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RESEARCH ARTICLE

Cover cropping impacts on soil water and carbon in dryland cropping system

Hanlu Zhang[1,2]*, Afshin Ghahramani[1,2]*, Aram Ali[3a], Andrew Erbacher[4]

1 Centre for Sustainable Agricultural Systems, Institute for Life Sciences and the Environment, University of Southern Queensland, Toowoomba, Qld, Australia, 2 Cooperative Research Centre for High Performance Soils, Callaghan, NSW, Australia, 3 Soil and Water Science Department, College of Agricultural Engineering Sciences, Salahaddin University-Erbil, Erbil, Kurdistan Region, Iraq, 4 Department of Agriculture and Fisheries, Queensland Government, Goondiwindi, Qld, Australia

* hanlu.zhang@usq.edu.au (HZ); afshin.ghahramani@usq.edu.au (AG)

Abstract

Incorporating cover crops into the rotation is a practice applied across many parts of the globe to enhance soil biological activities. In dryland farming, where crop production is highly tugh'y

d%Endent onrainfal andsoilwater storage,cover cropping can soil water. yet its

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effa:ts on soil and biological health require further investigation. The ot this study was to evaluate the effectof cMferent timing of summer so.um covercr%) termination on soil water. totaland labile organic carbon, arbuscular mycorrhizal fungi arr.' their mediating effects wheat yield. Through on-farm trial, soil characteristics abng with wheat biotnass, yield and graü•l quality were rnonnored. In comparison with the cmtrol (fak»w). the early cover crop was the most effective at retaining greatersoil water at wheat sowing by 1 —4% in 0—45cm soi prone. An increase in water use efficiency, yield and grain protein by 10%, and 5% was chservedunder earty terrnftatiom Under hte termirated sumrner covercrc», there was 7% soil water depletjm at wheatplanting whk:h resulted in 61 % decline in yield. However, late-terminaw] cover crcv achieved the greatestgain soil total and particulate organic carbon by 17% and 72% arbuscular myccwrhizal fungal Grot4) A B concentratim by 356% and 251 Surnrner cover crop incorporation resulted in a rapid gain in labile organic carmn, which constituted hotspcls for arbuscutar mycorrhizal fungi growth, conversely. fungal activities increased labde organic carbon avalabihty. The effect o' increased soil water atsowing and over the growing season. organiccarbon, and microbial wtivities ccrltrmuted to greater yield. The findings that surnrner cover

cropping with tirnely termination can have implications in managing soa waterat sowing time and enhancing sod water during the season, soil carmn, aM facilitating micrcbial ætivities while enhancing productivity in the dryiand cropping system.

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1. Introduction

Soil water is Often alimiting ßctor in Australian crop prcxiuction regions particularlycropping in the statesofNew South Wales (NSW) and Queensland (Qld), where stored mow ture inthe profile:at *Mingtimeis critical emergence, crop ßtabliåmentand yield II —51. However, can be bymanagement that changes biolog- iCal activities and nutrient availabilities 16.71. soil water availability can impair nutrient availability by affecting nutrient concentration in soil solution and the rate of nutrient trans• to the rootyaffecting plantgrowth and yield On the other hand. soil water availability can also microbial growth, microbial activities and their physical andchemical processes that mobilise organic matter via root exudates 191. There is a range ofcropping practicessuch as early crop rotations, stubble retention, minimum tillage or no•till and weed control to improve water u.æ efficiency byenhancing capture and preservation ofrainfill I IO, I I I. Alnongtheæ, the ofcover crops has been adopted across manyparts ofthe globe to manage both mil water and nutrients but different on soil water have been reported for these practices | 12—161. Integrating cover crops into a system can be a method to replace or shorten thefillow duration, which allows longer duration ofsoil surfacecoverage befi»re plantingthe cash crop 1171. Fallow replacement with a cover crop can affect soil water dynamics by regulating soil water evaporation, runoffand drainage 1181 and micro• bialcommunity structure and consequently biological activities 1191. 'Ihe ofcovercrops in cropping systems provides benefits ofrnodihring the soil environmentand enhancingsoil physical properties through its effect on root-soil interactions, but their impacts on soil physi• cal and biological characteristics Were reported to vary in different environmentsand cropping syÄems 120—241. Long-term cover crop practices can lead to changes in soil hydraulic proper• ties, such as mil bulk density, aHegate stability, soil water retention, infiltration, saturated hydraulic conductivity and B're•si7Æ distributions across the soil profile 117 Nevertheless. the magnitude ofchanges can be highly siteand management•dependent 125—271.

Cover crops can be the source ofplant residues from above-ground biomass and root bio, massthat contributes to the organic matter pool after decoml»sition, which improves soil hydrology that can potentially soil vvater storage and plant available water 128, 291_ Studies showed that long-term cover croppingcontributed to a tktter•developed Äructure by improving soil pore sire distribution and soil hydraulic proFk•rties, such as soil Water conductiv-ity and retention at the plot scale 1301. However. the impact of cover crop practice on soil water can vary across yearsand regions that are affected by climate variability and soil types 127, 31, 321. Underdryland conditions cover cropsare more likely to competefor soil water and nutrient with cash crops 115, 311_ Iherefiyre appropriate termination time Ikcomes crucial for cover crop management to avoidthe competition and reduce soil water loss from evapotranspiration, particularly in water-limited regions where soil nutrients and water effciency are often low 133—351. Covercrop management has also been reported as an effective practice to improve soil chemical and biological characteristics, such as enhancing nitrogen recycling via reduced nitrate leaching risks, increasing soil organic carbon (OC), and microbial biomas and activities 136—391. In general, the main drivers ofthe netchange ofsoil total cartx»n are the organic matter from plant residues, soil biota metabolisms, and organic amendments which the first two can be supplied or sustained by cropping 140, 411. Cover crops affect soil organic matter (SOM) and different forms ofcarbon in soil, i.e,, total carbon, organic carbon and different fin-ms ofactiveor labile organic carbon (LOC) that are often known asthe particulate organic carbon (POC) and permanganate oxidinblecarbon (POXC or MnoxC). Soil OC is the carbon componentofSOM. which can be 58-60% ofSOM 1421. POC and POXC are the small and active fractionsofthe soil TOC BJOI, and their lability (undergoing breakdowns) has been reported to have a relationship with the biomass of living organisms |43, 441. LOC fraction asan active soil OC component is mostly derived from fresh organic materialsand often correlated with the dynamic ofSOM. and is highly sensitive to soil management 145, 461. Soil with improved SOM management is likely to have higher prtxiuctivity due to increased LOC 1441 In a semi-arid drylandcropping system, planting cover crops to replace can vitalise soil aæregation through directaddition OfSOM. pro- mating microbial activities, binding ofsoil particles by roots or fungalbyphae; andaæravation Ofwet•dry cycles due to evapotranspiration 1471.

Improved SOM or soil OC Can lead to changes in mil physical characteristics and poten- tially u»il water characteristics 1481. Hm«ver, the response of plant available water capacity (PAWC) and soil water retention to variation ofSOM ormil OC were reported to differ as SOM varies with Mil texture 149, 501_ For example. an increase in SOM can decrease evalu)ra• tion and suppreß infiltration and hence increasing soil water retention during cover crop growth Stages and improving water efficiency | 511. On the other hand, an increase in SOM maydecrease soil Water retention for heavy clay soils 1491.

