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Agronomic benefits and risks associated with the irrigated peanut–maize production system under a changing climate in northern Australia

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Abstract. With the aim of increasing peanut production in Australia, the Australian peanut industry has recently considered growing peanuts in rotation with maize at Katherine in the Northern Territory—a location with a semi-arid tropical climate and surplus irrigation capacity. We used the well-validated APSIM model to examine potential agronomic benefits and long-term risks of this strategy under the current and warmer climates of the new region. Yield of the two crops, irrigation requirement, total soil organic carbon (SOC), nitrogen (N) losses and greenhouse gas (GHG) emissions were simulated. Sixteen climate stressors were used; these were generated by using global climate models ECHAM5, GFDL2.1, GFDL2.0 and MRIGCM232 with a median sensitivity under two Special Report of Emissions Scenarios over the 2030 and 2050 timeframes plus current climate (baseline) for Katherine. Effects were compared at three levels of irrigation and three levels of N fertiliser applied to maize grown in rotations of wet-season peanut and dry-season maize (WPDM), and wet-season maize and dry-season peanut (WMDP). The climate stressors projected average temperature increases of 1°C to 2.8°C in the dry (baseline 24.4°C) and wet (baseline 29.5°C) seasons for the 2030 and 2050 timeframes, respectively. Increased temperature caused a reduction in yield of both crops in both rotations. However, the overall yield advantage of WPDM increased from 41% to up to 53% compared with the industry-preferred sequence of WMDP under the worst climate projection. Increased temperature increased the irrigation requirement by up to 11% in WPDM, but caused a smaller reduction in total SOC accumulation and smaller increases in N losses and GHG emission compared with WMDP. We conclude that although increased temperature will reduce productivity and total SOC accumulation, and increase N losses and GHG emissions in Katherine or similar northern Australian environments, the WPDM sequence should be preferable over the industry-preferred sequence because of its overall yield and sustainability advantages in warmer climates. Any limitations of irrigation resulting from climate change could, however, limit these advantages.

Additional keywords: APSIM, fertiliser, irrigation, peanut, maize, rotation.

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Introduction

Most of the currently cropped regions of Australia have insufficient irrigation water to supplement the crop water demand (Chartres and Williams 2006). In addition, it is recognised that climate change is likely to put additional pressure on water availability for agriculture through further increases in crop evaporative demand coupled with decreases in rainfall (Chartres and Williams 2006). Dwindling water supplies, and projections of climate change in the main agricultural regions of Australia, are forcing planners and industries to investigate the possibility of expanding agriculture into the northern tropical region, comprising parts of the north of Western Australia, the Northern Territory and northern Queensland (Nikolakis *et al*. 2011). The northern tropical region currently accounts for over half of Australia's stream flows (200 000 GL), which coupled with the sparse population of the region, endows it with surplus water (Chartres and Williams 2006; Nikolakis *et al*. 2011).

Although expanding agriculture into the tropical region has promise to solve the critical constraint of water availability, the task of accomplishing this expansion is beset with many social and logistical challenges. These challenges include remoteness, limited availability of farm labour and lack of markets adjacent to production areas (Marshall *et al*. 2014). With these limitations, cropping industries that are likely to consider seriously growing crops in the tropical region are expected to be primarily those that face a significant decline in existing production areas resulting from current water shortages or climate change.

The Australian peanut industry is one such industry and has faced significant declines in production over recent years, which has increased the supply–demand gap. The yearly peanut production, which peaked at 50 000 t of pods some 25 years ago, is now hovering around 25–30 000 t (G. Wright, PCA, unpubl. data). This decline is associated with the frequent failure of peanut crops in the traditional dryland production region in the Burnett district of south-eastern Queensland. It is, therefore, not surprising that the Australian peanut industry was among the few industries that developed a strategy to expand production into the northern tropics, where peanuts could be grown with irrigation in rotation with other crops, including maize (Marshall *et al*. 2014). Implementation of this strategy resulted in the establishment of a pilot farm of >12 000 ha at Katherine, Northern Territory, ~3000 km away from the traditional production areas in Queensland (Marshall *et al*. 2014).

In the initial stages of implementation of the strategy at Katherine, the industry preferred to grow peanuts in the dry season, in rotation with maize to be grown in the wet season. A major reason for preferring this sequence was that it would complement the existing schedule of peanut production in the dryland and other regions, thereby ensuring year round availability of peanuts for processing. However, during the initial stages, it was not known whether this was the best cropping sequence for the cropping region in terms of overall productivity and profitability.

Chauhan (2010), using simulations with the Agricultural Production System Simulator (APSIM) model and limited field data, showed that the potential productivity of the two crops was up to 28% more when peanut was grown in the wet season than in the dry season, whereas the irrigation requirement for both sequences were similar. This study also showed that the irrigation requirement in the new region was influenced by the La Niña and El Niño weather patterns. These weather patterns were not as much of an issue in the traditional production region. This tropical peanut expansion strategy, the scale of which can be truly considered transformational (Stafford Smith *et al.* 2011; Rickards and Howden 2012; Marshall *et al*. 2014), was implemented on an assumption that the availability of irrigation would insulate against possible adverse effects of climate variability as well as climate change occurring in the region. The effects of climate change on crop performance in the new region, however, were not examined.

Large-scale agricultural developments such as those attempted through this peanut expansion strategy might be attractive in the short term but could have large environmental consequences (Pingali and Rosegrant 1994), and ignoring these could create potential sustainability issues. Little information was available on whether the inclusion of peanut or other rotational crops in the tropics could create sustainability issues, for example, reduction in soil organic carbon (SOC), increased nitrogen (N) losses to aquifers and increased greenhouse gas (GHG) emission. There was also a need to understand how climate change might influence these sustainability issues, as well as the crop irrigation demand. Unfortunately, no information was available on the types of weather patterns likely to be witnessed in the new region when the new peanut cropping project commenced. The recent availability of climate-change projections for the northern tropical region (Bruget *et al*. 2012) allows the potential impact of a range of climate-change scenarios on crop productivity and sustainability to be examined by using a modelling approach.

In this study, we examined possible effects of climate change on crop productivity and relative water requirements of two sequences of peanut–maize rotation when each crop is grown as either a summer or a winter crop. We also examined possible sustainability impacts including SOC and N losses and GHG emissions that are likely to affect the adoption of this strategy into the tropical environment of Katherine.

Materials and methods

For this simulation study, we chose Katherine (–14.48°S, 132.25°E) as the target environment where the peanut industry first trialled a peanut–maize rotation as part of its transformational strategy to augment declining peanut production in the traditional dryland production region. The soil of the target location was sampled and characterised as Kandosolic Redoxic Hydrosol (Isbell 2002), which was sandy in appearance and held ~140 mm of plant-available water to a depth of 2 m. The drained upper limit of water retention (0.33 MPa) ranged from 0.19 to 0.21 mm/mm, the permanent wilting point of water retention (1.5 MPa) ranged from 0.01 to 0.025 mm/mm, and saturation water retention ranged from 0.33 to 0.40 mm/mm in different soil layers. The bulk density ranged from 1.54 to 1.7 g/cm^3.

