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Modelling the impacts of diverse cover crops on soil water and nitrogen and cash crop yields in a sub-tropical dryland

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ABSTRACT

Understanding the implications of replacing fallows with cover crops on plant-available water (PAW) and soil mineral nitrogen (N) and their carry-over effects on subsequent cash crops is critical for understanding their potential for ecological intensification in water-limited environments. We modelled the impacts of different cover crop functional types over historical climate to predict how climate variability influences soil water and N acquisition and subsequent availability to a maize crop in a dryland farming system of subtropical Australia. Following local validation of simulation models (APSIM) with 3-site-years of field data, 70 years of crop-fallow rotations were simulated comparing conventional fallow against a diverse range of cover crops comprising monocultures and mixtures of grass vs. legume vs. brassica. Cover crops consistently reduced soil water and mineral N at maize sowing compared to conventional fallow. In dry to normal precipitation years, this induced a maize yield penalty of up to − 18% relative to fallow, primarily due to reduced water availability. In wet years, increased in maize grain yield (+4%) was predicted following legume and grass-associated cover crop mixtures with concomitant reductions in N leaching and soil surface runoff of up to 40%. Cash crop yields following grass-cover crops were more stable and carried lower downside risks; multi-species (grass-legume-brassica) cover crop mixtures carried higher yield penalties and greater downside risks due to high biomass accumulation and high soil water extraction. These long-term predictions in water-limited environments indicate that increasing cover crop complexity by using mixtures with diverse functional traits can lead to a greater risk of yield losses and increased yield instability unless they are managed differently to monoculture cover crops. Therefore, for successful integration of cover crops into dryland agroecosystems, cover crops should be considered as a flexible choice grown under favourable precipitation and economic scenarios rather than for continuous fallow replacement.

1. Introduction

Dryland cropping systems are characterized by lengthy and repeated fallows – periods when a paddock is left out of production to recharge soil water and nitrogen – with the aim of stabilizing future crop yields and reducing crop failure risk (Cann et al., 2020; Reiss and Drinkwater, 2022; Verburg et al., 2012; Zeleke, 2017). Such fallows have been reported to have low fallow efficiency and can increase risks of soil N losses (Garba et al., 2022a; Mesbah et al., 2019; Reiss and Drinkwater, 2022; Wunsch et al., 2017). Furthermore, fallow periods have also been linked to soil organic matter (SOM) decline, thus adversely affecting soil fertility and the long-term resilience and sustainability of dryland cropping systems (Ghimire et al., 2018; Restovich et al., 2019; Schillinger et al., 2010; Williams et al., 2022).

Recent literature has shown that ecological intensification practices that reduce the length of fallow periods have the potential to foster crop yield stability and address problems associated with repeated and lengthy fallows, i.e., with SOM loss and soil fertility decline (Garba et al.,

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2022a; Gaudin et al., 2015; Williams et al., 2022; Williams and Bell, 2019). Cover cropping – growing non-harvested crops outside the main growing season – has frequently been used in agroecosystems around the world to build soil health, reduce soil erosion and nutrient losses, and develop more resilient and sustainable farming systems (Daryanto et al., 2018; Ghimire et al., 2018; Mitchell et al., 2017; O'Connell et al., 2014; Wittwer et al., 2017; Yang et al., 2019). Intensification of crop-fallow rotations with cover crops has been shown to improve soil water conservation (Daryanto et al., 2018; Lyon et al., 2007; Wunsch et al., 2017), nitrogen (N) supply and retention (Finney et al., 2016; White et al., 2017), cash crop productivity (Basche et al., 2016; Eash et al., 2021; Malone et al., 2022; Toler et al., 2019) and long-term soil carbon sequestration (Bommarco et al., 2013; Cates et al., 2019; Plaza-Bonilla et al., 2016; Poeplau and Don, 2015).

While cover crops have the potential to provide a wide range of ecosystem services, their adoption in water-limited environments has been constrained by perceived ecosystem disservices associated with soil water and N reduction, high management costs, and potential yield penalties on subsequent cash crops (Daryanto et al., 2019; Ghimire et al., 2018; Rose et al., 2022). In addition, dryland cropping systems are often opportunistic, and the risks and economics associated with precipitation expectations and soil water storage dictate cropping decisions (Farooq and Siddique, 2017). Furthermore, decisions are made more complex by seasonal and inter-annual variability in precipitation, underlying soil biophysical properties, and interactions with crop management histories that together make it difficult to predict cash crop yield responses (Alonso-Ayuso et al., 2018; Verburg et al., 2012).

The dryland cropping system of Northern Grains Regions of Australia (NGR) has high crop diversity offering wide range of crop types (legumes vs. cereals vs. oil seeds), growing seasons (winter vs summer) and cropping intensities (Hochman et al., 2021, 2020). The extent of winter of summer fallows in the region has high temporal and spatial variability. A recent study by (Zhao et al., 2020) estimated the extent of winter fallows in the NGR in range between 50% in 2017 winter (3.3 million ha) and 85% in 2019 winter (5.6 million ha). Wheat, barley, chickpea and canola are the dominant winter crops while sorghum, mungbean, maize and cotton dominated in the summer (https://www.aegic.org.au/australian-grain-production-a-snapshot/). However, the often low winter rainfall and highly unpredictable summer rainfall necessitated the need for short summer/winter fallows (6–8 months) or long fallows (14–16 months) to accumulate soil water for the main crop and reduce risk of crop failure (Hochman et al., 2020; Whish et al., 2009; Wunsch et al., 2017; Zeleke, 2017). Recent studies have shown that the minimal or lack of groundcover in conventional fallow increases rainfall runoff, thus increasing risk of erosion, decreased fallow efficiency and subsequent cash crop yields (Erbacher et al., 2020; Thomas et al., 2018; Wunsch et al., 2017). Studies have shown cover crops can be sown instead of conventional fallow to provide additional groundcover and to mitigate some of the limitations of conventional fallow in the dryland cropping system of NGR.

A key step in establishing the viability of planting cover crops in dryland cropping systems of NGR is to understand the balance between soil water and N, and the risks for subsequent cash crop yields. In addition, increasing cropping complexity with cover crops could increase subsequent cash crop sensitivity to changes in soil water and N availability, altering temporal yield variability and stability patterns that limit cover crop adoption. In the NGR, the potential of cover crop to replace part of fallow period when rotating from summer to winter crop phase can address both fallow soil water and mineral N challenges associated with conventional fallows. Previous stidues in this region have focused on evaluating efficacy of cover crops in winter wheat-fallow rotation (e.g Whish et al., 2009; Wunsch et al., 2017). Studies on efficacy of diverse winter cover crops are limited and no previous work has evelauted the legacy effects of diverse winter cover crop choice on summer maize crop in the subtropical NGR.

Furthermore previous studies that explored how cover crops impact the risk of soil water and N depletion in a crop sequence in subtropical dryland agroecosystems generally only considered a single cover crop type or monocultures. A given cover crop species can only provide a limited subset of ecosystem services based on their functional traits attributed to species- or genus-specific taxonomic groups. In addition, growing a single cover crop species often leads to ecosystem service trade-offs. For example, grass cover crops often have high biomass production with a high C:N ratio that provides persistent ground cover, but can also have higher water and nitrogen use that potentially diminishes the benefit to subsequent crops. Recent evidence has shown that using mixtures of cover crops with different phenology and divergent resource acquisition and use strategies could enhance the multifunctional provision of different ecosystem services and could mitigate these potential trade-offs (Garba et al., 2022b; Holman et al., 2021). However, there is a need for further study on which cover crop combinations (grass vs. legume vs. brassica) minimize these trade-offs, i.e., that optimize fallow soil water and mineral N fallow management and improve subsequent crop yield and stability.

To undertake such research empirically would require many field experiments run over many years to capture the diversity of climatic conditions across multiple growing seasons. One option to overcome this costly and resource-intensive approach is to extrapolate from short-term experiments and account for climate variability using process-based simulation models (Basche et al., 2016). The Agricultural Production Systems sIMulator (APSIM) is a modular cropping systems model capable of simulating the various biophysical processes influenced by cover crops in farming systems (Holzworth et al., 2014; Keating et al., 2003). APSIM has been used extensively to determine the ecological outcomes of crop management decisions and to define strategies for crop production, improve risk management (Chauhan and Ryan, 2020; Chen et al., 2020), improve cropping system sustainability (Eyre et al., 2019; Hochman et al., 2021; Rodriguez and Voil, 2019), and to asses climate change impacts (Pembleton et al., 2016; Zhao et al., 2022).

We coupled field experiments with the APSIM modelling framework to explore how long-term integration of cover crops with differing functional traits into a conventional crop-fallow rotation alters fallow soil water and N dynamics and their legacy impacts on subsequent cash crop outcomes. Understanding soil water, N, and potential production risks associated with cover crops can provide clarity for growers on the potential benefits and pitfalls of integrating cover crops into dryland cropping systems. This also supports efforts toward designing useful crop rotation systems that can improve the resilience and adaptive capacity of dryland cropping systems under increasing climate variability. Specifically, our study aimed to answer the following questions (i) do cover crop effects on fallow soil water and N management vary with cover crop functional type and initial soil conditions at cover crop sowing? (ii) what are the legacy impacts of cover crops on subsequent maize yields relative to conventional fallow? (iii) under what conditions are cover crops most likely to cause crop yield reductions relative to conventional fallow, and (iv) which cover crops minimize downside risk and maintain stable yield along a precipitation gradient?

