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Effects of ecological and conventional agricultural intensification practices on maize yields in sub-Saharan Africa under potential climate change

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Abstract

Much of Africa is among the world's regions with lowest yields in staple food crops, and climate change is expected to make it more difficult to catch up in crop production in particular in the long run. Various agronomic measures have been proposed for lifting agricultural production in Africa and to adapt it to climate change. Here, we present a projection of potential climate change impacts on maize yields under different intensification options in Sub-Saharan Africa (SSA) using an agronomic model, GIS-based EPIC (GEPIC). Fallow and nutrient management options taken into account are (a) conventional intensification with high mineral N supply and a bare fallow, (b) moderate mineral N supply and cowpea rotation, and (c) moderate mineral N supply and rotation with a fast growing N fixing tree *Sesbania sesban*. The simulations suggest that until the 2040s rotation with *Sesbania* will lead to an increase in yields due to increasing N supply besides improving water infiltration and soils' water holding capacity. Intensive cultivation with a bare fallow or an herbaceous crop like cowpea in the rotation is predicted to result in lower yields and increased soil erosion during the same time span. However, yields are projected to decrease in all management scenarios towards the end of the century, should temperature increase beyond critical thresholds. The results suggest that the effect of eco-intensification as a sole means of adapting agriculture to climate change is limited in Sub-Saharan Africa. Highly adverse temperatures would rather have to be faced by improved heat tolerant cultivars, while strongly adverse decreases in precipitation would have to be faced by expanding irrigation where feasible. While the evaluation of changes in agro-environmental variables like soil organic carbon, erosion, and soil humidity hints that these are major factors influencing climate change resilience of the field crop, no direct relationship between these factors, crop yields, and changes in climate variables could be identified. This will need further detailed studies at the field and regional scale.

Keywords: sustainable agriculture, environmental change, soil health

S Online supplementary data available from stacks.iop.org/ERL/9/044004/mmedia

1. Introduction

Maize is the most important staple food and accounts for nearly 20% of total calorie intake in sub-Saharan Africa (SSA) (FAO 2012). It is mostly cultivated under rainfed conditions

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Table 1. Crop management scenarios. Throughout the text, *Sesbania*(+N) and Cowpea(+N) refer to both scenarios of each cover crop with and without supplementary N.

Scenario name	Scenario description	N fertilizer input	Fallow/rotation
Conventional intensification (CI)	High mineral N fertilizer with bare fallow	150 kg N ha^{-1} with 1/3 applied at planting, and 2/3 one month after germination	Bare fallow
Cowpea+N	Cowpea rotation with supplementary N	50 kg N ha^{-1} at planting	Cultivation of cowpea between maize seasons. Plant residue left on field.
Sesbania+N	*Sesbania* rotation with supplementary N	50 kg N ha^{-1} at planting	Cultivation of *Sesbania* between maize growing seasons. All biomass left on the field
Cowpea	Cowpea rotation without supplementary N	No supplementary N	Cultivation of cowpea between maize seasons. Plant residue left on field.
Sesbania	*Sesbania* rotation without supplementary N	No supplementary N	Cultivation of *Sesbania* between maize growing seasons. All biomass left on the field

with an extent of irrigated areas $<3\%$ across the sub-continent (Portmann *et al* 2010). From the 1990s to the 2010s average maize yields have increased from around 1.4–1.8 t ha^{-1} in SSA, and from 2.5 to 4.5 t ha^{-1} in South Africa, but are still at the very bottom of globally reported maize yields (FAO 2012). Main reasons include soil nutrient depletion, soil erosion, and erratic or low precipitation in many parts (Rosegrant *et al* 2005, Rockström *et al* 2009). The fact that SSA is expected to face adverse impacts of climate change on crop production adds further pressure on the future food security of the region (IPCC 2007, Schlenker and Lobell 2010, Müller 2011, Roudier *et al* 2011, Liu *et al* 2013).

The prevailing practice of low-input agriculture is not only providing little outputs, but also detrimental to soils (Akinnifesi *et al* 2010). Various approaches have been proposed to overcome soil nutrient limitations. These can be grouped into three major categories: (a) conventional intensification based mainly on increased use of mineral fertilizer (Larson and Friesvold 1997, Quiñones *et al* 1997, Kelly *et al* 2003, Crawford *et al* 2006), (b) soil conservation and 'eco-intensification' using legumes as a green manure in short- or long-term rotation or intercropping systems (Rockström *et al* 2009, Akinnifesi *et al* 2010), or (c) a mix of both by rotation with legumes and supplementary mineral N supply (Denning 2009, Sánchez 2010). Such a mixed eco-intensification approach is the rotation with fast growing N fixing tress like *Sesbania* or *Glyricidia* species combined with supplementary N fertilizer supply (Denning 2009, Palm *et al* 2010). Due to strong evidence that detrimental consequences on soil productivity are likely if western-style industrialized agriculture is adopted in the tropics (Stocking 2003), the mixed approach is widely being promoted in agricultural development programs for small-scale farming in SSA (Akinnifesi *et al* 2010, Palm *et al* 2010), while conventional intensification is the approach mostly taken currently in large-scale farming.

An open question is how these management options will perform under conditions of climate change and whether they can add resilience to crop production systems in terms of slowing and reducing the adverse impacts of climate change on crop yields. Up to now, most crop modeling studies covering SSA are based on the assumption that current management practices and levels of inputs will be maintained over the coming decades (Parry *et al* 2004, Fader *et al* 2010, Liu *et al* 2013). Few regional studies addressed climate change interactions with fallow duration (Gaiser *et al* 2011) or sowing dates and crop choice (Waha *et al* 2013a), but without specification of agricultural intensification. Provided the economic growth and political and social stabilization in SSA continues, it is likely that agricultural intensification will increase in the coming decades (Rosegrant *et al* 2005). In addition, there is a gap remaining in the investigation of changes in agro-environmental variables like soil OC, erosion, runoff, and soil humidity and their interaction with yields although the problem has been raised partly a decade ago (Feddema and Freire 2001).

Here, we use an agronomic modeling framework GEPIC to project climate change impacts on yields of rainfed maize grown (a) under conventional intensifications with high mineral N input and a bare fallow, (b) in rotation with cowpea with or without supplementary mineral N, or (c) in rotation with *Sesbania* with or without supplementary mineral N (see section 2.2 and table 1 for details). As there is a wide range of possible crop rotation schemes, cowpea should be considered as representative for an 'herbaceous fallow', and *Sesbania sesban* as a short-term 'improved fallow' using fast growing N fixing shrubs. A business as usual scenario was not considered here as (a) the currently very low or even absent fertilizer application rates would lead to ever decreasing yields in the simulations as well as in practice and (b) an outlook for current management conditions has been provided already in several other studies.

