Ecosystem Services 39 (2019) 101008

Contents lists available at ScienceDirect

Ecosystem Services

journal homepage: www.elsevier.com/locate/ecoser

The impacts of climate change on ecosystem services in southern California

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ARTICLE INFO

Keywords:
Biodiversity
Carbon storage
Recharge
Resource management
Runoff
Sediment export

ABSTRACT

Climate change is projected to impact ecosystem functioning, however its effect on the provision of ecosystem services is uncertain. This is particularly relevant on federal lands which harbor extensive tracts of natural vegetation. We assessed change in four ecosystem services (water runoff, groundwater recharge, carbon storage, and biodiversity) and one disservice (sediment export) in southern California between current and end-of-century (2070–2099). We used five general circulation models ranging from warmer wetter (CNRM-CM5, CCSM4) to hotter, marginally drier (IPSL-CM5A-LR) to hotter drier (FGOALS-g2, MIROC-ESM) under RCP8.5. We found greatest projected change in water runoff, from an increase of 127% under a warmer wetter GCM to a decrease of −60% under a hotter drier future. Carbon storage is projected to change the least, from an increase of 52% to a decrease of −31% across GCMs. We also determined that one-third of high biodiversity areas are threatened by high change in climatic water deficit. We estimated the current monetized annual value of sediment removal costs to be $172 million per year and the economic value of carbon storage as $7.5 billion. Understanding the impacts of climate change on ecosystem services can help develop climate-smart strategies for the sustainable management of natural resources.

1. Introduction

The processes and interactions of a healthy, functioning ecosystem deliver resources and services of benefit to society such as food, water, erosion control, and cultural values (Mooney et al., 2009). Projected changes in climate are known to have important effects on biological communities that will impact ecosystem functioning (Fischlin et al., 2007; Thomas et al., 2004; Shaver et al., 2002), but how these impacts manifest in terms of provisioning ecosystem services is less clear. Climate-induced changes will modify the production, distribution and quality of ecosystems and consequently the value we derive from the ecosystem services they provide will also change (Shaw et al., 2011), such as the provision of water, habitat for biodiversity, or climate regulation through carbon sequestration. Understanding how climate change will impact the stocks and flows of ecosystem services in the future is a critical input for proactive resource management to develop strategies to sustain these services (Scholes et al., 2008; Runting et al., 2017).

Studies of the impact of climate change on ecosystem services have been undertaken, but are not plentiful in the literature. Reasons for this include the challenges associated with understanding regional variations in climate change, uncertainties over long timescales, and the interaction of climate change with other drivers of change (Martinez-Harms et al., 2017; Runting et al., 2017; Van Vuuren et al., 2007). Furthermore, once undertaken, there is often limited adaptive capacity to respond to these projections, particularly in developing countries (Martinez-Harms et al., 2017; Oteros-Rozas et al., 2015; Ngoc, 2019). A review by Runting et al. (2017) found climate change impacts on services were overwhelming negative (59% of studies) and only 13% of studies showed a positive impact. For example, a study in the Mediterranean-type region of Chile found carbon storage, wine production, and scenic beauty would experience substantial pressures from climate change, urbanization, and their interactions by 2050 (Martinez-Harms et al., 2017). Estimating the future provision of ecosystem services is further complicated by socio-economic changes occurring in parallel, such as changes in population, demand for food and other services, and technology (MEA, 2005).

Changes in the provision of ecosystem services and their economic

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https://doi.org/10.1016/j.ecoser.2019.101008
Received 26 November 2018; Received in revised form 25 July 2019; Accepted 29 August 2019