2. Materials and method

2.1. Site description and experimental design

Field experiments were conducted on self-mulching vertosol soils at The University of Queensland, Gatton campus (27.545°S; 152.340°E) at two locations (Mendel and T-block) over two years (2020/21 and 2021/22). A full description of soil physical and chemical properties is provided by Garba et al. (2022b). Plant-available water-holding capacity at these sites averaged 200 mm to a depth of 120 cm (Table S1). Gatton has a subtropical climate with an average (1950–2020) annual precipitation of 766 mm. At one location, experiments were conducted over two consecutive winter (March to October) and summer (November to February) crop seasons spanning 2020/2021 and 2021/2022 (Fig. 1); at

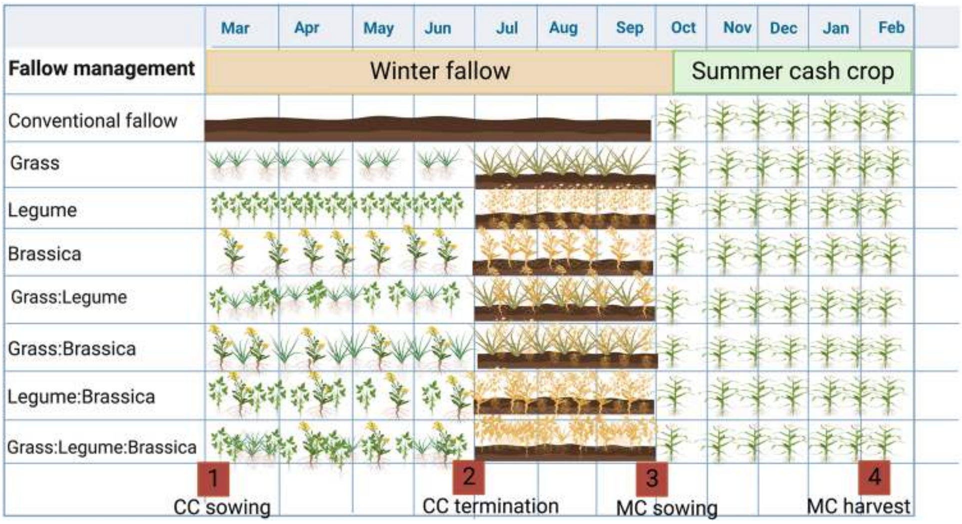

Fig. 1. Typified annual crop-fallow/cover crop modalities showing the different cover crop sowing proportions as % of the recommended seeding rates. The yellow square showed the soil sampling for soil water and mineral N.

the other location, the experiment was conducted once over winter-summer 2020/2021. Thus, the experiments provided a total of three site-years of data over a winter cover crop/fallow and the following cereal maize crop. Each site included eight experimental treatments (Table 1) on 8 m × 5 m plots. The cover crop species used included a grass (forage oat - *Avena sativa* L, cv. Comet); a legume (common vetch (*Vicia sativa* subsp. *sativa* L.) in Year 1 and fababean (*Vicia faba* L., cv. Nasma) in Year 2; and a brassica (forage rape - *Brassica napus* L, cv. Greenland SF). The trial was laid out in a randomized complete block design with four replications in two locations at Gatton. The treatment comprised: 1) a conventional fallow as control, three cover crop monocultures: 2) 100% grass, 3) 100% legume, 4) 100% brassica, three two species mixtures: 5) 50% grass + 50% legume, 6) 50% grass + 50% brassica, 7) 50% legume + 50% brassica), and a three-species mixture 8) 33% grass:33% legume: 33% brassica.The sowing proportions of each species were applied as an adjustment to the standard (100% monoculture) sowing rates of 40 kg seeds ha^{-1} forage oat, 4 kg seeds ha^{-1} forage rape, and 200 kg seeds ha^{-1} fababean (Fig. 1). A 30 kg ha^{-1} application of Granulock Z (11% N, 21.8% P, 4% S, and 1% Zn) fertilizer (Incitec Pivot Fertilizers, Melbourne) was incorporated before cover crop sowing. Cover crops were direct-drilled at 35 cm row spacing and grown until Zadoks growth stage (GS-32) and were terminated with glyphosate. Conventional fallow plots were kept weed free with glyphosate Cover crop residues were left on the soil surface and plots were maintained as chemical fallows until cash crop sowing. Maize (*Zea mays* L.) and mungbean (*Vigna radiata* (L.) R. Wilczek) were planted as the summer cash crops in 2020/2021 and 2021/2022, respectively. Maize was sown at 5.6 plants m^{-2} on 81 cm row spacing while mungbean was sown at 30 plants m^{-2} on 50 cm row spacing. Details of the field conditions and study sites are provided in Garba et al. (2022b).

Table 1
Statistical measures of model performance at predicting a range of soil, cover crop, and cash crop parameters over 3 different experimental years. Root mean squared error (RMSE), coefficient of determination (R^2), index of aggregation (*d*-index), and mean bias (MB) between measured and simulated values.

Measurements	*N*	*RMSE*	Validation statistics		
			R^2	*d*-index	*MB*
Soil conditions					
PAW (mm)	56	16.81	0.91	0.86	-0.21
soil mineral N (kg N ha^{-1})	40	25.47	0.81	0.76	0.23
Cover crop					
Aboveground biomass (kg DM ha^{-1})	18	503.6	0.83	0.87	-45.0
Leaf area index (LAI)	72	1.08	0.78	0.56	-0.87
Total N uptake (kg N ha^{-1})	14	37.9	0.76	0.63	-26.9
Biomass C/N ratio	14	2.8	0.69	0.07	2.6
Cash crop					
Grain N uptake (kg N ha^{-1})	16	21.63	0.67	0.51	13.2
Grain yield (kg ha^{-1})	16	539.21	0.99	0.93	-164.6
Aboveground biomass (kg N ha^{-1})	16	1105.26	0.98	0.89	-845.8

2.2. Field soil and plant measurement

Soil samples were taken at cover crop sowing, cover crop termination, cash crop sowing, and cash crop harvest in each year (Fig. 1). At each sampling, three cores (43 mm diameter) to a depth of 120 cm were taken and sectioned into five depth increments (0–10 cm, 10–30 cm, 30–60 cm, 60–90 cm, and 90–120 cm) for the determination of soil water and mineral N. Baseline soil characteristics including bulk density, organic carbon (Walkey-black), pH (in $CaCl_2$), and electrical conductivity using an electrode, Colwell P and K, available N (NH_4^+–N + NO_3–N), drained upper limit (DUL) and lower limit (LL15) were determined on 11core samples before the establishment of the experiments. Crop samples were collected from a 1 m^2 quadrat from the four middle rows of each plot at cover crop termination. Cover crop biomass was partitioned into the different crop types and oven-dried at 65 ^{o}C until constant weight to determine total dry matter production. A sub-sample of the dried materials was ground in a Retsch ZM 200 centrifugal mill through a 2 mm sieve. The ground samples were analyzed for total N and C by Dumas combustion and analyzed in a LECO C-N analyzer (CN 928 Series, LECO Corporation, The Netherlands) (Rayment et al., 2011). In each year, cash crop was harvested at physiological maturity, and yield and yield components were measured from a 4 m^2 quadrat. The details of the soil water, mineral N, and cash crop parameters used for model evaluation have been described in Garba and Williams (2023a, 2023b).

2.3. APSIM model configuration protocol

The released version (v. 7.10-r4218) of APSIM was used to simulate the various crop-fallow rotations (outlined above). This modelling framework represents the response of underlying physiological and biophysical processes of different crops to weather inputs and management decisions to simulate crop growth, soil water, nutrient use, accumulation, and surface organic matter decomposition. APSIM was configured using data collected at the experimental sites describing the soil, weather, and crop management. Soil parameter values were based on site-specific measurements provided in Table S1. The soil water and N modules (Probert et al., 1998) in APSIM were used to describe soil water and solute (nitrate) characteristics and movement within the soil focusing on DUL, LL15, SAT, and initial soil water. The soil water module is a cascading water balance model that simulates daily runoff, drainage, soil evaporation, the saturated and unsaturated flow of water, and associated solute fluxes. The fate of crop residues was simulated using the surface organic matter (SURFACEOM) module that describes addition, removal, incorporation, in-situ residue decomposition, as well as soil cover. We set the initial residue load to wheat stubble at 1000 kg ha^{-1} with C:N ratio of 80:1 of which 10% was still standing. The soil water module implements the effects of crop and residue cover on infiltration as well as effects on soil evaporation and runoff (Probert et al., 1998). Soil carbon balance was simulated with the SoilN module that describes mineralization, nitrification, and denitrification processes in the soil, crop residues, and subsequent supply for plant uptake. Partitioning soil carbon into active and passive organic pools followed the procedure described in Dalgliesh et al. (2016).

Daily weather data (rainfall, minimum and maximum temperatures, and solar radiation) was obtained from the SILO climate database (https://www.longpaddock.qld.gov.au/silo/) (Jeffrey et al., 2001) from Bureau of Meteorology station No. 040082, located $<$ 1 km from both experimental sites. After the initial model configuration, subsequent steps involved a comparison of predicted with observed crop growth variables such as phenology, aboveground biomass, N uptake, and final biomass and grain yields. Cover crops and cash crops were simulated with their corresponding crop modules. The oat cover crop was simulated using the OATS module (cv. 'Mitika') (Peake et al., 2008). The APSIM-Field pea module was used to simulate the common vetch in year 1 and the FABABEAN module (cv. 'Fiord') was used to simulate the fababean cover crop (Turpin et al., 2003). The observed aboveground biomass, N uptake, and leaf area index (LAI) for common vetch Year 1 were particularly low due to the inferior performance of the common vetch. Therefore, we used fababean instead in the second experimental year and for the long-term simulation. The CANOLA module (Robertson and Lilley, 2016) was used as a reference module to simulate the forage rape cover crop based on the cultivar-specific parameter for "Winfred rape" described in Watt et al. (2022). No modifications were made to the cultivar-specific parameters given the base values were sufficient to replicate most field measurements. We used reference cultivar Pioneer_39G12 to simulate the maize cash crop (cv. PAC 606-IT) while second-year mungbean (cv. Celera) was simulated with the MUNGBEAN module (cv. Emerald) (Robertson et al., 2002).