In dryland environments. soil microbial communitiesare considered asanothercrucial component, which play an important role in coordinating Water and nutrient inputs and out• puts. which consequently Can affect nutrient cycles and hydrological cycles 1521. In particular. arbu«ular mycorrhizal fungi (AMF) play acritical rolein soil•plant interactions suchas stimulating residue decomposition. ficilitating plant nutrient and Water uptake, and facilitating soilcarbon cycling 153, 541. The interaction between soil water and AMP is often associated with host plants. Soil water availability has a direct impact on plant rc»t lifespan and turnover. consequently, affecting AMF communitycomposition andsymbiosis 155, 56J. AMF regulate A'il water content through hyphal colonisation and glomalin•related soil proteins (GRSP), which promotes soil aggregation and soil physical structural stability 157, 581_ Meanwhile, GRSP consists of30-40% carbon and its related comB»unds were to be beneficial in improving water holding capacity and hydraulic conductivity, andsubsequently positively correlated with plant availablewater content | 601. The preRnce and decomposition of cover crops can affectthe characteristics ofthe microbial communities, such asvariation and structure. 1611. Cover croppinb particularly with no-till practice can not only enhance rootcolonimtion from AMF and possibly shifting AMF community structureduring cover cropping rau•n 1621, but also enhance early mycorrhiml colonization ofthe following crop and assist the success ofseedling establishment 163.641. Cover cropping can be a potential way to improve available carbon, AMP colonimtion and population nutrient accessibility |65, 661, •and potentially facilitate the symbiotic relationship between AMFand crop "Kits firexchanging water and nutrients for carbon 1671_

Overall, cover crop incorporation provides range ofenvironmental benefits, such as improved soil physical and biological improved soil water and nutrient availability, and reduced soil carbon decline rate 122, 68—711. Facing the uncertainty ofclimate variability and increasing food demand, strategic deploymentofcover crop practices can beofsupport for maintaining thefunction and resilience ofagroecosystems 1721. effectiveness ofcover croppinghas been reported to vary• across many parts ofthe globe and lirnited previous works exist on how cover crops affectsoil and productivity within acropping systemin Aus, tralia, in particular, the state ofQld 173, 741. Theobjectives ofthis studywere to evaluate the effect ofsummer cover crop practices On I) soil OC (i.e,, TOG POC and POXC) and soil AMY DNA sequence concentrations at termination time ofsummer cover crop; 2) soil water acros the soil profile (i-e-O- 150 cm) over the growing and at the sowing time Ofthe f»llowing cash crop; and 3) investigate the delkndencies between soil OCand soilwater at planting. wheat biomass, yieldand grain quality.

To addrøs the questions and explore the e*ects OfCovercrop On soil health and cash crop yield production over growing in the rainfed agricultural system, on•farm trial was conducted to monitor soil water across the soil profile, soil OC andAMF DNA concentrations, wheat biomass, yield and grain qualityin awheat cropping system planted after a sum• mer cover crop-terminations of ummer covercrops were applied to manage soilWater and carbon- nlis aimedto improve ourunderstandingofthe plant• soil•water relations in the rainfed cover cropping system in the eastern region ofthe wheat belt, Where crop production is highly deirndent on soil Water at planting time and to investigate Whethercover management can influencesoil Water characteristics and soil carbon accumulation.

2. Material and methods

2.1 Study site

The field experiments werecarried out on a firm located north ofGoondiwindi in the SouthweÄ ofQueensland State. Australia (Fig I)- Theaver+ annual rainfall oftheregion is approximately 486 mm (summer dominant), with monthly mean temperature ranging from I IS to 27.0•C [751. study site a crop growing region in Australia, as it is within the northern part ofthe grain belt region, where cereal crops (such as wheat,oats, barley, sorghum and maize)are grown in an extremelyvariable climate 1761. Water supply and storage (soil water storage) are the major limiting factors for dryland grain production in the region 1771. In 2015/2016, the Goondiwindi region•s cerealproduction was the *cond largest commodity ofagricultural production in the region, which accounted of Goondi-
Windi Regional Council's total agricultural output in value terms (AUS530 million) 1781.

The studysite had been managed undergrain cropping• systems by the landowner.

The site experienced long fillow in 2019 due to the drought condition which could potentially •alter soil microbial composition and activities (e*, microbial decomposition ofsoil organic matter) With a in soil carbon and nitrogen balance•1791_ In 2020, Winter wheat wasplanted in May and in October, With Wheat stubbleleftstandingin the fielcL

Experimental trials are part ofthe project the Broadacre Cropping Initiative (BACI) supported bythe Queensland Government (Department ofAgriculture and Fisheries) and the University ofSouthern Queensland. All the approvals ha-ve been obtained for conducting this research and such as property name and coordinatescannot be di.sclosed tar confidentiality Our trials wereconducted in 2021 with extended summer rainßll (Jan— May) 2% below the 1990—2020 average, which rainfill distribution Overthree months was greater than average onlyat the ofsummer (sowing time ofsummer cover crop) but became significantly lower than average three months beÉ»re planting the winter wheat in late May (Fig I Thus, the examined year is a good example Ofa seasonalcondition in an area where wintercropyield is highly dependent on soil water storage The soil is classified as a vertosol | | With a high clay content that ranged between 40 and 60%. have shrinking and swelling characteristics in to the changing soil water content which ik related to the changes in interparticle and intraparticle porosity |821. Fig (C) shoys examples ofthe crackingsoil suråceat the trialsite.

2.2 Trial design

Field trials wereconducted duringthe202VsummerandWinter T%etrial design for the cover crop season "as arandomised complete bltxk design 1831 underthe uniform paddock condition With five replicates treatment. including Gillow treatmentas com trol. CINer crop plotswere terminated by spraying at three differentstages early, mid and late stages (Table I). For the comparison, the control plots remained as fallow as is a common practice during the summer æason before planting the cash crop, Therefore, a total numkn•rOf 20 zero-tilled plots were used for the summer cover crop trial with 5 replicates for each treat• ment- For the winterEason, thetrial dßignWas based on asplit-plotdesign [841 whichequally

(a) (b)

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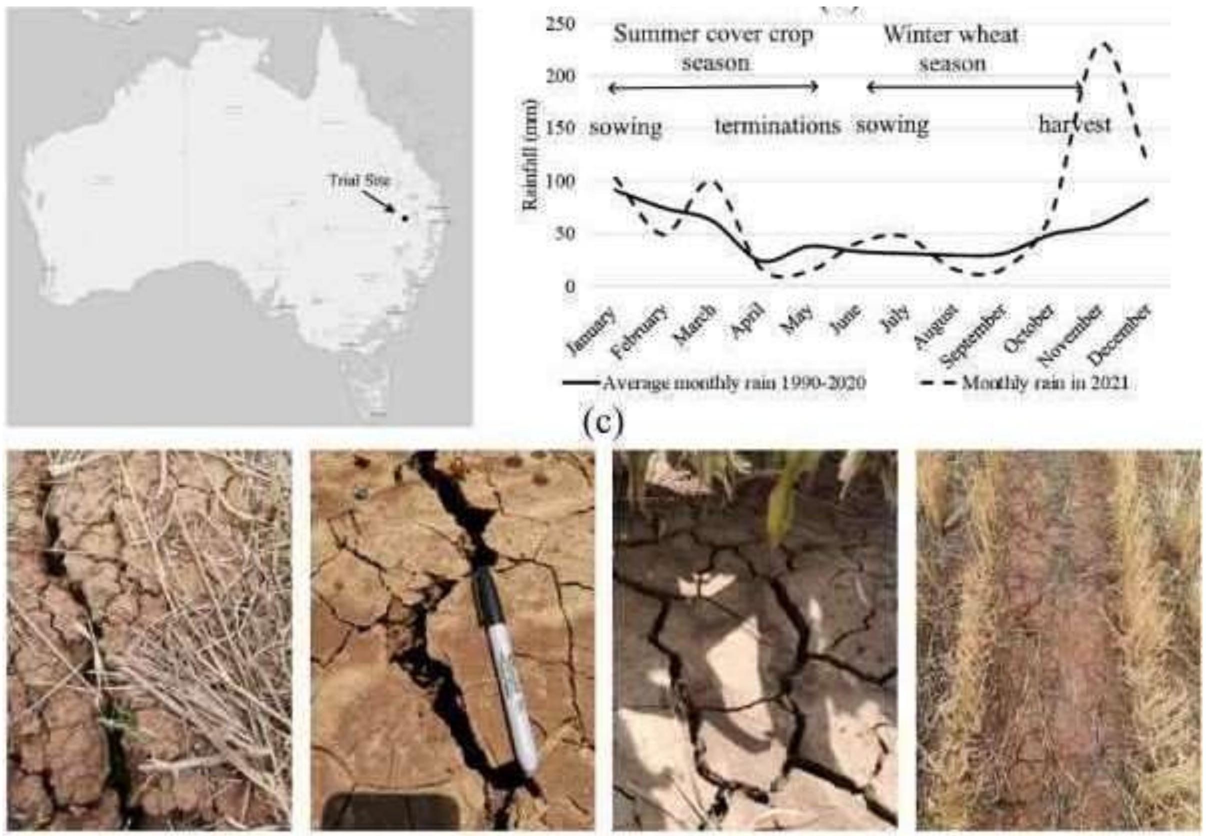