The APSIM model was used to simulate and compare the effects of current and projected future climates of Katherine. APSIM was selected because it integrates numerous biophysical concepts to simulate responses of both peanut and maize crops and was one of the most models suitable for simulating crop rotations (Keating *et al*. 2003; Holzworth *et al*. 2014). Recently, the model has been used to study climate-change effects and characterise environments (Chauhan and Rachaputi 2014; Holzworth *et al*. 2014). Further, this model has been previously validated for both yield and water requirement of maize and peanuts in Australian environments (Carberry *et al*.1989, 1996; Robertson *et al*. 2002). The peanut and maize modules of the model have been extensively used to analyse historical performances of individual peanut and maize crops, or rotations based on these crops (Meinke and Hammer 1995; Nelson *et al*.1998; Birch *et al*. 2008; Hammer *et al*. 2009). APSIM is now increasingly being used to predict performance of farming systems under a changing climate (Wang *et al*. 2009; Rodriguez *et al*. 2011; Biggs *et al*. 2013).

Version 7.4 of APSIM (Holzworth *et al*. 2014) was configured to simulate two generic sequences of peanut–maize rotation (Fig. 1). In the first cropping sequence, maize was to be grown in the wet season (3 December) and peanut in the dry season (3 May), which was the industry-preferred sequence and is referred to as WMDP. The alternative sequence of maize sown in the dry season and peanut in the following is wet season referred to as WPDM.

These two sequences of peanut–maize rotation were created by including sowing dates of the two crops in the manager module. For both rotation sequences, plant population was specified as 7 plants/m^2 for maize for the medium-maturing variety Pioneer 3527 and 15 plants/m^2 for peanuts for the full-season variety Wheeler (a Virginia Bunch type). The other required modules were: Peanut, Maize, SoilWat, Met, SoilN, Fertilizer, Irrigation.

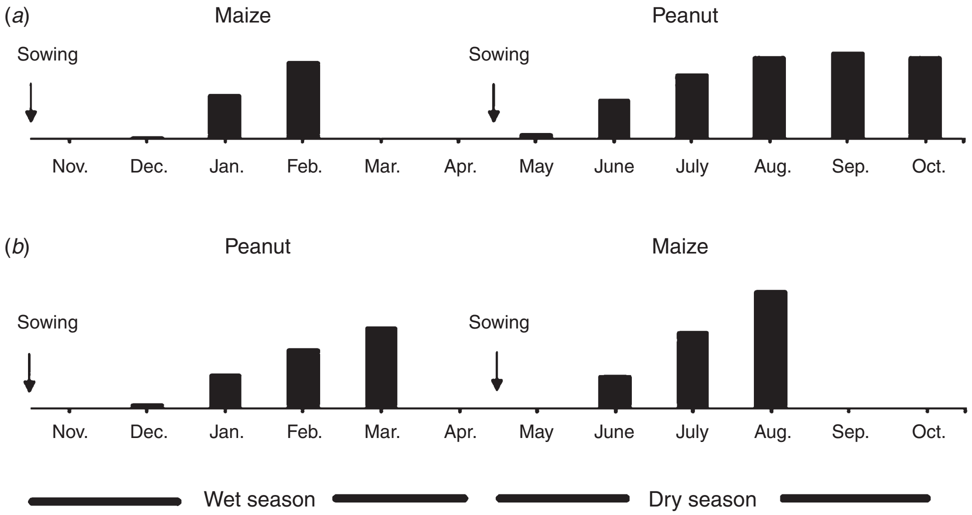

Fig. 1. Schematic presentation of (*a*) industry-preferred wet-season maize–dry-season peanut rotation (WMDP) and (*b*) alternative sequence of wet-season peanut–dry-season maize (WPDM) at Katherine. Heights of the bars are in proportion to dry matter production in different months under the two sequences (not to exact scale).

The above generic simulations were then used to generate further factorial combinations of different climate projections, agronomic factors including three levels of irrigation to both crops and three fertiliser rates to maize, and 17 meteorological files containing daily data, including one to represent current climate, by using SIMGEN4 software (A. Doherty, DAFF, pers. comm.). Thus, 153 simulations were created for each cropping sequence. An irrigation input of 25 mm (85% efficiency) in the model was triggered when available soil water fraction in the top 100 cm layer dropped below 50%, 70% and 90% of fractional available soil water to 1 m depth, and no irrigation had been applied in the previous 7 days. These irrigation triggers mimicked the range of commercially feasible options to the potential irrigation requirement. Three rates of N fertiliser were chosen for the maize crop including 30, 100 and 260 kg N/ha, applied as urea, assuming that different farmers will vary these rates depending upon availability, response and soil fertility. The initial fertiliser basal input of 30 kg N/ha was common to all three fertiliser treatments. Of the remaining fertiliser in the 100 and 260 kg N/ha treatments, 6% was input at week 3 after sowing, 7% at week 4, 10% at week 5, 12% at week 6, 14% at week 7, 15% each at weeks 8 and 9, 12% at week 10, and the last 9% at week 11.

For these simulations, 16 weather files of synthetic daily climatic data consisting of maximum and minimum temperatures, radiation and rainfall for different climate projections from 1960 to 2010 were obtained from the Queensland Climate Change Centre of Excellence (QCCCE). These climate data for the climate-change scenarios were generated using the Coupled Model Intercomparison Research Program 3 (CMIP3) global model database (www-pcmdi.llnl.gov/ipcc/about_ipcc.php), OzClim (www.csiro.au/ozclim/home.do), UK Met Office/Hadley Centre (www.metoffice.gov.uk/climate-guide). Information about the methodology used in generating these data files is available from Bruget *et al.* (2012). For simulations, we used only four of the 17 available global climate models (GCM), including ECHAM5, GFDL 2.1 (worst), GFDL2.0 and MRIGCM232 (best), and two (A1FI and A2) of the eight available Special Report on Emissions Scenarios (SRES) projections for two timeframes including 2030 and 2050 (Parry 2007). The methodology used in generating these assumes no changes in the extent of variability in temperature and rainfall from the current climate. The emission scenarios and projection years, in addition to differing in temperature and rainfall, differed in CO_2 concentration. However, these were not considered for simulations because of lack of parameterisation in peanuts as well as an indication that adverse effects of high temperature in peanuts were not reversed by increased CO_2 concentration (Vara Prasad *et al*. 2003), and because maize does not respond to increased CO_2 concentration, being a C_4 plant. The baseline simulations were generated using actual daily weather files from 1960 to 2010 for the Katherine Research Station, available in the SILO database (www.longpaddock.qld.gov.au/silo/).

The output from the simulations included maize yield, peanut pod yield and irrigation requirement per season, cumulative (over the 50-year period) SOC, cumulative N losses from runoff and leaching, and cumulative GHG emissions. The methodology used in simulating these attributes was described in the APSIM documentation (Holzworth *et al*. 2014). The N losses were calculated in the runoff as described by Biggs *et al*. (2013) and as nitrous oxide gas by Thorburn *et al*. (2010).

