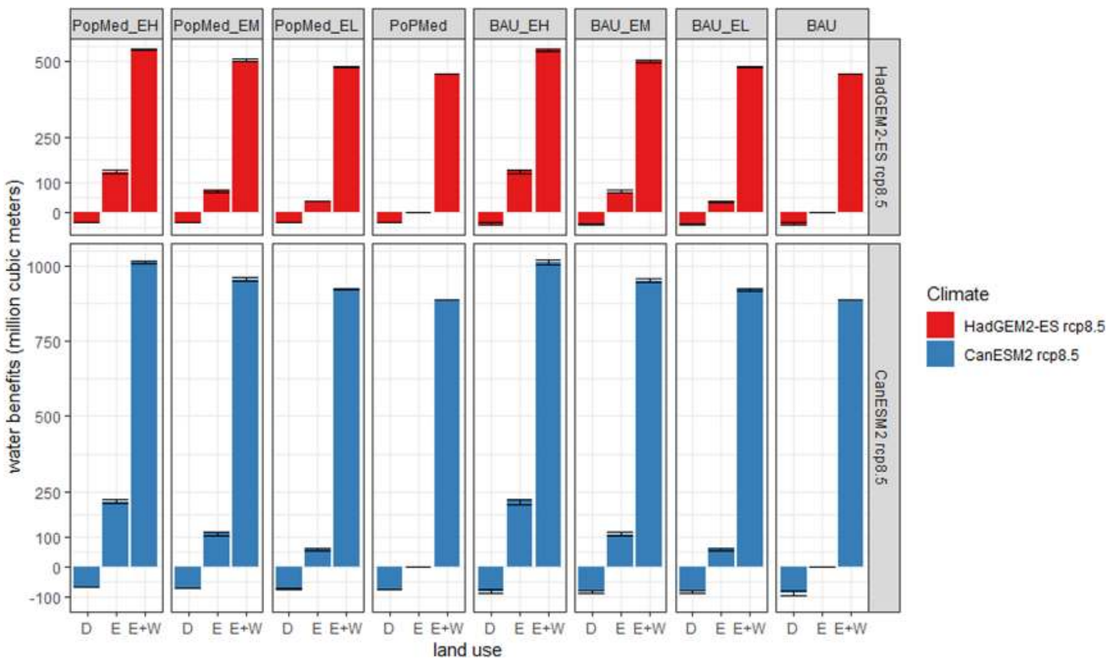


**Figure 2.** Statewide summaries of hydrologic outcomes of soil management by climate and land use scenario. See table 1 for scenario definitions. $D =$ Loss in potential water benefits from development, $E =$ gain in potential water savings on easements, $E + W =$ gain in potential water savings from easements and Williamson Act lands combined. Error bars represent minimum and maximum values of land area converted state-wide based on 10 Monte Carlo iterations per scenario.