Sileshi *et al* (2010) report yield decreases of 50–100% due to soil degradation under low-input conditions in the tropics depending on soil type and cover. Using EPIC simulations, Gaiser *et al* (2011) found that climate change may account for maize yield losses of up to 18% in the sub-humid savanna of West Africa until 2050 under current land use intensity in the worst-case climate scenario. Without considering climate change, a decrease in fallow duration due to projected population increase would in the same time period outweigh this impact with losses of up to 24%. The combined effect would lead to a yield loss of up to 38%. Also an earlier study of ours using the GEPIC model framework (Folberth *et al* 2012) showed that maize yields decrease continuously in SSA under present crop management conditions due to soil N depletion. This results in a yield reduction by 70% after 30 years if prior uncultivated soils are used as a starting point.

Recent estimates vary greatly for yield changes caused by climate change in Africa: they range from −30 to −5% for cereals in the 2050s and 2080s, respectively, with SRES emission scenario A1FI (Parry *et al* 2004) to mostly up to −30% in tropic regions and up to +30% in presently arid regions and highlands in the 2060s and 2080s for maize under SRES emission scenario A1B (Waha *et al* 2013b) and further to −3 to +5% (mainly positive trends) for major cereals in the 2030s and −15 to +3% (mainly negative trends) in the 2090s with different GCM projections for SRES emission scenarios A1FI and B2 (Liu *et al* 2013).

2. Methods and data

2.1. GEPIC framework for large-scale agronomic modeling

We used the field scale agronomic model Environmental Productivity Integrated Climate (EPIC; Williams 1995) within a GIS-based framework GEPIC (Liu 2009) to simulate impacts of climate change on maize yields and agro-environmental variables in SSA. GEPIC runs EPIC for each grid cell of the sub-continent at a spatial resolution of 0.5° × 0.5° using grid cell specific climate, soil, growing season, and topographic data. The (G)EPIC model has been validated and applied for simulating maize growth at the global scale (Liu 2009, Liu *et al* 2013) and at the regional scale in SSA (Gaiser *et al* 2011, Folberth *et al* 2012, 2013). Further information on the GEPIC framework, the EPIC model, and input datasets is provided in SI1 available at stacks.iop.org/ERL/9/044004/mmedia.

Simulations were carried out for the time period 1996–2090, while the first five simulation years were considered a spin-up period and hence not evaluated. To bracket a range of possible changes in climate, we used projections from three GCMs for the highly contrasting representative concentration pathways (RCP) 2.6 (lowest emissions) and 8.5 (highest emissions). In order to compare long-term cultivation with and without climate change, baseline climate data for 2001–2010 were cycled for the whole simulation period as an additional climate input dataset. (Supplementary SI3 available at stacks.iop.org/ERL/9/044004/mmedia presents an overview of changes in climate variables).

Besides time-continuous annual results, outputs were averaged over ten years for the periods 2001–2010 (baseline), 2041–2050 (near future) and 2081–2090 (far future) for spatial analyses and direct comparison.

2.2. Crop management scenarios

All grid cells were assumed to be rainfed only in order to ensure spatial comparability. As the current extent of irrigated areas in SSA is <3% (Portmann *et al* 2010), the ignorance of irrigated areas will not affect the general conclusion.

We defined five management scenarios concerning N supply (table 1). A Conventional Intensification (CI) was mimicked by planting maize as a single season crop with high mineral N supply and leaving the fallow bare. 'Eco-intensification' consisted of maize with or without low mineral N supply and planting of *Sesbania sesban* as a fallow outside the maize growing season. Plants were cut and incorporated into the soil shortly before the next maize season. As a step in between these two scenarios, cowpea (*Vigna unguiculata*) was planted outside the maize growing season. The crop was harvested at maturity and plant residue treated as described for *S. sesban*. In all management scenarios, one maize crop was planted per year and the management differed only outside the maize growing season apart from different mineral N application levels.

High mineral N supply was provided by mineral N application only at a level of 150 kg N ha^{-1}. Moderate supplementary mineral N supply took place at a level of 50 kg N ha^{-1}. 150 kg N ha^{-1} correspond to the level that is currently common in industrialized countries or regions like the USA, China and EU (FAO 2007) and has prior been found to be close to sufficient N supply in most regions of SSA (Folberth *et al* 2013). A mineral N fertilizer supply of 50 kg N ha^{-1} has been set as a target for N application by the African Union (2006) and was here used for the rotations with cowpea or *Sesbania sesban*. Phosphorus (P) was applied in all scenarios in sufficient amounts as it is solely available from mineral sources in contrast to N.

Further information on the parameterization and evaluation of the crops in the model are provided in SI2.

3. Results

3.1. Average temporal changes in maize yields and agro-environmental variables

All management scenarios resulted in an increase in maize yields for the initial simulation years from 2000–2020 for both RCPs (figure 1(a)). In the case of RCP8.5, yields decreased thereafter for CI and Cowpea+N throughout the simulation period until 2090. For *Sesbania*+N, they continued to increase into the 2030s, reaching a peak of around 6.2 t ha^{-1}, and then slightly decreased to about 5.1 t ha^{-1} in 2090. For CI and Cowpea+N, yields were predicted to peak at 6.1 and 5.8 t ha^{-1} in the early 2020s and then decline to about 4.6 t ha^{-1} by the end of century. For *Sesbania* without supplementary mineral N, yields increased first rapidly and from the 2030s more slowly until the 2060s where after they decreased towards the end of century. Cowpea rotation without supplementary mineral N followed the pattern of Cowpea+N, but at an overall lower level.

In the case of RCP2.6, average yields showed a similar development until the 2060s as for RCP8.5 in all management scenarios with mostly (except for scenario CI) slightly lower values. As a main difference to RCP8.5, yields increased during the last three decades in all management scenarios, except for Cowpea, where they remained rather stable.