Results

Climate

The average temperature during both wet (November–April) and dry (May–October) growing seasons was expected to increase under all climate projections considered in this investigation (Table 1). However, the magnitude of the temperature increase over the baseline temperature (current climate) could differ with the GCM, emission scenario and timeframe. By 2030, dry seasons could be 0.9°C to 1.2°C warmer under the A1FI scenario and 0.8°C to 1.1°C warmer under the A2 scenario. For this timeframe,

Table 1. Summary of average ambient temperature (°C) and rainfall (mm) in dry and wet seasons under different global climate models (GCM) projections at two Special Report on Emission Scenarios and two timeframes and respective differences with baseline (current) values

For all projections, projected global annual rises in temperature were 0.87°C and 1.81°C under A1FI and 0.79°C and 1.44°C under the A2 emission scenarios for 2030 and 2050 timeframes, respectively. For both emission scenarios and timeframes, the projected percentage change in annual rainfall per 1°C rise in temperature was 1.04% for ECHAM5, −12.89% for GFDL 2.0, −12.69% for GFDL2.1, and −2.68% for MRIGCM 232; Change in annual rainfall is per 1°C rise in temperature

GCM	Dry season					Wet season				
	Baseline	A1FI		A2		Baseline	A1FI		A2	
		2030	2050	2030	2050		2030	2050	2030	2050
Average seasonal temperature										
ECHAM5	24.4	25.4	26.6	25.3	26.1	29.5	30.7	32.0	30.6	31.4
Change (°C)		1.0	2.2	0.9	1.7		1.2	2.5	1.1	2.0
GFDL 2.0		25.2	26.3	25.2	25.9		30.6	31.8	30.5	31.3
Change (°C)		0.9	2.0	0.8	1.5		1.1	2.3	1.0	1.9
GFDL 2.1		25.2	26.2	25.1	25.8		30.8	32.3	30.7	31.7
Change (°C)		0.9	1.8	0.8	1.4		1.4	2.8	1.2	2.2
MRIGCM 232		25.5	27.0	25.4	26.4		30.5	31.6	30.4	31.2
Change (°C)		1.2	2.7	1.1	2.1		1.0	2.1	0.9	1.7
Average in-season rainfall										
ECHAM5	20	18	17	18	17	748	755	774	752	765
Change (%)		–11.0	–14.5	–10.4	–15.2		0.9	3.5	0.5	2.2
GFDL 2.0		13	11	13	12		678	615	684	640
Change (%)		–33.9	–42.3	–31.9	–40.8		–9.3	–17.8	–8.5	–14.4
GFDL 2.1		9	8	9	8		684	629	691	652
Change (%)		–54.5	–61.2	–52.8	–60.7		–8.5	–15.9	–7.6	–12.9
MRIGCM 232		16	16	17	15		735	729	735	730
Change (%)		–17.9	–19.4	–16.2	–25.1		–1.7	–2.6	–1.7	–2.4

wet seasons could be 1–1.2°C warmer under the A1FI scenario and 0.9–1.2°C warmer under the A2 scenario. By 2050, dry-season temperature could increase by 1.8–2.7°C under the A1FI scenario and by 1.4–2.1°C for the A2 scenario. For this timeframe, wet seasons could be warmer by 2.1–2.8°C under the A1FI scenario and 1.7–2.2°C under the A2 scenario. In the dry season, the largest increase in ambient temperature could occur in the MRIGCM232 and the smallest in the GFLD 2.1. In the wet season, the largest increase could occur under GFDL-2.1 and the smallest under MRIGCM232. These increases for the region were generally more than the average global anticipated increases in temperature (Table 1).

Compared with temperature, changes in rainfall in relation to temperature were predicted to be less consistent (Table 1). The dry-season rainfall in the current climate was low, which was typical of a semi-arid tropical climate, and was expected to decrease further under climate change under all scenarios. In the wet season, the overall average rainfall in all, except ECHAM5, was expected to decrease by 1.7–9.3% by 2030 and by 2.6–17.8% by 2050 under the A1FI scenario. Under the A2 scenario, the wet-season rainfall could decrease by 1.7–8.5% for the 2030 and by 2.4–14.4% for the 2050 timeframes. For both A1FI and A2, there could be a small increase in rainfall for the ECHAM5 GCM.

Crop productivity

The total yields of both maize and peanut under the highest level of fertiliser (260 kg/ha) applied to maize and the highest irrigation intensity to both crops were expected to decline under different warming scenarios (Fig. 2). The magnitude of decrease depended on the cropping sequence and projection. In the WMDP sequence under non-limiting N and irrigation, the increase in temperature was expected to decrease peanut pod yield by 3.2–11.6% and maize yield by 6.5–32.5% compared with the current climate. By contrast, in the WPDM sequence, change in peanut pod yield could range from a 1.9% increase to a 9.5% decrease, and maize yield could decrease by 6–18.9%. The relative advantage of the WPDM sequence, which was 41% (4.8 t/ha) more than under the current climatic conditions, was expected to increase to 53% (5.1 t/ha) under the climate combination of GFLD 2.1, A1FI and 2050 timeframe. The main advantages of the WPDM sequence were a nearly 2-fold higher yield of maize and the relative stability of peanut yield in the wet season compared with the other sequence.

The relationship between the extent of increase in temperature obtained under different projections (including SRES and the projection timeframe) and decrease in yield of both crops compared with the current climate was significantly negative for both seasons (Fig. 3). Irrespective of the season, for a given increase in temperature, the rate of decline in yield was greater for maize than for peanut. In addition, for a given increase in temperature, the rate of decline was greater in the wet season than the dry season. Although the relationship was highly significant in both cases, the relationship between temperature and yield of both crops was closer in the dry season (R^2 >0.97) than in the wet season (R^2 <0.88).

Productivity in both rotation sequences was also differentially influenced by irrigation levels and by fertiliser regimes of maize crops. Maize responded much more to application of N and irrigation in WPDM than in WMDP (Fig. 4). At all levels of irrigation and fertiliser, the baseline climate scenarios were generally the best, and because of interactions with irrigation