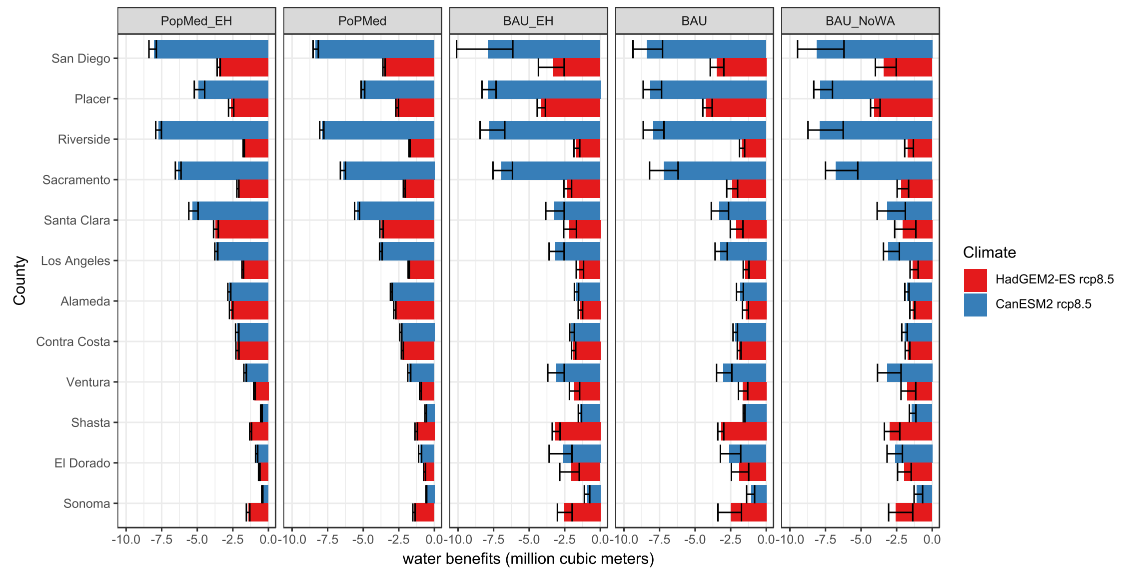


**Figure 3.** For year 2050, top 12 counties where lost potential for hydrologic benefits due to development is highest. Values represent average, plus minimum and maximum values based on 10 Monte Carlo iterations per scenario. See table 1 for scenario definitions.

There is an uneven geographic distribution of lost potential for hydrologic benefits where development is likely to occur in 2050. Future development in general leads to lost potential for reduced CWD and increased AET, as development occurs more often on the Central Valley floor, where precipitation-driven groundwater recharge potential is low (table S1). Sacramento, Riverside, San Diego and Santa Clara Counties experience the greatest potential losses of hydrologic benefits due to development (figure 3).

## Opportunities on conservation lands; Williamson act lands

By 2050, overall opportunity for hydrologic benefits on all Williamson Act lands varies from an annual average of 460.2 $m^3 \times 10^6$ in a dry climate to 888.7 $m^3 \times 10^6$ in a wetter climate (figure 2, table S2). Water savings on Williamson Act lands are an order of magnitude greater than potential losses related to future development. As with losses from development, water benefits from soil management are unevenly distributed across California, with a limited number of counties providing a majority of the benefits: Tehama ranked the highest, with water benefits of 94.8 $m^3 \times 10^6$ in a dry climate to 152.1 $m^3 \times 10^6$ in a wetter climate, followed by Shasta, Santa Barbara, San Luis Obispo, Mendocino and Humboldt (figure 4). These are high ranking counties for various reasons; in some cases, due to the large amount of land area enrolled in Williamson Act (table S3) and in others because of soil properties or climate. For example, the ratio of cubic meters of hydrologic benefits to square kilometers of Williamson Act lands (expressed as meters) range from 0.007 in Fresno County, a semi-arid region with over 4554 $km^2$ of working land in contract, to 0.070 in Shasta County, a wetter region, with 654 $km^2$ of working land in contract (table S3), though both counties provide some of the highest benefits on Williamson Act Land.

## Opportunities on conservation easements

The spatial allocation of conservation easements across California's working lands can maximize opportunities for water savings through soil management (figure 5) (see data release: (Sleeter 2017)). In our scenario analysis, hydrologic outcomes from soil management on easements were similar for BAU and PopMed growth scenarios. As with Williamson Act lands, water savings on future conservation easements are unevenly distributed across California, with a limited number of counties providing a majority of the benefits: Tehama, Shasta, Monterey, Mendocino, Humboldt and Butte (figure 6). Hydrologic benefits from soil management on easements are similar in magnitude to lost potential for benefits due to development. Counties with high benefits on easement lands that are also subject to lost water savings opportunities from development include Santa Clara and Shasta Counties. Also by 2050, the dominant land covers with the most area in conservation easements and providing the most hydrologic benefits are grassland and forest (figure 7, table S4).

