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Assessing the effectiveness of Sustainable Land Management for large-scale climate change adaptation

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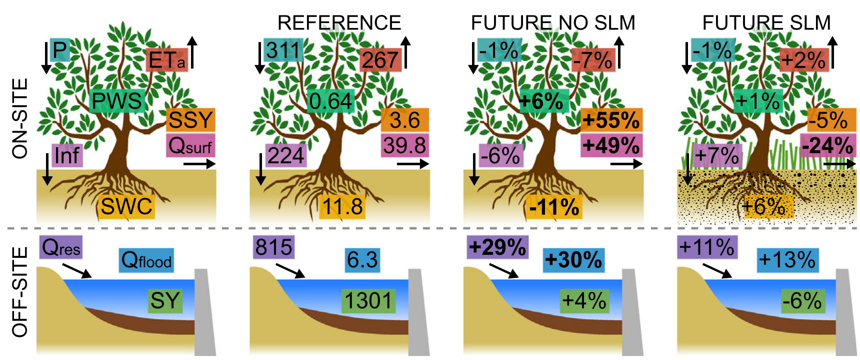
HIGHLIGHTS

- Climate change significantly affects on-site and off-site ecosystem services.
- Large-scale implementation of SLM reduces on- and off-site impact on water security.
- SLM can reverse the impact on water security under moderate climate conditions.
- Additional adaptation measures are required under extreme climate conditions.
- Large-scale assessment of SLM measures is important to support decision making.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change will strongly affect essential ecosystem services, like the provision of freshwater, food production, soil erosion and flood control. Sustainable Land Management (SLM) practices are increasingly promoted to contribute to climate change mitigation and adaptation, but there is lack of evidence at scales most relevant for policymaking. We evaluated the effectiveness of SLM in a large Mediterranean catchment where climate change is projected to significantly reduce water security. We show that the on-site and off-site impacts of climate change are almost entirely reversed by the large-scale implementation of SLM under moderate climate change conditions, characterized by limited reductions in annual precipitation but significant increased precipitation intensity. Under more extreme reductions of annual precipitation, SLM implementation reduces the impacts on water security, but cannot prevent significant increased plant water stress and reduced water availability. Under these conditions, additional adaptation measures are required considering their interactions and trade-offs regarding water security.

1. Introduction

In the coming decades, climate change will strongly affect global socio-ecological systems by altering the hydrological cycle, agricultural production potential and essential ecosystem services. For many areas worldwide, climate projections foresee less rainfall and more extreme weather events (Sun et al., 2007; O'Gorman and Schneider, 2009; Sillmann et al., 2013), causing decreased water availability and food production, and increased soil erosion and flood frequency (Donnelly et al., 2017; Zhang and Nearing, 2005; Nearing et al., 2005; Schroter, 2005; García-Ruiz et al., 2011; Eekhout et al., 2018a). To prevent devastating impacts for human well-being and help prepare society achieve the Sustainable Development Goals, climate change mitigation and adaptation are major priorities for the coming decades.

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Recent scientific studies and policy initiatives suggest that Sustainable Land Management (SLM) practices can contribute significantly to climate change mitigation and adaptation objectives (Chabbi and et al., 2017; World Bank, 2008). SLM refers to a range of technologies, policies and activities aiming for integrated management of soil, water, vegetation, and biodiversity to support long-term productive ecosystems by integrating biophysical, socio-cultural and economic needs and values (Dumanski and Smyth, 1993; Schwilch et al., 2009). SLM supports the prevention and reduction of land degradation, protects biodiversity, and includes established approaches such as conservation agriculture, cover crops, organic amendments, crop diversification, and integrated nutrient and water management (Griscom et al., 2017; Sanz et al., 2017). Some studies have identified SLM even among the most cost-effective agricultural pathways to mitigate climate change due to its potential to increase carbon storage and avoid GHG emissions (Griscom et al., 2017).

SLM also contributes to climate change adaptation by reducing ecosystem's vulnerability to climate extremes like droughts and floods. However, knowledge of SLM's effectiveness is mainly based on plot-scale and laboratory experiments, demonstrating how SLM enhances soil quality, reduces on-site runoff and erosion, and increases water use efficiency and food production (Zhang and Nearing, 2005; Zhang et al., 2009; Klik and Eitzinger, 2010; Lanckriet et al., 2012; Zhang et al., 2012; Routschek et al., 2014; Verhulst et al., 2010; Maetens et al., 2012a; Delgado et al., 2013; Palm et al., 2014; Almagro et al., 2016). Very few studies assessed the effectiveness of large scale implementation of SLM to reduce off-site impacts of climate change on flood intensity, sediment yield or water security (e.g. Azari et al., 2017). There is actually very little knowledge about the potential of SLM to alleviate the impact of climate change at large spatial scales (catchment/regional) and the resulting trade-offs between ecosystem services. The off-site impacts of climate change, such as an increased flood frequency and a reduction of fresh water provision, have large societal impacts. Policy makers, therefore, require quantification of the on-site and off-site impacts of large-scale implementation of climate change adaptation strategies.

The objective of this research is to quantify the on-site and off-site impacts of SLM based climate change adaptation on soil and water resources and related ecosystem services. We focus specifically on two types of SLM practice that were identified in an extensive participatory process, namely reduced tillage and green manure. We applied a coupled hydrology-soil erosion model (SPHY-MMF, Eekhout et al., 2018b) to a large Mediterranean study area, where climate change is expected to have a significant negative impact on water security in the coming century (Eekhout et al., 2018a). The effectiveness of SLM was evaluated with on-site (plant water stress and hillslope erosion) and off-site (reservoir inflow, flood discharge and reservoir sediment yield) water security indicators. The results aim to increase insight in the effectiveness of SLM to alleviate the on-site and off-site impacts from drought and extreme weather at regional scales, most relevant for policy makers.