The cover crop mixtures were simulated as intercrops using the APSIM-CANOPY module (Keating et al., 2003) within APSIM which allows for resource competition between component crop species in mixtures. The mixtures were simulated as mixed within rows not alternate row mixtures without changing weather, soil, or management variables. The CANOPY module arbitrates the competition for intercepted radiation between the component crops in a mixture on the assumption of horizontally homogenous layer boundaries being defined by the top of each canopy (Keating et al., 2003). This utilized the LAI extinction coefficient and height for water and nitrogen uptake was done based on APSIM changing the order each day (on a rotational basis) in which the competing species are allowed to capture soil resources (Berghuijs et al., 2021; Chimonyo et al., 2016). To further improve model capacity to simulate interspecific interaction in cover crop mixtures, we used the relative proportion of each cover crop to adjust a key APSIM parameter that relates to how crop access and soil water resources: '*kl*'– the fraction of plant available water extracted each day from each soil layer based on alternating days' approach of sharing of soil resources The initial (100% monoculture) values for 'kl' is provided in Supplemental Table S2. This improves the dynamic in which competing species are allowed to capture soil resources.

2.4. Model performance statistics

To evaluate model performance, field-measured data were compared with simulated cover crop biomass, soil water status, soil mineral N, crop N uptake, leaf area index (LAI), maize grain yield, and aboveground biomass. Four statistics were used to evaluate model performance. The root mean square error (RMSE) (Eq. 1), R-square (Eq. 2), the index of agreement (*d-index*) (Eq. 3), and the mean bias (MB) (Eq. 4). The lower the RMSE values relative to the mean, the better the model fitness. The model fitness improves as $RMSE$ approaches 0 and R^2 approaches 1. The *d*-index is recommended for making cross-comparisons; it is relative and has bounded measures (Willmott, 1982). Positive or negative MB values indicate under or over-prediction, respectively.

$$RMSE = \sqrt{\left[\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}\right]} \tag{1}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i - O_{avg}\right)^2\left(S_i - S_{avg}\right)^2\right]}{\sqrt{\sum_{i=1}^{n}\left(O_i - O_{avg}\right)^2} \times \sqrt{\sum_{i=1}^{n}}} \tag{2}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n}\left(\left|S_i - O_{avg}\right| + \left|O_i - S_{avg}\right|\right)} 0 \leq d \leq 1 \tag{3}$$

$$MB = \frac{1}{n}\sum_{n}^{1}(S_i - O_i) \tag{4}$$

Where O_i and S_i refer to measured and simulated values, respectively; O_{avg} and S_{avg} are the mean measured and simulated values, respectively; *n* is the number of samples. The validation statistic was obtained using the "ModStats" function from the "openair" package (Carslaw and Ropkins, 2012) in *R v4.1.0* (R Core Team, 2021).

2.5. Model application

The validated model was then applied to a scenario analysis to understand the impacts of alternative cover cropping decisions on fallow soil water and N management and their legacy impact on subsequent maize yields. We focused on maize only because of its higher sensitivity to soil water and N availability rather than to examine how cover crops best-fits within a crop rotation, e.g. after cereal or legume cash crops. The simulation scenario analysis had a factorial design involving 8 cover crop types × 4 starting soil PAW conditions (25%, 50%, 75%, and 100% of the profile PAWC (216 mm)) × 4 starting soil mineral N conditions: 25%, 50%, 75% and 100% of the profile soil mineral N corresponding to 54 kg N ha^{-1}, 108 kg N ha^{-1}, 162 kg N ha^{-1}, 216 kg N ha^{-1}. This resulted in 128 treatment combinations across 70 years resulting in 8960 simulations. We chose these levels of PAW and mineral N as criteria for deciding whether planting cover crops offer growers higher and more stable yields than conventional fallow. This also allowed the determination of conditions under which cover crop sowing is likely to reduce downside risk associated with rainfall variability. Thus, we simulated annual fallow-crop rotation involving conventional winter fallow/cover crop and summer maize crop rather than crop sequence from 25 March 1950–28 February 2020with annual resets to exclude the "carry-over" effects) of soil water and mineral N and surface organic matter on 24th March to maintain consistent soil starting conditions for all simulated years. No increasing CO_2 effects were considered, and the simulations were conducted under ambient CO_2 concentrations of 350 ppm on the assumption that CO_2 concentration does not influence cover crop sowing date in the model, but influence crop radiation use efficiency and overall transpiration use efficiency. Cover crops were sown on 25 March each year and terminated on 13 June (~80 days after sowing), corresponding to a medium termination time that maximized soil fallow water and mineral N benefits (Garba et al., 2022a). The conventional fallow was simulated with the similar APSIM-Manager rule as the cover crop with the absence of a cover crop module. The subsequent maize crop was planted and fertilized with 100 kg N ha^{-1} (urea) according to the sowing rule combining a variable "must" sowing window (18 September –18 October) and rainfall conditions (25 mm accumulated in five days); if these conditions are not met in a particular year, the crop is sown at the end of the sowing window. The sowing window was selected as the premium sowing window for maize in southern Queensland (GRDC, 2017). Cover crop residues were left standing (no-till). We compared the soil water and mineral N status of the conventional fallow with the cover crop system at cover crop termination and at the end of the next fallow to calculate the soil water and N deficit due to cover cropping.

2.6. Cash crop yield penalties

To determine the relative change in maize yield due to cover cropping, we calculated relative yield change (RYC) based on Eq. (5).

$$RYC \quad (\%) = \frac{Y_{cc} - Y_{ncc}}{Y_{ncc}} \times 100 \tag{5}$$

Where; Y_{cc} = simulated mean maize grain yield of the j^{th} cover crop while Y_{ncc} = simulated mean maize grain yield of the conventional fallow. To determine when cover crops provided the greatest yield benefits (RYC) relative to conventional fallow, we calculated annual rainfall quintiles from the annual crop-fallow rotations by splitting long-term annual rainfall distribution into quintiles. This yielded five precipitation categories: very dry (quintile 1; 216 – 596 mm), dry (quintile 2; 597 – 718 mm), normal (quintile 3; 719 – 823 mm), wet (quintile 4; 824 – 934 mm), and very wet (quintile 5; > 934 mm).

To determine the contribution of cover crop variables, soil, and precipitation inputs as a source of variance to maize grain yield variability, we calculated two indices that describe the variance of importance to the simulated yield along the precipitation quintiles: Main effects, ME (0−1) showed the shared contribution of a given variable to maize yield variability and residual (other factors not accounted for). The total effect (TxE) provided an estimate of the total contribution of a given variable in interaction with others and has no upper bound (Saltelli, 2002). All figures were produced using the "ggplot2" package (Wickham, 2016).

