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Water and nitrogen use and productivity of dryland mixed farming system under climate change

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Abstract: Mixed farming comprising crop, pasture and livestock is more self-sufficient and has lower environmental costs than crop farming system. Mechanisms contributing to yield advantage in mixed system is unclear, water and nitrogen balances in mixed system under changing climate is not well assessed. This study used the pre-validated APSIM model, driven by climate data from 27 Global Climate Models (GCMs) under two Shared Socioeconomic Pathways (SSP245 and SSP585). Six mixed farming system including lucerne pasture, livestock and different crop rotation (WCWC, WFWC, WFWO, WWB, WWC, and WWO) were simulated, pure crop rotations were set as the benchmark. The effects of pasture crop and sheep grazing on soil water and nitrogen balances and crop productivity in mixed farming were assessed during the historical period (1985-2008), near future (NF, 2033-2056), and far future (FF, 2057-2080) in Riverina, southeast Australia.

Results showed the mixed system returned much more nitrogen (N) back into soil than crop system. N return during crop phase ranged in 28.1-28.3 kg ha^{-1} in history and 32.2-36.4 kg ha^{-1} under future climate. N returned as organic matter and urine in pasture phase, being 66.3, 80.4, and 83.8 kg ha^{-1} in history, NF and FF under SSP245 respectively, and 85.5 and 94.4 kg ha^{-1} in NF and FF under SSP585 respectively. Temporal N facilitation occurred in mixed system, crop depleted 25.4-58.2 kg ha^{-1} yr^{-1} N from soil over different rotations and climate scenarios. As for water balance, deep drainage was significantly reduced in the mixed system, rainfall harvesting efficiency increased by 11.0%-12.3% than crop system. More water was used as transpiration in mixed system, the fraction of T in ET (T/ET) increased by 38.1, 38.9 and 40.1% than crop system in history, NF, and FF, respectively, under SSP245; by 42.0 and 44.6% in NF and FF under SSP585, respectively. Crop grain water use efficiency (WUE_{grain}) in crop system averaged at 9.81, 10.71, and 11.03 kg ha^{-1} mm^{-1} in history, NF, and FF under SSP245, respectively, increased to 10.67, 11.60, and 11.99 kg ha^{-1} mm^{-1} in the mixed system, and further increased to 12.33 and 13.60 kg ha^{-1} mm^{-1} in NF and FF under SSP585, respectively. Crude protein water use efficiency ($WUE_{protein}$) in the mixed system was increased by 33.1, 47.1, and 54.9% than crop stems in history, NF, and FF under SSP245, respectively, and increased by 53.6% and 61.6% in NF and FF under SSP585 respectively. Finally, crop grain and crude protein yield in mixed system was greatly improved. WCWC had the greatest yield improvement of 26.5, 27.3, 29.5, 31.5, 31.2% under history, SSP245 NF, SSP245 FF, SSP585 NF, SSP585 FF, respectively, among the 8-yr rotations; WWO showed the highest yield improvement among 6-yr rotations but it had the lowest yields. Therefore, mixed system with WCWC performed the best in grain and protein yield and yield improvement.

This study indicated that mixed farming system relied less on N input, reduced water drainage and evaporation loss, and improved water use efficiency and system production. The water use and yield advantage could be enhanced under future climate. Mixed system with WCWC are suggested to be applied in dryland areas in southeast Australia to combat future climate risk.

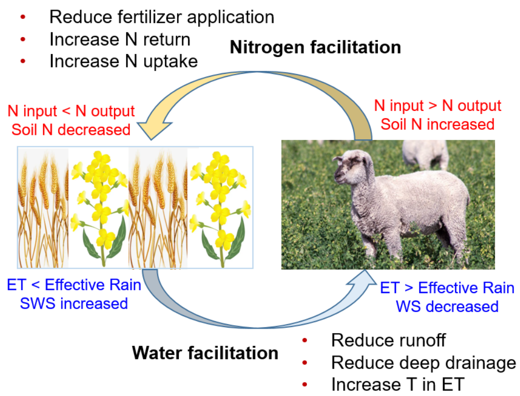

Figure 1. The proposed conceptual framework template for water and nitrogen balances in mixed farming

Keywords: *Farming system modeling, mixed farming, temporal resources facilitation, water use efficiency*