When using constant climate and CO_2 data as an input, yields would remain rather constant and close to those at the

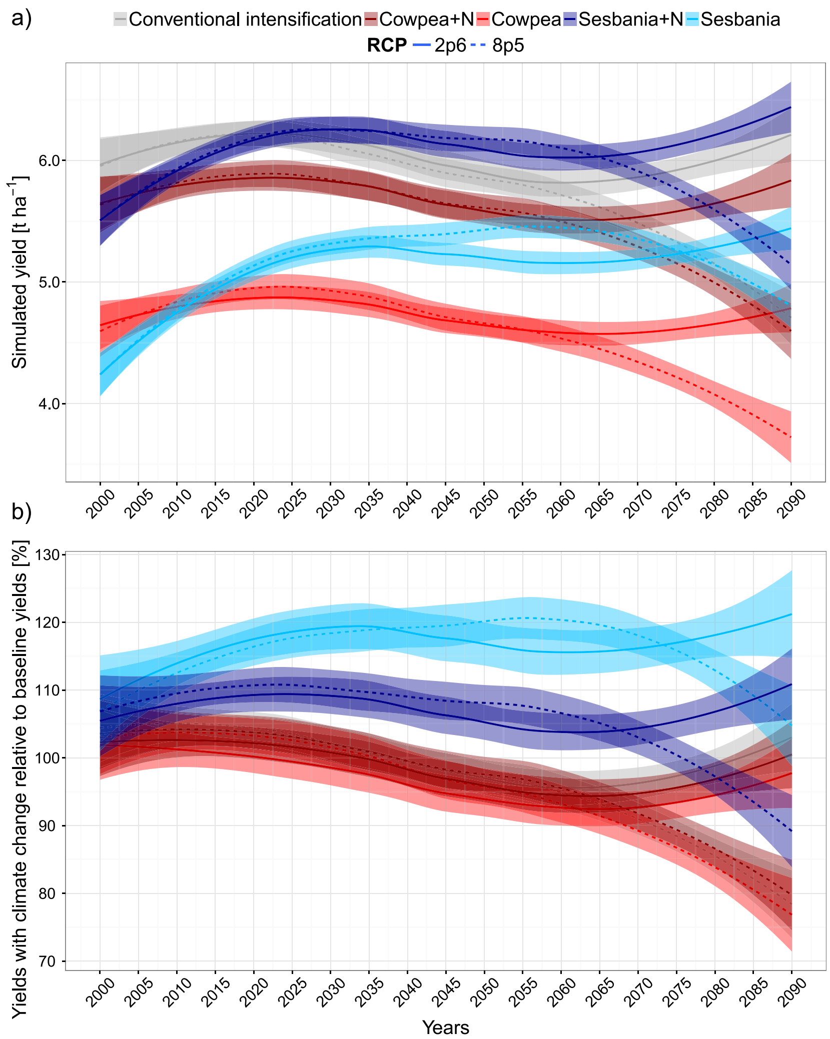

Figure 1. Evolution of maize yields under different intensification scenarios as smoothed regression across the means of 3 GCMs for each RCP. The ribbon reflects the 95% confidence interval. (a) Maize yields under climate change using GCM projections and (b) relative difference between maize yields under cycled baseline climate data and maize yields under climate change.

baseline level of 2001–2010 in the order CI > Cowpea+N > *Sesbania*+N > Cowpea > *Sesbania* (not shown). The order of performance of management scenarios would change after the 2030s, when *Sesbania*+N slightly outperforms Cowpea+N. As figure 1(b) shows, yields would be lower in the management scenarios CI and Cowpea(+N) for both RCPs under climate change beyond the 2030s with a recuperation in RCP2.6 towards the end of the century. The two management scenario with *Sesbania*(+N) in contrast show an increase in yields under both RCPs and only *Sesbania*+N decreases below 100% at the end of the century. This renders *Sesbania* the only management scenario with an average net yield increase at the end of the century under RCP8.5.

Soil OC and N contents were fairly similar in all management scenarios after the model equilibration and during the baseline period (figures 2(a) and (b)). Both variables declined for CI and N stocks started to level off in the rotations with Cowpea+N between 2040–2060, while they continued to increase for *Sesbania*+N. In addition, *Sesbania*+N caused lower runoff rates and provided more water for the subsequent maize crops with high root zone water (RZW) at a fairly constant level while keeping soil erosion (figures 2(c)–(f)) low. Differences in OC and N stocks between the two RCPs could mainly be found in higher values for RCP8.5 for Cowpea+N and *Sesbania*+N and lower values for the same RCP with CI management. Runoff and RZW values were very similar in the first half of the century and higher in the second half with RCP8.5. Also water erosion was quite similar in both RCPs during the first simulation decades and increased with Cowpea+N and CI in RCP8.5 thereafter, while it was slightly higher with RCP2.6 and *Sesbania*+N in the same time period. Wind erosion exhibited a very distinct temporal pattern with higher values with RCP2.6 after the 2040s with management CI, but lower values with Cowpea+N, while it was negligible with *Sesbania*+N for both RCPs at all times.

Cumulative water stress decreased in all management scenarios over time (figure 3(a)) with less stress in RCP8.5 than in RCP2.6. Water stress was lowest in the *Sesbania*(+N) scenarios followed by Cowpea(+N) and CI. N stress decreased over time constantly with RCP8.5 and increased in RCP2.6