2. Material and methods

2.1. Study area

This study is performed in the Segura River catchment in the southeast of Spain (Fig. 1a), covering an area of 15,978 km^2, with an elevation ranging between sea level and 2055 masl. Catchment-averaged annual rainfall amounts to 361 mm (for the period 1981–2000) and mean annual temperature ranges between 9.3 and 18.7 °C (1981–2000) from the headwaters to the downstream area. The climate is Mediterranean (Csa according to the Köppen-Geiger climate classification) in the headwaters (19%) and semi-arid (BSk) in the rest of the catchment (81%).

The dominant landuse types are shrubland (28%), forest (26%), cereals (14%) and almond orchards (9%), based on a detailed landuse map (Fig. 1c). Agriculture covers 44% of the catchment. The main soil classes are Calcisols (41%), Leptosols (35%), Luvisols (4%) and Kastanozems (4%) (Hengl et al., 2017). There are 33 reservoirs in the catchment, with a total capacity of 1230 Hm^3 (Fig. 1b). Fourteen reservoirs are allocated exclusively for irrigation purposes, the other reservoirs have mixed functions for electricity supply and flood prevention.

2.2. Model description

We applied the SPHY-MMF model (Eekhout et al., 2018b), a spatially distributed hydrological model, fully coupled with a soil erosion model. The model is applied on a cell-by-cell basis, with a resolution of 200 m and a daily time step. The hydrological model (Terink et al., 2015) simulates most relevant hydrological processes, such as interception, evapotranspiration, surface runoff, and lateral and vertical soil moisture flow. The soil erosion model (Morgan and Duzant, 2008) simulates most relevant soil erosion processes, such as soil detachment by raindrop impact and runoff, sediment routing and sediment deposition. The model also incorporates a dynamic vegetation model based on the spatial and temporal variation of the Normalized Differenced Vegetation Index (NDVI), which determines actual evapotranspiration, interception, canopy storage, throughfall and canopy cover. For the reference and future periods, for which no NDVI images were available, we simulated NDVI based on a landuse-specific log-linear relationship between NDVI and climate conditions (precipitation and temperature) obtained from a calibration period (2000–2012), see Eekhout et al. (2018b) for details. The hydrological model was calibrated in a headwater subcatchment for the period 2001–2010 with daily discharge data. The soil erosion model was calibrated for the period 2001–2010 with literature data for hillslope erosion per land use class (Cerdan et al., 2010; Maetens et al., 2012b) and local reservoir sedimentation data from 5 headwater subcatchments (Avendaño Salas et al., 1997). See Eekhout et al. (2018b) for details about model calibration and validation.

2.3. Sustainable Land Management scenarios

Large-scale implementation of SLM strategies for climate change adaptation is only viable if measures are co-developed and suited to local environmental, socio-economic and cultural conditions (Schwilch et al., 2012; de Vente et al., 2016). Therefore, we identified realistic SLM practices for the study catchment based on a review of previous stakeholder consultation processes in the study catchment and scientific literature reporting on the impacts of SLM practices obtained from field experiments (Aguilera et al., 2013; Almagro et al., 2016). Low-cost practices like reduced tillage, green manure or organic amendments for cereals, tree crops and vineyards were identified as most promising and feasible SLM practices providing benefits for soil quality, erosion reduction and soil water retention. Therefore, we assessed the impacts of SLM application in three landuse classes, i.e. cereals, tree crops (almond, lemon, olive, among others) and vineyards (Fig. 1c), which account for 37.8% of the total catchment area. Fig. 1b shows the percentage of SLM implementation in each of the 34 subcatchments.

We applied two types of SLM, i.e. reduced tillage (RT) for cereals, and reduced tillage in combination with green manure (RT + GM) for tree crops and vineyards. While SLM may refer to a wide range of practices, throughout the article we use the term SLM to refer to the two applied practices in this study only, i.e. RT and RT + GM. Green manure is a SLM technique where a mixture of cereals and leguminous cover crops (*Vicia sativa*) are seeded in autumn and ploughed into the soil in early spring. Several input parameters in the soil, vegetation and sediment modules were changed to simulate SLM in