## Opportunities on conservation lands: easements and Williamson Act lands

Despite substantial overlap in land area between easements and Williamson Act lands, in 2050, for a dry climate scenario, there is approximately a 24.7 $m^3 \times 10^6$ increase in water savings overall between the zero to low and between low to medium easement

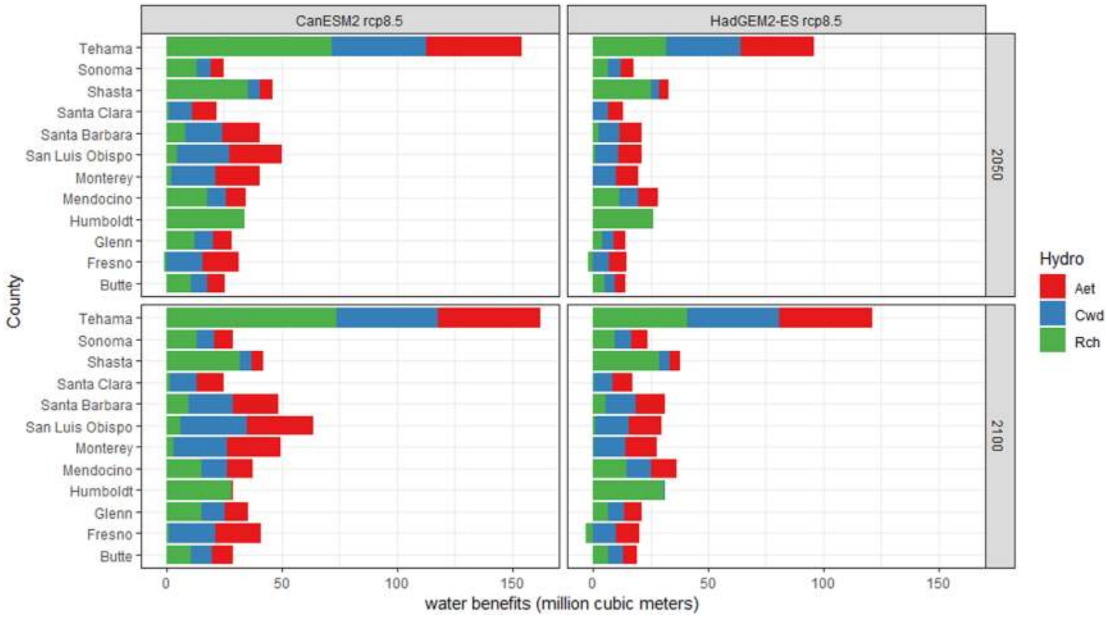


**Figure 4.** Future potential hydrologic benefits on Williamson Act lands by hydrologic variable for the top 12 counties, for 2050 (top) and 2100 (bottom), for two climate scenarios. AET = increase in actual evapotranspiration, CWD = reduction in climatic water deficit, RCH = increase in groundwater recharge.

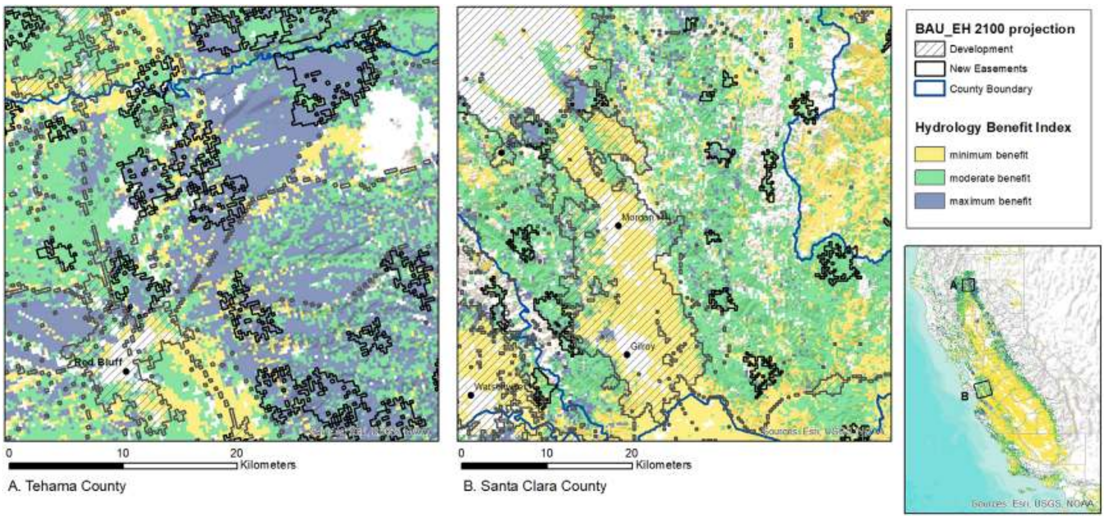


**Figure 5.** Land use projections for a Business as Usual, High Conservation Easement (BAU_EH) scenario in 2100. A: Future conservation easements targeted for hydrologic benefits in Tehama County; B: Projected development in Santa Clara County on working lands with moderate to high potential for hydrologic benefits.

scenarios, and a 37.0 $m^3 \times 10^6$ increase between the medium and high easement scenarios (figure 1, table S2). Associated with this increase in hydrologic benefits is an overall increase of 2023 $km^2$ (500 000 acres) of protected working lands between the zero and high easement scenarios.