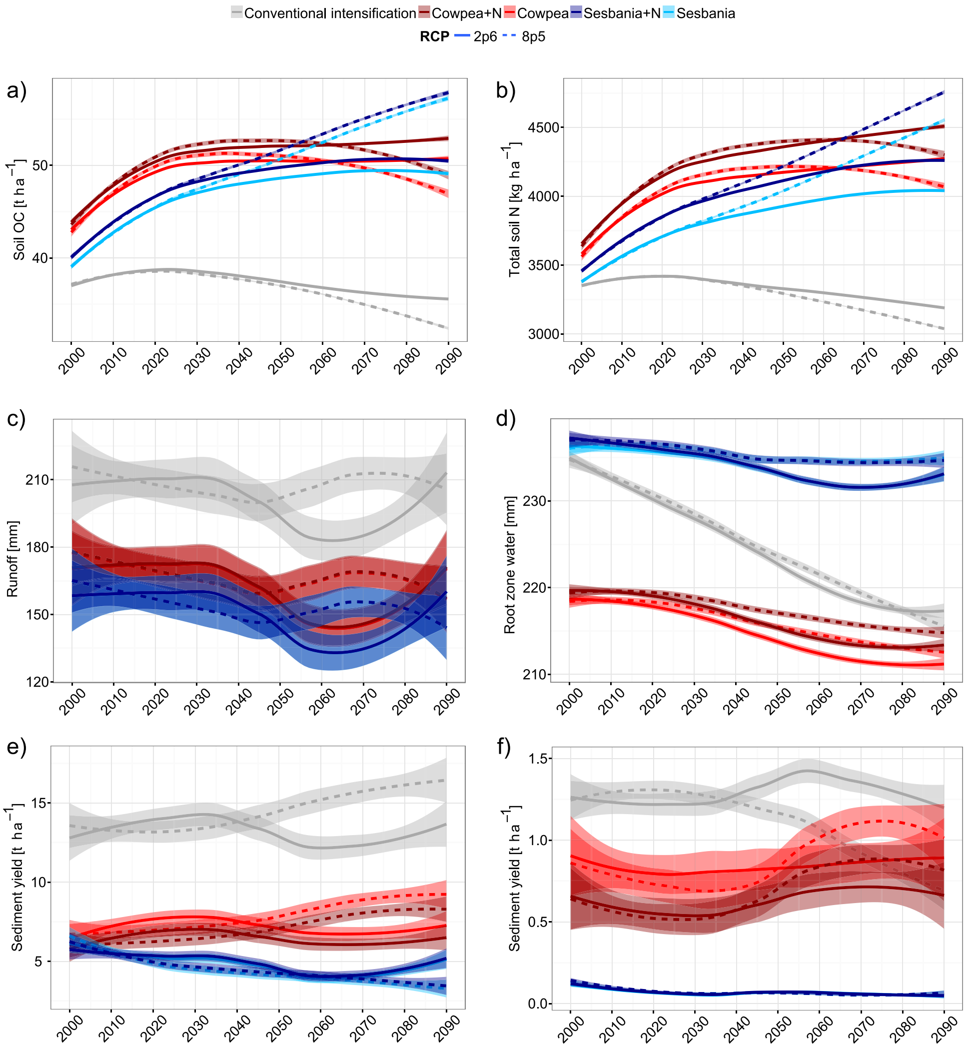

Figure 2. Evolution of agro-environmental variables under different intensification scenarios as smoothed regression across the means of 3 GCMs for each RCP. The ribbon reflects the 95% confidence interval. (a) Total soil OC, (b) total soil N, (c) runoff, (d) root zone water content, (e) water erosion, (f) wind erosion.

in all management scenarios (figure 3(b)). It was for each RCP lowest with CI followed by Cowpea(+N), and highest with *Sesbania*(+N). Temperature stress was lower than water stress in all scenarios and increased for RCP8.5 massively after the 2040s, while it remained fairly constant in RCP2.6 (figure 3(c)).

3.2. Spatial differences and changes in maize yields

In all management and RCP scenarios, the lowest yields were initially obtained in arid regions and the highest yields in the warm tropics of Central Africa (figure 4). Cowpea+N gave the most extreme yield pattern. As cowpea has the highest stomatal conductance of the crops studied here (see SI2 available at stacks.iop.org/ERL/9/044004/mmedia), competition for water between cowpea and maize can be considered a comparative trade-off under water-scarce conditions with respect to the other management scenarios. The yield pattern was more balanced for CI, with yields varying mostly in the range of 6–8 t ha^{-1} in semi-arid and tropic regions. *Sesbania*+N produced a similar pattern, but with lower yields in tropical regions of Central Africa and higher yields in the West African Guinea zone. Slight differences between the RCPs within each management scenario were mainly found along the borders of (semi-)arid regions.

For RCP2.6, yields decreased with CI or Cowpea+N in most arid regions, but also in parts of the tropics until the 2040s (figure 4). *Sesbania*+N led to increases in most non-arid grid cells and lower rates of decrease in tropic regions of Central Africa. The largest yield increases in all management scenarios occurred for the Gulf of Guinea, southern Mauritania, and northeastern Kenya/southern Somalia, where growing season precipitation is expected to increase (figure SI3.4). For RCP8.5, the picture was quite similar with more and stronger increases under *Sesbania*+N management. A major difference to RCP2.6 was the large increase in all management scenarios in southern Africa due to increases in presently very low growing season precipitation.

Until the 2080s, the pattern of yield increases and decreases remained fairly stable for all management scenarios,

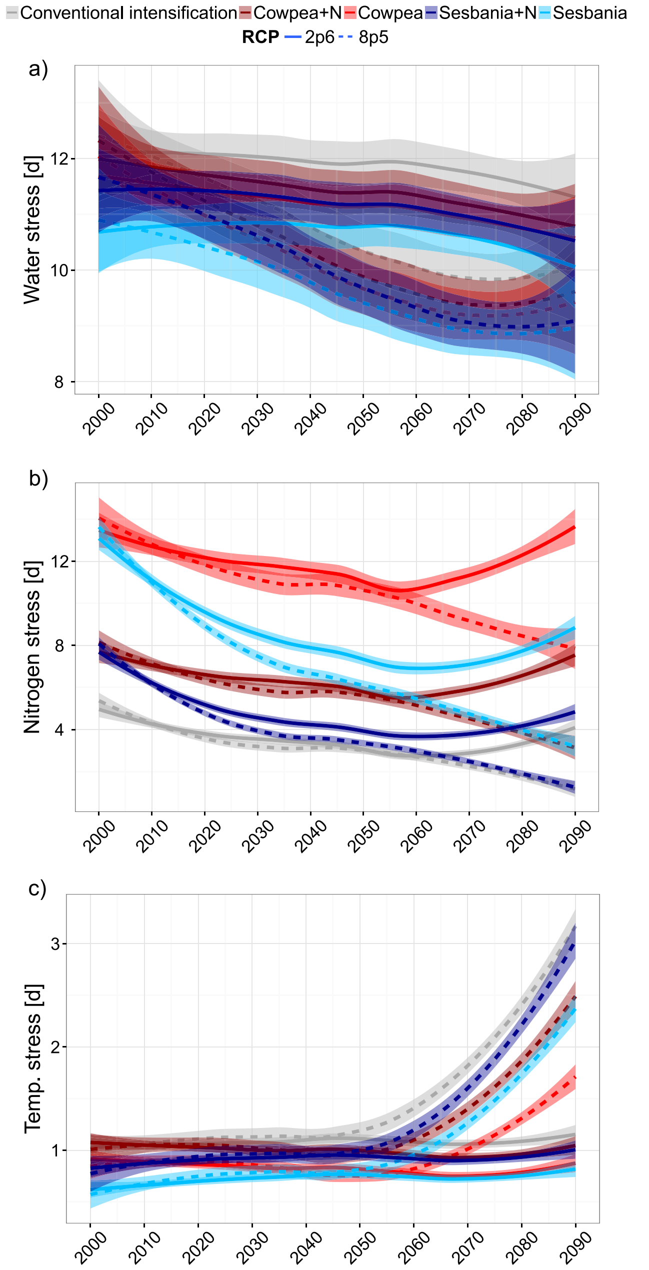

Figure 3. Evolution of (a) water, (b) nitrogen and (c) temperature stresses under different intensification scenarios as smoothed regression across the means of 3 GCMs for each RCP. The ribbon reflects the 95% confidence interval. The unit 'stress days' (d) is the cumulative stress throughout the growing season and can range on each day from 0 (no stress) to 1 (complete inhibition of biomass accumulation).