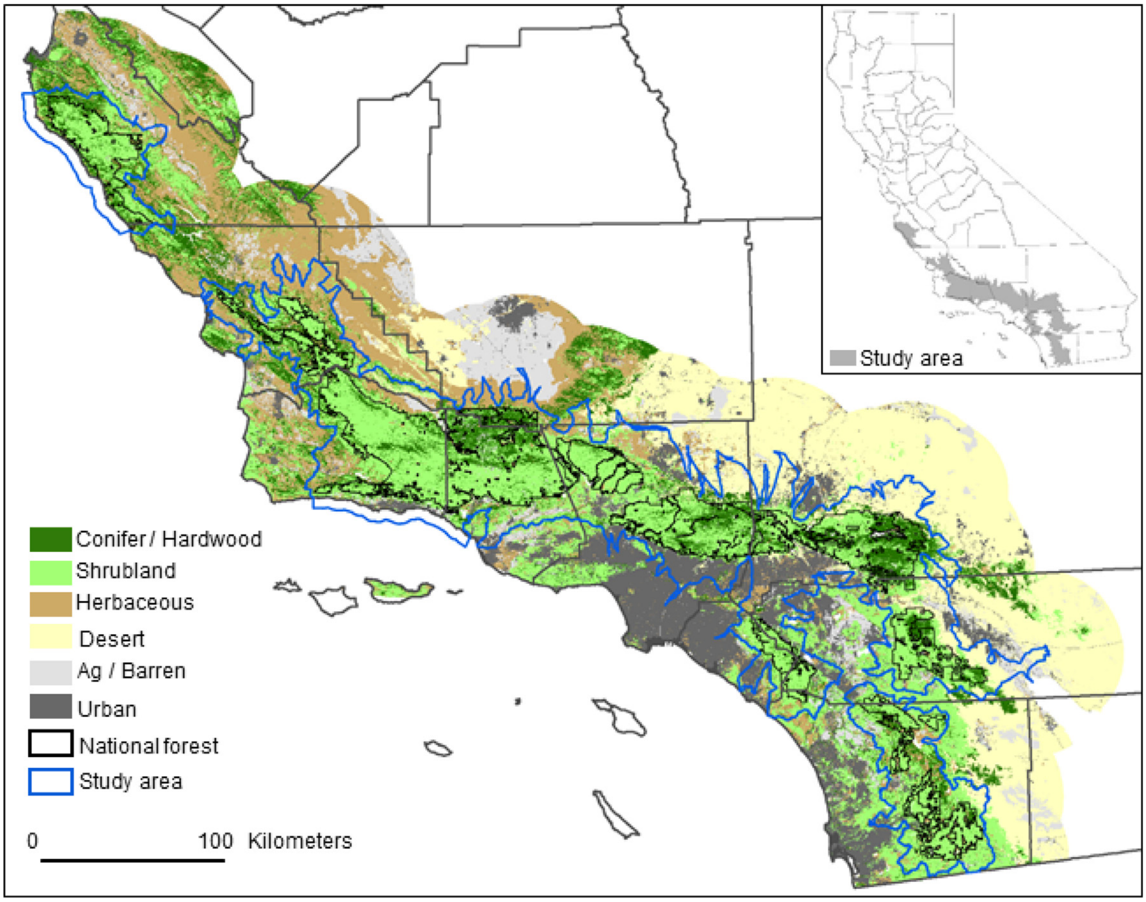

Fig. 1. Southern California study area which totaled 3.5 million ha (8.7 million acres), covering 375 watersheds (USGS HUC 12), and encompassed the Angeles, Cleveland, Los Padres, and San Bernardino National Forests. Major vegetation types (FRAP, 2015) are shown within a 40 km buffer around the study area to illustrate proximity of major urban areas to natural vegetation and dominance of shrubland vegetation. Inset map shows location of study area within the state of California.

value mean economies at local to global scales are vulnerable to climate-induced changes. Estimating the economic value of ecosystem services has become increasingly common over the last 30 years. In undertaking valuation, this information can provide insights to managers and policy makers and raise awareness among the beneficiaries of ecosystem services (Wright et al., 2017). The valuation of ecosystem services is often undertaken using valuation studies around the world, however, there is an increasing trend, and need, to use data and values local to a particular region to be relevant from a national welfare perspective and to be informative to policy-makers (Turpie et al., 2017).

To investigate the vulnerability of ecosystem services to climate change, we focused on five services in southern California (Fig. 1), one of the world's five Mediterranean-type climate regions. By combining spatial and climate models, together with monetized values for two of these services, we highlight the impacts of climate change on services in a spatial context. Terrestrial ecosystems in southern California are heterogeneous, and include shrubland ('chaparral'), woodland, and grassland, as well as forest in more humid (marine-influences) and at higher elevations. The role of these natural landscapes has long been recognized for providing water and preventing erosion-related damages to downstream populations. In the late 1800s, a series of federal forest reserves were designated which formed the foundation of today's National Forests (albeit dominated by chaparral) (Safford et al., 2018). Today, however, this global biodiversity hotspot (Myers et al., 2000) faces many challenges with high population density, invasion of non-native annual grasses, and increasing occurrence of fire at much shorter intervals than historically experienced (Safford, 2007; Safford et al., 2018; Keeley, 2006).

The natural landscapes contained within four National Forests in southern California provide numerous services including water resources, retention of sediment, clean air, and climate regulation to one of the most densely populated areas in the United States. Understanding how climate-induced changes will affect the natural landscape is essential for maintaining its integrity and the provision of ecosystem services essential to the health, well-being, and safety of over 22 million people (CDF, 2018). In this study, we estimated how climate change is likely to influence five ecosystem services (water runoff, groundwater recharge, carbon storage, sediment erosion, and biodiversity) in southern California that are provided by these shrub dominated ecosystems and estimated the current monetized value of two of these services.

While an increase in temperature in southern California is supported across all General Circulation Model (GCM) outputs published by the Coupled Model Inter-comparison Project Phase 5 (CMIP5, IPCC, 2014; Taylor et al., 2012), the direction and change in projected precipitation is less clear. Change between current (1981–2010) and end-of-century (2070–2099) precipitation projections in southern California range, for example, from +32% in CNRM-CM5 to −30% in MIROC-ESM (Fig. 2). In addition, the topographic complexity of the region and inherent variability in its hydroclimate will increase the level of uncertainty in projections of precipitation (Dettinger et al., 2011; Allen and Luptowitz, 2017). The impacts of opposing precipitation projections is substantial: an increase in precipitation can lead to saturated soils, massive landslides, and poor water quality from sedimentation, but also greater biomass and carbon sequestration; however, a decrease in precipitation can lead to less water quantity, pervasive wildfires, and potentially desertification of the landscape.