1. INTRODUCTION

Mixed farming system integrating crop and livestock production has long served as the backbone of sustainable agriculture. However, it was gradually simplified in the process of agricultural modernization worldwide (Liebman and Dyck, 1993). The simplified farming systems which specialize in the production of one or two grain crops rely on greater external inputs such as irrigation, fertilization, and energy, causing a decline in resource use efficiencies (Basso et al., 2021). In addition, simplified farming systems are more vulnerable to pest and weed invasion, heat and drought stress, and greenhouse gas emission, which created concerns about their sustainability under climate change. Mixed faming system mimics natural ecosystems and can provide solutions for designing agroecosystems that rely more on natural processes and could harness land productivity and ecosystem services. Understanding the mechanisms by which the mixed farming systems operate can provide pathways for the sustainable intensification of agriculture in other regions.

Grain crops and perennial pasture rotations are usually applied in the mixed farming system to support both grain and livestock production. Perennial pastures such as alfalfa have a deep root system and can dry soils to lower water contents and to greater depths than annual crop species, which offers the potential to reverse the water imbalance caused by current cropping systems based on annual plants (Hirth et al., 2001). For example, crop season is short in the annual crop system, long fallow periods usually result in water waste through soil evaporation and deep drainage, crop-pasture rotation is effective in increasing rainfall use efficiency. In the Northern Great Plains of USA large areas of alfalfa planting effectively reduced soil evaporation and dryland salinization (Black et al., 1981). In some high rainfall areas in Australia, a lucerne pasture may also enable land considered too wet for cropping to be successfully cropped in most years and increase the proportion of the farm that could be cropped (Riddy et al., 2001). However, over soil water storage depletion by pastures might also limit the benefits of perennial crops and reduce the yield of following crops in semi-arid environments (Ents et al., 2002). In environments with summer-dominant rainfall the potential yield penalty for first-year crops after lucerne was greatest in years of low rainfall. Soil water storage is depleted by pasture crops, which was recharged during the crop phase. Contribution of soil water storage to alfalfa water use could be as high as 43%, depending on rainfall conditions (Hirth et al., 2001). Previous studies usually assessed water balance and use efficiency during the crop or pasture phase, water temporal facilitation between different phases was rarely assessed in the perspective of a long-term rotation.

Temporal nitrogen (N) facilitation from legume pastures to annual crops in crop-pasture rotation was also extensively reported. Perennial species contribute three to seven times more C and N to the litter pool than annual species, so large amounts of organic carbon and N were accumulated in the pasture phase (Pravia et al., 2019). N requirements of non-legume annual crops are partially contributed from the pasture crops, so soil nitrogen decreases during the annual cropping phase and recovers again during the perennial pasture phase (Díaz Rosello, 1992). On a red brown earth in northern New South Wales, lucerne grown for 3.5 years maintained the yields of 3 wheat crops without fertilizer N, with the maximum benefit obtained in the second crop (Holford 1980). Livestock in mixed system also play an important role in N cycling. Studies showed that grazing of cattle in a mixed farming system increased soil N levels and improved crop yields. Water and N simultaneously affect the yield of farming system, and a shortage in one factor usually limits the use efficiency of the other. The study by Angus and Fischer (1991) found that pasture N facilitation on crop performance was better realized in growing seasons when the water supply does not limit. Mineralization of lucerne N was slower when the growing season following removal was drier, lucerne would supply N to a minimum of 2 crops when cropping commences in wet years, and 3 crops when cropping years are average to dry (Hirth et al., 2001). How crop species and the length of crop and pasture species in the mixed system affect N balance, and how N facilitation affect the water use efficiency and yield advantage under different climate condition needs further study.

Objectives of this study were to: 1) quantify the effect of pasture and livestock incorporating on rainfall harvesting efficiency and soil water balance; 2) investigate N return, N leach and soil N balance in crop and pasture phases in the mixed system; 3) clarify how water and nitrogen interacted to increase water use efficiency and system productivity in the mixed system as compared to crop system, and how the water use and production advantage change under future climate scenarios; and 4) put forward management strategies for farming practice in the study area.

2. METHODS

2.1. Study area and data collection

This study selected Riverina cropping region in southern NSW as the study area. Mixed and crop systems on 204 sites across the region were simulated. The annual total rainfall is low in the west and high in the east, the annual mean temperatures range from 12 to 18 °C. The main soil types are Chromosols, Dermosols, and Vertosols. Soil data from APSoil database were used within the simulation. 41 soil sites were used, the geographically closest APSoil soil profiles was used for each simulating site.