but the magnitude of changes became more evident in RCP2.6. In general, strong increases were found in northern Botswana, northeastern Kenya, and the Gulf of Guinea. Strong decreases occurred for Central Sudan in all management scenarios, while they had been pronounced only in scenario CI in the 2040s. In many parts, *Sesbania*+N exhibited again more positive impacts than the other two management scenarios, which had yield decreases e.g. in northern Angola, northern Nigeria, eastern South Africa, and the western half of Tanzania.

Correspondingly to figure 1, yields decreased in most parts of the continent with management scenarios CI and Cowpea+N for RCP8.5. Yield increases occurred only in the Guinea and Sudano-Sahelian zones of West and Central Africa, at the Horn of Africa, and in southern Africa, for Cowpea+N also in few central parts. For *Sesbania*+N increases were found mostly in the same regions, but covered larger areas, e.g. in West Africa, and stretched in Central Africa out to parts of the western coast.

3.3. Management mix for obtaining highest maize yields

Figures 5(a)–(c) shows the management practice that provides the highest yield in each grid cell for each time period in RCP2.6. Figures 5(d)–(f) shows the corresponding yield and future yield changes. During the first simulation decade, CI covered the largest number of grid cells, especially in (semi-)arid and some tropic regions along the Rift Valley, while Cowpea+N provided the highest yields in very humid regions of Central Africa, Madagascar, and parts of the East African coast (figures 5(a) and (d)). *Sesbania*+N provided the highest yields in semi-arid parts of West Africa and parts of East Africa. From the 2000s to the 2040s, yields would increase or remain stable in the majority of grid cells (figures 5(b) and (e)), except for the eastern Sahel, Kalahari, southern parts of the Rift Valley, eastern Madagascar, and parts of Central Africa, which are expected to experience decreases in precipitation (figure SI3.4 available at stacks.iop.org/ERL/9/044004/mmedia). By the 2080s, yields were predicted to decrease substantially in the entire Sahelian belt and the Kalahari and to a lesser extent around the east African coast and northern Madagascar (figures 5(c) and (f)). Regions with still increasing yields were mostly those that gave the highest simulated yields under *Sesbania*+N management.

For RCP8.5, the pattern and yields of the baseline period (figures 5(g) and (j)) was nearly identical to the ones obtained for RCP2.6. Until the 2040s, yields increased significantly in southern Africa, to a lower extent in the Guinea zone of West Africa and in the Central African tropics. While the grid cells with increases in southern Africa showed a mix of all three major management scenarios, grid cells with increases in the tropics were mostly planted with *Sesbania*+N or in regions with very high precipitation (figure SI3.4) with Cowpea+N. Until the 2080s, yields decreased in the majority of grid cells. Stable or increased yields occurred only in very few places, where maize was mostly planted with *Sesbania*+N, except for western South Africa, where Cowpea+N provided the highest yields with some increases compared to the baseline period.

3.4. Impact of changes in precipitation on maize yields

Change in yield showed a weak correlation with change in growing season precipitation (figure S4.1 available at stacks.iop.org/ERL/9/044004/mmedia) and no relationship with changes in mean annual precipitation or minimum and maximum temperatures (figures S4.2–S4.4 available at stacks.iop.org/ERL/9/044004/mmedia). As figure 6 illustrates, however, there was a strong correlation between yield change and precipitation change in grid cells with growing season