Fig 1. Case study site (a) approximate location of trial site, (b) monthly average rainfall of the season in comparison with the long-term average, (c) soil surface at the trial site (Photos taken by Hanlu Zhang in 2021). Cracking soil surface is a characteristic of the vertosols of the study site.

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divided each plotinto 2 sub-plots. 'me the subplots Were wheatand fal-low (as control)- "lherefore, a total number 20 sub-plots Wereplanted withWheat and another 20 plotswer Jen asfallow.

2.3 Sampling

Soil from replicate plotsOfeachtreatment conducted during the summer cover crop trial and wheat trial in 2021. Thesampling included collecting soil cores for measuring soil physical characteristics such as bulk density, particlesixk distribution, soil water content acrossthe profile,andsurface soil samples measuringsoil OC and its active fractions and the AMF DNA concentrations (Table 2). The related soil attributes were collected to evaluate the effect Of covercrop and its termination management on soil water, OCand labile fractions, and AMF DNAsequenceconcentrations over the growing seasons asprexnted in Table 2. These relevant soil åttributes were collected for analysis at a system leveL

2-3.1 Soil water. Soil profile samples w•ere collected measurement ofbulk density, partide sin distribution. and gravimetric and volumetric soil water content- Intact soil cores (43 cm diameter by 50 cm) up to IS m ofsoil profile were collected from each treatment plot using a hydraulicsoil sampling Soil cores were cut into 10.0 cm height sections and placed into PVC columnsfor storageand transportatiom soil coreswereprtxesu•-d in the mum of4* hours to

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Table 1. Components of the farm system at the trial site. Weather records are for the growing season (Jan-Nov 2021).

Weather	**Records**
Rainfall (mm)	542.8
Mean max temperature (°C)	25.7
Mean min temperature (°C)	12.3
Summer cover crop trial	**Trial information**
Plot size (m)	18 x 6
Crop cultivar	sorghum (MR Bazley)
Summer control (SC)	Fallow (sprayed and no weeds)
Planting date	15/01/2021
Sowing depth (cm)	3
Row space (cm)	25
Early termination (ET)	2/03/2021 (flag leaf emergence)
Mid termination (MT)	30/03/2021 (soft dough)
Late termination (LT)	21/04/2021 (hard dough)
winter wheat trial	**Trial information**
Crop cultivar	wheat (Suntop)
Winter control (WC)	Fallow (sprayed and no weeds)
Sowing depth (cm)	30
Row space (cm)	25
Planting date	28/05/2021
Harvest date	27/10/2021
Chemical used	**Application rate**
Herbicide application	Roundup UltraMax 0.2 ml/ha applied at each termination (Active ingredient 570g/L Glyphosate)
Fertiliser application	Starter Z 25kg/ha on 15/01/2021 and 40kg/ha on 28/05/2021 (Mono ammonium phosphate plus zinc, containing 10% N, 22% P, 2% S and 1% Zn)

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laboratory for initial field weight and oven-dried weight through oven dry at 105°C for a minimum of 48 hours to determine the bulk density and gravimetric soil water content. Due to the cracking clay characteristics of the vertosol soils, it is challenging to accurately measure soil water content among various proximal sensors [85]. For this study, neutron moisture meters

determine the bulk densityand gravimetric soil water content. Due to the cracking clay characteristics ofthe vertosol soils, it is challenging to accuratelymeasure soil water content among various proximal senuyrs 1851. For this study, neutron moisture nkters (NMM) were used to regularly measure point•source soil Water in the field- Soil water content measurement using NMM has a better representativevalue as themeasurement sphere is up to a 15 cm radius around the emitted neutron source- In this way. soil cracks are less likely to affect the reading (Fig 2). Soil Svater monitoring using the NMM approach was based on the physical interaction ofradioactive neutrons with hydrogen atoms,and it had better control of tx»th bulkdensity andhydrogen atoms during the calibration process 1861. On the basis ofthe positive relationship between the relative neutron Count rate and volumetric soil water, soil watercontent was estimated from the NMM readings (Fig 2). Prior to the plantingofthe sum• Inercovercrop, atotal number of20 aluminium NMM access tubes were installed at the cen• tre ofeach plot. which allows taking neutron counts for each soil depth at 15cm, 35cm, 45cm. 55cm, 75cm, 105cm and 135cm- Atthe end ofthe summer trial, NMM access tubes wereall removed the preparation ofwinter wheat planting- 40 tubes were reinstalled after planting and resumed NMM reading measurements for all 40sub,plots. NAIM readings were taken regularly as part ofsoil watermonitoring duringthe growing seaNM1. NMM readingswere soil water

Why measure? What does this represent?	
sical characteristic of soil represents soil structure and compaction. Can be an tor of soil health in response to changes in management.	Blake and Hartge 1986 [87]
sical characteristic of soil that drives water holding capacity and flux movement.	Gee and Bauder 1986
e % soil water on a dry-mass basis; critical to plant growth, nutrient movement icrobial activity	Reynolds 1970 [89]
e ratio of soil water volume to the volume of soil, can be calculated from measured multiplied by BD	
l in soil organic matter; C component of organic compounds; An indicator of soil and biology.	Sweeney and Rexroad 1987 [Etheridge et al. 1998 [91]
or partially decomposed plant residue and animal matter with identifiable cell ure. Makes up 2–25% of total soil organic matter; labile OC pool [92]	Blair et al. 1995 [93]
-pool of labile soil OC is defined as the C that can be oxidized by potassium nganate ($KMnO_4$) [92]	Cambardella and Elliot 1992
tant microbial communities that regulate plant growth [58] and contribute to soil ate formation and stability [57]	Sanders et al. 1995 [95]; Senés-Guerrero and Schüßler 2016 [9

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Table 2. Soil attribute tests performed in this study and the purpose of conducting those tests.