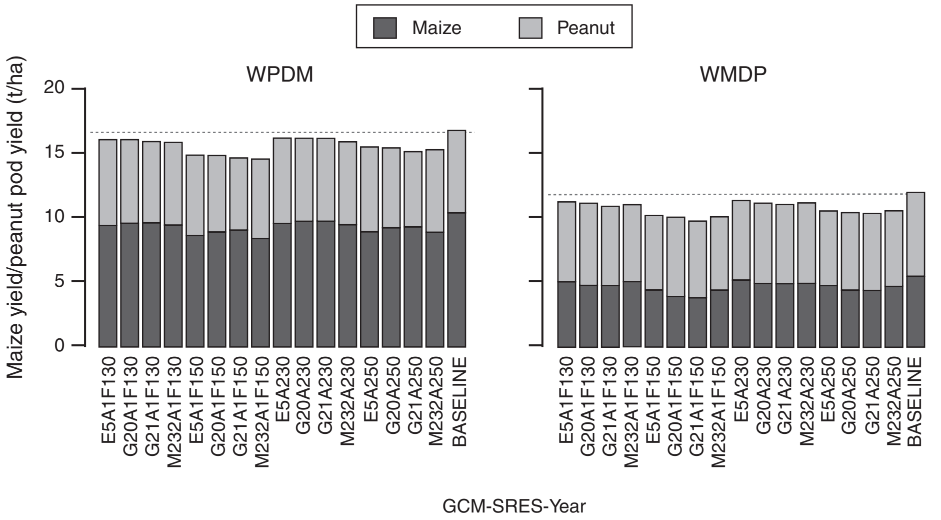

Fig. 2. Total potential yield of maize and peanut in wet-season peanut–dry-season maize (WPDM, left column) and wet-season maize–dry-season peanut (WMDP, right column) rotations simulated at four global climate model (GCM) projections and two Special Reports on Emission Scenarios (SRES), A1FI and A2, under 2030 and 2050 timeframes against the baseline scenarios (right-hand bars and dotted lines). Maize was grown with 260 kg N/ha and both crops were irrigated at 90% fractional available water. The GCM projections: E5, ECHM5; G20, GFLD-20; G21, GFDL-21; M232, MRIGCM232.

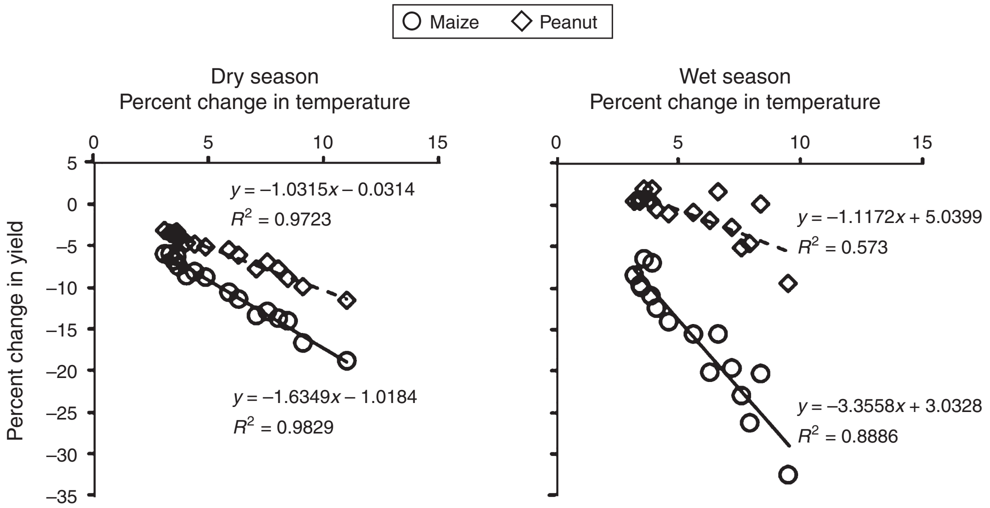

Fig. 3. Relative changes in yield of peanut and maize when grown either in dry or wet season in response to increases in mean ambient temperature caused by different projections, Special Report of Emission Scenarios and timeframes over the baseline ambient temperatures at Katherine. Decline in yield of maize was greater than of peanut, and for maize was greater in the wet season than the dry season.

and fertiliser, the difference between the projections widened in the WPDM sequence. Peanut also responded to irrigation in the dry season, but the interaction with climate projection was not as pronounced as for maize. However, for both crops in the dry season, the best response to irrigation was with the baseline scenario, and there were indications that the response was decreasing under different climate projections. For peanuts in the dry season, differences among the climate-change projections varied in a narrower range than with maize.

Irrigation requirement

The total irrigation requirement in the baseline scenarios was not affected by the type of cropping sequence (Fig. 5). In WPDM with warming, there was up to a 5% greater irrigation requirement by 2030, and an 11% increase by 2050. There was a difference in irrigation requirement of >1.5 ML/ha between the two rotations with the worst case climate-change scenario (A1F1–2050–G2.1). In WMDP, irrigation requirement, however, increased as the level of trigger increased from fractional available soil water 0.5 to 0.9