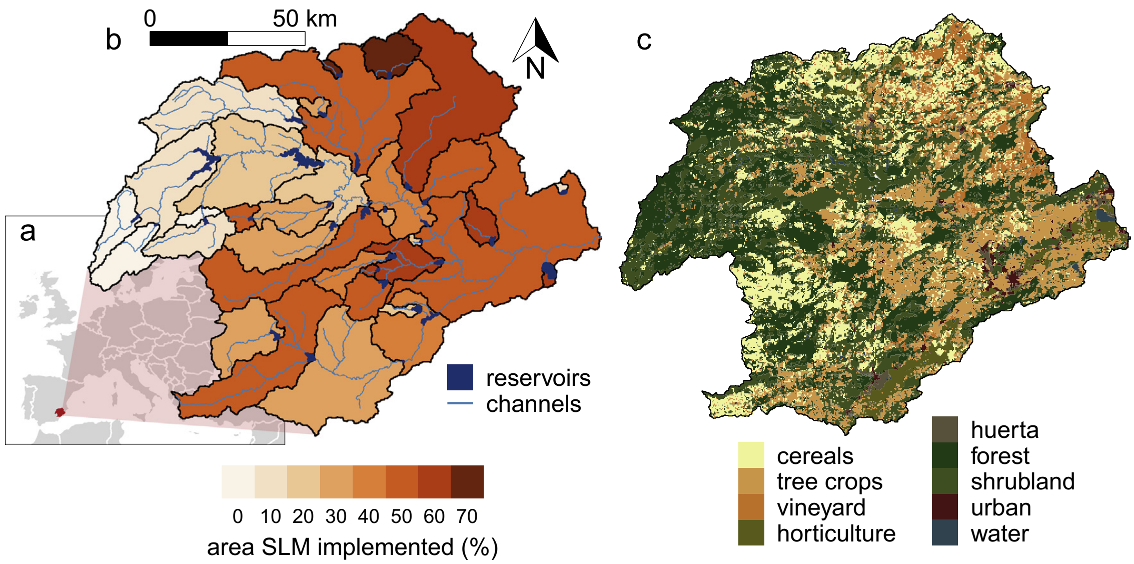

Fig. 1. Location and characteristics of the Segura River catchment: (a) location of the catchment within Europe, (b) the percentage of each subcatchment of SLM implementation (orange scale), the channels (light blue), and the reservoirs (dark blue), and (c) landuse map (MAPAMA, 2010). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the SPHY-MMF model, based on values obtained from experimental work reported in literature (Table 1). We increased the soil organic matter in the root zone (0–25 cm depth), respectively, with 15% (RT) and 31% (RT + GM) (Aguilera et al., 2013; Almagro et al., 2016). We reduced the bulk density of the root zone for both types of SLM with 4% (Aguilera et al., 2013). Regarding vegetation parameters, under conventional conditions (no SLM) cereal fields are frequently tilled in the period between harvest and sowing, which is parameterized by setting all vegetation characteristics to 0 (Table 1). With reduced tillage, after harvest the cereal fields are not tilled until the next sowing. We parameterized this by setting only the plant height to 0 and leaving all other input parameters unchanged. The characteristics of green manure were mainly obtained from cereals under conventional conditions. We applied the sowing-harvest cycle of cereals to green manure, i.e. sowing in September and harvest in May. In the soil erosion model, we substituted the plant height, number of stems, stem diameter and ground cover for tree crops and vineyards with values for cereals. Bare soil conditions were assumed in the period between harvest and sowing. In the vegetation module we used a log-linear relationship for each landuse class to obtain NDVI. In the period September–May, when green manure is present, we applied the log-linear relationship for cereals to determine the NDVI for tree crops and vineyards.

2.4. Climate change scenarios

To assess the effectiveness of SLM under future climate conditions we applied four different future climate scenarios, divided over two future periods (i.e. 2031–2050 and 2081–2100) and two Representative Concentration Pathways (i.e. RCP4.5 and RCP8.5). We obtained data from a total of nine climate models (GCM-RCM combinations; Table S1) from the EURO-CORDEX initiative (Jacob et al., 2014), with a 0.11° resolution. The raw climate data were bias-corrected using quantile mapping (Themeßl et al., 2012). Precipitation data for the reference period (1981–2000) were obtained from the SPREAD daily dataset (Serrano-Notivoli et al., 2017), with a 5 km resolution, and temperature data from the SPAIN02 daily dataset (Herrera et al., 2016), with a 0.11° resolution. Table 2 shows the catchment-average climate signal for the reference and the four future climate change scenarios.

2.5. Water security indicators

We evaluated the impact of SLM on soil and water resources relevant for water security and related ecosystem services, such as flood prevention, water availability and erosion control, under present and future climate conditions, using a number of on-site and off-site indicators. We included indicators that are most relevant for the expected increase in drought, flood and erosion risks and the expected redistribution between green and blue water under climate change (Eekhout et al., 2018a). The on-site indicators include plant water stress and hillslope erosion. Only data from the cells where SLM is implemented are used to determine average values of the on-site indicators. Plant water stress is an indicator of the amount of stress plants experience and ranges between 0 (no stress) and 1 (fully stressed). Plant water stress is determined by comparing the soil

Table 1
Model parameters to simulate SLM implementation: change in soil organic matter (SOM), change in bulk density (BD), plant height (PH), number of stems (NV), stem diameter (D) and ground cover (GC). The values corresponding with no SLM are obtained from Eekhout et al. (2018b).

				Before harvest				After harvest			
Crop	Scenario	SOM	BD	PH	NV	D	GC	PH	NV	D	GC
Cereals	No SLM	n.a.	n.a.	0.75	500	0.025	0.3125	0	0	0	0
	SLM (RT)	+15%	−4%	0.75	500	0.025	0.3125	0	500	0.025	0.3125
Tree crops	No SLM	n.a.	n.a.	1–2	0	0	< 0.01	2	0	0	< 0.01
& vineyards	SLM (RT + GM)	+31%	−4%	1.375[1]	500	0.025	0.3125	2	0	0	< 0.01

[1] Average of cereals and tree crops.

Table 2
Catchment-averaged climate signal for the reference and four future climate change scenarios. Values for the reference scenario are presented in absolute values. All other values are differences with respect to the reference and are accompanied with percentages in parentheses. Values marked in bolt are significantly different ($p < 0.05$).