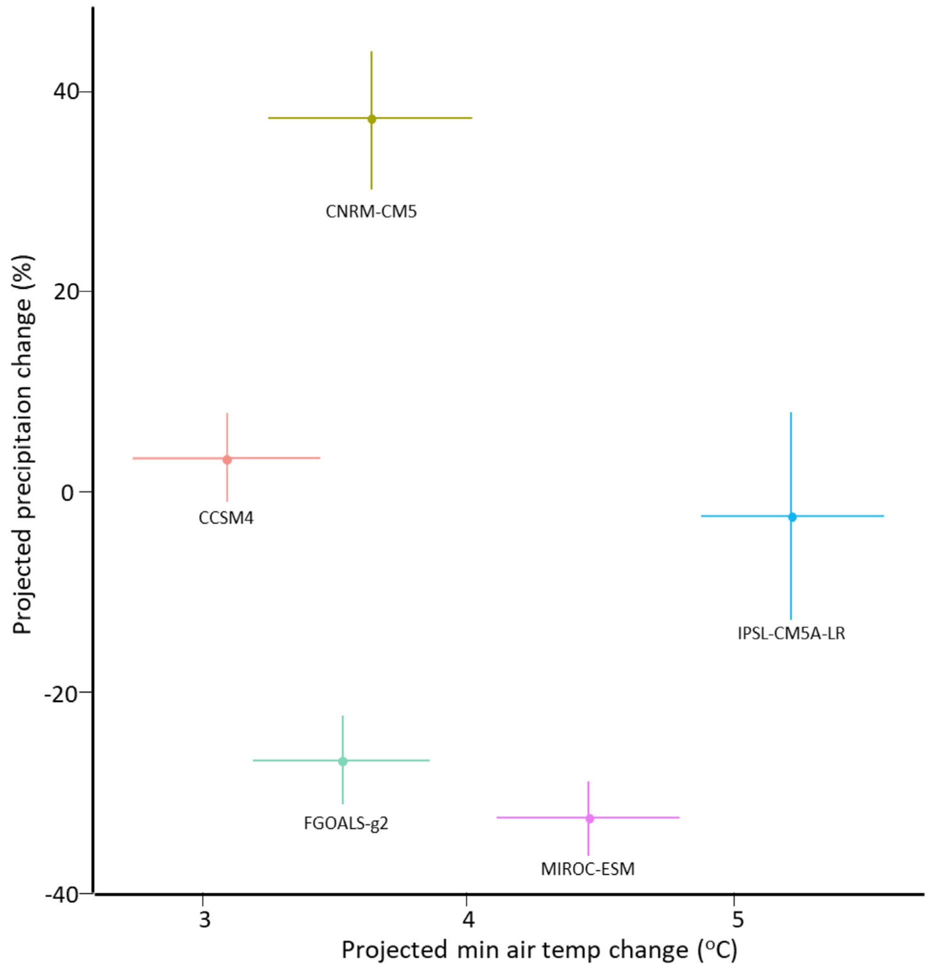

Fig. 2. Change in projected precipitation (%) and minimum air temperature (°C) by five general circulation models (GCMs) for the southern California study area. Calculations compare current (1981–2010) to end-of-century (2070–2099) conditions (plus or minus one standard deviation).

In this inter-disciplinary study we built on initial estimates of ecosystem services under current climate conditions made in a previous study (Underwood et al., 2018a) and expanded this in two ways. First, we undertook a spatially explicit assessment of the change in quantity of five ecosystem services in southern California by assessing the amount of services under current conditions with an alternate state (counterfactual) under five future climates. Second, we estimated the monetized values of two of these services under current conditions using an economic value (carbon storage) and a public cost (sediment export). The results of this study create meaningful inputs for resource managers and decision makers, particularly given the increasingly central role of ecosystem services within federal land management (e.g., the USDA Forest Service 2012 Planning Rule).

2. Materials and methods

The study area totaled 3.5 million ha (8.7 million acres) spanning from Monterey County in the north to San Diego County in the south (Fig. 1) and consisting of 375 watersheds at the HUC12 scale (USGS Hydrologic Unit Code, USGS and EPA (2018)) which intersected with the four southern National Forests: the Angeles, Cleveland, Los Padres and San Bernardino.

To assess the change from current to end-of-century (2070–2099) conditions, we used five GCMs from a suite of 18 from NEX-DCP30, which comprise GCM outputs published by Coupled Model Inter-comparison Project Phase 5 (CMIP5, IPCC, 2014; Riahi et al., 2011) using the 'business as usual' scenario RCP8.5. The five GCMs, downscaled to 30 arc seconds (~800 m) (Thrasher et al., 2013), capture the range of variation for current climate in southern California (Flint and Flint, 2014): a warmer wetter projection by CNRM-CM5 (Centre National des Recherches Météorologiques, France); two hotter drier projections by MIROC-ESM (Center for Climate System Research, Japan) and FGOALS-g2 (State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, China); a hotter, marginally drier projection by IPSL-CM5A-LR (L'Institut Pierre-Simon Laplace, France); and a projection by CCSM4 (National Center for Atmospheric Research, USA) which is closest to the ensemble mean of all 18 models.

We used four different models to estimate ecosystem services for water, carbon storage, sediment export, and biodiversity across the southern California study area. While using the outputs from one model to inform another is desirable, the specifics of each model prohibited this. For example, while vegetation cover plays a key role in sediment erosion modeling, the spatial resolution of the modeled biomass (from the MC2 dynamic global vegetation model) is too coarse to link with the sediment erosion modeling inputs.

2.1. Carbon storage

Forested ecosystems are well recognized sinks for carbon storage, helping to regulate climate change, thereby providing a service for humans at local to global scales. In contrast, the role of shrub dominated ecosystems in storing carbon is less appreciated, despite the fact that some shrublands can absorb more carbon than old growth forests in wet years (Luo et al., 2007).

To estimate carbon storage under current conditions for shrublands, we combined aboveground live biomass data from biomass maps created by the California Air Resources Boards (ARB) for 2001 and 2010 (Gonzales et al., 2015). The ARB data are based on Landsat-derived vegetation maps produced through the Landfire program (Ryan and Opperman, 2013) together with vegetation inventory plots from the USDA Forest Service Forest Inventory and Analysis (FIA) program (N = 220) that occurred in shrublands. For each plot, an estimate of aboveground live biomass was developed based on allometric equations using species identity and measurements of height and cover. These plots were assigned to the vegetation classes mapped by Landfire in 2001 and 2010. We reduced the number of Landfire classes to reflect only vegetation subclass and height (e.g., 'evergreen shrubland with height 0.5 m–1 m'), following the approach used in the California Forest and Rangeland Greenhouse Gas Inventory Development (Battles et al., 2014; Gonzales et al., 2015). Mean biomass values for each Landfire shrubland class were assigned through combining data for the vegetation classes used in the ARB data with data in the FIA and LFRD plots, weighting these sources by the per-class variance in the data. Biomass estimates were cross-referenced with field estimates summarized in Bohlman et al. (2018) to ensure they were realistic. For biomass values of forest vegetation types within the study area we used the spatial data developed by Gonzalez et al. (2015). We used the 2010 data to estimate current biomass and converted it to carbon by multiplying by 0.47 (approximately half of woody biomass is carbon [McGroddy et al., 2004]), and then to CO_2 equivalent (by multiplying by 3.67) before applying an economic value.