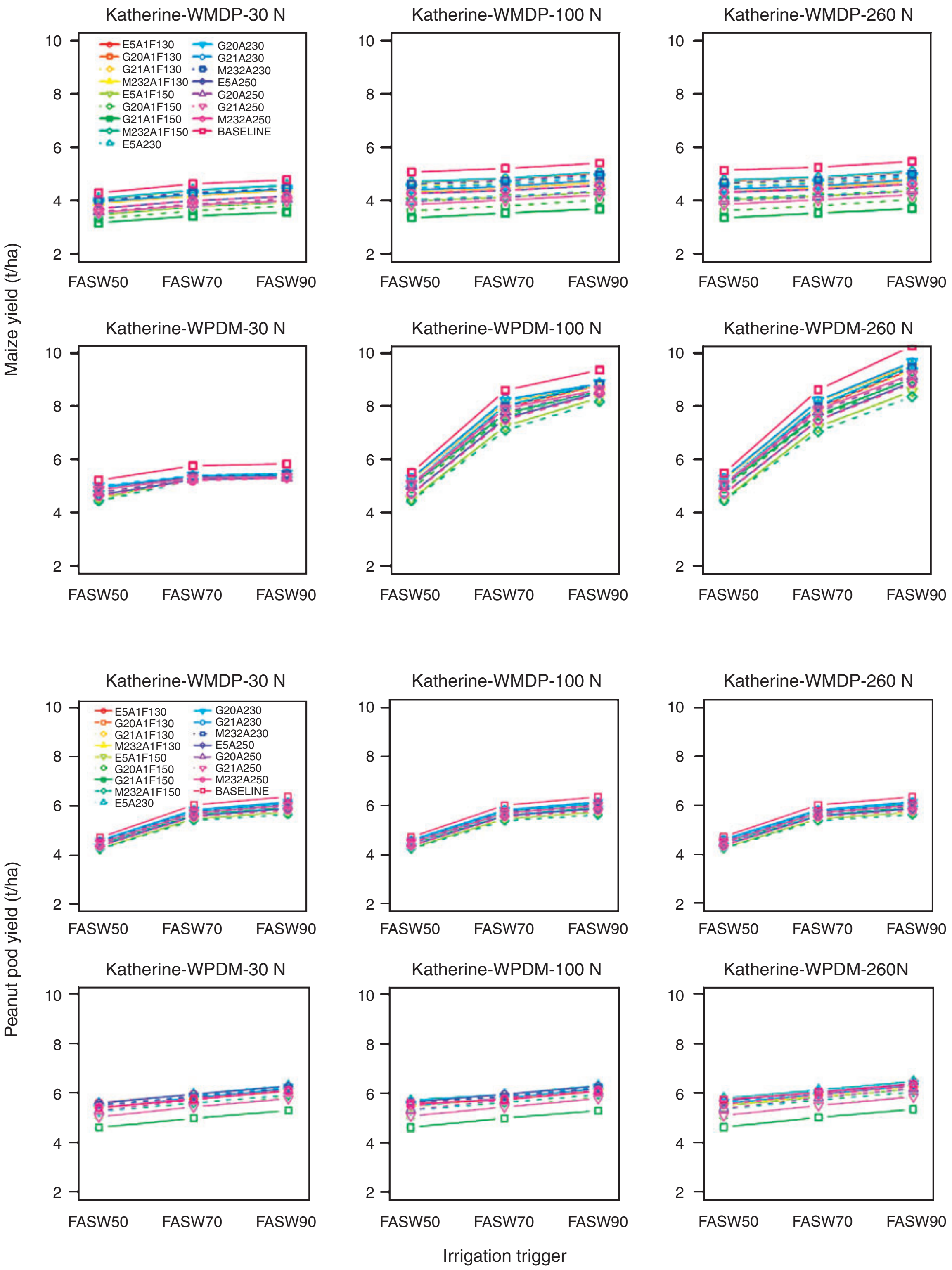

Fig. 4. Interaction plots of maize and peanut pod yield (t/ha) under different fertiliser and irrigation treatments for wet-season maize–dry-season peanut (WMDP) and wet-season peanut–dry-season maize (WPDM) at Katherine. See Table 1 for projection names included in the legend. FASW50, 70 and 90 are fractional available water at which irrigation was timed. Fertiliser levels are 30, 100 and 260 kg N/ha.

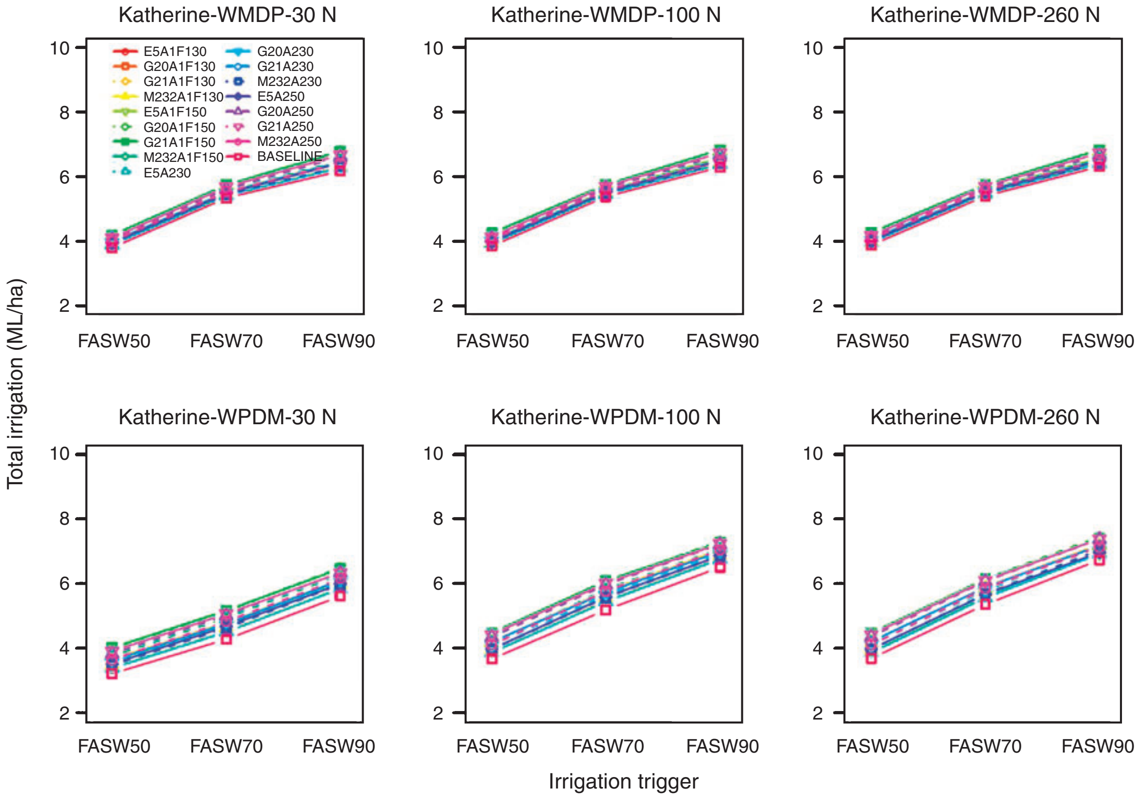

Fig. 5. Interaction plots of total annual irrigation requirement (ML/ha) under different fertiliser and irrigation treatments for wet-season maize–dry-season peanut (WMDP, upper row) and wet-season peanut–dry-season maize (WPDM, lower row) at Katherine. See Table 1 for projection names included in the figure legend.

under different climate-change scenarios, but no interaction effect was apparent for fertiliser levels.

Sustainability indicators

Total soil carbon

The difference in the total C content under the baseline scenario and the climate projections was far greater under the WPDM rotation, where total C accumulation was much more than under the WMDP rotation (Fig. 6). The increase under the baseline scenario was even more as levels of irrigation and fertiliser increased. Total soil C was lowest under the 2050 timeframe. By comparison, the extent of such interaction was less pronounced under the WMDP rotation. However, the total C content at all levels of irrigation and fertiliser under all climate scenarios was more in WPDM than WMDP.

Cumulative nitrogen leaching and runoff

Cumulative N leaching was slightly more under the WMDP rotation under all the projections (Fig. 7). Nitrogen leaching under WMDP increased with fertiliser application and, within a fertiliser–irrigation combination, tended to decrease under some climate projections. Nitrogen leaching also tended to decrease with irrigation under WPDM. However, N leaching was greater under several climate projections in the 2050 timeframe than in the baseline scenario.

Similarly, N lost via runoff was more pronounced under WMDP, compared with the small amounts of N lost via runoff under WPDM (Fig. 7). In the WMDP rotation, the effect of warming on N in runoff was more pronounced than in WPDM. There was also an obvious effect of fertiliser application and climate-change projections on N runoff in the WMDP rotation, whereas no such effect was obvious in WPDM.

Cumulative greenhouse gas emissions

Under all of the projections, cumulative GHG (nitrous oxide) emissions were greater under the WMDP rotation than the WPDM rotation (Fig. 8). In both rotations, GHG emissions tended to increase interactively with irrigation and fertiliser levels. The projected effect of climate change was less obvious at lower levels of irrigation and fertiliser, although the differences with the baseline scenario became more obvious as the N level increased, especially in WPDM. However, the level of emissions in this sequence was still far less than that for WMDP.