3. Results

3.1. Model evaluation

3.1.1. Soil water and mineral N outputs

The APSIM modules performed reasonably well in reproducing the

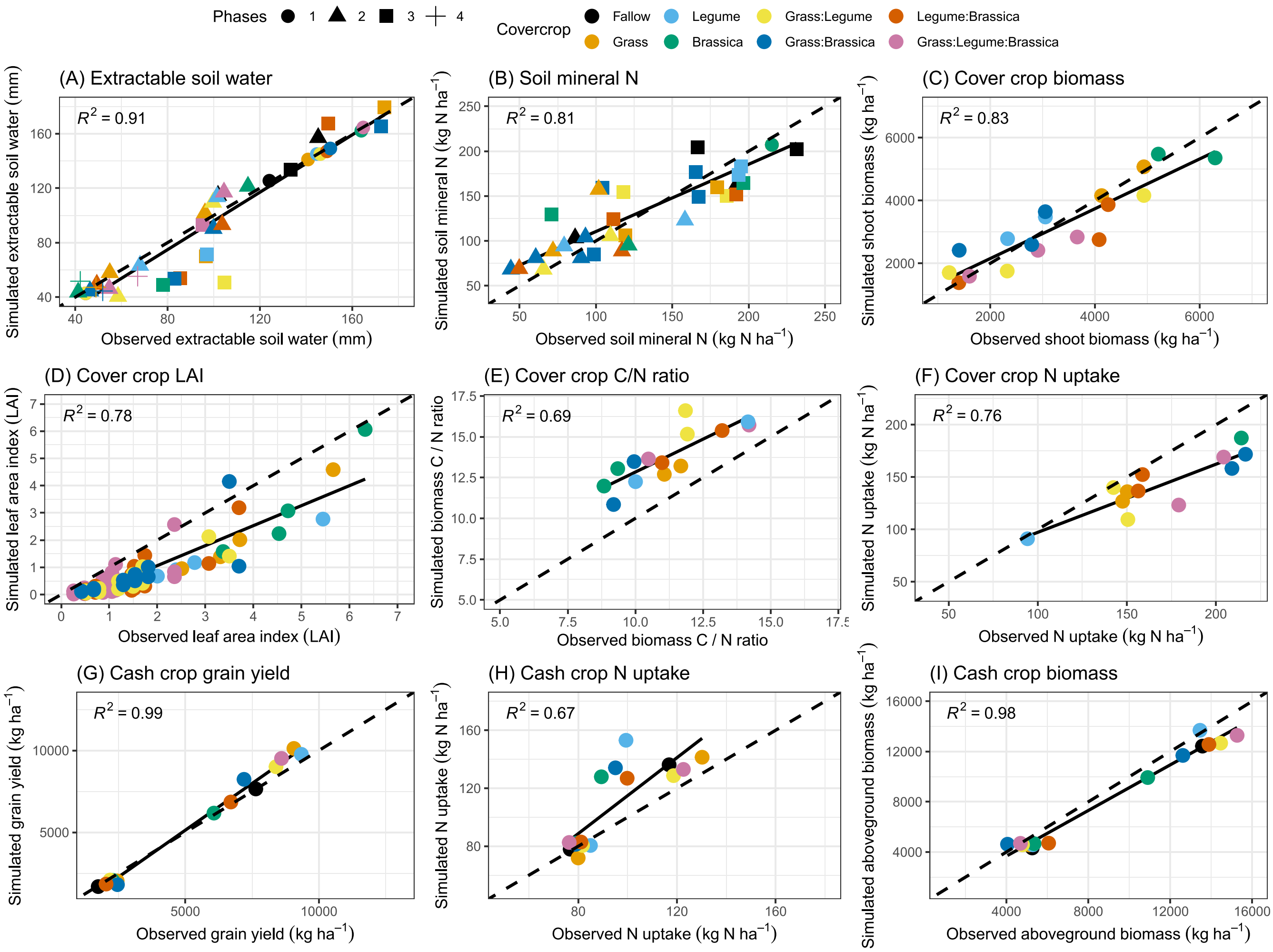

Fig. 2. Comparison of observed and simulated (A) Extractable (PAW) water content (mm; 0–120 cm depth), (B) soil mineral N (kg N ha^{-1}; 0–120 cm depth), (C) cover crop biomass (kg ha^{-1}), (D) cover crop leaf area index (LAI), (E) biomass C/N ratio, (F) cover crop N uptake (kg N ha^{-1}), (G) cash crop grain yield (kg ha^{-1}), (H) cash crop N uptake (kg N ha^{-1}), and (I) cash crop biomass yield (kg ha^{-1}), across the 3-site years. The solid circle (●), triangle (▲), square (■), and (+) showed the measured PAW and soil mineral N at cover crop sowing (1), cover crop termination (2), cash crop sowing (end of fallow) (3), and cash crop harvest (4).

measured soil water and mineral N values for most sampling times (phases) in both years albeit with some deviance (Fig. 2A-B; Fig. S1; Table 1). The best correspondence between simulated and measured soil variables was for plant-available water (RMSE $<$ 20 mm; $R^2 > 0.80$; *d*-index $>$ 0.7; MB $<$ 5). Simulated soil water values under the conventional fallow treatment were higher than field-measured values at cover crop termination indicating an overestimation of soil water by the model (Fig. S2). Similar trends were observed between simulated and measured soil mineral N (Fig. S3).

3.1.2. Aboveground plant outputs

The APSIM modules performed reasonably well in reproducing measured aboveground plant values including groundcover, biomass, N uptake, and LAI for the range of cover crop species grown in both monocultures and mixtures (Fig. 2C-F; Table 1). Overall, there was good correspondence between measured and simulated cover crop aboveground biomass in both monoculture and mixture cover cropping ($R^2 >$ 0.7; *d*-index $>$ 0.6; MB $<$ 5). The model slightly over-estimated biomass of grass cover crops (RMSE = 205 kg DM ha^{-1}), legume (RMSE = 648 kg DM ha^{-1}), and legume:brassica mixture (RMSE = 171 kg DM ha^{-1}) (Fig. S3). The model underestimated the biomass for the three-species mixture (RMSE = 933 kg DM ha^{-1}). Across the various mixtures, the model simulated well the contribution of each species to the total biomass (Fig. S3). The simulated and measured biomass N accumulation, C/N ratio, and N uptake were also well-matched across the cover crop species and mixtures ($R^2 >$ 0.6; d-index $>$ 0.5). The model predicted the cover crop legacy effects on the subsequent cash crop growth and yield with some deviations (Fig. 2G-I). The cash crop grain yield was slightly overestimated (RMSE = 539 kg DM ha^{-1}; $R^2 >$ 0.9; d-index $>$ 0.6; MB $<$ 5). A similar trend was with N uptake. However, total aboveground biomass was slightly underestimated by the model. (Table 1; Fig. 1I).

3.2. Cover crop productivity and interactions with starting soil water and mineral N conditions

Cover crop water use and biomass accumulation varied across years and initial soil water and mineral N conditions at cover crop sowing (Fig. 3; Fig. S4). Cover crop biomass production was greatest under high resource conditions, especially during high rainfall years, and lower in the low initial soil water and N and low rainfall years. The cumulative dsitrubtion functions in Fig. 3 showed the probable highest cover crop biomass was ~7000 kg ha^{-1} at 95% level nd the lowest was ~800–1000 kg ha^{-1} at 5% probability level. Cover crop mixtures were the most consistent in generating biomass across the different soil water and mineral N conditions at cover crop sowing. Under high soil water and mineral N supply (216 mm and 216 kg N ha^{-1}), there was relatively little difference in biomass productivity across the different cover crops with more than 75% probability of the biomass being $>$ 3500 kg ha^{-1}. The only exception was the legume monoculture, which had substantially lower predicted biomass ($<$ 3500 kg ha^{-1}). Under low soil water and mineral N supply (54 mm and 54 kg N ha^{-1}) conditions, biomass production by the brassica and grass monocultures was limited, while the legume monoculture was favoured with predicted median (50% probability) biomass of 2100 kg ha^{-1}. Consequently, while legume productivity did not increase under higher N and water, mixtures including a legume were the most favourable as the production of both legume and non-legume components was additive. The brassica was the most responsive to increasing resource conditions with average biomass production increasing from $<$ 1000 kg ha^{-1} under the low water and N

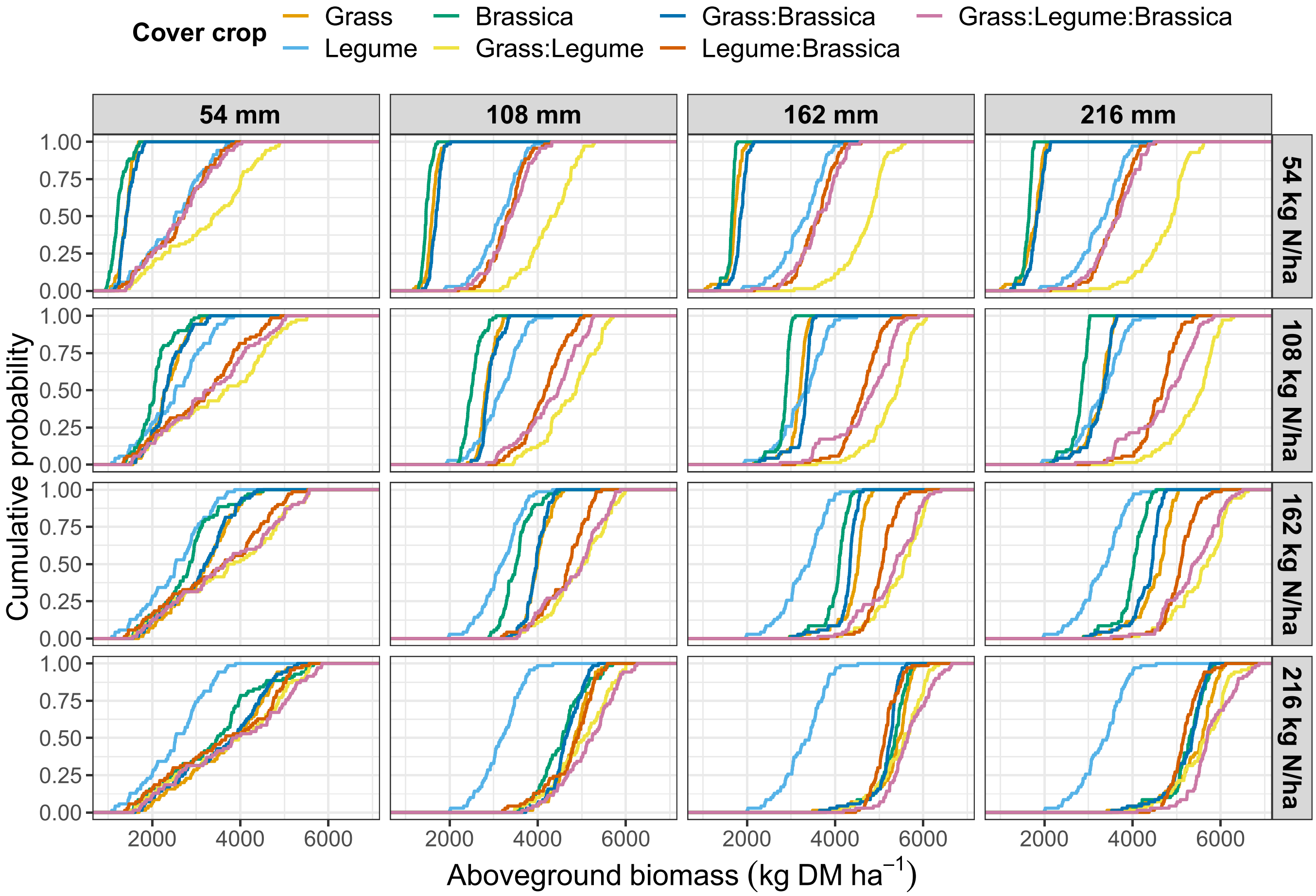

Fig. 3. Cumulative probability of cover crop aboveground biomass (kg ha^{-1}) during the 70 years of crop-fallow rotations (1950–2020).

scenarios to > 5000 kg ha^{-1} in the high soil water and N condition (216 mm and 216 kg N ha^{-1}) conditions.

Total cover crop biomass production was closely related to soil water use and hence the deficits created by the cover crops relative to conventional fallow. Consequently, the mixtures showed greater soil water deficit at the end of fallow (maize sowing) irrespective of soil water or mineral N status at cover crop sowing. These soil water deficits were predicted to occur in more than 80% of the years of the simulation period (Fig. 4). The three-species mixture extracted 53–84 mm soil water between sowing and termination relative to conventional fallow. Soil water extraction by the grass and brassica monocultures relative to conventional fallow ranges from 15 to 78 mm. The net accumulation post-termination and then the resultant soil water at the end of the fallow (maize sowing) in October also differed between cover crop treatments and the conventional fallow. The conventional fallow accumulated the lowest soil water (26 mm) while the legume:brassica mixture accumulated the most soil water (42 mm). The predicted median (50% probality) soil water deficit at maize sowing relative to conventional fallow ranged from 15 mm to 43 mm under low soil water and mineral N scenario (54 mm and 75 kg N ha^{-1}). Under moderately high soil water and mineral N conditions (162 mm and 150 kg N ha^{-1}), the soil water deficit was highest for the three-species mixtures (−80 mm) and lowest following legume monoculture (−56 mm) (Fig. 4). Under high water and N scenarios most cover crops had similar water deficits, except the fababean was less due to its lower biomass production in this scenario.