Scenario	Period	Precipitation (mm)	Extreme precipitation (mm)	Dry spells (days)	Average temperature (°C)
Reference	1981–2000	361.5	29.8	63.7	15.2
RCP 4.5	2031–2050	−8.2 (−2.3)	**4.1 (13.6)**	**7.6 (11.9)**	**1.2 (7.9)**
RCP 4.5	2081–2100	−3.7 (−1.0)	**5.5 (18.4)**	**9.3 (14.7)**	**1.8 (12.0)**
RCP 8.5	2031–2050	−9.0 (−2.5)	**5.9 (19.6)**	**7.1 (11.2)**	**1.4 (9.0)**
RCP 8.5	2081–2100	**−65.4 (−18.1)**	**7.1 (23.6)**	**26.0 (40.8)**	**3.9 (25.7)**

moisture content with the plant-specific soil moisture content from which stress starts to occur (adapted from Porporato et al., 2001):

$$PWS = \frac{\theta_{PWS} - \theta(t)}{\theta_{PWS} - \theta_{PWP}} \tag{1}$$

with PWS the dimensionless plant water stress, $\theta(t)$ the soil moisture content at timestep t, θ_{PWS} the plant and soil specific soil moisture content from which plant water stress starts to occur and θ_{PWP} the soil moisture content at permanent wilting point. PWS equals zero when $\theta(t) > \theta_{PWP}$, where θ_{PWS} is determined by (adapted from Allen et al., 1998):

$$\theta_{PWS} = \theta_{FC} - d(\theta_{FC} - \theta_{PWP}) \tag{2}$$

with θ_{FC} the soil moisture content at field capacity, and d the depletion fraction. The plant specific depletion fraction is a function of the potential evapotranspiration (Allen et al., 1998):

$$d = d_{tab} + 0.04(5 - ET_P) \tag{3}$$

with d_{tab} the tabular value of the depletion fraction and ET_P the potential evapotranspiration obtained from the hydrological model. We obtained values for d_{tab} from Allen et al. (1998). Hillslope erosion was determined per subcatchment as the average annual soil erosion of all the cells with an upstream area smaller than 10 km^2.

The off-site impact indicators of water security include reservoir inflow, flood discharge and reservoir sediment yield. Reservoir inflow of the 33 reservoirs is defined as the cumulative discharge in the upstream area of a reservoir. In this calculation, only the area directly draining to one reservoir is considered. If the upstream area of a reservoir contains other reservoirs, the discharge in these areas is omitted. Flood discharge was determined, from the daily discharge time series at each reservoir, as the median yearly maximum discharge over the 20 year simulation period. Average annual reservoir sediment yield was determined from the sediment yield time series at each reservoir.

2.6. Uncertainty analysis

To account for uncertainty, we evaluated the robustness and significance of the climate projections and the model predictions within the ensemble of 9 climate models. Robustness is defined as the agreement of the simulations in terms of the direction of change, i.e. changes in which more than 66% of the models agree in the direction of change were called robust changes. A paired U-test (Mann–Whitney–Wilcoxon, significance level 0.05) was applied to test the significance of model outcomes for the 9 climate models. The pairs consisted of the model output for (1) the reference scenario and (2) the 9 climate models. The paired U-test is also applied to determine the significance of the catchment-averaged change with respect to the reference scenario.

3. Results

3.1. Plant water stress and reservoir inflow

Plant water stress in the reference scenario without SLM shows a clear spatial pattern with low values in the headwaters and high values in the downstream parts of the catchment (Fig. 2, upper left). The average on-site plant water stress equals 0.64 (Table S2). A similar pattern is obtained from the reservoir inflow, with high values in the headwaters and low values in the downstream part of the catchment. The catchment-total reservoir inflow for the reference scenario equals 815 $Hm^3\ yr^{-1}$.

All scenario results are presented as a change with respect to the reference scenario without SLM. Climate change leads to a significant increase of plant water stress throughout the catchment (Fig. 2, upper right). In scenarios S1–3, a moderate average on-site increase of plant water stress is projected of around 0.034 –0.038 ($p < 0.01$), while for S4 a more severe increase of 0.086 ($p < 0.01$) is projected. Catchment total reservoir inflow increases significantly in scenarios S1–3 with 24–29% ($p = 0.01$ –0.03). In general, decreased reservoir inflow is projected for the headwaters and increased for the downstream located reservoirs. The decreased reservoir inflow in the headwaters is caused by a significant decrease of annual precipitation in this area, while the increased reservoir inflow in the downstream located reservoirs is mainly caused by an increase of extreme precipitation and, hence, an increase of surface runoff. See Eekhout et al. (2018a) for a detailed description of the redistribution of water as a result of climate change in the study area.

A decrease of plant water stress (−0.027) and reservoir inflow (−120 Hm^3) is projected when SLM is implemented in the reference scenario (Fig. 2, lower left). Most plant water stress decrease is projected for tree crops (−0.030), which suffer the most plant water stress in the reference scenario without SLM (Fig. S1).

Large-scale implementation of SLM mitigates the increased plant water stress under climate change in scenarios S1–3 (Fig. 2, lower right), for which only a small but non-significant average on-site increase of 0.005–0.010 is projected ($p = 0.20$–0.65). However, also after implementation of SLM, plant water stress still significantly increases with 0.060 in scenario S4 ($p < 0.01$). Catchment total reservoir inflow still increases in scenarios S1–3 with 66–89 Hm^3 (8–11%; $p = 0.20$–0.25), while in scenario S4 a decrease of reservoir inflow of 76 Hm^3 (−9%; $p = 0.43$) is projected. The upstream-downstream difference in reservoir inflow remains, although not as pronounced as in the scenarios without SLM.