Attribute	Why measure? What does this represent?	Method reference
Bulk density (BD)	A physical characteristic of soil represents soil structure and compaction. Can be an indicator of soil health in response to changes in management.	Blake and Hartge 1986 [87]
Soil Particle Distribution	A physical characteristic of soil that drives water holding capacity and flux movement.	Gee and Bauder 1986 [88]
Water (VSW)	ik It i• [illegible]	[illegible]
Total Organic Carbon (TOC)	Stored in soil organic matter; C component of organic compounds; An indicator of soil health and biology.	Sweeney and Rexroad 1987 [90]; Etheridge et al. 1998 [91]
Particulate Organic Carbon (POC)	Fresh or partially decomposed plant residue and animal matter with identifiable cell structure. Makes up 2–25% of total soil organic matter; labile OC pool [92]	Blair et al. 1995 [93]
Permanganate-oxidisable Carbon (MnoxC or POXC)	A sub-pool of labile soil OC is defined as the C that can be oxidized by potassium permanganate (KMnO4) [92]	Cambardella and Elliot 1992 [94]
Arbuscular Mycorrhizal Fungi (AMF)	Important microbial communities that regulate plant growth [58] and contribute to soil aggregate formation and stability [57]	Sanders et al. 1995 [95]; Senés-Guerrero and Schüßler 2016 [96]

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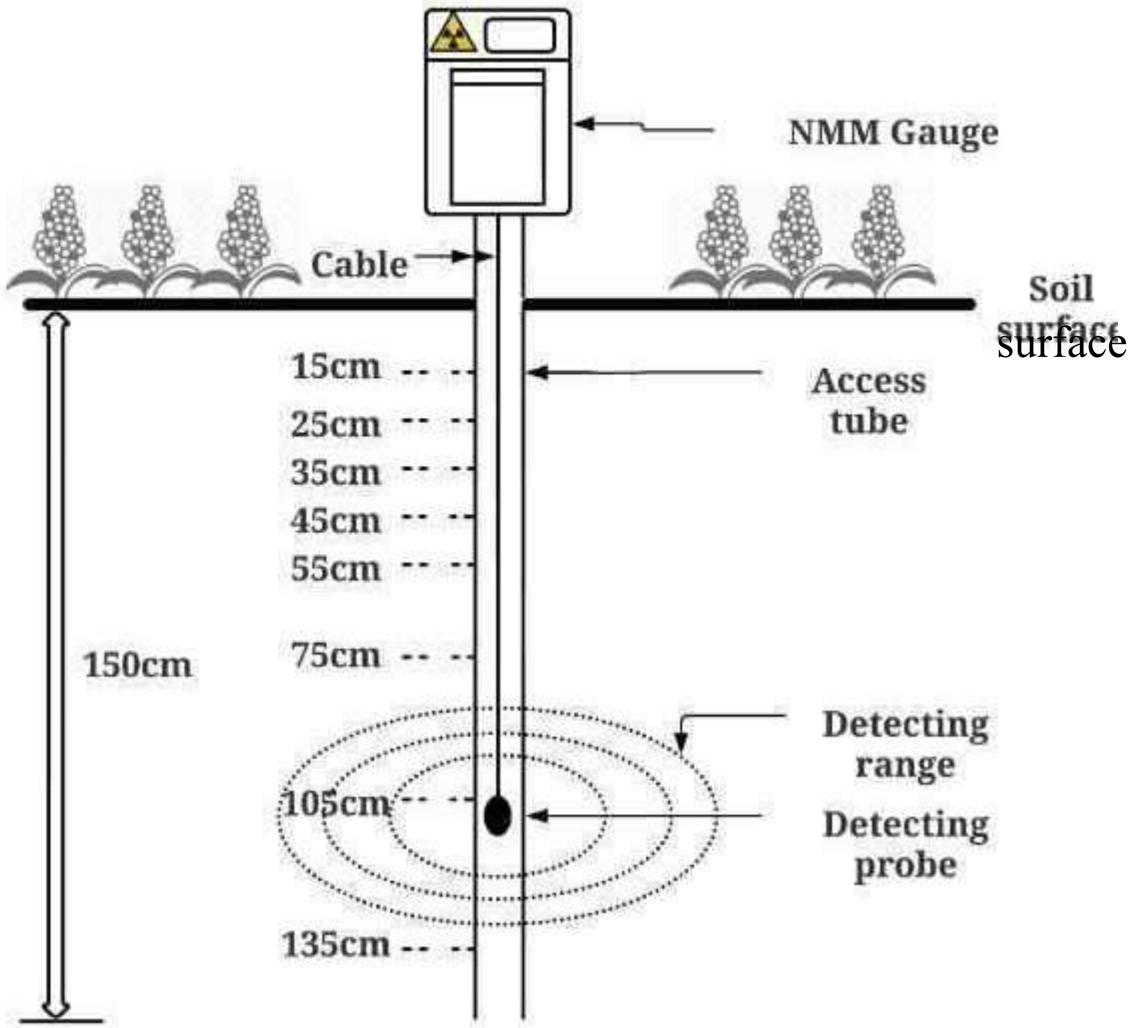

Fig 2. Use of neutron moisture meter probe in the field.

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cOUected bya licenced technician at weeks Byusing the dryweight ofthesoil cores (43 mm diameter by 500 mm length) collected from each depth at the timeofneutron probe accßs tube installation, soil bulk density and gravimetric water content were measured. then converted to volumetric soil water content_ The neutron probe was calibrated against gravimetric soil wratercontent, soil textureand bulk density each plot. Soil particle si7.e dis• tribution ofthe whole soil profile was measured forall plots.

2-3.2 carbon. Top I(krn soil samples were collected (10 subkåmples plot) atthetermination time ofsummer cover crop to monitor soil OC contentand its labile fractions POC and POXC (Table 2) to be explored along with soil watercontent- At theend ofthewinter trial, soilsamples were sampled IOC and POC contents (10 subslmples for subplot). The soil Nmpleswere tested by commercial laboratories (Chemistry Centre, Department ofEnviron• ment and Science, Queensland Government. QId; the Environmental Analysis Laboratory, South Cross UniversityyNSW), to determine total OC content |89, 901, POC 1941 and POXC contents 1931. •Ille samples wxre air-dried at 40•C and ground to paß through a 2 mm sieve bef»re the '1%e instrument used for u»il total OC meamrementvas TruMac Carfm•n/Nitrogen Deter-minator (LECO Corporation. St Joseph, MI. USA). '1%e carbon content ofthe soil Nmpleswas determined byanalysingtheamount ofcarbon dioxide produced from the com• bustion ofthe sample at a high temperature based on the Dumas combustion method 1971. Measurement of POC contentwas measured bydi+rsing soil samples in Calæn (sodium hexametaphosphate) to extract soil fraction >50um, then prcKessed for the carbon determination in LECO |94, 981.Soil POXC measurement used MnOa- solution (KMn04) to react with the soil sample and the POXC content based on the degree "oxidation 1931.

2.33 arbuscular mycorrhizal fungi (AMF). "1%e soil samples in the top 10 cm were collected from each summercovercrop treatmentand their corresponding control plot to test AMF DNA concentrations lifferent speciesgroups (Table 3). At each plot, 10 sub• per plot were cdlected to form one sample (approsimately 4K)gJsample) that repreEnts the whole plc* area. 'Ihe samples were tested at a commercial lab the South Austra• lian Research and Development Institute (SARDI) laboratory DNA-based characterintion andidentification ofAME from different phylogeny ta_xa groups. In the laixwatory, to identify the AMF DNA concentration ofeach functional group, AMF spores were extracted from the soilSimples using Sucrose centrifugation and flotation. followed by olymerasechain reaction (PCR) DNA extraction to 'krform molecular 195, 961. •Il-ve AMF test measured the DNAsequence concentration in each sample and assigned to their phylogeny taxa using the maximum likelihc«xi method based on near length small ribosomal subunit (SSU) rRNA xquences 1991. 'Iheresults exhibited the existence ofgroups A and B (Table 3), these two groups arefrom the genus OfFunneliformis and Claroideglomus 199, Ihe functional di•ær• sity ofAMF such as the function ofmycorrhiml symbiosis and its symbiotic efficiency is geno type dependent and can be complex to study the characteristics of species individually 11011. Therefore. for simplicity, the groups A and B were identified based on the DNA *quence. which Was used fyranalysisin this paper. rather than the individual slrcies in cach group

Table 3. AMF species groups and species in each group.