This reduction in soil mineral N for subsequent crops was predicted to occur more often and was more severe following grass, brassica and the mixtures involving non-legume cover crops. The brassica had the highest mean soil mineral N deficit across all scenarios and ranged from − 45 to − 170 kg N ha^{-1}. The legume-associated cover crops had lower soil mineral N deficits (−21 to −44 kg N ha^{-1}) and thus had higher mineral N accumulation compared to grass or brassica-associated cover crops mainly due to reduced soil mineral N extraction.

Soil mineral N content at end of the fallow is a function of cover crop N uptake and the subsequent N mineralization of cover crop residues in the fallow. The difference in soil mineral N extraction by the cover crops relative to fallow was most evident in the soil mineral N status at termination. At the end of fallow (maize sowing), the legume monoculture extracted the least, and the brassica extracted the most soil mineral N. The conventional fallow accumulated the lowest soil mineral N (27 kg N ha^{-1}) followed by the Oat (53 kg N ha^{-1}) while the legume: brassica mixture accumulated the most soil mineral N (71 kg N ha^{-1}). However, the potential fate of the mineral N during the fallow period between cover crop termination and cash crop sowing is driven by the movement of water through the soil profile, consequently, the model predicted a reduction in N leaching of 16–38% (~15 kg N ha^{-1}) following cover crops relative to conventional fallow, with higher reduction following grass and brassica cover crops (Fig. S5).

3.3. Legacy effects of cover crops on subsequent maize yield

The simulated maize grain yield showed different responses to cover crop type and variations in initial soil water and mineral N conditions at cover crop sowing (Fig. 6). The simulated maize grain yield had consistently lower yields than the conventional fallow following all the

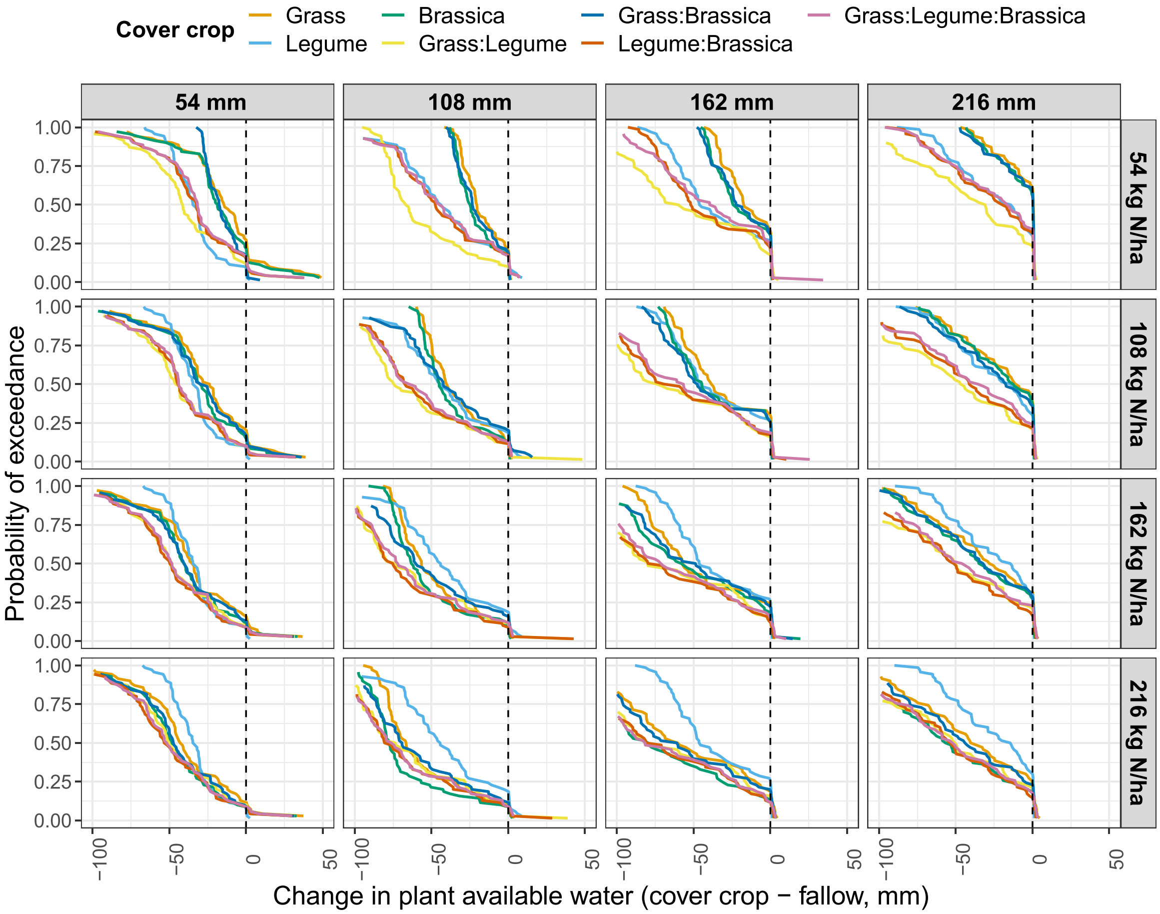

Fig. 4. Probability of exceedance showing the simulated difference in plant available water content (0–120 cm depth) at cash crop sowing (end of fallow) between the different cover crop types and conventional fallow treatment (dash line) during the 70 years of crop-fallow rotations (1950–2020). The long-term simulation showed that soil mineral N content at end of the fallow period was also reduced following cover crops in most years relative to conventional fallow (Fig. 5).

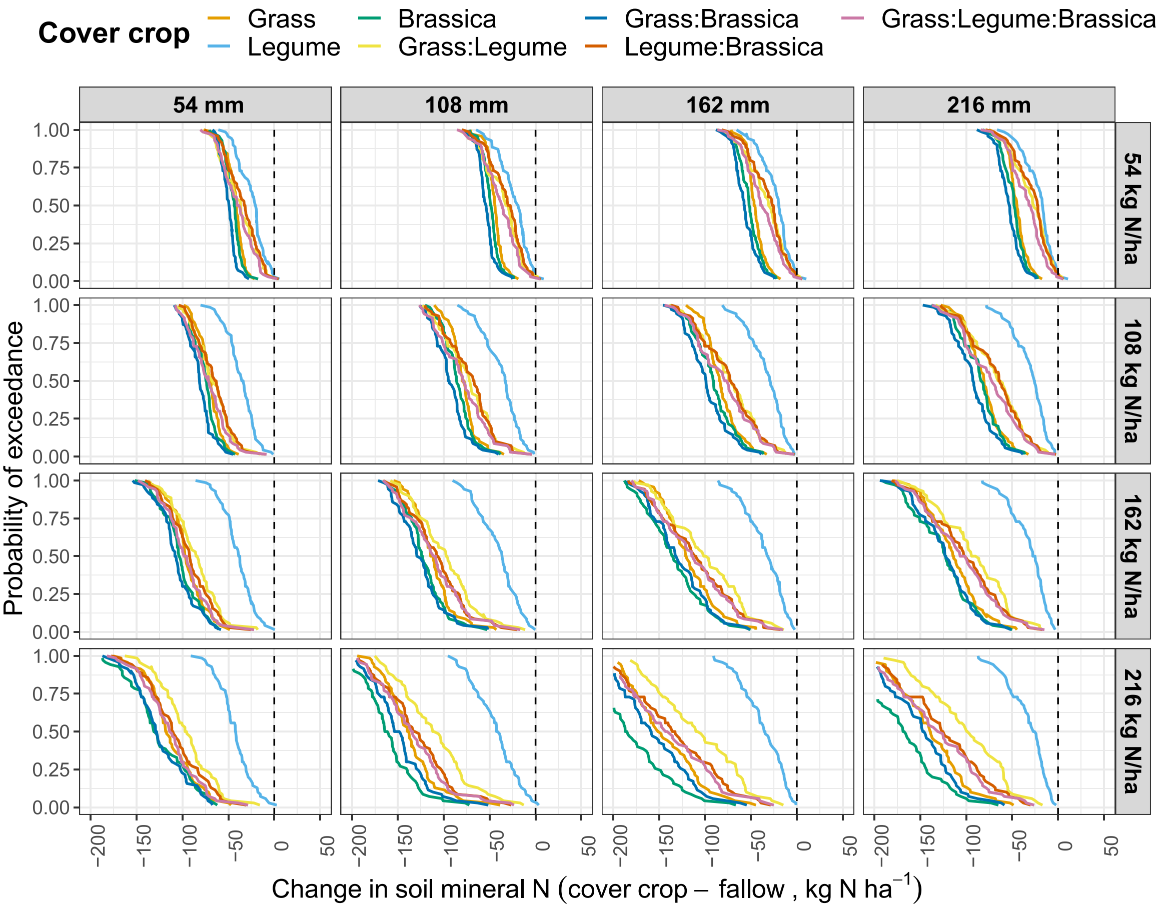

Fig. 5. Probability of exceedance showing the simulated difference in soil mineral N (0–120 cm depth) at cash crop sowing (end of fallow) between the different cover crop types and conventional fallow treatment (dash line) during the 70 years of crop-fallow rotations (1950–2020).

cover crop treatments except in certain years. Under high soil water and mineral N scenarios (216 mm and 200 kg N ha^{-1}) for cover crops, grain yield was highest after the legume monoculture (8563 ± 342 kg ha^{-1}) followed by the Oat monoculture (7932 ± 330 kg ha^{-1}), and lowest with the brassica monoculture (7428 ± 333 kg ha^{-1}). In low soil water and mineral N scenarios (54 mm and 50 kg N ha^{-1}), the highest average grain yield (5956 ± 369 kg ha^{-1}) occurred after the grass monoculture, while the grass:legume mixture produced the lowest average yields (5231 ± 243 kg ha^{-1}).