To estimate carbon stored under the five GCMs, we used the MC2 dynamic global vegetation model (DGVM) to simulate future vegetation carbon stocks (Bachelet et al., 2001; Conklin et al., 2016). We first ran a historical simulation spanning years 1895–2012 using 30-arc second resolution PRISM climate data (Daly et al., 2008), calibrating the model to estimate current plant biogeography (FRAP, 2015), net primary production (Zhao et al., 2005), and annual area burned by fire for 1992–2012 (Short, 2013). We calculated the relative change in live aboveground carbon between current (1970–1999) and five GCMs at the end-of-century (2070–2099), and applied this percent change to the current estimates based on the LFRD and FIA data.

To economically value the amount of current carbon storage, we used the social cost of carbon (SCC) as estimated by the United States Interagency Working Group on Social Cost of Greenhouse Gases (IWG). The SCC is an estimate of the net global monetized damages associated with an incremental increase in carbon emissions in a given year, and includes changes in agricultural productivity, property damages from increased flood risk, and human health (IWG, 2016). The underlying models upon which the IWG determines the SCC, assess the net economic costs from the year of emission out to 2300, given the long-term permanence of CO_2 emissions in the atmosphere. We apply a 3% discount rate to calculate the present value of future carbon damages resulting from current emissions, resulting in an economic value of $45.78 per metric ton (2017$) (IWG, 2016).

2.2. Water provision

The role of intact landscapes, particularly public lands, for providing fresh water for human use and consumption, as well as agricultural, environmental, and hydroelectric use has long been recognized (e.g., Forests to Faucets assessment in the US, Weidner and Todd, 2011). To estimate change between current and end-of-century water runoff and groundwater recharge, we used the Basin Characterization Model (BCM), a regional water balance model for the state of California (Flint et al., 2013; Underwood et al., 2018b). We extracted data on current (1980–2010) and future (2070–2099) water runoff and groundwater recharge.

While methods do exist to value water provision services (e.g., Young and Loomis, 2014; Jenkins et al., 2003; Griffin, 1990 which value municipally treated water), the valuation of water in southern California is extremely challenging for a number of reasons. It is unclear where the water from the National Forests goes and how it is used (or not used), in addition 86% of the water used in the Los Angeles Basin comes from sources outside the region via the State Water Project, the LA Aqueduct, or the Colorado River (LADWP, 2017) which confounds calculations of the runoff and recharge values. Furthermore, there are temporal issues associated with the process of groundwater recharge that further complicate valuation. Consequently, estimating the use and non-use values of water in southern California is a substantial and complex undertaking, and is not undertaken in the current study.

2.3. Sediment export

The movement of upstream debris and sediment associated with intense rainfall post-fire can lead to the destruction of infrastructure, decrease water quality, and threaten lives. As a response, over 200 debris dams have been built across southern California at the mouths of canyons to capture sediment and debris and reduce the risk of mudslides (Wohlgemuth and Lilley, 2018). Native vegetation mitigates erosion by stabilizing soil and trapping sediment with its roots and stems (Wohlgemuth et al., 2009, Fig. 3). Although the ecosystem service is sediment erosion *retention*, we present the data on the amount and monetized value of sediment export (technically an ecosystem disservice).

We used the InVEST sediment erosion module (Hamel et al., 2015) with specific inputs for the southern California area, including soil erodibility data from county scale SSURGO soils maps, and a cover factor (C) – which represents the influence of vegetation on soil erosion based on maximum rainy season NDVI (2014–2015) (see Underwood et al., 2018a and Supplemental Material for details). To assess the impact of the future climate scenarios, we modified the erosivity estimate based on the precipitation associated with each GCM. This used a regression model (Biasutti and Seager, 2015) based on erosivity data provided by Daly (Daly and Taylor, 2002). To address the difference in the amount of sediment delivered to the stream compared to the amount transported and deposited in a reservoir, we developed a linkage function between the InVEST model outputs and 60 years of data on sediment removal from 75 debris basins in the front range of the San Gabriel Mountains from the Los Angeles County Department of Public Works (Lavé and Burbank, 2004).

To estimate the current monetized value of sediment export, we used the InVEST output with the corresponding scaling factor, and applied costs information from the Los Angeles County Public Works Department. We used a value of $16.82 per m^3 (in 2017$), estimated based on a regression model of the historical sediment discharge, and examined the costs associated with sediment removed from 41 debris basins along the southern flank of the San Gabriel Mountains in Los Angeles County (Loomis et al., 2003). These costs reflect regular sediment removal as well as during emergency situations after substantial rainfall post-fire, over a 30–60 year period depending on the age of the debris basin. This represents the low end of this cost; costs associated with clearing individual debris dams and transport of material can be as much as $30 per m^3 (Wohlgemuth and Lilley, 2018). We do not attempt to value this service under future conditions as it is unclear how these public costs will change.

2.4. Biodiversity

There are multiple key roles that biodiversity plays in the provision of ecosystem services. First, as a regulator of ecosystems that underpin the ecosystem processes and functioning that deliver ecosystem services (Harrison et al., 2014; Mace et al., 2012; Reid et al., 2005). Previous research has focused on the functional link between biodiversity and the provision of ecosystem services, with studies focusing on single and groups of species with one or multiple ecosystem services (Diaz et al.,