Discussion

Australian agriculture has achieved considerable resilience to climatic variability by appropriately locating its various industries (Crimp *et al*. 2008). However, it is not known whether these industries will need to be relocated to remain resilient in response to the warmer climates anticipated during this century (Rosenzweig *et al*. 2001; Bruget *et al*. 2012). The attempted

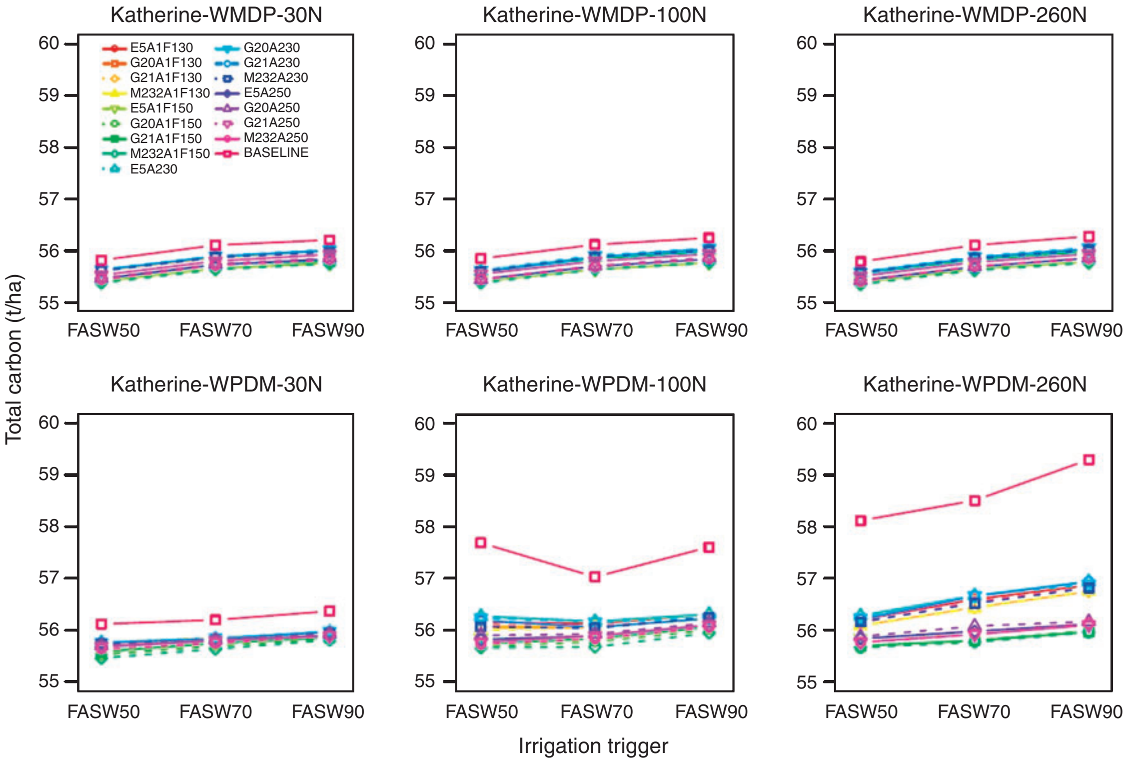

Fig. 6. Interaction plots of soil carbon (t/ha) content under different fertiliser and irrigation treatments for wet-season maize–dry-season peanut (WMDP, upper row) and wet-season peanut–dry-season maize (WPDM, lower row) at Katherine. See Table 1 for projection names.

expansion of the Australian peanut industry at Katherine was an interesting example of an industry trying to avoid the impact of climate change in the traditional production region (Chauhan 2010). A similar transformation by another peanut industry has taken place in the USA, where peanut production was moving from warmer southern Texas to cooler western Texas (Backlund *et al*. 2008) to avoid climate-related complications. In contrast to this USA example, the Australian peanut industry targeted a move to a warmer region, which may warm further under projected climate change. In this study, we analysed the range of benefits and risks that could occur from the expansion of peanut and maize, the two major tropical crops into the Australian tropics, and the possible impacts of climate change. These are summarised below.

Peanut and maize productivity would depend on crop rotations and the extent of climate change

The average temperature at Katherine during the dry season was ~24°C and during the wet seasons 29°C, which was 1.7–2.5°C higher than average ambient temperature during the summer season when peanuts and maize are grown in traditional production regions. The higher ambient temperatures in the tropical region of Australia in both dry and wet seasons was seen as an advantage by the Australian peanut industry, because it would make possible growth of two crops per year, allowing the opportunity to double the cropping intensity (Chauhan 2010). Higher temperature was also expected to allow the growing of peanuts in the dry season in the new region to keep the peanut-processing plants running in summer, when supplies from other producing regions were not available. The double-cropping strategy was difficult to implement in subtropical or cooler regions, where cultivation was largely limited to one crop per year owing to low ambient temperatures including occurrences of killing frost events, as well as the lack of irrigation. Although two peanut crops were possible in a year in the tropical climate of Katherine, the inclusion of maize was considered necessary as a break crop given the potential development of soilborne root and shoot diseases associated with continuous peanut cultivation (Bell *et al*. 2003).

Our simulation results showed that up to 16.8 t/ha could be harvested from two crops on an annual basis at Katherine. Realisation of such yield increases could offer a real incentive to moving agriculture into the northern tropics and could contribute to the target of doubling food production by 2050, when the world’s human population is expected increase to ~9 billion (Tilman *et al*. 2011; Ray *et al*. 2013).

However, such yield benefits may be difficult to realise in future warmer climates. The optimum temperature for reproductive development is 22−26°C for peanuts (Vara Prasad *et al*. 2003) and 18−22°C for maize (Muchow *et al*. 1990). For each 1°C rise in temperature beyond the optimum, peanut yield was expected to decline by ~6% and maize yield by ~8% (Lobell and Field 2007; Backlund *et al*. 2008; Schlenker and Roberts 2009). Consistent with these studies, our simulations also suggested that the yield of both crops could decrease because of climate