Daily minimum and maximum temperature, solar radiation and precipitation during the historical period of 1920-2020 were downloaded from the Scientific Information for Land Owners patched point dataset (SILO-PPD, https://www.longpaddock.qld.gov.au/silo). The representative Shared Socio-economic Pathways (SSPs) with intermediate (SSP245) and very high (SSP585) emission trajectories were employed to represent future climate scenarios during 2021-2100. In order to cover variations in future climate projections, an ensemble of 27 global climate models (GCMs) was used for downscaled climate projections. Gridded monthly radiation, temperature and precipitation data were extracted from the GCM simulations in the Coupled Model Intercomparison Project Phase 6 (CMIP6, https://pcmdi.llnl.gov/CMIP6). As APSIM requires daily climate data, these GCM-generated monthly gridded data were downscaled to each study site. The yearly atmospheric [CO_2] was calculated using empirical functions that were obtained by non-linear least-squares regression.

2.2. APSIM modeling and calculations

APSIM is a daily time-step model that contains a suite of modules to simulate the response of farming systems to different management practices and climate change (Keating et al., 2003). APSIM version 7.10 was used in this study. The APSIM module SoilWat was used to simulate the soil water balance at a daily scale. Module SoilN and SurfaceOM control the carbon transformation in the soil and on the soil surface. The SoilWat and SoilN, coupled with SurfaceOM, control the N dynamics on a daily step. Crop phenology is driven by thermal time of each specific growth stage, which is determined by accumulating growing degree-day (GDD, °C). Daily biomass production is determined by available water for transpiration or PAR, the minimum is the actual biomass production. Grain formation is simulated through assimilate partitioning, grain yield is calculated as the product of grain weight and grain number.

APSIM was initialized for each location using a 41-year spin-up period to establish stable SOC fractions before simulating management scenarios. During initialization, the model was run from 1920 to 1960 for a continuous wheat cropping system with 50 kg N ha^{-1} added as fertilizer at sowing and 25% residue retention. After the initialization, the designed 12 rotations were simulated from 1961 to 2092, with 50% of crop residue retention (Fig. 2). The cropping systems including six common rotations in the Riverina region, WCWC, WFWC, WFWO, WWB, WWC, and WWO. W, C, F, B, and O represents wheat, canola, field pea, barley and oats, respectively. The mixed systems have a rotation length of 6 or 8 years, in which a half period is crop phase and another half is pasture phase. Crop rotations during the crop phase was the same as in crop system (Fig. 2). For comparison of the 6- and 8-year rotated mixed system, a 24-year rotation period was used as it gives four and three complete rotation cycles, respectively. Three 24-year periods (1985-2008, 2033-2056, and 2057-2080) were used to represent the historical period, near future (NF) and far future (FF), respectively. Nitrogen fertilizer for cereals and canola varied between 43 and 121 kg N ha^{-1} based on the precipitation at each site, and was 10 kg N ha^{-1} for field pea.

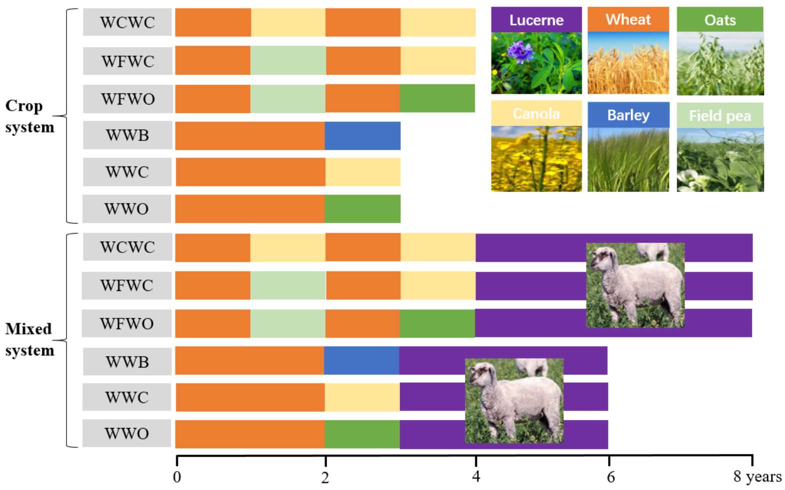

Figure 2. Rotation design for cropping system and mixed system

In the mixed farming system, a large part of pasture biomass was consumed by livestock when the amount of biomass reached the grazing standard, the other part of biomass was returned as residual. Within the intake biomass, it was assumed that 15% of N converted into livestock products while the other N was contained in the livestock waste, returned back into soil as organic matter and urine. In crop system and crop phase in mixed system, N was returned into soil as crop residual.