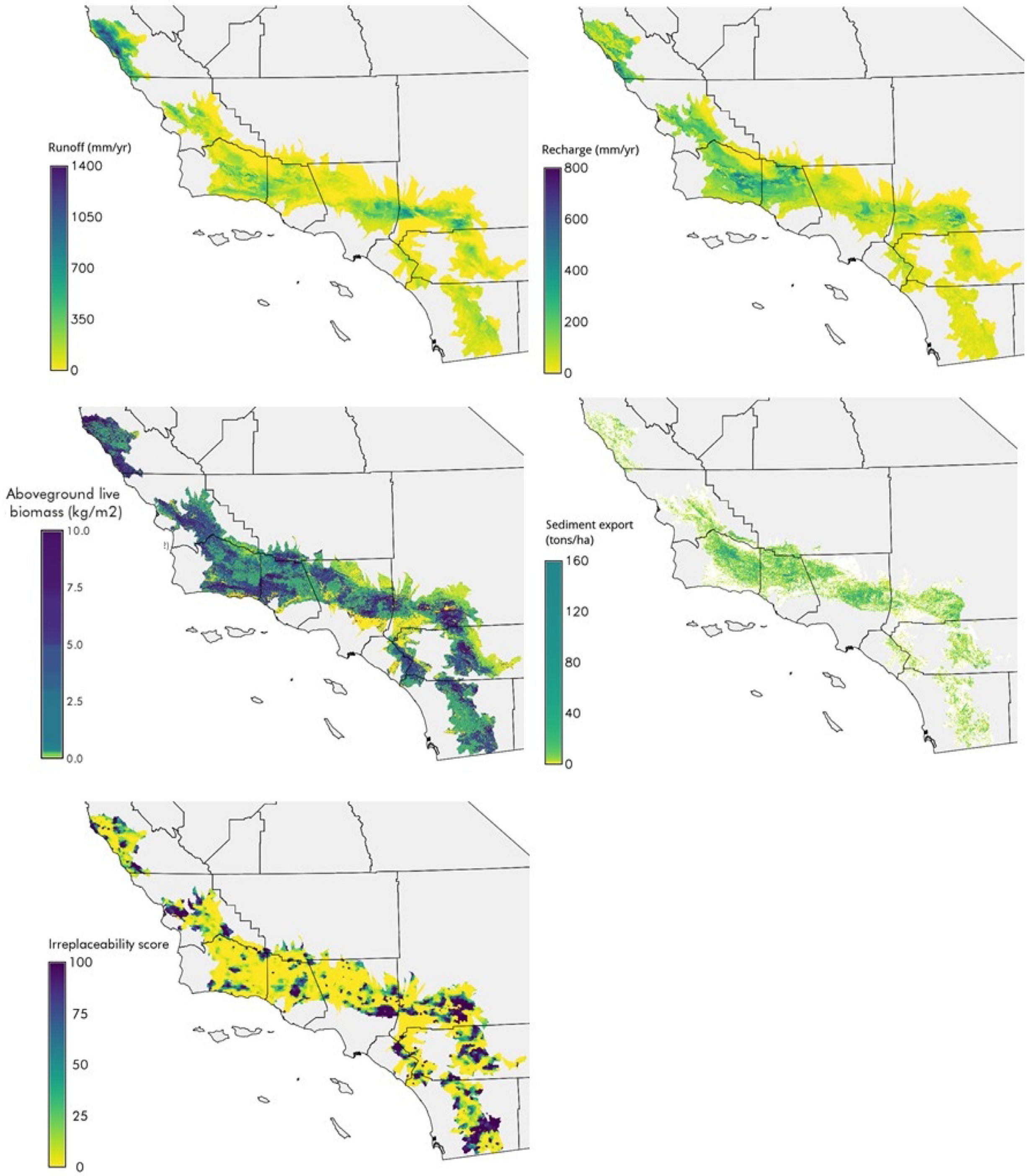

Fig. 3. Distribution by unit area of current ecosystem services across the southern California study area. Calculations of runoff (mm/y), recharge (mm/y), carbon storage (g/m^2), and the disservice sediment export (metric tons/ha) were made using 30 year averages. The irreplaceability score represents a biodiversity layer consisting of numerous inputs“: the higher the score, the higher the irreplaceability for meeting specified conservation goals (see text).”

2007; Harrison et al., 2014). A review of 530 studies used a network analysis to identify the linkages between different biodiversity attributes and ecosystem services, e.g., species abundance linking to freshwater fishing, pollination, species-based recreation service provision or species richness and timber production and pollination provision (Harrison et al., 2014). Second, biodiversity can be seen as a final ecosystem service, such as clean water provision or water regulation, or be valued in terms of its intrinsic value (Cardinale et al., 2012). Research has also focused on the relationship between biodiversity and human health, for example, linking exposure to microbial biodiversity to improved health and reducing allergic and respiratory diseases (Sandifer et al., 2015). Finally, biodiversity can be seen as a good (e.g., timber) that is subject to valuation (Mace et al., 2012).

However, warming climates are causing the redistribution of life on earth and the loss of diversity (Pereira et al., 2010). For the study area, we identified conservation targets with corresponding goals to represent biodiversity. Targets included the location of rare and endangered species guided by the USDA Southern California National Forest land management plan (USDA, 2004), wildlife linkages (Spencer et al., 2010), an indication of the quality of the aquatic biota from the

Watershed Condition Framework (Potyondy and Geier, 2011), and native and rare species richness (see Underwood et al., 2018a for full details). We used Marxan conservation planning software to determine the irreplaceability of ecological (planning) units within the study area (Ball et al., 2009). From this output, we selected ecological units with irreplaceability scores in the top 20% (scores of 80–100) to represent high biodiversity areas.

To assess the impacts of future climates, we identified areas of high and low change in climatic water deficit (CWD), an indicator of plant stress and overall ecosystem health (Stephenson, 1998) by subtracting current (1980–2010) from end-of-century (2070–2099) CWD values derived from the Basin Characterization Model. Change in CWD was defined on a percentile basis: areas of low change had percentile values between 0% and 20%, and areas of high change had percentile values between 80% and 100%. We calculated the overlap between high biodiversity areas and areas of both high and low CWD change under the five GCMs.

Biodiversity valuation in previous studies has been inconsistent (Bartkowski, 2017). Monetary values can be assigned to biodiversity attributes at the species level, functional group, and community scale (such as landscape aesthetics, species pollination, or species-based recreation). More recent studies suggest that the economic valuation of biodiversity should focus on the insurance value it provides (the ability of biodiversity to reduce uncertainty surrounding the provision of services) or the options that arise by having biodiversity available to reduce uncertainty (Bartkowski, 2017). Given the complexities of valuing biodiversity, particularly given the many input layers we use to develop our final biodiversity layer, we did not assign a monetary value in this study.