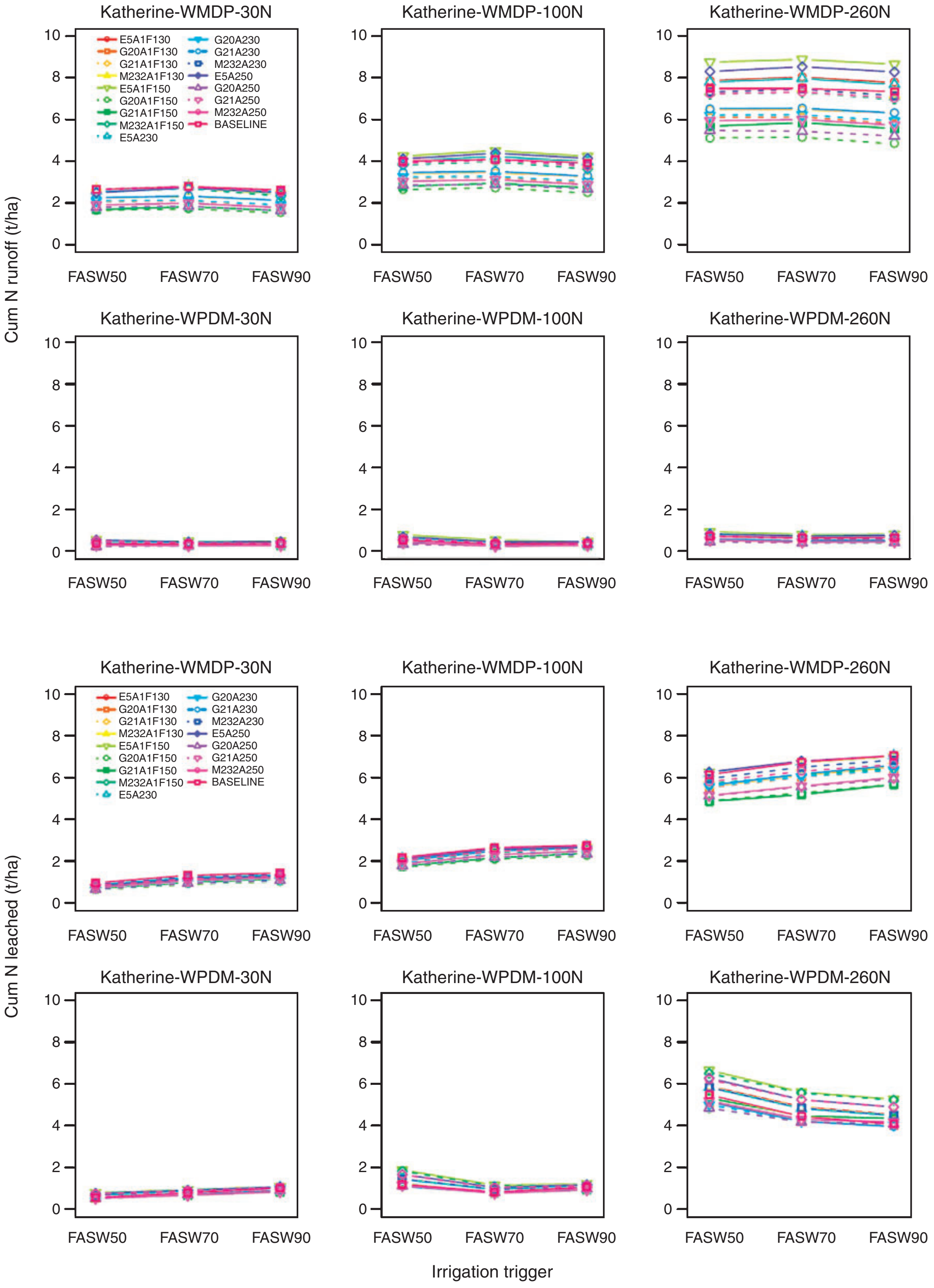

Fig. 7. Interaction plots of cumulative nitrogen lost via leaching and runoff (t/ha) under different fertiliser and irrigation treatments for wet-season maize–dry-season peanut (WMDP, upper row) and wet-season peanut–dry-season maize (WPDM, lower row) at Katherine. See Table 1 for projection names.

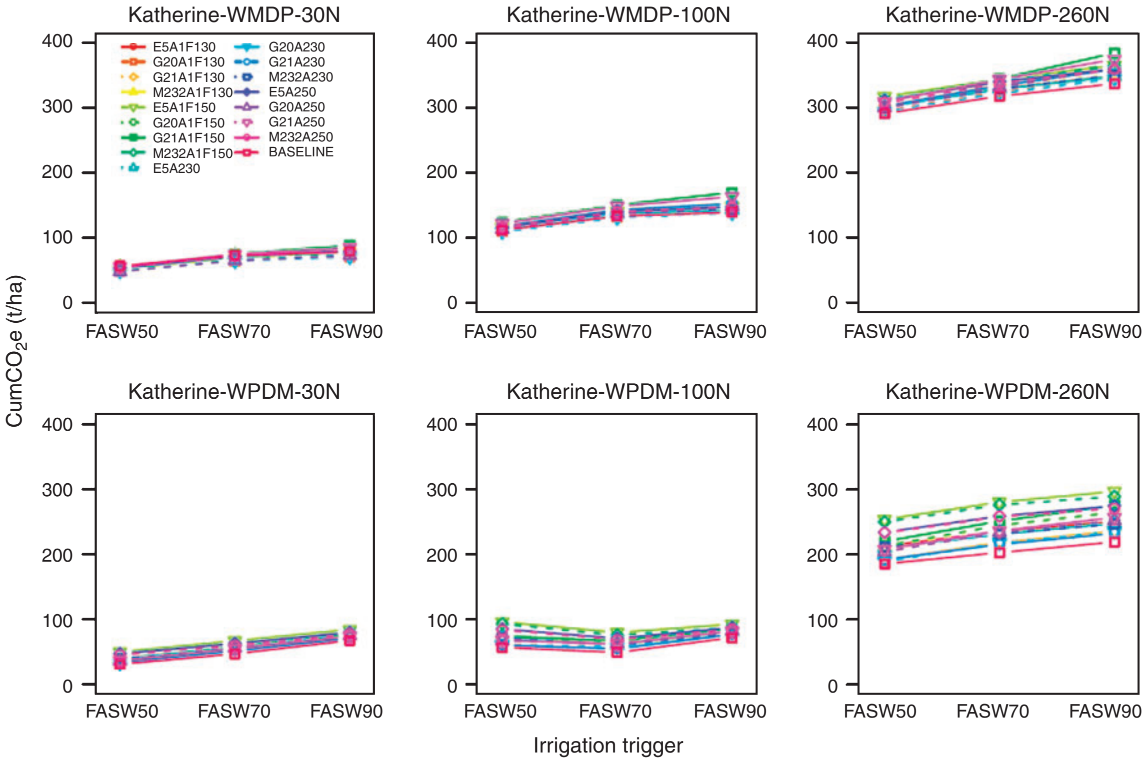

Fig. 8. Interaction plots of nitrous oxide emissions expressed as CO_2-equivalents ($\mathrm{CumCO_2e}$) (t/ha) under different fertiliser and irrigation treatments for wet-season maize–dry-season peanut (WMDP, upper row) and wet-season peanut–dry-season maize (WPDM, lower row) at Katherine. See Table 1 for projection names.

change. However, the decrease could be proportionately greater in maize than peanuts owing to differences in sensitivity to higher temperatures (Figs 3 and 4). Hence, breeding programs for both crops will need to take into consideration the likelihood of warmer growing conditions in the future. Varietal differences in adaptation to high temperatures have been documented in these crops, but there are few examples where this trait has been genetically enhanced in a suitable agronomic background (Wahid *et al*. 2007).

Differences in the sensitivity to high temperature of the two crops could also have implications for determining optimal cropping sequences to be followed in both current and future (warmer) climatic regimes. In our simulations, pod yield of peanut under the current climate was ~6.3 t/ha in both seasons, and yield of maize ~5.4 t/ha in the wet season and 10.3 t/ha in the dry season. The total productivity per year of peanut and maize crops at Katherine was ~41% more in the WMDP rotation than the WPDM sequence (Fig. 3). The relative advantage of WPDM over WMDP was expected to increase under climate change projections, although the overall yield levels may decrease. This suggests that cultivation of maize in the wet season and peanut in the dry season, which was the preferred rotation for the industry, may not be the best rotation in both current and future climates. These results also suggest that, with the projected warming due to climate change in the tropics, there should be a greater focus on including crops that are more sensitive to high temperatures (e.g. maize) in cooler periods of the year where such opportunities exist.