Indicator	Group	Species
Arbuscular mycorrhizal fungi (AMF)	Group A	*Funneliformis mosseae, Funneliformis constrictum, Funneliformis coronatum, Funneliformis geosporum, Funneliformis verruculosum, Funneliformis caledonium* and *Funneliformis fragilistratum*
	Group B	*Claroideglomus claroideum* and *Claroideoglomus etunicatum*

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(Table 3). AMF DNA sequences in soil and their variation under different summer cover crop treatments were observed to explore whether there were linkages to the changes (e.g., soil

treatments Water)-

23.4 Crop. During thesummer Cover crop trial, above-groundsorghum biomass Was Nmpled,at the time ofeach termination using a 0.25 m^2 quadratand five random sampling Within the plots. Thesamples were oven•dried at 70•C for 72 hours and then weighed to mea qlre dry biomassweight During the Winter above-ground wheat biomass from each plot was collectedat two differentgrowthstages grain filling and early maturity phenology Stages, and collectedyield at the harvest. 'Ihe biomass was oven-dried and wei#d using the sameprocedures explained earlier. Grain samples were analysed byacommercial lab (Leslie Reæarch Centre, Department ofAgriculture and Fisheries, Queensland Government) to test grain quality Le., grain protein, and wheatscreenings. Ahe near-infrared transrnittanceand Dumas combustion (LECO) were applied for the measurement ofthe nitrogen (N) Contentto calculate the protein content based on Protein% N% x 57 | 1021. The 'krcent+ of the grain samples that pas through a 2mm sievefslotter screen &sraS measured to determine gramsize.

2.35 Crop wateruseefficiency. Waterusebycrop (WU) was estimated as the difference between the sum ofin-crop rainfall and the soil water contentat times ofsowing and harvest 11031. should note that in here evalx»r-ation is assumed to be part of The water•ux efficiency (WOE) was defined as the amount ofgrain that is produced Fr unit ofwater used by the crop, (Le,, WUE - Yield/WU) 11031.

2.4 Statistical analyses

2-4.1 ANOVA. alualityofthe variances homoscedasticity) for the observed variables was assessed using Levene's test. The dataset was then subject to one-way ANOVA with TurkeyHSD (honestlysignificant difference) Post Hoctestto asRss the significant impacts of cover crop treatments on soil TOC POC and POXC,, soil water atwheat planting, wheat bio• mass grain filling and earlymaturity, yield, grain protein and screening size For those attri• butes that had unequal variances (resulting P•value <O.OS based on Levene's test), Games• Howell Wasconducted nonparametric poÄ hoc analysis Sources Ofvariation were partitioned into between•group 6ctors (treatment). The mean values of these variableswere com• pared under different coverCrop treatmentswith P<O.05 accepted as beingsignificant.

2.4-2 PCA. Kaiser-Meyer•Olkin (KMO) test was used to determine the sampling ade• quacy ofthe observed data, with KMO value closer to 1.0 is ideal while values less than 0-5 is considered unacceptable 1041. The KMO value in the acceptable range as it was equal to 0.687_ Bartlett's ofsphericity wasalso applied to ifthe observed variables were ideal åctor analysis with P<O.05 beingaccepted as suitable 11051. Then the datart was subjected to the principal component analysis (PC—A) to interpret our multi-dimension observed dataset and assist with exploring the underlying correlations among observed attributes IBM SPSS Statistics 270 Windows) Was •.ßed for theOne-w.y ANOVAand PCA analysis.

3. Results

3.1 *lil organic cartx»n affected by cover cropping

At the trial site, soil total or•ænic carbon (TOC), POC and POXCcontentsin topmils (O— I(km) increased at each termination time ofthe summercovercrop. Early. midand late terminated plots had greater TOC by 7%, 12%. 17%, and POC by 24%, 72% in comparimn with the control

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plots (Table 4. Fig 3). POXC contents in early, mid and late termination plotswere all lowerthan the control (Fig 3).

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Table 4. One-way ANOVA tests showing the significant level of the observed variables means under cover crop treatment in comparison to summer fallow (control). Comparisons without a significant level were considered statistically insignificantly different i.e., P-value>0.05. Grey shadowed values: a significance P<0.05 was observed.

Observed Items	Dependent Variable	Early Termination	Mid Termination	Late Termination
SOC at cover crop termination	TOC	0.579	0.123	0.016
	POC	0.806	0.744	0.001
	POXC	0.122	0.578	0.992
Soil water at wheat sowing	0-15cm	0.991	0.623	0.026
	15-30cm	0.611	1.000	0.0005
	30-45cm	0.996	0.082	0.002
	45-55cm	0.994	0.705	0.0001
	0-150cm	0.988	0.472	0.0002
Wheat biomass during growing season	Biomass, Grain Filling	0.238	0.936	0.010
	Biomass, Early Maturity	0.732	0.998	0.007
Wheat yield and grain quality at harvest	Yield	0.728	0.755	0.001
	Grain Protein	0.447	0.343	0.064
	Screening size	0.041	0.902	0.917
Soil OC at the end of winter	Fallow TOC	0.833	0.876	0.179
	Fallow POC	0.885	0.546	0.171
	Wheat TOC	0.636	0.294	0.652
	Wheat POC	0.962	0.138	0.361

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At the harvest of the winter wheat which was planted following the summer cover crop (Table 1), greater TOC contents were observed in plots that previously had early, mid and late termination, by 7%, 11%, 7%, respectively, and greater POC by 11%, 52%, 38%, in comparison With plots that were under control during qummer (Table 4. Fig 3).

3.2 Soil water storage affected by cover cropping

The termination time ofthesummer cover crop affected the soil Water atthesowing timeof winter wheat with the greatest soil observed in early termination plots (Fig 3). The soil Watercontent at 15cm»25cm and 35cm were lowest at late termination plots compared to the control (Table 4). nuesoil water of the whole profile (O— 150 cm) at wheat *'Wing Was obrrved to be in the order ofthe highest to the lowest: control>early termination>mid termina• tion>late termination (Fig 3). While a % decrease in whole profile soil water was CBserV«i for early termination. soil water increased by in 15cm.4% in 25cm and I in 35cm, com• pared to the control (Table 4). Mid terminated plots had lower soil water at Ikm, 35cm and across profile by 10%, and 3%, compared to the control plots, but no difference was observed at 25cm (Table 4). Soil water at I 2%m. and _3Scm and in the whole profile at late terminated plots were lowerthan the control by 28%, 18 and 7% (Table 4).

Soil water changed over time in all treatments across the soil profile, but the control plots had the least declineand fluctuation during observations (Fig 4). A decline in soil Water was observedfor all treatments(Fig 4) suggesting water uptake by the plant, and termination prevented further water loss through transpirationand plant usage. At the end ofthe sum• mer and Wheat sowing time, earlytermination had similar or even greatersoil water compared to the contml (fallow) and significantly greater than other treatments (Fig 4). As shown in Fig 5 there was no significant rainfall two months

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before wheat planting' but early termination was ableto store the received rainfall. In comparison with control plots, soil water contentsin mid and late terminations plots werebothaffected by the delayed