3.2. Flood discharge

Yearly flood discharge ranges between 0.08 and 42.7 $m^3\ s^{-1}$ among the 34 discharge stations in the reference scenario without SLM (Fig. 3, upper left) and averages to 6.3 $m^3\ s^{-1}$ (Table S2). In scenarios S1–3, a significant catchment-average increase of flood discharge is projected of 25.2–29.8% ($p < 0.05$), with a maximum increase of 130.4% (Fig. 3, upper right). An increase of flood discharge is projected in 44.1–58.8% of the discharge stations for scenarios S1–3. In scenario S4, significant 25.0–60.3% decrease of flood discharge is projected in 6 headwater subcatchments.

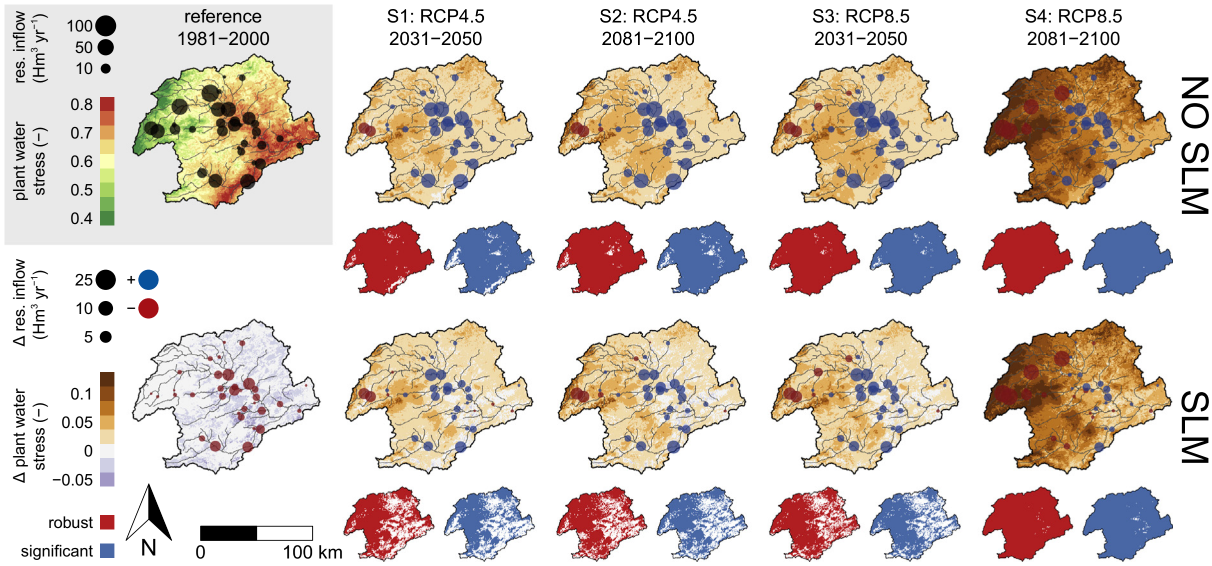

Fig. 2. Ensemble average reservoir inflow (dots, Hm^3) and plant water stress (PWS) (-) for the reference scenario (upper left) and changes between the reference scenario and the four future scenarios without SLM (upper right), the reference scenario with SLM (lower left), and the four future scenarios with SLM (lower right). For the SLM and future scenarios, the reservoir inflow is presented as an increase (blue) or a decrease (red). The small red and blue maps indicate the areas where, respectively, significant and robust changes are projected. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Flood discharge is projected to decrease when SLM is applied in the reference scenario (Fig. 3, lower left), ranging between 0.2 and 43.6%. In scenarios S1–3, a non-significant catchment-average increase of 7.7–13.6% ($p = 0.16$ –0.43) is projected when SLM is implemented (Fig. 3, lower right). In scenario S4, the catchment-average flood discharge decreases with 15.5% ($p = 0.13$), with a maximum decrease of 60.4% after implementation of SLM.

3.3. Hillslope erosion and reservoir sediment yield

In the reference scenario, reservoir sediment yield (SY) of all 33 reservoirs equals 1301 $Gg\,yr^{-1}$, which corresponds to a total annual reservoir storage capacity loss of 0.11% (Fig. 4, upper left and Table S2). The average hillslope erosion (SSY) in the subcatchments ranges between 129 and 622 $Mg\,km^{-2}\,yr^{-1}$. Under future climate conditions, a significant increase in hillslope erosion is projected in almost the entire catchment, especially in the central and downstream located subcatchments. The increase in the average on-site hillslope erosion ranges from 33.7% (S4, $p = 0.13$) to 55.0% (S3, $p = 0.01$). Reservoir sediment yield also increases in scenarios S1–S3, but significant changes are only observed in S4 with a decrease of 29.2% ($p < 0.01$).

Implementation of SLM in the reference scenario (Fig. 4, lower left) results in an average on-site decrease of hillslope erosion with 145 $Mg\,km^{-2}\,yr^{-1}$ (40.9%). Most decrease is projected for tree crops (47.7%), followed by vineyards (41.0%) and cereals (27.6%) (Fig. S2).