## Discussion

Our scenario results show an uneven distribution of hydrologic climate adaptation benefits resulting from soil management across California, driving an uneven distribution in both lost potential for water savings from development and potential gains on conservation lands. As indicated by statewide BCM model runs (Flint *et al* 2018a, 2019), a limited number of counties provide a majority of the hydrologic benefits given variations in climate, soil texture and soil water storage capacity. Lost potential from development is similar across scenarios in 2050, though losses increase in the BAU scenario by 2100. Santa Clara and Shasta Counties are two regions of the state where future development is likely to occur on soils with greater potential for response to soil management. However, development conversions and new easements with

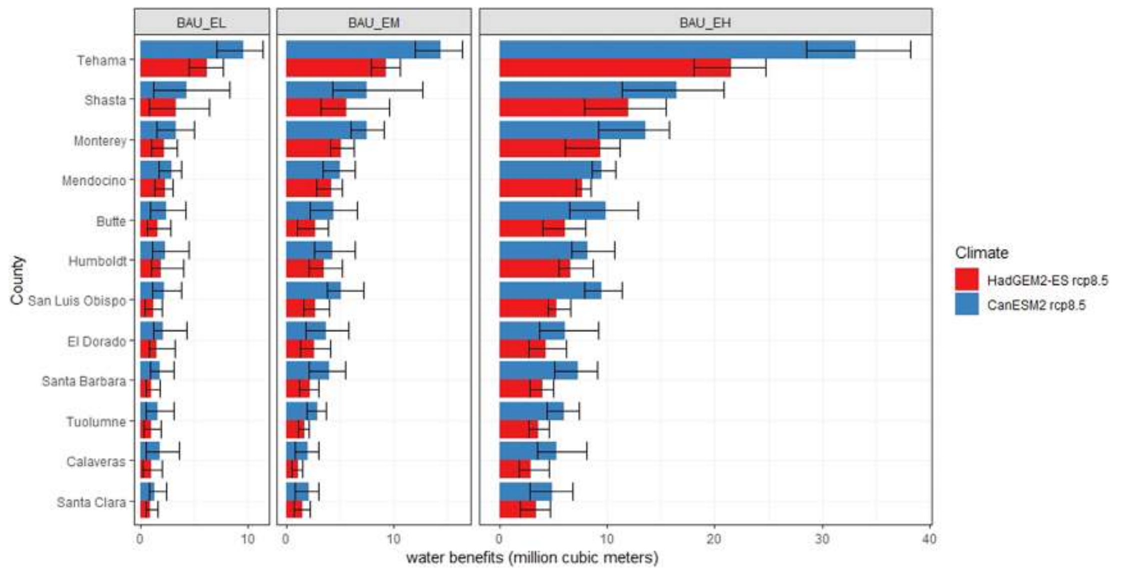


**Figure 6.** For year 2050, top 12 counties where potential for hydrologic benefits on conservation easements is highest. Values represent average plus minimum and maximum values based on 10 Monte Carlo iterations per scenario. See table 1 for scenario definitions.