The average predicted grain yield penalty after cover crops compared to the conventional fallow decreased with increasing soil water at cover crop sowing. Under the low soil water and mineral N scenario, the predicted median yield deficit of the subsequent maize crop was − 16% to − 18%, across all the monocultures, and mixtures. Under high soil water and mineral N conditions, the yield penalty due to cover cropping averaged − 10% with the lowest yield penalty following legume and grass monoculture and grass:legume mixture. The frequency that cover crops reduced yields by > 10% (i.e. temporal crop yield loss risks), varied with initial soil water and mineral N status at cover crop sowing. In low soil water and mineral N scenarios, > 75% of crop yield loss risks were predicted following the brassica monoculture and the mixtures. The simulation suggested that crop yield loss risks were large and more frequent following the brassica monoculture, legume:brassica, and the three-species mixture (> 50%) than following other cover crops.

3.4. Drivers of simulated yield penalties after cover crops

By separating the annual crop-fallow into precipitation quintiles (i.e. 20% of years in each) the model predicted lower yield reductions (−13 to +5%) occurred in years with normal to above-median rainfall (quintiles 3 – 5) while much larger yield reductions (−20 to −37%) occurred in years with below median rainfall (quintiles 1–2). In the very dry years (quintile 1), the grass monoculture had the least yield reduction (−20%; −1636 kg ha^{-1}) compared with the conventional fallow, while the brassica and grass:brassica mixtures had the greatest yield reductions (−37%; −2450 kg ha^{-1}). In median precipitation years (i.e. quintile 3), grass cover crops had a greater yield reduction (< −23%) compared to legume (−14%) and brassica (−18%). Interestingly, in the very wet years (quintile 5), both the grass and brassica monocultures had low yield reductions (<−5%) while there were predicted yield gains of + 1, + 4, + 3, and + 3% for legume, grass:legume, grass:brassica and the three-species mixtures relative to conventional fallow (Fig. 7).

Analysis showed that simulated maize yield penalties were more driven by soil water than soil mineral N availability across the diversity of simulations. Simulated maize yield penalty was mainly explained by soil water content at maize sowing (2–88% variation explained), in-crop rainfall (5–60%), and fallow rainfall (11–42%) with variation between cover crop types along the rainfall quintiles (Fig. 8). The yield penalty was driven more by cover crop biomass and water use in years with much below-normal to normal precipitation (quintiles 1–3) accounting for 11 – 87% of the simulated yield variances with significant variation between cover crop types. In the case of grass monoculture in very dry years, fallow rainfall had the highest contribution (31%) followed by the cover crop biomass (28%) and soil mineral N content at maize sowing (12%). In contrast, cover crop biomass and water use accounted for 23–50% of the yield variance in mixture cover crops. In wet years (quintile 4), the soil water stored at maize sowing had the highest contribution to the simulated yield variance for legume-associated cover

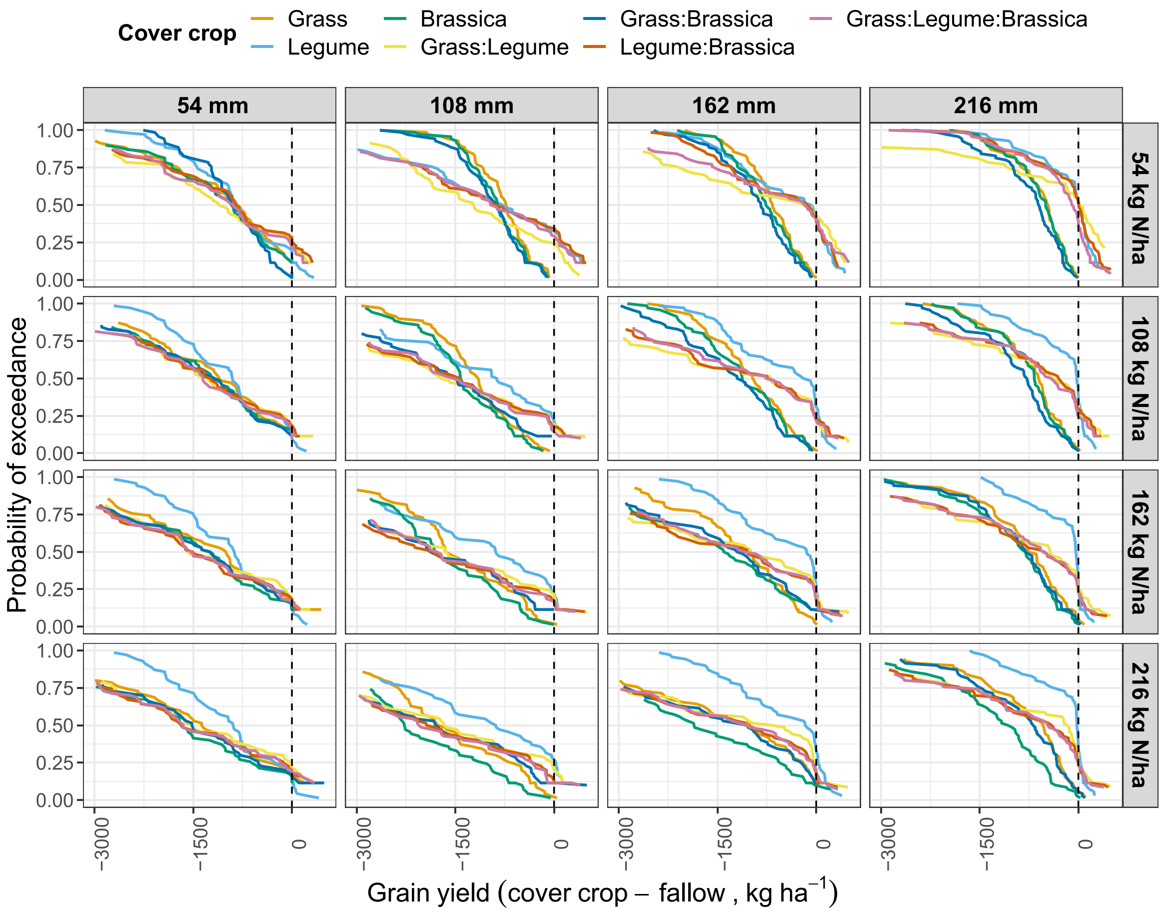

Fig. 6. Probability of exceedance showing the simulated difference in maize grain yield (kg ha^{-1}) of the different cover crop types relative to conventional fallow treatment (dash line) during the 70 years of crop-fallow rotations (1950–2020).

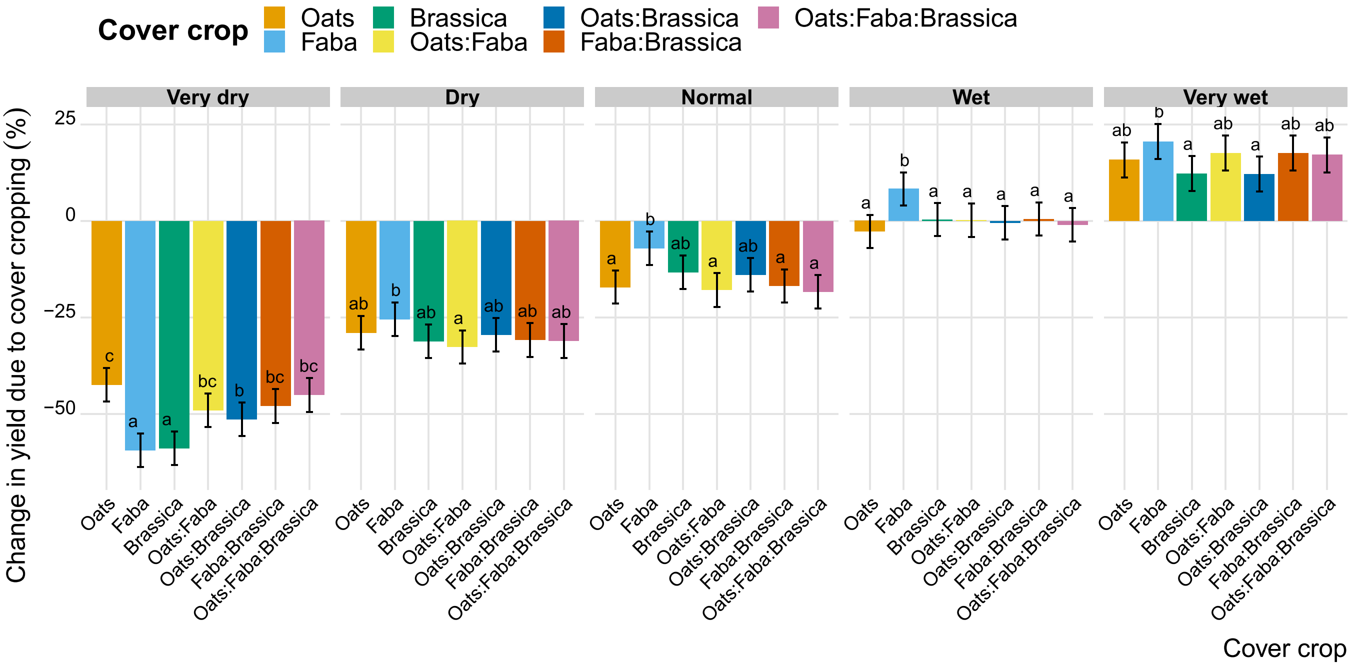

Fig. 7. Average change in simulated maize grain yield (%) induced by cover cropping relative to conventional fallow during the 70 years of crop-fallow rotations (1950–2020) along annual precipitation quintiles: very dry (quintile 1; 216 – 596 mm), dry (quintile 2; 597 – 718 mm), normal (quintile 3; 719 – 823 mm), wet (quintile 4; 824 – 934 mm), and very wet (quintile 5; > 934 mm). Bars show mean ± standard error for each cover crop treatment. Mean values followed by the same letter (s) are not significantly different at $p < 0.05$ based on the Bonferroni test.