Soil water balance during a certain year (including crop season and fallow season) was assessed using the water balance equation: $\Delta S = P - E - T - R - DP$.ΔS is the change in soil water storage in the root layer (mm); P

is precipitation (mm); R is the runoff (mm); E and T are soil evaporation and plant transpiration respectively (mm), DP is soil water deep drainage loss (mm). Some rainfall would be wasted through DP and R, so effective rainfall, P_e, equals to: $P_e = P - R - DP = E + T + \Delta S$.

Rainfall harvesting efficiency (RHE) was defied as the ratio of P_e to P. The effective rainfall is therefore used as evapotranspiration (ET) or contributed to the changes in soil water storage. The fraction of T in ET (T/ET) is another important indicator for water use as a high T/ET indicates less water is wasted through soil evaporation. The WUE (kg ha^{-1} mm^{-1}) was calculated for the crop grain yield (WUE$_{grain}$) and crude protein yield (WUE$_{protein}$). $WUE_{grain} = Y_{garin} / ET$ and $WUE_{protein} = Y_{protein} / ET$. Y_{grain} and $Y_{protein}$ represent the crop grain yield and crude protein yield (kg ha^{-1}), respectively.

3. RESULTS

3.1. Soil N balance

N application and N returned back to soil are the main N inputs into the farming system. Although N application in the mixed system was a half of the crop system, much more N was returned than crop system. As in crop systems, half of crop residual was returned into the soil during the crop phase in the mixed system. Average over different sites and rotations, yearly N return during crop phase changed little with climate scenarios, ranged in 28.1-28.3 kg ha^{-1} in history and 32.2-36.4 kg ha^{-1} under future climate, which was far higher than the values of 15.1-15.3 kg ha^{-1} in the crop system. During the pasture phase, more N was returned as organic matter and urine and the return was greatly enhanced by climate change, being 66.3, 80.4, and 83.8 kg ha^{-1} in history, NF and FF under SSP245 respectively, and 85.5 and 94.4 kg ha^{-1} in NF and FF under SSP585 respectively. Soil NO_3-N leach in crop system was very limited due to less available soil nitrogen, which was increased in the mixed system, especially during crop phase, with values ranged from 8.1-11.7 kg ha^{-1} yr^{-1} (Fig. 3B).

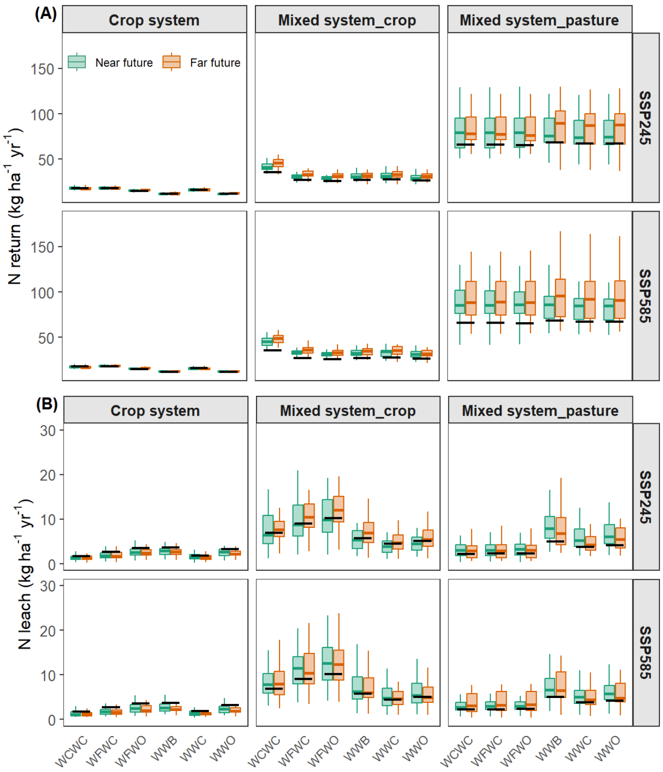

Figure 3. N returned into soil and the NO_3-N leach in the mixed system as compared to crop system. Boxplots show distribution over 27 GCMs. Blank line means history data