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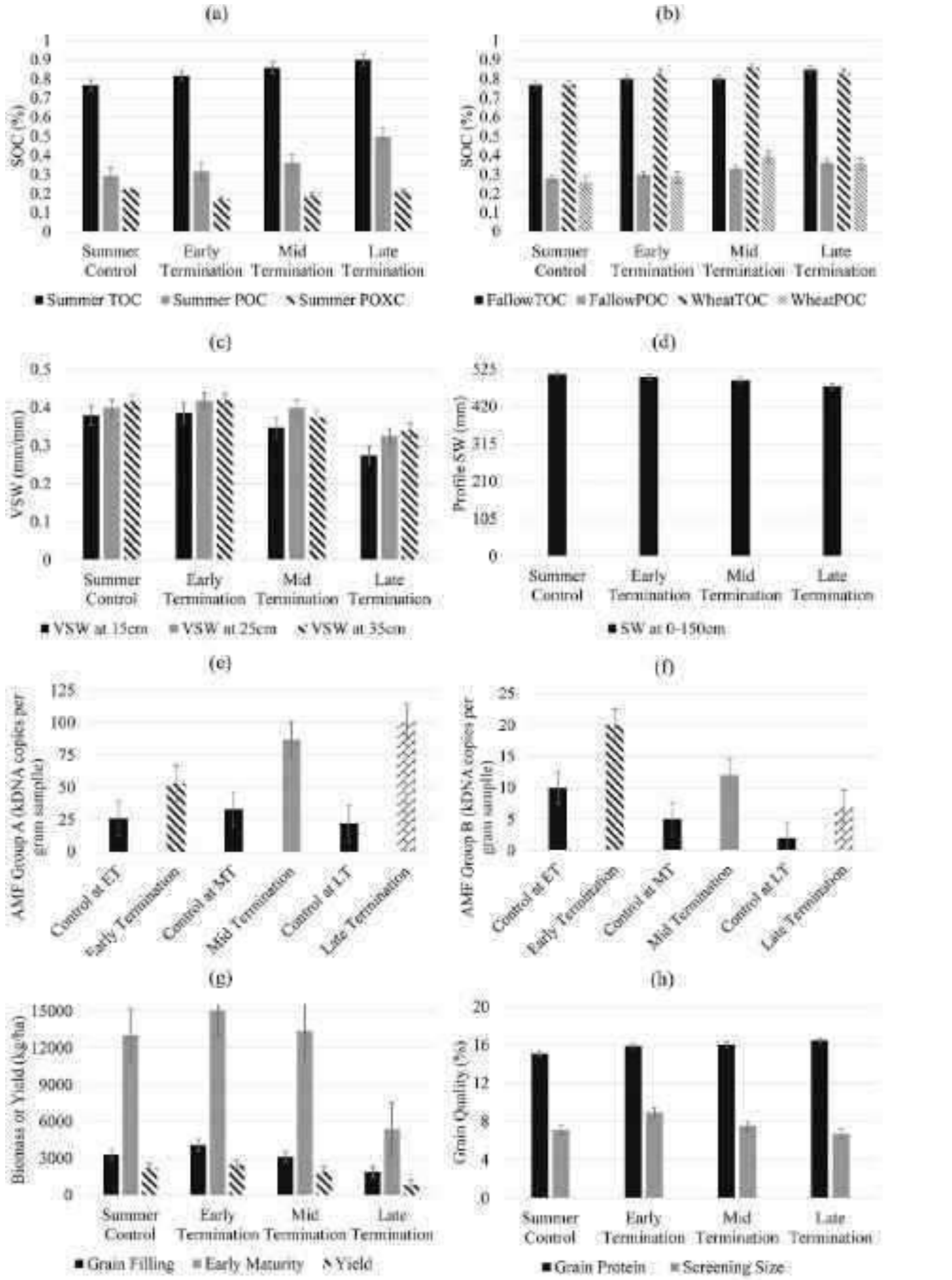

Fig 3. (a) Soil total organic carbon (TOC) and particulate organic carbon (POC) and permanganate oxidizable carbon (POXC) at 10 cm depth at the time of termination of summer cover crop; (b) TOC and POC measured at harvest time of winter wheat; (c) volumetric soil water (VSW) content at 15cm, 25cm and 35cm and (d) whole profile soil water at wheat sowing time; AMF Group A (e) and Group B (f) measured at the time of termination of summer cover crop; (g) wheat above-ground dry biomass measured at grain filling and early maturity phenology stages and yield at harvest; (h) grain quality. SC: Summer control; ET: Early termination; MT: Mid termination; LT: Late termination.

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termination, especially in deeper soil layers and the whole profile (Fig 4). There was a 14% decline in the whole profile under late termination compared to the control. Overall, mid and lateterminated cover crop did not show an advantage in preserving greater soil water

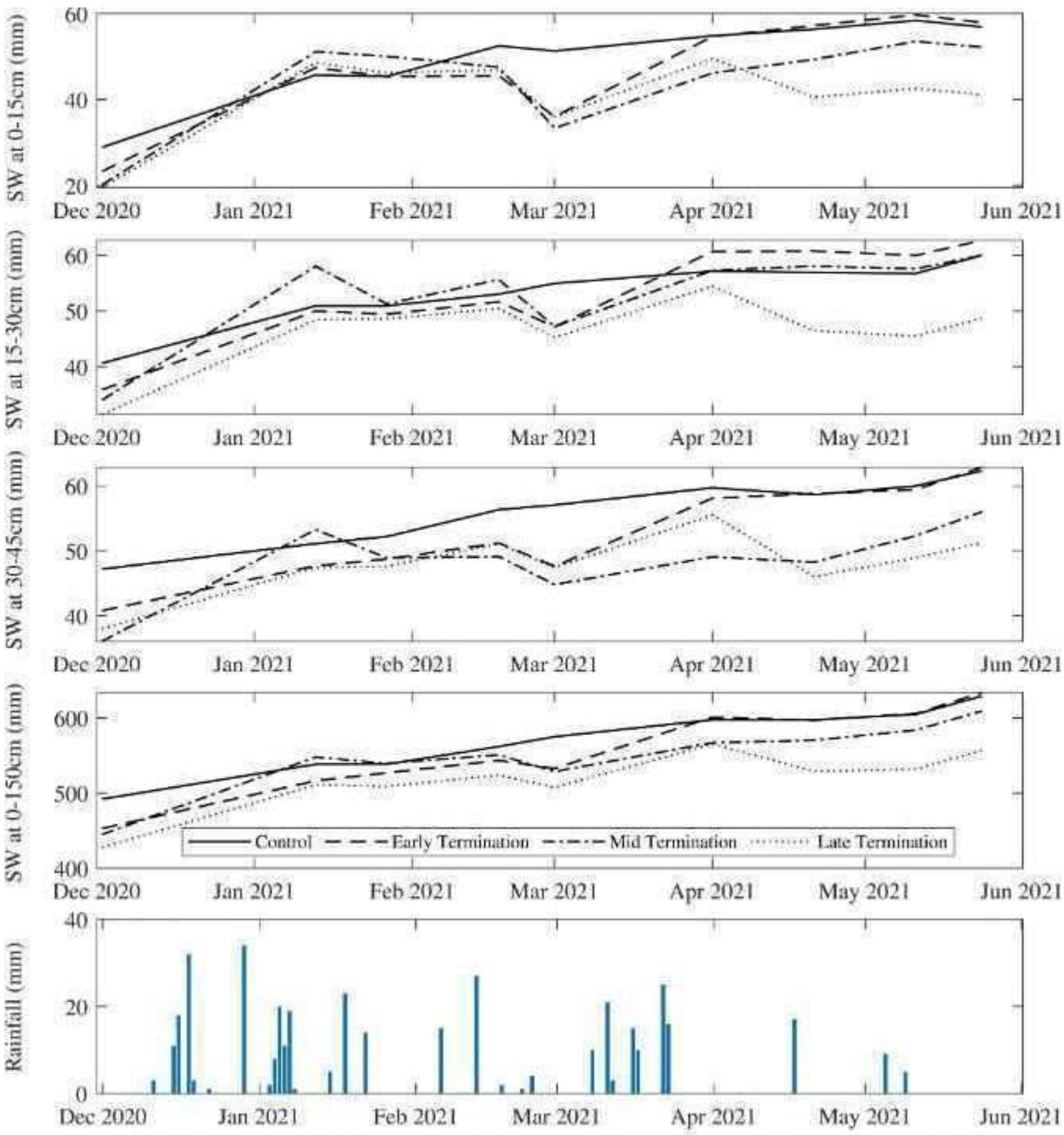

Fig 4. Soil water storage of top layers (0-15cm, 15-30cm and 30-45cm) and whole profile (0–150 cm) during summer cover crop. At the planting time, in the absence of rainfall for 18 days before planting, Early termination had stored higher water in surface soil (0-30cm) while performed same as fallow for all other layers and averaged for the whole profile.