3. Results

3.1. Carbon storage

The total amount of carbon stored in aboveground live biomass, under current (2010) conditions in southern California is 45 Tg (Table 1a). Areas of moderate and high carbon storage ranged across the study area, particularly in high elevations characterized by forest compared to shrubland (Fig. 3). Using the social cost of carbon (3% discount rate) the current value (standing stock of carbon at any one time one-time) of carbon stored aboveground across the study area was over $7.5 billion (2017).

Aboveground live carbon storage is estimated to rise under the two GCMs with a projected increase in precipitation: CCSM4 and CNRM-CM5 (by 11% and 52% respectively) (Fig. 4), and under IPSL-CM5A-LR (13%) with largest projected increase in temperature. In these GCMs the increase in precipitation (CCSM4, CNRM-CM5), and increase in temperature with slight decrease in precipitation (IPSL-CM5A-LR), lead to higher productivity and plant growth. In the MC2 simulations, increased temperatures during the rainy winter season, drove increases in productivity (Case et al., 2019; Kerns et al., 2017; Kim et al., 2018). In contrast, the large decreases in precipitation projected by MIROC-ESM were estimated to reduce carbon storage by −31% (Fig. 4).

3.2. Water provision

The current (30 year mean) for water runoff was 3675 million m^3 per year and 3051 million m^3 per year for groundwater recharge (Table 1a). Areas of high runoff included the northern part of the study area in Monterey County and higher elevation areas of the Los Padres and Angeles National Forests, and relatively high recharge across many areas of the Los Padres National Forest (Fig. 3).

Projected change in the quantity of runoff ranged from an increase of 127% (CNRM-CM5) to a decrease of −60% (MIROC-ESM). Groundwater recharge decreased in all but one of the GCMs, including up to −52% in MIROC-ESM. In contrast, under the CNRM-CM5

Table 1a
Amount of ecosystem services and sediment export disservice under current conditions and five general circulation models (GCMs) under RCP8.5 climate change scenario for southern California study area. Units for volumetric totals and standard deviation are: million m^3 for runoff and recharge; million metric tons for sediment export, and Tg for carbon storage. Units for mean by area are: mm/yr for runoff and recharge; metric tons/ha for sediment export; and kg/m^2 for carbon storage in live aboveground vegetation. Current values and end-of-century (2070–2099) values are 30 year averages, except for current carbon storage which reflects data from 2010. No SD are provided for carbon storage as this is calculated based on relative change outputs from MC2 and not mapped spatially.

Ecosystem service	Current (vol. total)	Current (mean by area, SD)	CNRM-CM5 (vol. total)	CNRM-CM5 (mean by area, SD)	CCSM4 (vol. total)	CCSM4 (mean by area, SD)	IPSL-CM5A-LR (vol. total)	IPSL-CM5A-LR (mean by area, SD)	FGOALS-g2 (vol. total)	FGOALS-g2 (mean by area)	MIROC-ESM (vol. total)	MIROC-ESM (mean by area, SD)
Runoff	3674.50	104.69 ± 147.57	8326.17	237.22 ± 256.33	4333.95	123.48 ± 171.67	5318.24	151.52 ± 154.19	1926.73	54.89 ± 74.12	1470.44	41.89 ± 81.82
Recharge	3050.51	86.91 ± 91.06	4095.84	116.69 ± 108.23	3013.51	85.86 ± 88.55	2596.01	73.96 ± 70.33	1558.92	44.41 ± 45.69	1451.26	41.35 ± 51.07
Carbon storage	45.00	1.28 ± 2.13	68.40	1.95	49.95	1.42	50.85	1.45	38.70	1.10	31.05	0.88
Sed. Export	21.15	6.93 ± 40.69	28.25	9.26 ± 49.03	21.20	6.95 ± 36.76	20.14	6.60 ± 35.34	14.90	4.88 ± 25.71	13.92	4.56 ± 24.18

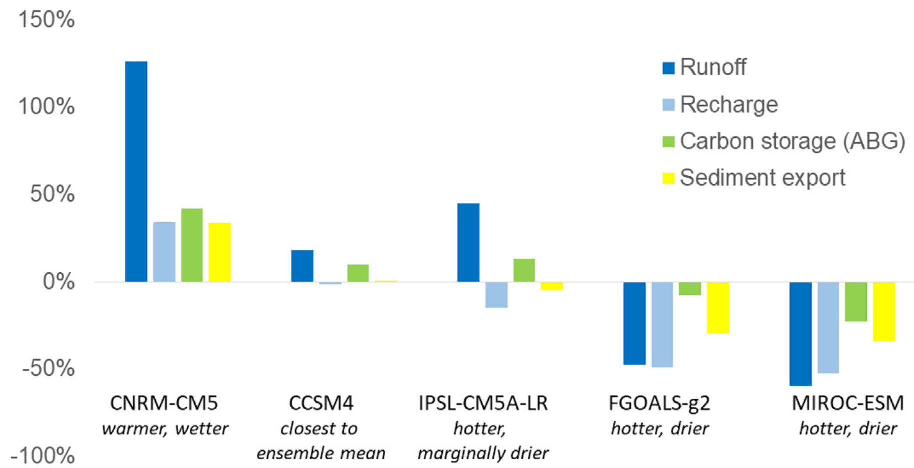

Fig. 4. Percent change in three ecosystem services and one disservice (sediment export) across the southern California study area. Data show change from current conditions using 30 year averages under five general circulation models (GCMs).

projection recharge increased by one-third (Table 1a, Fig. 4).

3.3. Sediment export

Using the InVEST sediment erosion module with modified rainfall erosivity component to reflect each of the five GCMs, we estimated the current amount of sediment exported or lost from the study area to be 21 million metric tons (Table 1a). Sediment export is medium to high in many parts of the study area, with less at the northern (Monterey County) and southern (Cleveland National Forest) reaches (Fig. 3). We estimated the savings in debris clearance associated with extant native vegetation on the landscape totaled $172 million per year.