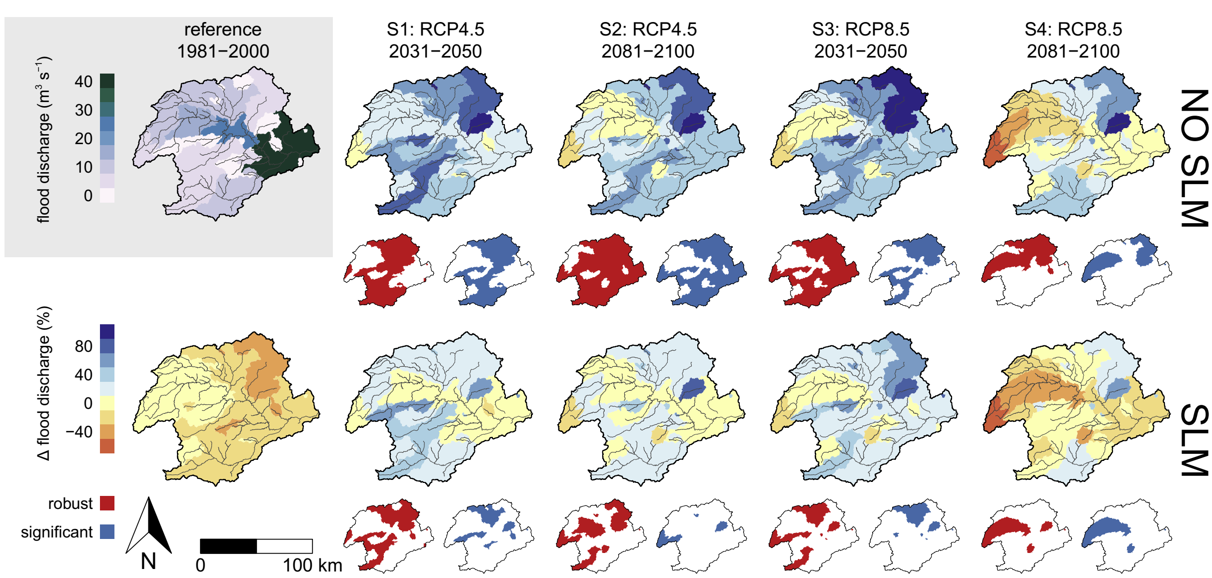

Fig. 3. Ensemble average flood discharge ($m^3\,s^{-1}$) for the reference scenario (upper left) and changes between the reference scenario and the four future scenarios without SLM (upper right), the reference scenario with SLM (lower left), and the four future scenarios with SLM (lower right). The small red and blue maps indicate the areas where, respectively, significant and robust changes are projected. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

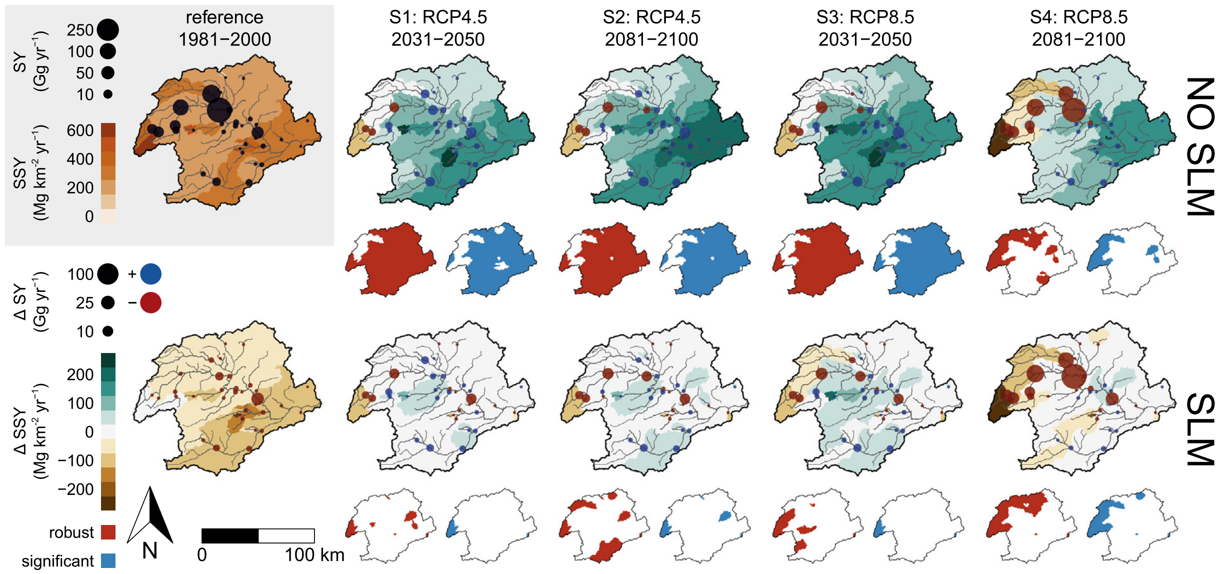

Fig. 4. Ensemble average sediment yield (SY) at the reservoirs (dots, Gg yr^{-1}) and average hillslope erosion (SSY) per subcatchment (Mg km^{-2} yr^{-1}) for the reference scenario (upper left) and changes between the reference scenario and the four future scenarios without SLM (upper right), the reference scenario with SLM (lower left), and the four future scenarios with SLM (lower right). For the SLM and future scenarios, the reservoir sediment yield is presented as an increase (blue) or a decrease (red). The small red and blue maps indicate the areas where, respectively, significant and robust changes are projected. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Reservoir sediment yield decreases with 7.0%. Implementation of SLM under future climate conditions leads to an average on-site decrease of hillslope erosion of 5.3–18.8% ($p = 0.13$ –0.82). Robust changes in hillslope erosion are projected in scenario S1 for tree crops (−18.5–18%) and vineyards (−10.9–10.9%) and in scenario S2 for tree crops (−14.6–14.6%). A decreased catchment wide reservoir sediment yield is projected for all future climate scenarios (S1–4), with robust changes projected for scenario S2 (−6.5%, $p = 0.25$) and significant changes for scenario S4 (−41.4–41.4%, $p < 0.01$).