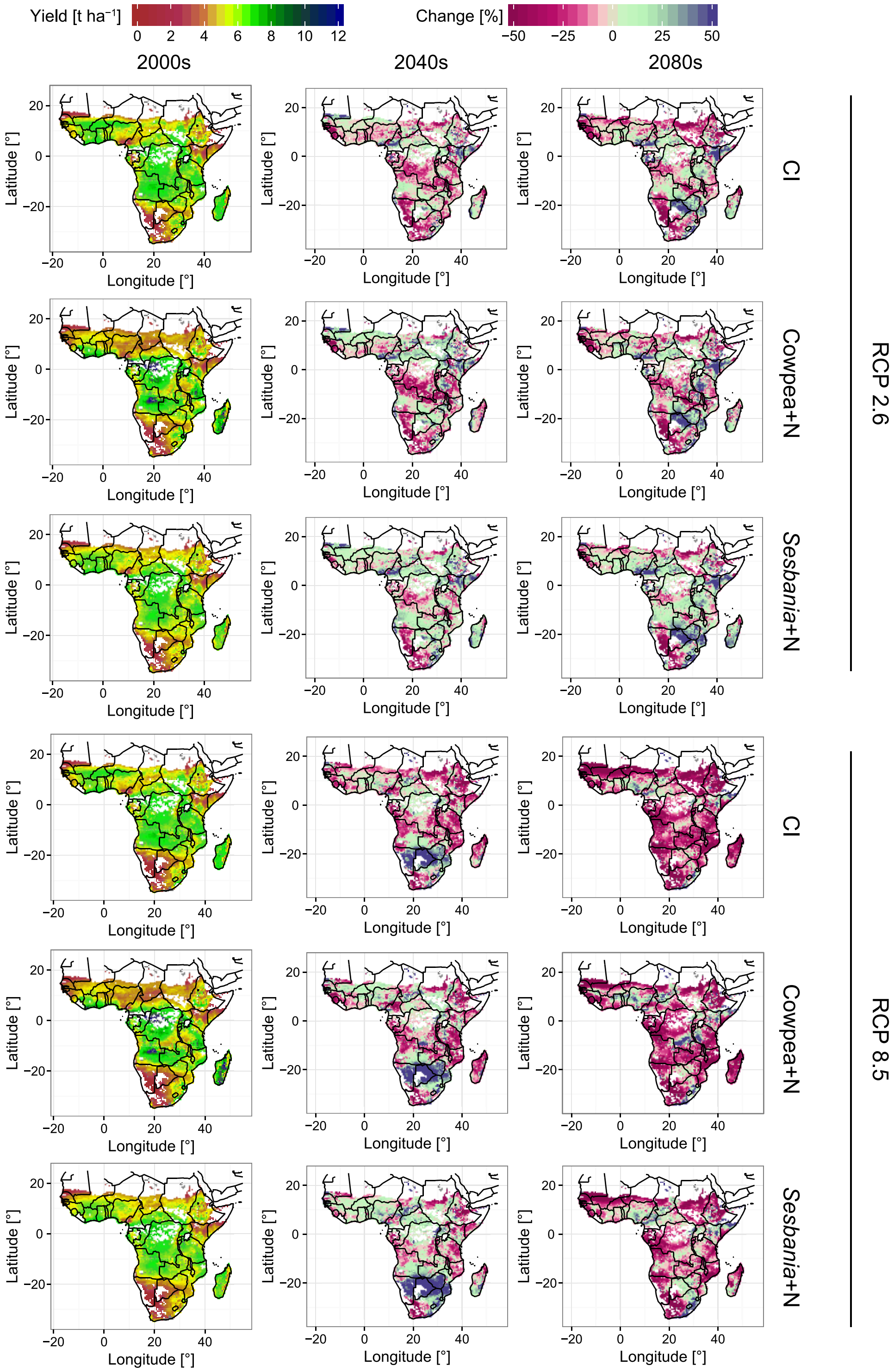

Figure 4. Absolute yields for the 2000s and changes in yields until the 2040s and 2080s for the three major intensification scenarios with mineral N supply (see table 1). All graphs show averages over 3 GCMs.

precipitation <500 mm yr^{-1}. For RCP2.6, this relationship was rather weak in the 2040s and became quite strong in the 2080s. The opposite was the case for RCP8.5. The slope of all area-weighted regressions regardless of management and climate change scenario was very similar, ranging between 2.13 and 2.69, except for the rather diffuse scattering of results with RCP8.5 in the 2080s. The intercepts in contrast showed a clear ranking according to the management scenario whereas *Sesbania*+N had always the highest intercept, followed by Cowpea+N and finally CI.

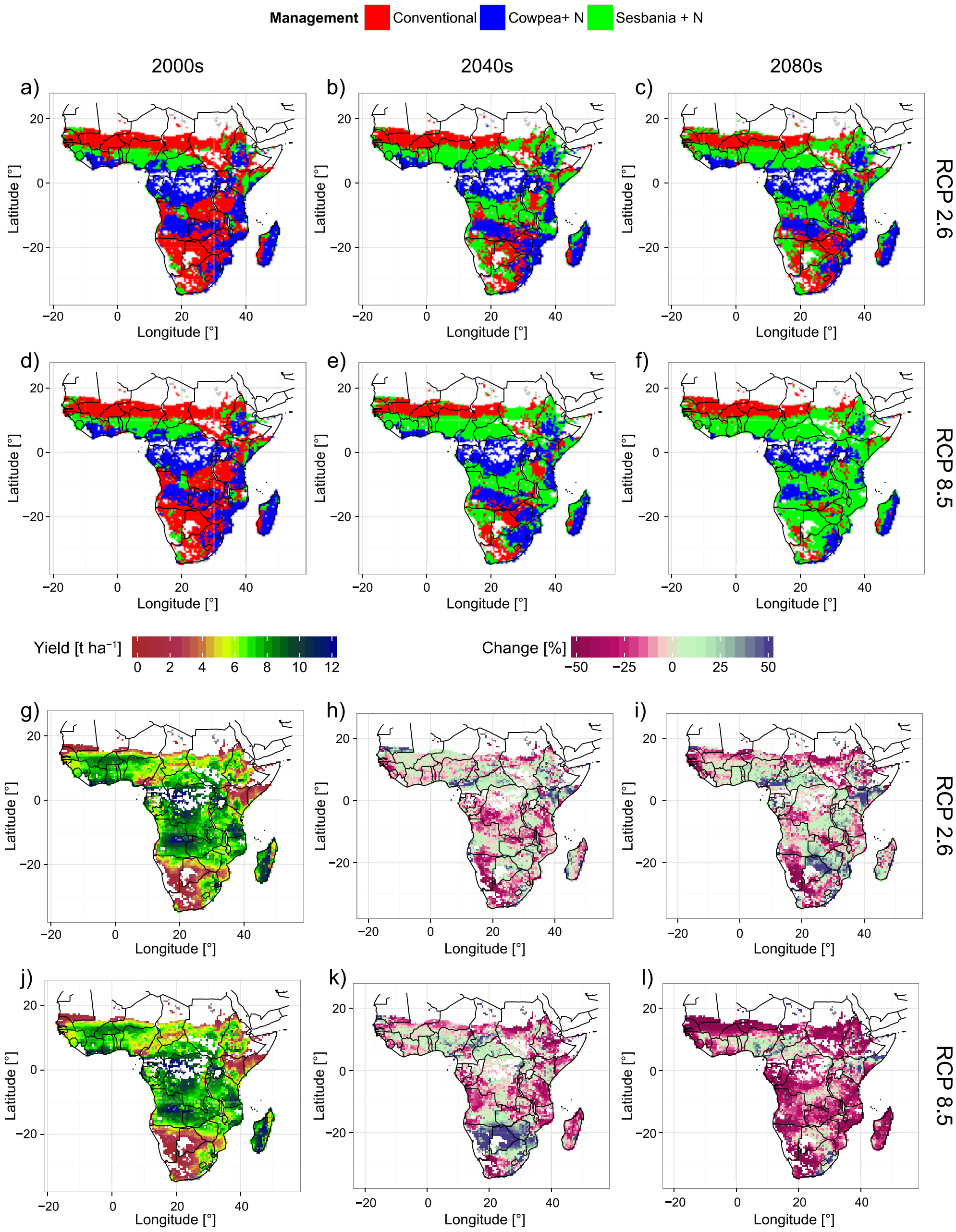

Figure 5. Management practice that can provide the highest yield in each grid cell and decade for (a)–(c) RCP2.6 and (d)–(f) RCP8.5. Absolute yields for the 2000s and changes in yields until the 2040s and 2080s for the intensification scenario that provides the highest yield for (g)–(i) RCP2.6 and (j)–(l) RCP8.5. The highest yield is assessed based on the mean from three GCMs for each RCP in each grid cell.