Patterns of change in sediment export reflected projected changes in precipitation. Where precipitation projections showed an increase, sediment export increased by 34% and 0.2% under CNRM-CM5 and CCSM4 respectively, while decreased precipitation in the remaining three GCMs resulted in decreased sediment export, e.g., −34% in MIROC-ESM (Fig. 4).

3.4. Biodiversity

Areas of high irreplaceability based on the conservation targets and associated goals informed by the USFS Forest Service plans are scattered throughout the study area, inter-mixed with areas of low irreplaceability (Fig. 3). Each National Forest had a selection of high irreplaceability areas within them. From this layer we extracted areas with scores of 80–100 to represent the highest biodiversity areas, and intersected these with areas of both high change in CWD and low change in CWD in each GCM (Fig. 5).

We found one-quarter to one-third of high biodiversity areas were also areas of high change in CWD (Table 1b), especially at high elevations. The IPSL-CM5A-LR GCM had the greatest overlap between the two data layers which, in part, is due to this GCM projecting the greatest increase in temperature (5.2 °C, Fig. 2) and thus greatest influence on CWD. In contrast, about one-fifth (Table 1b) of high biodiversity areas were refugia with low end-of-century change in CWD across the five GCMs (see Fig. 5 for an example using CCSM4).

4. Discussion

Changes in precipitation, temperature, and ecosystem distribution as a result of future climates affect the provision of ecosystem services. Water runoff, for example, had the greatest change in provision from current condition to end-of-century with GCMs projecting a decrease of −60% to an increase of 127%, followed by groundwater recharge (34% to −52%). One of the major ramifications of a warming climate is the change from snow to rainfall in mountainous areas (Kapnick et al., 2010; Belmecheri et al., 2016), causing temporal changes in runoff, recharge, and peak flows, as the delay mechanism associated with snowpack is removed. Alternatively, projections for carbon storage at end-of-century changed the least: from a decrease of –23% to an increase of 42% across GCMs. Findings show the direction of precipitation change is a key determinant in the provision of end-of-century ecosystem services. The increase in precipitation projected under the warmer, wetter GCM (CNRM-CM5) corresponded to increased runoff, recharge, carbon storage, and greater sediment export compared to the decrease in precipitation and provision of these services under the two hotter and drier GCMs (FGOALS-g2 and MIROC-ESM) (Fig. 4).

Studying climate change impacts can be challenging given the long spatial timeframes and high uncertainties (IPCC, 2014; van Vuuren et al., 2007). In addition to changes in precipitation and temperature that are critical factors to sustaining services (e.g., Lifeng et al., 2017), accounting for changes in vegetation, fire frequency, fire effects, and their interaction are all important. In this study, only the relative change in carbon storage which is derived using the global dynamic vegetation model MC2, accounted for these variables. While MC2-derived data would be valuable to integrate in the models to project runoff, recharge, sediment export, and biodiversity, the difference in spatial resolution between MC2-derived outputs and the inputs of the other models made this challenging.

Our quantification of ecosystem services was clearly dependent on the models selected. However, we feel these are the best available models for applying to our spatial scale of analysis. For example, while a regional climate model might bring advantages, the MC2 model is designed to capture long-term climate change effects and runs on monthly time steps and so does not respond to daily extremes that regional climate models may represent. Moreover, other hydrological models exist as alternatives to the Basin Characterization Model, however, the BCM is one of the most widely used models in California at the regional scale (Ackerly et al., 2015; McCullough et al., 2016).

The findings from this study can contribute to natural resource planning on public lands by providing data on the spatial patterning of services (Fig. 3). For example, the intersection of high biodiversity and high end-of-century change in CWD areas should be particularly concerning for resource managers where key species and communities occur, and require management interventions to ensure their continued sustainability. In contrast, the intersection of high biodiversity and low change present positive solutions for resource managers: areas of the landscape that are likely to provide refuges for species and habitats under future climates. Further analyses could be undertaken for some

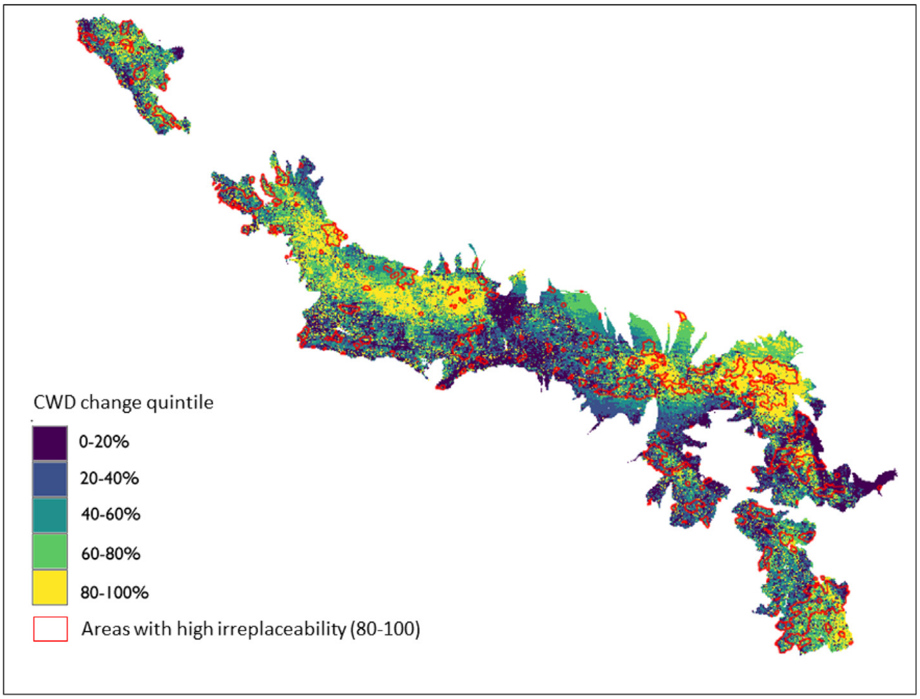

Fig. 5. Change between current (30 year average 1981–2010) and end-of-century (2070–2099) climatic water deficit (CWD) under the moderate scenario CCSM4 (shown in quintiles). Low change in CWD is defined as 0–20% and high change as 80–100%. Areas of high biodiversity, with irreplaceability values of 80–100 are outlined in red.