4. Discussion

Recent episodes of severe droughts and extreme rainfall in global Mediterranean climate regions (e.g. California, South Africa, Spain) resulted in casualties and large damage to infrastructure and crops, illustrating that many of these areas are still poorly prepared for future climate conditions. A comprehensive evaluation of the effectiveness of large-scale implementation of adaptation strategies based on SLM practices is lacking, therefore, policy makers often decide merely based on implementation costs, ignoring the catchment wide effectiveness, impacts on ecosystem services, and trade-offs (Goldstein et al., 2012). There are multiple challenges for large-scale assessments of the impacts of SLM as adaptation strategy. For example, the main part of soil erosion occurs during extreme rainfall events (Gonzalez-Hidalgo et al., 2013), for which we have little knowledge regarding the alleviating effect of SLM. The impacts of climate change and SLM practices have mostly been evaluated using laboratory and plot-scale field experiments, providing valuable insights into the local impacts (Maetens et al., 2012a; Almagro et al., 2016), but not reflecting catchment scale interactions. Therefore, in this study, we aimed to improve our capacity to quantify the effectiveness of SLM to alleviate the negative impacts from climate change on water security using on-site and off-site impact indicators.

Our results show that climate change significantly affects hydrology, soil erosion and water security in a large catchment, representative for many Mediterranean climate regions. The most important climate change signal in the study area is an increase of extreme precipitation and frequency of dry spells (Fig. S3). The annual precipitation sum is projected to change only slightly for scenarios S1–S3, but more severely for scenario S4, with a catchment average reduction of 18%. The change in precipitation frequency and intensity causes a redistribution of water, defined by a significant increase of surface runoff and decrease of soil moisture content (Fig. 5). On-site, this leads to significantly increased plant water stress and hillslope erosion. The off-site impacts include increased reservoir sediment yield (non-significant; n.s.) and a significant increase of reservoir inflow and flood discharge for most subcatchments in scenarios S1–S3. For the most extreme climate scenario (S4), we found no significant changes for reservoir inflow though.

Considering the potential of SLM for climate change adaptation, our results demonstrate that SLM, consisting of reduced tillage and green manure applied in nearly 38% of the catchment, significantly reduces both the on-site and the off-site impacts of climate change on water security. Under moderate climate change conditions (scenarios S1–S3), SLM can entirely reverse the climate change impacts or leads to non-significant changes with respect to the reference scenario (Fig. 5 and Tables S2 and S3). Under these moderate climate projections, SLM implementation shows a significantly decreased surface runoff, an increased infiltration and soil moisture content, a minor increased plant water stress (n.s.), and a decrease of hillslope erosion (n.s.) compared to the reference scenario without SLM. Furthermore, a non-significant increase of reservoir inflow and flood discharge is projected, while reservoir sediment yield slightly decreases (n.s.). Overall implementation of SLM under moderate climate change leads to a higher water security.

Under the more extreme climate change scenario (S4), implementation of SLM also strongly reduces the severity of impacts, however, it does not take them away entirely and still results in a significant negative impact for crucial water security indicators (Table S2). Plant water stress still increases significantly while reservoir inflow slightly decreases (n.s.). On the other hand, flood discharge, hillslope erosion and sediment yield reduce in scenario S4, which is the combined effect of strongly reduced annual precipitation and implementation of SLM resulting in soil water retention and erosion prevention. The consequence of these findings is that current rainfed and irrigated agriculture as well as natural vegetation will suffer