Fig. 4 shows soil N balance in the mixed farming system. Averaged over sites and the three 8-year rotations, N decrease was 52.9, 32.1, 25.5, and 25.4 kg ha^{-1} in the 1st, 2nd, 3rd, and 4th year of the crop phase respectively in history period; which was enhanced by climate change, being 58.2, 46.5, 44.0, and 36.1 kg ha^{-1} in FF under SSP585. For the 6-year rotations, N decrease was 44.7, 32.5, and 27.3 kg ha^{-1} in the 1st, 2nd, and 3rd year of the crop phase respectively in history period, increased to 56.4, 48.4, and 32.1 kg ha^{-1} in FF under SSP585. Soil N increase during the pasture phase was distributed almost evenly across different years, with values of 27.8 and 37.2 kg ha^{-1} yr^{-1} in history and FF under SSP585 respectively in 8-year rotations, and of 29.7 and 36.8 kg ha^{-1} yr^{-1} in 6-year rotations.

Summed over each year in crop phase in the mixed system, 8-yr rotations showed a higher N facilitation than 6-yr rotations. WCWC showed the highest N facilitation to crops among the 8-yr rotations, with values of 114.8 kg ha^{-1} in history, increased to 128.7 and 134.3 mm during SSP245 NF and FF scenarios respectively, and increased to 142.3 and 147.5 kg ha^{-1} during SSP585 NF and FF scenarios. The spatial distribution of N facilitation paralleled with rainfall availability, increased from west to east part of the study area. Lowest N facilitation ranged in 30-90 kg ha^{-1} in the west, increased to 90-150 kg ha^{-1} in a large area in the middle part. In the humid south east region, the facilitation could be as high as 270-330 kg ha^{-1} under SSP245 while exceeded 330 kg ha^{-1} under SSP585 (data not shown).

3.2. Soil water balance

Deep drainage is a main approach of rainfall loss when the amount of rainfall exceeds soil water capacity. The incorporation of pasture into the cropping system could significantly reduce this loss (Fig. 5A). Averaged over sites and rotations, deep drainage in crop system ranged in 71.9-77.1 and 76.6-84.1mm yr^{-1} under SSP245 and SSP585, respectively, which was reduced to 34.6-42.6 and 39.2-42.6 mm yr^{-1} during the crop phase in mixed system and to 16.4-17.4 and 17.3-22.2 mm yr^{-1} during the pasture phase. Runoff during the pasture phase in mixed system was also largely reduced. As a result, the mixed system significantly increased RHE compared to crop system under all climate scenarios (Fig. 5B). RHE of crops system ranged in 0.82-0.83, while that of the crop phase and pasture phases in mixed system ranged in 0.89-0.91 and 0.95-0.96, respectively. Climate scenarios showed little effect on the RHE. On system perspective, RHE in the mixed system was 11.0%-12.3% higher than crop system.