4. Discussion

4.1. Climate-related effects on plant physiology

Mean annual precipitation does not change dramatically in absolute terms (figure SI3.3(a) available at stacks.iop.org/ERL/9/044004/mmedia), but relative changes can be at up to −20 to +40% (figure SI3.3(b) available at stacks.iop.org/ERL/9/044004/mmedia). Hence, spatio-temporal shifts in annual and growing season precipitation (figure SI3.4 available at stacks.iop.org/ERL/9/044004/mmedia) are obviously of more importance. A clear relationship between changes in precipitation and changes in yields could be observed for grid cells with growing season precipitation <500 mm yr^{-1} (figure 6). But also there, a correlation between changes in yields and changes in precipitation was only evident in scenarios with modest changes in temperature and CO_2, while precipitation appears not to be a major or single driver for yield changes in RCP8.5 in the 2080s. The dramatic changes in temperature and atmospheric CO_2 may be especially in this time period and emission scenario of higher importance although again a direct relationship between relative changes in temperature and yields could not be detected (figure S4.4 available at stacks.iop.org/ERL/9/044004/mmedia). As shown by Waha

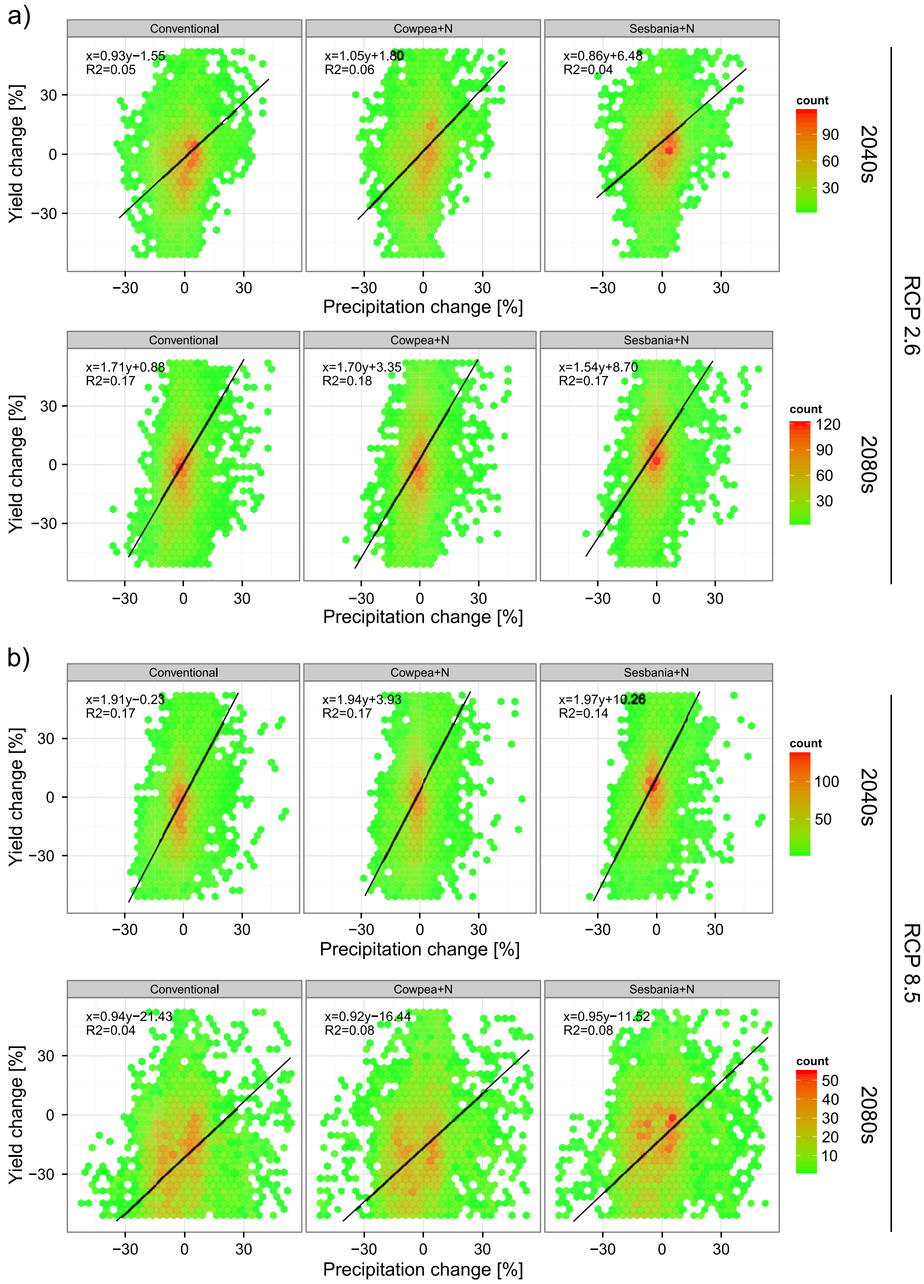

Figure 6. Density of grid cells based on similar change in yield versus change in precipitation for (a) RCP2.6 and (b) RCP8.5 for grid cells with growing season precipitation <500 mm. The black line and equations show the results of a regression weighted by spatial proximity in order to account for spatial autocorrelation.

et al (2013b), changes in precipitation and temperature affect maize yields in different regions of SSA to different extents. Such a detailed analysis of climatic drivers in yield changes is, however, beyond the scope of this management-related study.

Based on model routines, changes in temperatures (figures SI3.1; SI3.2; SI3.5; SI3.6 available at stacks.iop.org/ERL/9/044004/mmedia) impact crop yields by a two-fold effect. As laid out in SI1, temperature has (a) an impact on phenological development besides (b) causing temperature stress and damage if certain thresholds are crossed. The thermal time until maturity approach used in the model (see SI1 available at stacks.iop.org/ERL/9/044004/mmedia) has been observed in field experiments and historic cropping data for several plants including maize. Temperature increase leads to earlier maturing of crops, which allows for less time to accumulate biomass and form economic yield (Craufurd and Wheeler 2009, Olesen *et al* 2012, Sacks *et al* 2010, Dominguez-Faus *et al* 2013). Heat stress on the other hand constrains biomass accumulation directly e.g. by limiting photosynthesis due to enzyme inhibition (Crafts-Brandner and Salvucci 2002). However, a temperature increase by a certain percentage itself cannot serve for judging a negative or positive effect on crop yield as certain minimum and maximum temperature thresholds have to be taken into account and the physiological effects follow non-linear functions. In the simulations, temperature stress increased towards the end of the century especially in RCP8.5, but remained still fairly low in absolute terms compared to the other two major stresses (figures 3(a)–(c)). The decrease in absolute stress days for N and water over time indicates in combination with the fact that especially minimum temperatures increase (figures SI3.5 and SI3.6 available at stacks.iop.org/ERL/9/044004/mmedia) that the shortening of the time until maturity must be considered the main temperature effect on crop yields.