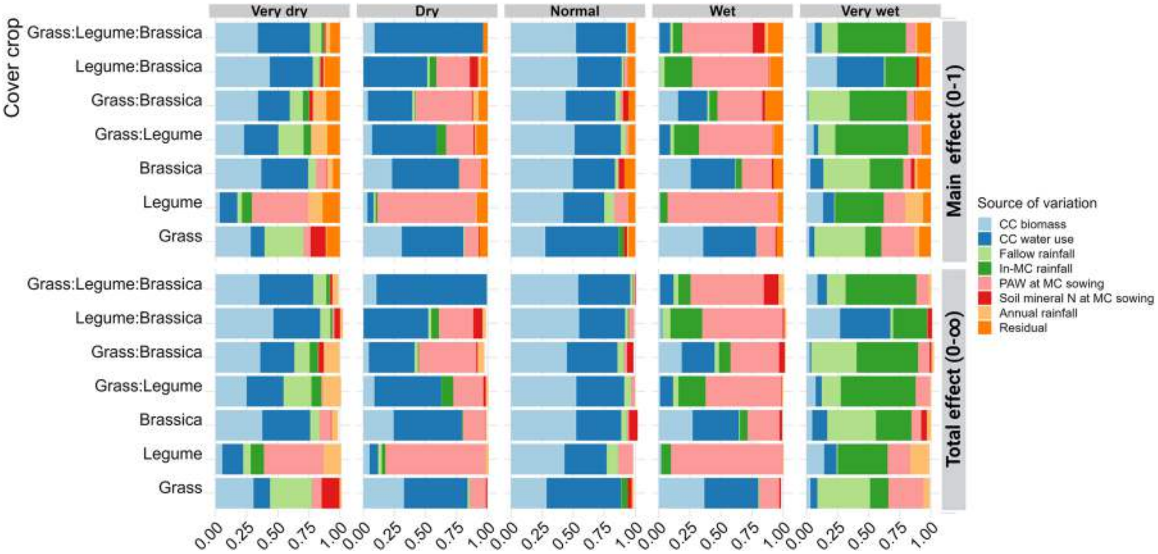

Fig. 8. (A) Main Effect (0−1) and (B) Total Effect; TxE (0–∞) of cover crop biomass, cover crop water use, fallow rainfall, in-cash crop rainfall, annual rainfall, soil water, and mineral N at maize sowing, annual rainfall, explaining variability in simulated maize grain yield across the 70-year simulations. CC = cover crop; MC = cash (main) crop.

crops (15–88%). In very wet years (quintile 5), in-crop rainfall and fallow rainfall were higher in the range of 13–59% and 13–41% of the simulated yield. The main effect of soil mineral N accumulation at cash crop sowing was consistently lower than 15% across the precipitation gradient. Cover crop biomass production and water use had larger interactions with other factors (total effects) very dry to normal precipitation quintiles. In wet and very wet years (quintiles 4 and 5), in-crop rainfall, fallow rainfall, and soil water content at maize sowing had higher total effects contributing to the simulated yield. We found that residual (other factors not accounted for) contribution was < 14% for all the cover crop types along the precipitation quintiles (Fig. 8).

4. Discussion

One of the main barriers to cover crop adoption in water-limited environments is the potential conflict between cover crops and subsequent cash crops for soil water and soil mineral N (Daryanto et al., 2019; Ghimire et al., 2018). This is because soil water and N availability generally dictate most cropping decisions and often moisture availability is the main driver of crop yield and profits. This study quantified the impacts of diverse cover crop functional types on fallow soil water and N management and their carry-over effects on subsequent maize crop productivity and stability. Given the water limitations in these environments, the appropriate cover crops are often those that generate rapid ground cover without excessive depletion of soil moisture and maintain higher soil mineral N stock at subsequent cash crop sowing (Rose et al., 2022). Consequently, the overall effect of cover crops on subsequent cash crops will depend on the net effects of soil water, and mineral N balance as well as other auxiliary benefits such as reduction of NO_3 leaching and suppression of soil-borne pathogens and weeds (Garba et al., 2022b; Daryanto et al., 2018). Overall, we found that cover crops that generated more biomass induced a higher soil water deficit, thus the impact on subsequent cash crops was associated with levels of biomass production. The results showed cover crops reduced soil water and mineral N at cash crop sowing, but the magnitude of the reduction varied with cover crop functional type and precipitation regime. We found higher yield penalties following mixtures compared to monocultures in drier seasons (soil water content at sowing and in-crop rainfall) driving yield variation. In the wettest years, cover crops were able to significantly improve subsequent cash crop yields.

4.1. *Productivity and functionality of different cover crop types*

The long-term simulations showed varied cover crop responses to different initial soil water and N availabilities at cover crop sowing. This confirmed our hypothesis that cover crop effects on fallow soil water and mineral N are cover crop type-specific and often determined by the species taxonomy or the functional traits that down- or up-regulate resource (soil water and N) acquisition and use. The model extrapolations were consistent with the field observations, predicting that cover crop mixtures produced higher aboveground biomass compared to their monocultures likely due to higher land equivalent ratio (LER) and complementarity of the component species in the mixture for the capture and utilization of abiotic resources (Tribouillois et al., 2021, 2015; White et al., 2017). In this regard, the mixtures comprising the legume and non-legume cover crops could have exploited soil water and mineral N across the soil profile more than a monoculture of either legume or non-legume cover crops. Consequently, the mixtures had higher N uptake. One reason could be that the legume cover crop was able to meet most of its N requirement through biological N fixation, producing very similar biomass and hence plant N across the different starting N conditions. In contrast, the non-legumes (grass and brassica) rely on N acquisition from the soil, and thus the availability of N at sowing was a critical driver of aboveground biomass.

Cover crop mixtures were the most stable in generating biomass across the different soil water and mineral N conditions at cover crop sowing. In high soil water and mineral N supply conditions, there was relatively little difference in biomass productivity of the various cover crops except for the legume monoculture. However, with decreasing soil water and mineral N supply, biomass production by brassica and grass monoculture was limited while legume monoculture was favoured. This trend supports the stress-gradient hypothesis that posits that facilitative interactions between plants vary inversely across abiotic stress gradients (Maestre et al., 2009). Thus, cover crop functional diversity increases under poor resource (low soil water and mineral N) conditions, and consequently, mixtures would outperformed monocultures (Reiss and Drinkwater, 2022). Consequently, mixtures involving legumes were the most favourable as the biomass production of both legume and non-legume were additive. Surprisingly, the legume:brassica mixture produced lower biomass than the grass:legume mixture. This could be due to greater competition for light under high resource conditions due to both crops having similar canopy architecture while in the case of the grass:legume mixture, the non-uniform canopy structure allows for the capture of light. This form of asymmetric competition in cover crop mixtures has been reported to occur when one of the component crops in mixtures confers a fitness advantage due to a particular suitable functional trait that favours its productivity over the component crop (Bybee-Finley et al., 2022). Therefore, cover crop mixtures are optimal choices under variable conditions, because of the potential compensatory interactions among the component crop in mixtures, thus growing mixtures provide more robust and resilient options across a greater diversity of conditions.

We found that cover crops that generated more biomass induced a higher soil water deficit. Overall, cover crops in our simulated system reduced soil water availability irrespective of their functional type or mixture composition. In the context of this farming system, there was limited soil water advantage of growing cover crops for fallow replacement. This was likely because there were sufficient levels of ground cover already in the fallow, so the cover penalty is low, and rainfall infiltration was not impeded by insufficient residue cover. Further, the simulated fallow after cover crop termination is short so there is less time for soil water to be refilled and or difference in ground cover to play out. In environments where there is a lack of stubble from preceding cash crops (e.g., a summer legume) or due to wide-row configurations with uneven residue cover and exposed soils, cover crops could have greater positive impacts on soil water by enhancing rainfall capture and increasing infiltration that fully compensates for cover crop water use. Similarly, in longer subsequent fallow periods, the higher residue load from the preceding cover crops may promote greater soil water storage where precipitation amount and distribution are not favourable (Rose et al., 2022).

Recently, there has been greater emphasis on increasing the multifunctionality and mitigating agroecosystem service trade-offs through the use of cover crop mixtures (Mitchell et al., 2015; Reiss and Drinkwater, 2022; Romdhane et al., 2019; Wortman et al., 2012). In terms of maintaining or improving soil mineral N, we did not find that growing mixtures had advantages over monocultures. We found there were small differences in the C:N ratio of all the species due to early termination ($<$ 90 days after sowing) and consequently the decomposition of their residue did not dramatically alter subsequent in-crop soil water and mineral N recovery. However, the simulation showed cover crops have the potential to provide other ecosystem services including N leaching and soil surface runoff reduction. The model predicted a reduction in N leaching of 16–38% ($\sim$15 kg N ha^{-1}) with cover crops relative to conventional fallow, with higher reduction following grass and brassica cover crops (Fig. S5). This is likely because cover crops dried the soil and thus reduced the size and frequency of drainage events. The cover crop residues enhanced rainfall infiltration and hence reduced surface runoff compared to conventional fallow. Similar results were reported by Whish et al. (2009) where millet (*Panicum miliaceum* L.) cover crop that produced high groundcover reduced runoff and soil loss compared to fallow. Hence, careful selection of cover crop type is needed to mitigate these trade-offs between the groundcover, and N retention services and the disservices of reducing water and N availability for the subsequent cash crop. Thus, value judgments and efficient trade-offs between different ecosystem services will be required to integrate cover crops into current crop-rotations in dryland agroecosystems. Furthermore, in dryland agroecosystems, cover crops are not likely to be grown under high soil water and mineral N conditions, and growers would more likely opt to double crop cash crops. Thus, in most cases cover crops are going to be grown under limiting resource conditions, which reduces the risks of soil water and mineral N deficits for the subsequent cash crop provided adequate precipitation is received during the subsequent cash crop growth period.