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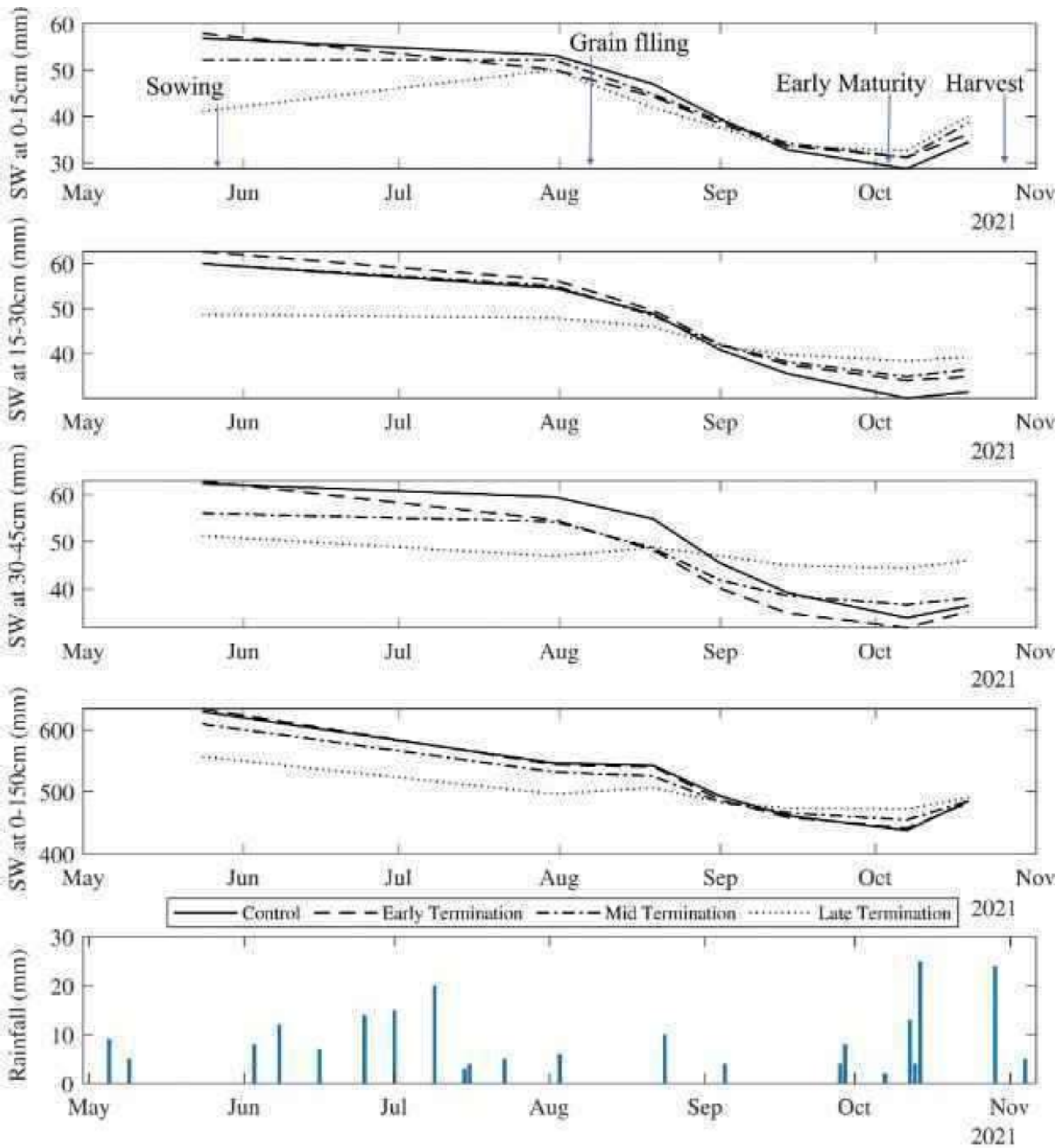

Fig 5. Soil water in topsoil layers (0–15cm, 15–30cm and 30–45cm) and whole profile (0–150cm) during the winter season.

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than the control at wheat sowing time, possibly due to little rain received after termination and prior to planting.

3.2.1 Changes in soil water storage over winter cover crop. Soil water in the surface layer (0–15 cm), where wheat was planted on early terminated summer cover crop plots did

layer (O—15 cm), where wheat was planted on early terminated summer cover crop plotsdid invadsm

not significantly over the season when compared to those planted in control plots (Fig 5b Fallow. early, andmid-terminated plots hadalmostsimilar water at the grain filling

Äage across the WholeSoil profile. but WaterWas higher in 15—30cm depth underearlyter• mination (Fig 5). However, soil water wassignificantly lower atsowing timein plots where Summer Cover Crop wastreated with mid and late termination.

At the flowering stage, wheat plots that were planted on earlyterminated summer cover crop plots had 0.5% less profile soil water compared to the control, followed by 2% lesin mid termination and 9% lessin late termination. When the wheat crop reached initial grain•filling stage, the in profile soil water compared to the control were •O I% and in wheat plots fallowing early, mid and late terminated cover crops. At the end ofgrain filling. the whole profile's water differences were lower than the control by I.8%, 2.I% and 2.5% in wheat plots early, mid. and late termination. Wheat planted on late termination had the lowest soil watercontent until the grain filling stagecompared to the control and the other treatment plots. however, for 0—1Scm layer,soil water was notsignificantly to other treatments at the flowering stage. By the end ofwinter (harvest rips). the highest soil water contents top layers and whole profile were in wheat plots followinglate terminadon. followed bymid and then early termination.

3.2-2 Covercrop and water ug and Covercm'" Wereterminated at dif• ferent dates. so the amount ofWU by crop and in•season rainfall received at each termination treatment Was different (Table 5). The early terminated covercrop plots had the opportunity to receive the least in,season rainfall during growth (9Imm), therefore this treatment had less opportunity to water (73.Imm) compared to the other treatments (Table 5). Contrary. late termination plots used 187.8mm from 208mm ofrainfill that they received. In winter, all wheat plots received the amount ofrainåll 164mm), but their WU and WUE varied in differentplots due to the effect ofthe previous cover crop treatment in summer (Table 5). Wheat planted on earlyterrnination Cover crops had the highest WU and WUE compared to the wheat planted On summer control by and 10%. The wheat planted on mid termination plots had 2% greater WUE, though its WU was 14% lower than the wheat planted on summer control plotx The Wheat planted on late terminationplots had lover WU and WUE than the wheat planted on summer control plots.

3.3 Arbuscular mycorrhizal fungi affected bycover cropping

in control plots. AMY group A DNA sequence concentration (SC) increased from the time of earlytermination towards the time ofmid termination but then declined at late termination (Fig 3). The greatßtAMF Group A SC wasobservedin latetermination plots, follo»æd by mid

Table 5. Water use (WU) by summer cover crop and water use efficiency (WUE) in wheat plots following cover crops.