The effect of increasing CO_2 levels lies mainly in the CO_2 fertilization of plants, leading to higher potential biomass accumulation (see SI1 equations (2)–(4) available at stacks.iop.org/ERL/9/044004/mmedia). Being C3 plants, the two legumes profit from this effect more than the C4 crop maize (Rogers *et al* 2009). Hence, maize yields increased strongest in the management scenario with *Sesbania* and without mineral N supply towards mid-century. This can be attributed to CO_2 fertilization of the cover crop and thereby elevated N fixation up to a level close to that of the scenarios with supplementary mineral N application resulting in a massive decrease in N stress (figure 3(b)). However, in later periods, especially for RCP8.5, the gains from CO_2 fertilization could apparently not outweigh losses due to temperature increase leading to shortening growing seasons and stress reactions, although yields were still higher than under cycled baseline climate of the 2000s and N stress decreased further. An additional effect of CO_2 is its impact on transpiration efficiency (Ainsworth and Rogers 2007), which leads to lower transpiration at higher CO_2 concentrations. This can be considered a reason, why *Sesbania*+N and partly Cowpea+N became more suitable in semi-arid regions in RCP8.5 over time (figures 5(a)–(f)).

4.2. Management-related effects

The different management scenarios mainly have an impact on soil functions like nutrient provision and soil water regimes. In both RCPs, CI and Cowpea+N had higher runoff rates (figure 2(c)) and lower RZW contents than *Sesbania*+N (figure 2(d)), whereas RZW even decreased over time for CI. The low runoff and high RZW contents with *Sesbania*+N allowed for buffering of adverse changes in precipitation. Hence, CI showed stronger adverse impacts of negative changes in precipitation than *Sesbania*+N, which is also indicated by the lower intercepts in figure 6, while the slope as an indicator of sensitivity was very similar.

On the side of nutrient supply, increasing atm. CO_2 levels contribute to higher biomass accumulation by the legumes, which in turn allows for proportionally higher N fixation (Rogers *et al* 2009) as laid out above. This effect is apparently stronger for *Sesbania*(+N) than for Cowpea(+N) (figure 2(b)) as *Sesbania* is a perennial plant and can grow from shortly after the end of the maize growing season until shortly before the next maize planting besides having a higher rate of biomass accumulation (SI2; table S2.1 available at stacks.iop.org/ERL/9/044004/mmedia). Correspondingly to maize, the time until maturity for cowpea decreases with increasing temperature, which limits in turn biomass accumulation and N fixation. A perennial cover crop can hence be considered more effective for biological N fixation, if climatic conditions allow its cultivation. The strong impact of increasing CO_2 is most apparent in the fact that maize yields with *Sesbania* exceed those of Cowpea+N in the 2060s and beyond under RCP8.5 (figure 1(a)) before temperature becomes strongly limiting. *Sesbania* is thereby also the only management scenario with higher yields in the 2080s under RCP8.5 than in the 2000s (figure 1(b)).

The issue most difficult to address is the cultivation history of a site. If soil structure is affected by adverse or beneficial climate conditions during earlier decades within the continuous cultivation, this will also affect yields during the later time periods, which makes it more difficult to disentangle climatic or atmospheric drivers for yield changes. As both types of erosion depend on soil cover and OC contents among others in EPIC (see SI1 available at stacks.iop.org/ERL/9/044004/mmedia), the permanent soil cover by *Sesbania* outside the maize growing season and the increase in soil OC can be considered major drivers of the erosion assessment. The fact that *Sesbania*(+N) limits soil erosion indicates that it additionally contributes to maintaining water holding capacity and rooting space through soil conservation.

5. Conclusions and limitations

Our results suggest that until the 2060s, crop management may be the main driver for obtaining certain yield levels and sustaining environmental functions of the agro-ecosystems. Beyond this point, yields with the on average optimal management scenario *Sesbania*+N decreased in the highest emission scenario RCP8.5 below those of all scenarios with high mineral and mineral+biological N supply in RCP2.6 (figure 1(a)). This highlights that under highly adverse climate change, climate variables will become the limiting factor. Still, *Sesbania*(+N) can be considered the most resilient cultivation systems under (adverse) climate change in this study. However, due to local agro-climatic characteristics, an herbaceous rotation may be more favorable in humid climates and CI appears to be most adequate in arid regions, where the main crop would otherwise compete for soil water with the studied cover crops. Despite the enhanced resilience provided by eco-intensification approaches, they alone will not be sufficient to overcome the adverse impacts of climate change from increasing temperature in the long run. This will require in addition the development and dissemination of other improved agricultural technologies and practices, such as heat tolerant cultivars and potentially irrigation systems. The fact that the adverse impacts of temperature continuously increase over time under worst-case conditions, however, indicates that the breeding of tolerant cultivars might need to be the first priority on the large scale.

Yield changes presented in this paper are roughly in the range of earlier studies using crop models, in terms of magnitude as well as the spatial distribution of increases and decreases (Liu *et al* 2013, Waha *et al* 2013b). The results presented herein for different crop management strategies, however, will have to be verified by experimental studies and more detailed modeling at the field and homogeneous regional scales. This would also allow for disentangling management-related and climatic drivers for yield changes, which is presently not feasible at a large heterogeneous scale. Further limitations of this study result from processes not taken into account by EPIC. As reviewed by St Clair and Lynch (2010), climate warming and decreasing precipitation may also limit soil productivity by inhibition of microbial processes, which are especially important for symbiotic N fixation. Hence, our assessment has to be considered rather conservative, especially for the scenarios resulting in severe soil degradation. Last but not least, plant growth limitations due to deficiencies in P (van der Velde *et al* 2013) and micronutrients (Voortman *et al* 2003), which both are viable for biological N fixation besides maize growth, were not considered in this study.

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