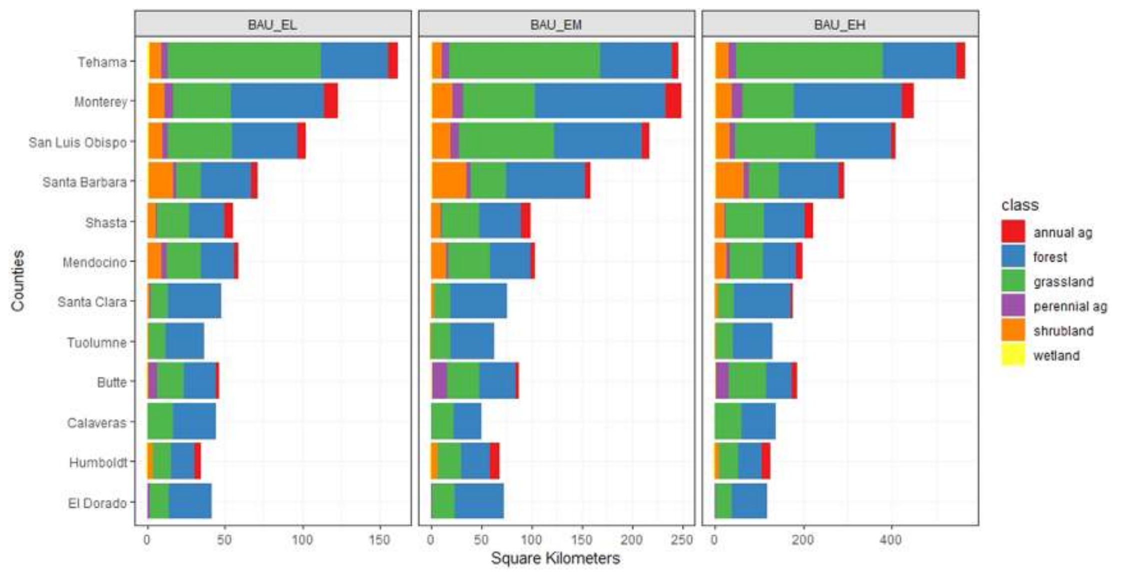


**Figure 7.** Land area in easements for the top 12 easement counties, at 2050, for three easement scenarios. Values are averaged from 10 Monte Carlo iterations of easement locations.

potential to maximize hydrologic benefits may often occur in different places, with different outcomes.

Combining soil management with easement acquisition can increase the opportunity for hydrologic benefits and offset the lost potential for water savings on lands subject to development. These benefits on easements are similar in magnitude to the lost potential on newly developed lands, and models suggest benefits vary based on climate, more than growth or conservation scenario. In the hot, dry climate scenario, a state-wide low easement acquisition rate (EL) can offset lost potential in hydrologic benefits due to development, while in a warm, wet climate scenario, a moderate easement acquisition rate (EM) is needed to compensate for these losses. Potential water savings from soil management on Williamson Act lands are an order of magnitude greater than potential losses related to future development, totaling over 460 $m^3 \times 10^6$ annually state-wide in a dry climate scenario by 2050. Despite many easements co-occurring on Williamson Act lands, a high easement acquisition rate could increase combined recharge, ET and reduced water stress hydrologic benefits over those on Williamson contract lands alone by approximately 80 $m^3 \times 10^6$ of water annually in a dry climate scenario, creating a combined total benefit on Williamson Act and easement lands of 544 $m^3 \times 10^6$ of water (table S2). This volume of water is approximately equivalent to the water used in 880 000 California households, where average yearly gross water use is approximately 617 cubic meters (0.5 acre-feet) (Hanak *et al* 2011).

The BCM model outputs show increased soil water holding capacity up to approximately 1/3 m of water per meter of soil resulting from a 3% increase in SOM above baseline across all California working lands. The rate of increase in water holding capacity is variable depending on soil texture, soil management practices, land type (rangeland versus cropland, for example) and land use configuration, and climate (Poulton *et al* 2018). In comparison to hardwood woodland, soil management practices are more feasible on grassland, and likely to be even more feasible on agricultural land intensively managed to increase soil organic carbon (Chambers *et al* 2016, Paustian *et al* 2016, Minasny *et al* 2017). By 2050 in all scenarios, grassland and woodland are the dominant land covers across all conservation easements, though Tehama and San Luis Obispo are the two counties with the greatest proportion of grassland area within their modeled easement locations. Most of the land area on Williamson Act lands (18 616 $km^2$) is grassland and remains grassland by 2050 in a BAU scenario without additional easements, though approximately 1311 $km^2$ are subject to conversion to another form of agriculture, assuming historical trends continue.