Responses of maize to fertiliser and irrigation depended whether it was grown in the wet or dry season. Maize responded much more to N application and irrigation in the dry season than in the wet season (Fig. 4). Controlled soil moisture regime and better growth in the dry season, combined with split applications of N, was expected to enable N to be primarily used for dry matter and yield production. Whereas in the wet season, some of the applied N would be lost due to runoff, leaching caused by excessive rains (Fig. 7) and de-nitrification (Fig. 8). This suggests that under warmer and wetter environments, maize will not be able to make efficient use of irrigation and fertiliser inputs. Peanut grown in the wet season appeared less sensitive to such limitations (Fig. 4). Further, wet seasons run the risk of cyclones, which could cause lodging in maize but might have little effect on peanuts, and this may further justify inclusion of peanuts in the wet season.

In the future warmer climates in the tropics, different crops may also lead to different sets of pests and diseases. Because the APSIM model cannot simulate the indirect effects of biotic constraints, these were ignored in the present study. In any case, under intensive management, it is expected that pests and diseases will be better managed. In addition, non-climate impacts related to CO_2 fertilisation were not considered in this study. There is considerable uncertainty with respect to these effects given that some studies project a decrease in CO_2 emissions, and others argue that crop responses to elevated CO_2 may be less than previously thought, thus complicating the modelling of these effects (Gornall *et al*. 2010). Extreme weather events including rainfall and temperature may also increase, which have not been modelled in this study.

Irrigation requirement in northern regions will increase with climate change

Adaptive transformation to the tropical climate of Katherine investigated in this study was essentially based on the premise that the new regions where irrigation would be available could provide insurance against warmer temperature and lack of rainfall for extended periods. Double cropping with two tropical crops in the semi-arid tropical environments could be possible only if sufficient water was available for irrigation. At Katherine, the total irrigation requirement in the baseline scenarios (current climatic conditions) was not affected by the type of crop rotation (Fig. 5). The projected increase of up to 11% in the irrigation demand under WPDM was comparable to an average increase of up to 11.2% predicted for Oceania for the 2070 timeframe (Döll 2002). Such increases occurred despite the fact that, with a rise in temperature, the growing duration may become shorter as the required heat units are accumulated more quickly (Backlund *et al*. 2008). This is probably the major negative aspect of the WPDM rotation identified in our simulations and can be attributed to the rise in temperature during the dry season when maize would be grown, thus leading to an obvious increase in the irrigation frequency and amount.

If irrigation requirement did increase with climate change, changes in irrigation practices to improve irrigation water-use efficiency, or through the adoption of more water-use-efficient early-maturing hybrids, will be needed to reduce the irrigation water requirement. The use of irrigation-scheduling programs, such as those designed for peanuts (Chauhan *et al*. 2013) and maize (Payero *et al*. 2011), and the use of shorter maturing varieties, could assist in more efficient use of irrigation water.

Sustainability of production in the Katherine environment will decrease under climate change

Soil carbon stocks will decline

Increasing soil C sequestration is critical not only to reduce CO_2 present in the atmosphere, but also to increase sustainability of agriculture because soil C is a repository of many nutrients, including N, and improves soil water-holding capacity. SOC in most agricultural soils in the tropics is low and declining, requiring ameliorative practices such as crop intensification to arrest this decline, especially in a changing climate (Lal 2004). With intensification examined in this simulation study, it was found that growing two crops per year can increase SOC irrespective of rotation. The increase appears to be more under the WPDM rotation. Our simulations for different climate projections also suggest that the benefit of crop intensification to increase SOC levels may decline with climate warming (Fig. 6). The negative effect of climate change on soil C increase was greater in the WPDM rotation than the WMDP rotation, but did not dent the overall superiority of the WPDM rotation (Fig. 6).

Nitrogen runoff and leaching could decrease if rainfall also decreases

Up to 89% of the N applied to crops can be lost (Peoples *et al*. 1995). Losses of N via runoff and leaching pollute the environment and eventually contribute to GHG emissions upon denitrification (Galloway *et al*. 2008). It was a major concern for expanding agriculture in the northern region (Biggs *et al*. 2013). At Katherine, losses of N via leaching were predicted to be greater in the WMDP rotation than the WPDM rotation, especially as increased amounts of N and irrigation were applied (Fig. 7). These losses tended to decrease in WPDM under some climate projections. At higher levels of N application (100 and 260 kg/ha), N leaching was somewhat reduced with increasing irrigation intensity under WPDM, but increased under WMDP. This may be because increased frequency of irrigation may be supporting greater N uptake to meet the increased crop N need.

Nitrogen losses due to runoff were also more pronounced under the WMDP rotation, mainly because it was applied to maize grown in the wet season when uncontrolled rainfall is expected to cause some N to be lost due to this process. For this reason, growing maize in the wet season was undesirable. This suggested that a more moderate, seasonal-demand-based N application regime would need to be implemented as has been suggested recently for sugarcane systems by Thorburn *et al*. (2011) in order to reduce such losses. The inconsistent effects of climate projections on N losses may also be related to differences in rainfall, which under some projections increased.

Greenhouse gas emission will increase

The role of agricultural practices in mitigating climate change by reducing GHG emissions has been recognised (Smith *et al*. 2008; Young *et al*. 2009). It is expected that transformational adaptation in the quest to increase the resilience of crops to climate change should not itself contribute to the climate-change footprint. Consistent with this requirement, and irrespective of climate change, we found that the WPDM crop sequence had up to 50% less nitrous oxide emissions than the WMDP rotation, especially as N application rates increased (Fig. 8). The simulated values of nitrous oxide emissions were within the potential range for warm dry and wet regions (Smith *et al*. 2008). Differences in the nitrous oxide emissions between the different climate projections were large, and all climate-change projections indicated an increase in nitrous oxide emissions. However, the overall cumulative amount over the 50-year period of simulation was much less even with the worst climate scenario in WPDM rotation, indicating the overall superiority of this rotation under both current and future climates.

Conclusions

The results of this simulation study suggest that the new area in the tropics, where the Australian peanut industry is planning to expand to avoid adverse climate impacts on cropping industries in the traditional production regions, seems to have a high yield potential. It was also suggested that climate change might pose a few difficulties in realising this potential and reduce sustainability of such expansion. By using the example of the wet-season peanut and dry-season maize rotation compared with industry-preferred sequence of dry-season peanut and wet-season maize, it is shown that the adverse impacts of climate change on both yield and sustainability can be minimised by choosing appropriate crop rotations. Given that this fast-paced society is unforgiving for making tactical errors with substantial financial implications (Marshall *et al*. 2014), this study highlights what can be achieved if prior assessment is made before embarking on such a transformation. Clearly, there is a role for modelling research in assessing the potential of the new alternative approaches. This will become increasingly important to inform various industries about how such transformational strategies could be made more effective. The results will need to be verified in the field in long-term experiments designed to study these effects.

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