Table 1b
Biodiversity related ecosystem services: the proportion (%) of high irreplaceability locations in the study area which have low percentile change (0–20%) and high percentile change (80–100%) in climatic water deficit (CWD) under the five GCMs under RCP8.5.

Ecosystem service	CNRM.CM5	CCSM4	IPSL.CM5A.LR	FGOALS.g2	MIROC.ESM
High biodiv/low change (%)	17.26	17.27	17.04	21.45	17.12
High biodiv I high change (%)	28.01	26.67	34.92	25.75	29.33

services to partition the landscape into finer units such as watersheds. For example, the benefit of natural landscapes to retain sediment is more important in some areas than others – such as where sediment export contributes valuable material for the replenishment of farmland or beaches.

Another use of these data for public lands management is to contribute to natural resource damage assessments after wildfire. The impact of wildfire on services can be estimated by integrating data on the change in vegetation post-fire, although, again, the methods to do this are complex. This is particularly the case for water provision as the removal of vegetation and decrease in evapotranspiration leads to an increase in runoff and recharge post-fire. However, only a portion of this water could potentially be available for use and, for the purposes of residential use, would likely incur additional treatment costs given the decreased water quality owing to post-fire erosion. Consequently, more research at finer spatial resolutions needs to be conducted for assessing the impacts of wildfire on water.

We recognize there is substantial variation between the five climate models, particularly given the variability in precipitation in southern California, and the impact of these projections on the provision of ecosystem service (as in other modeling studies). Understandably, this makes a confusing situation for resource managers in the region and the variability of results limits our ability to provide clear guidance. However, given that National Forest lands in southern California protect the most intact terrestrial ecosystems – including critical habitat for 331 rare plant and animal species (California Natural Diversity Database) – and areas of high service provision, there is a critical need to incorporate climate projections into land and resource management planning.

Often it is useful to have a single climate change projection to contemplate in planning, rather than a multi-member ensemble. Frustratingly, recent observations of climate cannot be relied upon to have predictive ability (van Vuuren et al., 2011; Manning et al., 2010). Given that the earth's climate system has built-in momentum for warming, it is not until mid-century that warming trends significantly diverge, even when comparing low-emissions (intense climate mitigation) scenarios with high-emissions scenarios (van Vuuren et al., 2011). This underscores the uncertainty planners must grapple with when planning is undertaken on shorter timeframes of say 10–15 years. If projections based on a single GCM need to be selected as an illustrative case for planning in the short-term, one option is to use CCSM4 – the GCM exhibiting temperature and precipitation change closest to the mean of the 18-member original ensemble. However, given the spread of values present in end of-century projections, resource managers interested in planning over the long-term may wish to adopt a scenario planning approach (e.g., NPS, 2013).

5. Conclusion

The relative magnitude of just two of the ecosystem services we considered (combined monetized value of $7.7 billion) compared to the USDA Forest Service annual budget (2018) for the four southern National Forests ($20.2 million[1]) underscores the importance of effectively managing southern California's natural resources to ensure their continued provision. These valuations are just a starting point to a more comprehensive assessment. For example, the carbon storage value would have been higher if we considered belowground biomass: for

[1] Reflects appropriated budget only and excludes fire preparedness and cost pool budget.

some dominant shrubland species such as *Adenostoma fasciculatum* and *Arctostaphylos glauca* this can account for over 40% of the species biomass owing to the deep and extensive root system (Kummerow et al., 1977; Miller and Ng, 1977; Bohlman et al., 2018). Other opportunities for calculating the monetized valuation of the region's services include recreational services, or air quality and health benefits of these extensive natural landscapes in close proximity to heavily urbanized areas. Such a valuation process highlights the role of federal lands for the benefits they provide to the public and the need to manage them effectively to ensure the sustained provision of services.

Effective management is particularly essential given that the population of some counties within the study area are projected to increase by 50% between 2017 and 2050 (CDF, 2018), resulting in potentially greater demand for ecosystem services and more pressure on this already human-dominated landscape. In addition to the impacts of climate change, other pressures such as land conversion and development, increasing wildfire frequency, and conversion from native shrubland to non-native grasses (Safford, 2007; Safford et al., 2018; Keeley, 2006) place the security of ecosystem service provision over the long-term in question. This is even more concerning, given that the USDA Forest Service budget for resource management has declined in real and relative terms over recent decades.

Ecosystems are already under pressure to deliver essential ecosystem services, and the additional stresses imposed by climate change will require extraordinary adaptation (Mooney et al., 2009). Fortunately in southern California, where public lands cover a large proportion of the landscape, there is the potential to incorporate data on the current distribution of ecosystem services (Fig. 3) and climate change projections to ensure forward-looking, innovative solutions. The implementation of adaptation strategies can then help to ensure the healthy functioning of ecosystems and the services they provide.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was funded by the USDA Forest Service Pacific Southwest Region, the USDA Forest Service's Western Wildland Environmental Threat Assessment Center (WWETAC), and the California Landscape Conservation Cooperative. The authors thank Hal Mooney for input on the manuscript, Patrick Huber for assistance with data analysis, Michela Biasutti for erosivity data, and Jim Quinn and Nancy Grulke for insightful discussions.

Author Contributions

ECU and HDS designed the study. ADH, ECU, JBK, RJD undertook data compilation and spatial modelling and LS contributed the monetized valuations. ECU and HDS wrote the paper with contributions from ADH, JBK, and LS.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2019.101008.

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