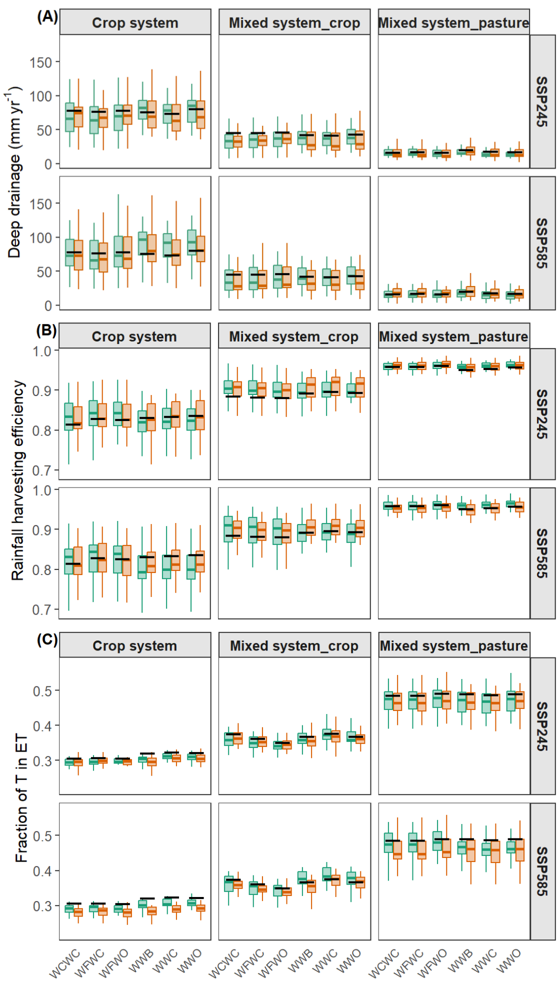

Figure 5. Drainage, RHE and fraction of T in ET in the mixed system as compared to crop system. Boxplots show distribution over 27 GCMs. Blank line means history data

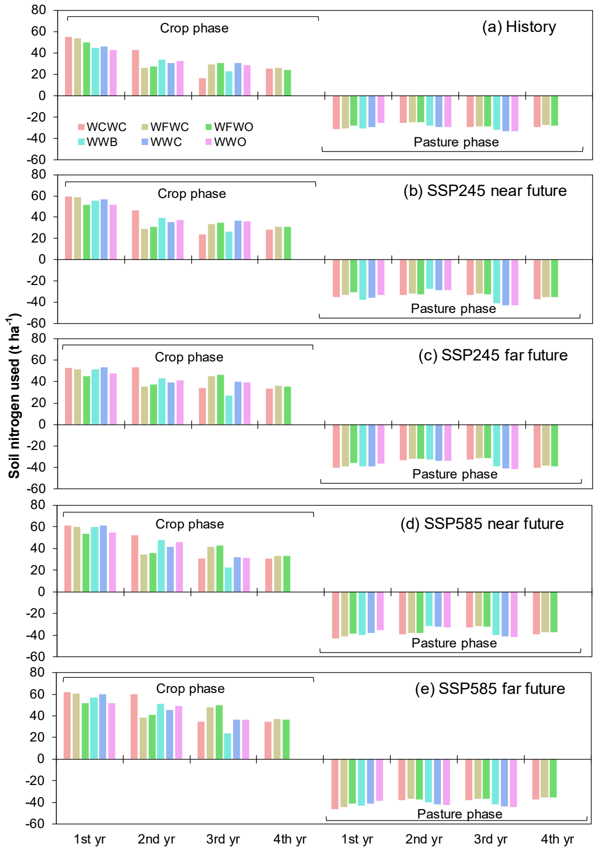

Figure 4. Soil N depletion in each year during crop phase (soil N decreased) and pasture phase (soil N increased) in the mixed farming system

Within ET, the mixed system significantly partitioned more water to plant transpiration compared to crop system (Fig. 5C). T/ET of crop system ranged in 0.28-0.31, which was increased to 0.35-0.37 in the crop phase in mixed system, and increased to 0.46-0.48 in the pasture phase in mixed system. Averaged over different phases in the mixed system, the T/ET in mixed system was increased by 38.1, 38.9 and 40.1% compared to crop system in history, NF, and FF, respectively, under SSP 245; and was increased by 37.9, 42.0 and 44.6% in history, NF, and FF, respectively, under SSP585.

Throughout the rotation cycle, soil water storage was generally recharged during the crops phase and depleted during the pasture phase. Specifically, alfalfa depleted soil water storage to meet its high water consumption in the first year after planting. Averaged over different cropping system, the water depletion was as high as 31.9 mm yr^{-1} in history, reduced to 30.2-30.7 mm yr^{-1} under SSP245 scenarios, and further reduced to 26.8-27.9 mm yr^{-1} under SSP585 scenarios. However, no apparent soil water depletion occurred in the following years, and soil water was even replenished in the last year of the pasture phase (data not shown).

Summed over the whole pasture phase, WCWC also showed the highest water facilitation to pasture phase among the 8-yr rotations, with values of 32.1 mm in history, which decreased to 30.9 and 30.2 mm in NF and FF under SSP245, respectively; and decreased to 29.6 and 25.2 mm in NF and FF under SSP585, respectively. WWB showed the highest water facilitation among the 6-yr rotations, with values of 35.7 mm in history, which decreased to 34.0 and 29.9 mm in NF and FF under SSP245, respectively; and had values of 35.0 mm and 38.7 mm in NF and FF under SSP585, respectively. On the spatial view of water facilitation in WCWC, a large part of the middle and west had a water facilitation of only 0-30 mm. The facilitation distributed similarly with the rainfall pattern, increased from west to east, ranged in 30-90 mm in most areas in the southeast (data not shown).