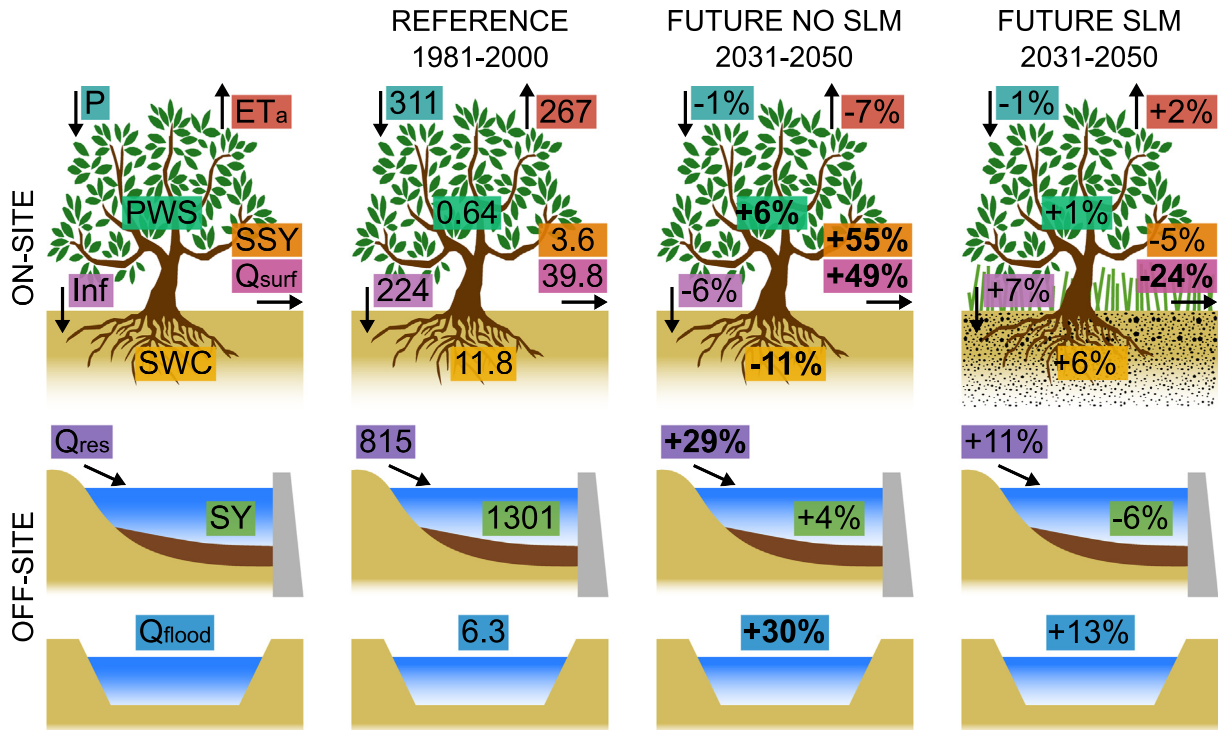

Fig. 5. The on-site and off-site impacts of climate change and implementation of SLM. The left panel defines the indicators, where P is precipitation (mm), ET_a is actual evapotranspiration (mm), PWS is plant water stress (-), Inf is infiltration (mm), SSY is hillslope erosion (Mg km^{-2} yr^{-1}), Q_{surf} is surface runoff (mm), SWC is soil water content (mm), Q_{res} is reservoir inflow (Hm^3), SY is reservoir sediment yield (Gg yr^{-1}) and Q_{flood} is flood discharge (m^3 s^{-1}). The next panel shows the average values for the reference scenario. The last two panels show the impact of climate change and SLM of one of the future scenarios (S3). The panels show the percent change with respect to the reference scenario and values in bolt indicate a significant change ($p < 0.05$). All values are obtained from Tables S2 and S3.

from increased water shortage and may become unsustainable under future extreme climate conditions (Lobell et al., 2011; Peñuelas et al., 2017; León-Sánchez et al., 2018). This implies that additional (SLM) measures are required to adapt to these extreme climate conditions.

Our results of the on-site impacts of SLM are comparable with findings from previous plot-scale empirical assessments of SLM, reporting increased soil moisture, decreased runoff and decreased soil erosion (Maetens et al., 2012a; Liu et al., 2013; Thierfelder et al., 2013; Opolot et al., 2016; Palm et al., 2014; Almagro et al., 2016). Some studies also showed that SLM might reduce evaporation due to surface cover by mulch or cover crops (Palm et al., 2014). While this may be the case for some SLM types, we found a 9% increased on-site evapotranspiration with implementation of SLM in the reference scenario (Table S3) that can be explained by the combined effect of an increased vegetation cover (i.e. green manure) and an increased soil moisture content (less plant water stress) leading to higher evapotranspiration. While this may suggest some competition over water resources between the crops and green manure, part of the increased evapotranspiration due to lower plant water stress may also imply a higher crop yield (Doorenbos and Kassam, 1979; Allen et al., 1998). Furthermore, the addition of green manure would make the crops more resilient to irregular rainfall, which is an important aspect of climate change adaptation.

Large-scale implementation of SLM in nearly 38% of the catchment resulted in a better performance of most off-site water security indicators (Table S2). These findings corroborate previous studies reporting how soil conservation measures in agricultural land are effective for reducing sediment yield (Verstraeten et al., 2002; Shi et al., 2012; Hunink et al., 2012; Hunink et al., 2013). Other studies reported how alternative measures in natural land, such as check dams and reforestations may contribute to climate change adaptation by reducing sediment yield and flood discharge (Boix-Fayos et al., 2007; López-Moreno et al., 2008). However, there are also strong indications of the possible limitations and trade-offs. For example, the construction of check dams may be less cost-effective than landscape restoration and short-lived due to their rapid siltation (Boix-Fayos et al., 2008; Quiñonero Rubio et al., 2016). Furthermore, by reducing runoff (Grum et al., 2017) and discharge (Beguería et al., 2003; Nosetto et al., 2005; Zhang et al., 2008; López-Moreno et al., 2008; Molina et al., 2015; Pérez-Cutillas et al., 2018), adaptation measures like reforestation or water harvesting may negatively affect water availability for other water uses like irrigation and drinking water supply. So, while adaptation to climate change may require a combination of SLM practices in agricultural and natural lands, the design of adaptation strategies should consider cost effectiveness, sustainability, interactions and trade-offs regarding water availability and other ecosystem services (Sanz et al., 2017). This is especially the case for most extreme climate scenarios characterized by severe water shortage affecting agriculture potential and natural vegetation development with potentially severe environmental and socio-economic consequences.

5. Conclusions

Large-scale implementation of SLM in agricultural lands can significantly reduce the on-site and off-site impacts of climate change on water security. Climate change significantly affects a number of on-site and off-site processes and related ecosystem services, such as increased surface runoff, plant water stress, hillslope erosion, reservoir inflow and flood discharge, and decreased soil moisture. The on-site and off-site impacts of climate change are almost entirely reversed by the implementation of SLM in rainfed farming systems under moderate climate conditions, which are characterized by limited reductions in precipitation sum but significant increased precipitation intensity, temperature and frequency of dry spells. Under more extreme reductions of annual precipitation, SLM implementation reduces the impacts on water security but cannot prevent significant increased plant water stress and reduced water availability. These extreme conditions require additional adaptation measures, considering their interactions and trade-offs regarding water security.

Our results demonstrate that evaluation and assessment of SLM measures considering on-site and off-site indicators, at spatial and temporal scales most relevant for policy makers, is extremely important to support decision making on climate change adaptation. Moreover, while it remains difficult to monitor and predict progress towards achieving the Sustainable Development Goals, these methods and results are relevant to support regional assessments for multiple SDGs, including SDG 2 (zero hunger), SDG 6 (clean water and sanitation), SDG 13 (climate action) and SDG 15 (life on land).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.10.350.

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