### Implementation of soil management on protected lands

Our modeling exercise assumed that conservation and soil management activities were adopted in areas that would achieve the greatest benefits. However multiple factors may influence landowners to adopt conservation practices, such as financial incentives, land tenure, residency, past management, future plans, and information received (Farmer *et al* 2017). For example, conservation easements for protection of private land are established according to a wide range of customized permitted and restricted uses, and may include variable approaches to land management in their terms (Rissman *et al* 2013). Many easements limit options for altering land management to achieve conservation objectives, though easements with specific purposes like species protection tend to allow for more monitoring, management, or mechanisms for change (Rissman *et al* 2013). By initially developing easement terms and purposes, adoption of conservation-oriented climate adaptation practices can be more feasible (Rissman *et al* 2013, 2015). Conservation easements that include processes for adaptive management, monitoring conservation targets, and stewardship will likely provide the flexibility to sustain ecosystem services and resiliency given climate change over time (Rissman *et al* 2015, Stroman and Kreuter 2015).

Climate adaptation practices are also incentivized by several programs and organizations, some of which include land protection as a program component. For example the NRCS Agricultural Conservation Easement Program provides financial and technical assistance to help conserve agricultural lands and wetlands and their related conservation values (USDA Natural Resources Conservation Service 2019a). The area of land enrolled in a program and the perception that implementation of practices will improve the ecological functioning of the land are two key factors in determining participation in a conservation program (Farmer *et al* 2017). Among landowners with conservation easements, adoption of management practices is related to the motivation for land ownership, such as agricultural production, investment or consumptive recreation, personal land stewardship goals, as well as the level of outreach by easement holders to landowners (Stroman and Kreuter 2015). Haden *et al* (2012) suggest that adoption of management practices by farmers is motivated more by their concern for long-term risk to society rather than near-term personal risk, which, in contrast, is one of the goals of adaptation.

Across California Resource Conservation Districts (RCDs), producers are motivated to implement climate beneficial practices such as soil management to increase productivity (crop yields and range carrying capacity), increase resilience to climatic factors (drought, wind, flooding), and gain environmental cobenefits beyond climate, such as erosion control and improved water resources (survey of 32 RCDs, P Alvarez, 2019, unpublished data). In addition, practices that increase carbon sequestration provide the opportunity for landowners to offset enterprise-wide emissions, access future carbon market opportunities, access new or alternative grant funding streams such as the California Healthy Soils Program, meet corporate sustainability goals and work toward production of carbon-beneficial products as a marketing tool, similar to relevant factors in forest carbon markets for small-scale forest landowners (Charnley *et al* 2010). Landowners also seek additional economic benefits from conservation practices that include earning market premiums, diversified revenue from cash cover crops or animal integration post harvest, or on cover crops, savings on fertilizer and other inputs, and savings on labor, as associated, for example with no-till practices.

## Conclusion

This analysis specifically evaluates the potential for soil management on protected working lands to increase water benefits, as well as losses due to lost management opportunities resulting from urban and suburban development. It does not consider change in GHG stocks or flux due to land conversion alone, nor change in water balance. Conversely, it does not consider avoided loss of baseline carbon stocks or avoided loss of baseline water supply from land protection, such as groundwater recharge that would occur without the increase in impervious surfaces associated with conversion to urban land use (Byrd *et al* 2015b). Next steps should include calculation of combined hydrologic and GHG reduction benefits that result from co-occurring avoided conversion and land management on protected lands.

Overall, model results indicate high potential for climate adaptation and drought resilience through realization of water benefits from managing soils on protected working lands, though outcomes are spatially variable. Results show where implementing practices will have greatest outcomes for hydrologic climate adaptation on conservation lands, and where combined land conservation and management can offset lost potential for adaptation due to development. Changes in land management and land conservation can play a large role in meeting California emission reduction targets (Cameron *et al* 2017), while also increasing climate resilience. Gains in ancillary ecosystem services also vary by agricultural practice and adoption rate, land use type and configuration, and terms of conservation agreements. Therefore, the effectiveness of programs designed to improve climate adaptation at large scales will likely increase by taking this potential, and spatial variability, into consideration.

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## Data availability statement

All LUCAS land use change model outputs are freely available on sciencebase.gov, https://doi.org/10.5066/F7W37VFJ. The data release citation is:

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