3.3. Crop grain yield and system CP yield

Water and nitrogen facilitations in the mixed system benefited the crop production. Averaged over the study region, crop grain yield in the mixed system was greatly improved compared to pure cropping system, for all of the rotation sequences. Wheat yield was greatly enhanced while canola yield was only slightly improved in the WCWC. Yield of field pea was negatively affected in WFWC and WFWO, WCWC had the highest yield improvement among 8-yr rotations. Yield of wheat, barley, canola, and oats were all improved in the 6-yr rotations, WWO showed the highest improvement. The yield of crops improvement was slightly enhanced under SSP245 NF under SSP254 FF, and further enhanced under SSP585 NF and SSP585 FF.

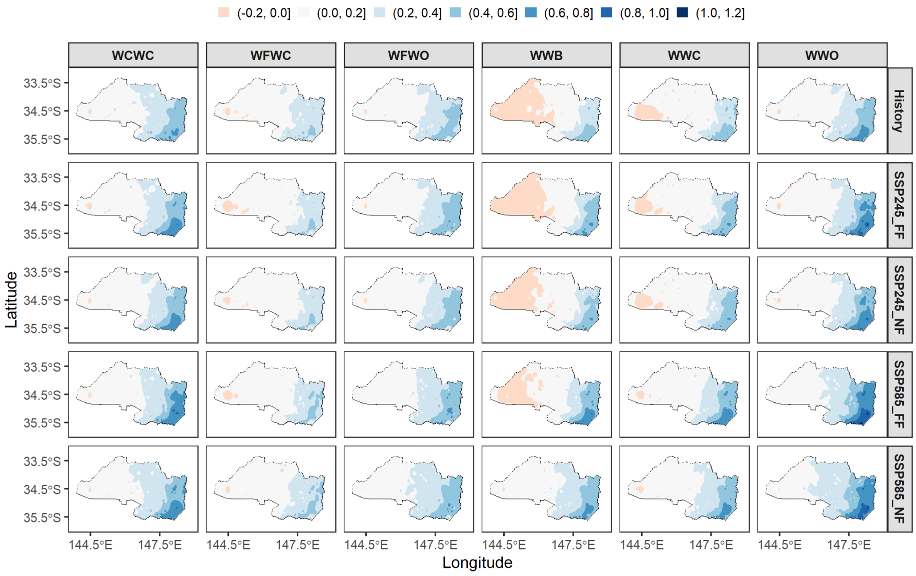

Figure 6. Spatial distribution of crop grain yield improvement for different mixed systems over corresponding crop rotations.

On a spatial view (Fig. 6), there were only a few regions in the west part showed yield reduction, large areas in the middle and west showed yield improvement rate of 0-20% in all 8-yr rotations under history scenario, yield increment in the southeast was most significant in WCWC. Among the 6-yr rotations, WWO showed the most apparent yield improvement and had a similar distribution with WCWC. WWB and WWC showed large areas of reduction in the west. Highest improvement in the southeast ranged in 0.4-0.6 under WFWC, WFWO, WWB, and WWC, while attained 0.6-0.8 in WCWC and WWO. Yield improvement rate in the southeast could be as high as 0.8-1.2 under future climate scenarios.

CP yield during the crop phase in mixed system was largely improved compared to the corresponding crop system in all rotations under all climate scenarios (Fig. 7). During the pasture phase, the protein yield in mixed systems were similar or lower than the corresponding crop system in history scenario; however, protein yield of lucerne increased more quickly than crops under future climate, the protein yield in mixed systems exceeded that in the crop systems under both SSP245 and SSP585 in FF. On a system perspective, WCWC and WFWO had the similar increments under the history scenario but WCWC performed better under all future scenarios, with protein yield increments of 31.6 and 37.5% in near and FF under SSP245, respectively, and 40.7 and 48.4% in near and FF under SSP 585. WWO performed the best among 6-yr rotations with protein yield increment of 38.1% in history, 53.6 and 58.7% in near and FF under SSP245, respectively, and 60.1 and 68.4% in near and FF under SSP585.