4.2. Implications of using cover crops on maize yield

The results demonstrate that risks that cover crops can have on reducing water and nutrient availability for subsequent crops depends on the initial soil conditions at cover crop sowing. Replacing part of the fallow periods with cover crops led to lower grain yields following cover crops compared to the conventional fallow in most years. The magnitude of the yield declines following cover crops varied with the cover crop type. The mixtures had consistently lower subsequent yields than monocultures of legume, grass, or brassica, indicating that the impacts of cover crops on maize yields were cover crop type specific. We found that the grass monoculture and the grass: legume mixture generated the least maize yield reductions ($<$ 15%). This is partly consistent with previous research where maize yields were reduced following grass cover crops compared to conventional fallow (Abdalla et al., 2019; Hisse et al., 2022; Qin et al., 2021). Qin et al. (2021) showed in a simulation study with the *Ecosys* process-based model that grass cover crops reduced maize grain yield; however, legume cover crops had neutral effects on maize grain yields because residues from legume cover crops can rapidly release mineral N following termination. In the current studies, both legume and non-legume cover crops led to maize yield reductions, and this was largely due to soil moisture depletion rather than soil mineral N. Wunsch et al. (2017) reported similar trends in a drier subtropical environment, where winter wheat yields were reduced following both legume and grass cover crops due to reduced water availability. We found that the mixtures predicted several mechanisms that could lead to grain yield declines that are different from those under monocultures. These included greater biomass accumulation, higher water use, and consequently reduced soil moisture availability during the succeeding maize growing seasons, including high soil water and N stress during critical growth periods. This was particularly apparent in years with greater soil water stress (due to low in-crop precipitation) and soil water demand.

Another mechanism for maize yield reduction following cover crops could be the increased water during maize growing seasons, particularly in years where there was low in-crop rainfall. The variance of importance sensitivity analysis also showed that in-crop rainfall and the soil water content at maize sowing contribution outweighed the contribution of other factors such as soil mineral N content or cover crop biomass accumulation in wet years. This suggests in the absence of adequate soil water recharge by rainfall at cover crop termination, cover crops would compromise subsequent cash crop yields irrespective of the levels of biomass they produced. We found that in the mixture cover crops, maize experienced significant soil water stress on the three main crop development processes: leaf expansion, photosynthesis, and phenology in dry years. This reduced the water availability ratio (supply/demand) for the maize crop, thus potentially reducing final grain yields. Several studies have reported a decrease in the photosynthesis rate, leaf expansion, abnormal phenology, and consequently low yields due to water stress during maize growth (Çakir, 2004; Sah et al., 2020; Song et al., 2019; Wang et al., 2019). Hunter et al. (2021) recently found that even under ambient or drought conditions, cover crops do not improve soil water availability via root-channel effects irrespective of their functional traits, thus aggravating maize yield declines.

The results show the impact of cover crops was greatly influenced by climatic conditions and there were greater risks in drier conditions. We found that the predicted decline in cash crop yields occurred more frequently in the annual precipitation quintiles 1–3 ($<$ 820 mm). We also found that the model predicted significantly higher soil water stress in these years and consequently lower grain yields following cover crops than the conventional fallows. These values align with the results of a recent meta-analysis which found that cash crop yield responses following cover crops were positive compared to a conventional fallow where annual precipitation regimes exceeded 700 mm (Garba et al., 2022a). In years with above-average rainfall, both the mixtures and the monocultures had a smaller magnitude of yield reduction ($< -10\%$), likely because there was more or less similar resource acquisition irrespective of the cover crop species. Bybee-Finley et al. (2022) reported similar observations where cover crops that shared similar growth seasons are likely to have access to available resources in a similar manner irrespective of their functional type or mixture composition. Interestingly, in years with much above normal precipitations (annual precipitation $>$ 934 mm), the mixtures had lower yield declines compared to the monocultures of the brassica or grass, and yield gains of + 1%, + 4%, + 3%, and + 3% were predicted for legume, grass:legume, grass:brassica and the 3-species mixtures relative to conventional fallow (Fig. 8). Within APSIM, crop competition for water and N uptake is modelled in such a way that there is a biased priority for resource capture on alternating days, therefore, there was likely lack of sufficient capture of the plant plasticity mechanisms (Githui et al., 2023). Our improved model parametrization by modifying "*kl*" for mixtures enhanced the arbitration for water and N uptake and the wayin which the component species are given the opportunity to capture soil resources. In the three-species mixtures, the combined large tap roots from the brassica and legume accessing soil water and N from deep soil layers with fibrous roots of the grasses with the N fixation of the legume component could have promoted greater resource capture, utilization, and efficiency where soil water and N are not limiting. Consequently, this enhanced biomass accumulation, N accumulation, and potentially improved maize yields in high precipitation years. This could be one of the reasons why cover crop mixtures are more popular in high-rainfall regions (Restovich et al., 2022). The implication here is that for successful integration of cover crops into crop-fallow rotation in dryland agroecosystem, cover crops should be considered as a flexible option (grown under favourable precipitation and economic scenarios) rather than for continuous fallow replacement.

In addition, the magnitude frequency of yield penalties with cover crop compared to conventional fallow varies with the different cover crop types. We found that the grass and legume monocultures generally had higher stable yields and lower downside risks compared to all other cover crop mixtures. The high yield stability indicates that these cover crops maintained high maize grain yields under the poorest soil initial conditions at cover crops and consequently had a smaller downside risk when used for fallow replacement. Previous studies have reported the potential of cover crop monoculture to maintain smaller downside risks and variability compared to their mixtures depending on the cover crop species and the location-specific pedo-climatic conditions (Abdalla et al., 2019; Oliveira et al., 2019; Thapa et al., 2021; Wang et al., 2021). This could also be due to the high sensitivity of dryland cropping systems to climatic variability where a relatively small water deficit change can have large impacts on yields and ultimately dictate most cropping decisions (Reynolds et al., 2007). Our results also support the previous finding by Rosa et al. (2021) where the grass cover crop had the lowest downside risk compared to other cover crop species likely due to higher residue C:N and consequently high groundcover that could reduce soil water loss by evaporation and gradual N mineralization. The results of this study showed a consistent yield loss and increasing yield volatility in dry years with increasing cover crop mixture complexity. For example, the potential of cover crops to reduce N leaching, and runoff and provide additional soil carbon could potentially incentivize growers despite the reduction in subsequent crop yields. Further studies are necessary to understand these trade-offs and the mechanism of reducing them.

4.3. *Limitations of the current study and future research*

The modelling framework applied in the current study focusses heavily on the impact of aboveground biomass of cover crops and effects on soil water and N management and their legacy impact on subsequent maize yields. While this provides a robust agronomic implication of cover crop impact on maize productivity and contributes significantly to the understanding of some of the barriers to cover crop adoption in the water-limited environment, the lack of data to quantify and incorporate belowground processes and/or biotic factors that may influence crop growth and soil conditions. In some cases, cover crop adoption relies on the potential of cover crops to provide multifunctionality (simultaneous enhancement of ecosystem services), for example, cover crop impacts on soil microbial processes and pest dynamics. These are difficult to incorporate into the modelling framework due to the substantial data required to calibrate and validate the model. These factors are a critical component of soil health and could provide further insights into the potential trade-offs in ecosystem services and disservices associated with cover crops that could inform public policy or other avenues to incentivize growers to adopt cover crops despite yield reductions. Further studies are therefore needed that are cognisant of other ecosystem services from cover crops to maximize ecosystem multifunctionality in the dryland agroecosystem.

Our analysis showed that simulated maize yield penalties were more driven by soil water than soil mineral N availability across the diversity of simulations. This may be due to high soil mineral N stock (~200 kg N ha^{-1}) at the experimental sites. Consequently, the validation of the APSIM may not adequately capture low mineral N levels tested in the long-term simulation. Furthermore, are therefore needed to examine the cover crop performance under low soil fertility or N-limited environments.

Our results focused on winter-based cover crops with a short rotation to a summer cereal crop in a sub-tropical environment with summer-dominant rainfall. Hence, there are range of other use patterns and environments where the various trade-offs and impacts of cover crops should be considered. For example, in this environment cover crops could potentially be more useful if grown during summer compared to winter-based cover cropping. Further studies should explore what are the likely seasonal benefits of winter versus summer-based cover cropping. Additionally, there is a need for future work to integrate economic analysis to unravel the cost-benefit and risks associated with the adoption of cover crops for fallow replacement in dryland cropping systems.

5. Conclusions

The results showed replacing a conventional fallow period with cover crops showed varied impacts on soil water and N dynamics and the legacy impacts on subsequent cash crop productivity. The long-term simulation showed maize yield reduction following cover crops compared with conventional fallow in dry to normal years. This reduction was induced via a reduction in soil water availability at maize sowing and increased water stress during maize growth. In wet years with above-average precipitation, cash crops yield reduction following cover crops was much less ($<$ 5%) and yield gains of up to + 4% were predicted. We found the grass monoculture had consistently higher stable yield and small downside risks whereas the legume:brassica and the 3-species mixtures carried higher yield penalties and larger downside risks, indicating that increasing cover crop complexity by using mixtures with diverse functional traits could lead to greater yield losses and increased yield volatility in a water-limited environment. Therefore, for successful integration of cover crops into crop-fallow rotation in dryland agroecosystem, cover crops should be considered as a flexible option under favourable precipitation scenarios rather than for continuous fallow replacement.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2023.109019.

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