Averaged over different sites and rotations, WUE_{grain} in crop system averaged at 9.81, 10.71, and 11.03 kg ha^{-1} mm^{-1} in history, NF and FF under SSP245, respectively, increased to 10.67, 11.60, and 11.99 kg ha^{-1} mm^{-1} in the mixed system, further enhanced to 12.33 and 13.60 kg ha^{-1} mm^{-1} in NF and FF under SSP585, respectively. WCWC showed the highest WUE_{grain} increment of 10.5% and 10.9% under SSP245 and SSP585 respectively. WUE_{CP} of mixed system was increased by 33.1, 47.1, and 54.9% than crop stems in history, NF, and FF under SSP245, respectively, increased by 53.6% and 61.6% in NF and FF under SSP585 respectively.

4. DISCUSSION AND CONCLUSION

This paper discussed the mechanisms contributing to yield advantage in dryland mixed farming system. We found that water capture efficiency was improved by reducing deep drainage and soil evaporation loss, water use efficiency was enhanced by well soil water and nitrogen conditions that resulted from water and nitrogen temporal facilitation. Both water capture and use efficiency contributed to crop grain yield and system protein yield in the mixed farming system. We also found that nitrogen facilitation, water use efficiency, and yield advantage were gradually enhanced under future climate scenarios, which suggested that the mixed system is more resilient to future climate risks such as high temperature and uneven rainfall distribution.

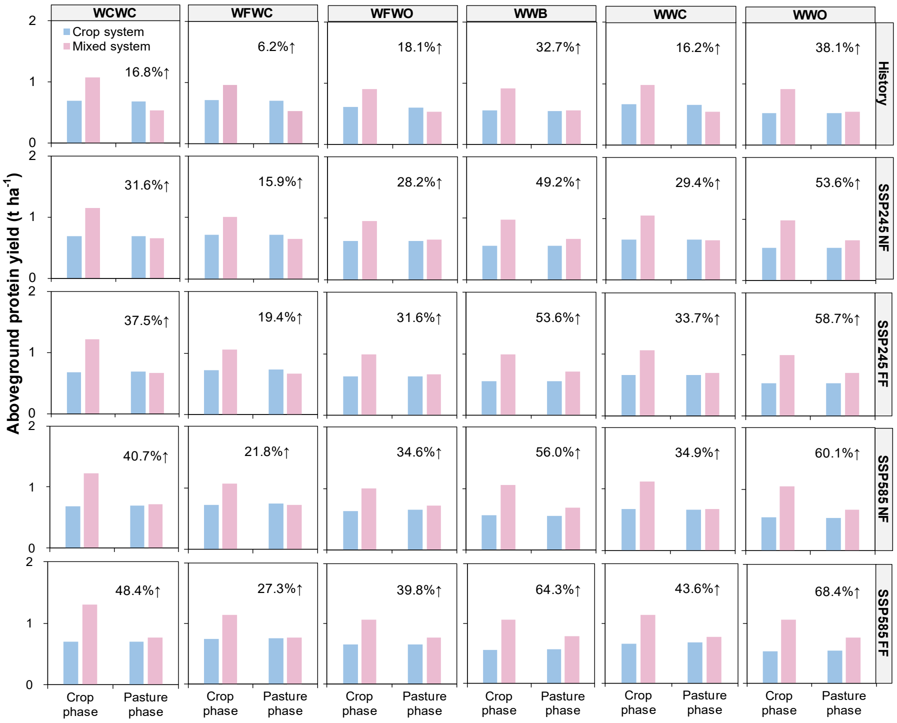

Figure 7. Increments in aboveground protein yield for different mixed systems, as compared to corresponding crop rotation system

Some limitations occurred in this study. First, although we found a large amount N was accumulated during pasture phase in the mixed system, we did not test the effect of reducing N input in following crop phase, a large amount of N fertilizer could be save theoretically, which need to be validated. Second, we assumed that 50% of residual was returned after harvest, other common practices such as 100% retention and no retention needed to be assessed. And finally, we only considered lucerne as a pasture crop in this study, annual pastures and cereal-legume mixtures should be assessed in the context of mixed farming system in the future work, and further improve the system design.

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