Variables	Summer Cover Crop Treatment			
	Control (Fallow in summer)	Early Termination	Mid Termination	Late Termination
Summer cover crop season				
Rainfall, planting to termination (mm)	-	91	191	208
WU (mm)	0	73.1±16.9	170.3±7.9	187.8±13.2
Rainfall, termination to planting (mm)	-	131	31	14
Wheat planted following summer cover crop				
Rainfall, planting to harvest (mm)	164	164	164	164
Wheat yield (kg/ha)	2226±219	2500±221	1965±154	870±133
WU (mm)	289.7±13.2	296.8±10.1	250.5±14.3	178.3±10.1
Wheat WUE (kg/ha.mm)	7.7±0.7	8.5±1.0	7.9±0.8	4.8±0.6
ΔWU, Treatment Vs planted on summer control	-	2%	-14%	-38%
ΔWUE, Treatment Vs planted on summer control	-	10%	2%	-37%

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and eadytermihation (Fig 3). AME group B SC control and over cropped plots all decreased ή-στη the time ofearly termination towards the time oflate terminatioll- Overall, DNA SC ofboth AME Gmup A and H ',vere between the treatment plots and control plots. AMF Group A DNA SC increased by 356% in late termination plots. I in mid temli• nation plots and IIμ4% in e-arly termination plots compared to the coatr01. DNA SC "fAME Group B ίπ late termination plots was 25I% greater than the contml. I 19% greater mid ter• millation and I greater άη eady terTllinati011-

3.4 Wheal biomass, yield and grain quality

growth Aages, with the tirst biomass M111Ples collected during lhe grain tilling stage and the =cond biomass samples collected during early maturity- Ohservations that Wheat above•gmund dry matter from late termination pIOts waS 43% and lower than the control plots, in two biomass sampleobservations. 'l%e biomass άη early terminated plots Was 23% greateratthe grain ti11ing stage and I6% greater,at early maturity compared with coatrol plots The biomass ofmid termination plots v,ras 7% lowerat the grain hlling but 3% greater duri11g eady maturity compared to the control plots

The grain yield was highest in early termination plots i-e,, higher than corltrol.The yield under mid late termination treatmellts was I 2% and 6] % lower cmnpared to the control (Table 6, Fig 3). Among au wheat plots. the highest grain protein content was observed inlate termination plots (Fig 3). Grain protein from late termination plot$ was 9% higher tham control. while eaHy and mid•termination plots had 5% and 6% higher grain proteill 6). Grain screening size eady termination plots was 26% higher lha11 control, followed by mid termination (6%), but latetermination plots had 6% lower screefling sil± (Tahle 6).

The one•way ANOVA resu1tsshowed a significant difference between the variance ofcover crop treatment and the control (Table 4). TOC and POC contents measured at termina• tion times ofsummer cover crop showed a signiticant between late termination and the control (P-value = 0.016 and 0.001). No significant difference in soil POXC content was

Table 6. Relative change in soil carbon, soil water, wheat biomass, yield and grain quality affected by summer cover crop compared to the control (fallow).

		Summer cover crop treatment		
Plots	Variables	Early Termination	Mid Termination	Late Termination
Summer cover crop	Δ TOC	7%	12%	17%
	Δ POC	9%	24%	72%
Winter control	Δ TOC	4%	4%	11%
	Δ POC	10%	19%	30%
Winter wheat	Δ TOC	7%	11%	7%
	Δ POC	11%	52%	38%
Crop after summer cover crop				
Wheat, sowing time	ΔVSW, 15cm	2%	-8%	-28%
	ΔVSW, 25cm	4%	0%	-19%
	ΔVSW, 35cm	1%	-10%	-18%
	Δ Profile SW	-1%	-3%	-7%
Wheat, during season and harvest time	Δ Biomass, grain filling	23%	-7%	-43%
	Δ Biomass, early maturity	16%	3%	-59%
	Δ Yield	12%	-12%	-61%
	Δ Grain Protein	5%	6%	9%
	Δ Screening Size	26%	6%	-6%

https://doi.org/10.1371/journal.pone.0286748.t006

taund treatments and thecontrol in summer cover Wheat above-ground dry biomass during grain fillingand early maturity phenologystages showed significant plots with a history ofsummer late terrnination and the control (IL value — O.OI and u007). Wheatyield in plots with a history of late termination was also significandy lower compared to the grain yield from the summer control plots (P•value — O.001).

No significant was observed in grain protein content between plots with cover crop treatments and the controL PlotsWith a history ofearly termination had significantly higher grain screening si7e (P-value — 0.041) in comparisonwith control plots (Table 4). I-ate termination exhibited significantly les soil *rater across the profile (O—150cm) at wheat planting compared to the control (P•value 0.026). Overall. the late-terminated cover crop diRd• vantaged preserving soil water,and consequently grain yield, though itwas ableto significantly increase TOCand POC by termination time.

3.5 Relationships among the variables

PCA results (Fig 6) showed thatwithin the dimension of I Ofvariance). Wheat yield and biomas were closely related to soil Water at 15—30cm and e»ecially in plots with a history of the early terminated cover crop during summer, followed by soil water in 3045cm and 0—15cm- In comB»nent 2 (19.4% ofvariance). PCA revealed an under• lyingcorrelation between soil OC contents (TOC POCand POXC) and ciay content (Fig 6). PCA did not exhibitan underlying relationship between grain quality and the other observed variables- Overall, an underlying correlation ofOC with claycontent and yield With soil Wateratplanting time was observed-

3.6 TOC and Labile OC relationships

Results show that soil POC had a relationship With 'IOC content, and a greatercorrelation -betweensoil 'IOC and IOC wasfiund in Nimmercoyercrop plots and wheat plotsunder

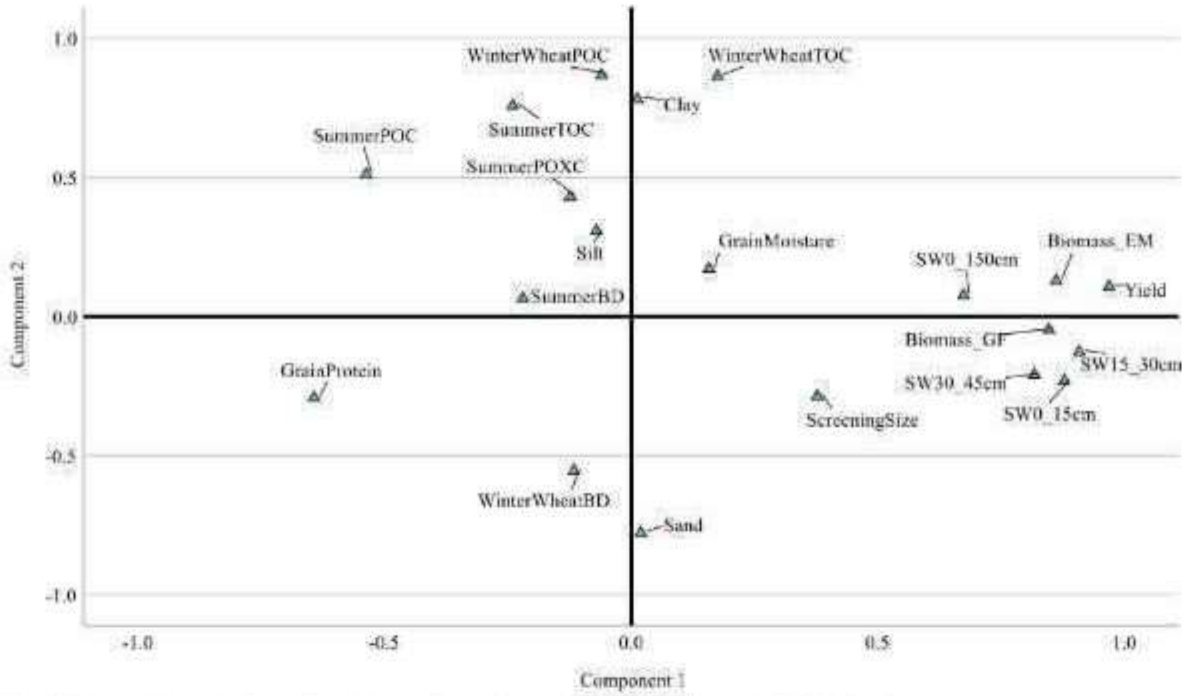

Fig 6. The two-dimensional principal subspace for the observed data. SW: Soil water; BD: Bulk density.

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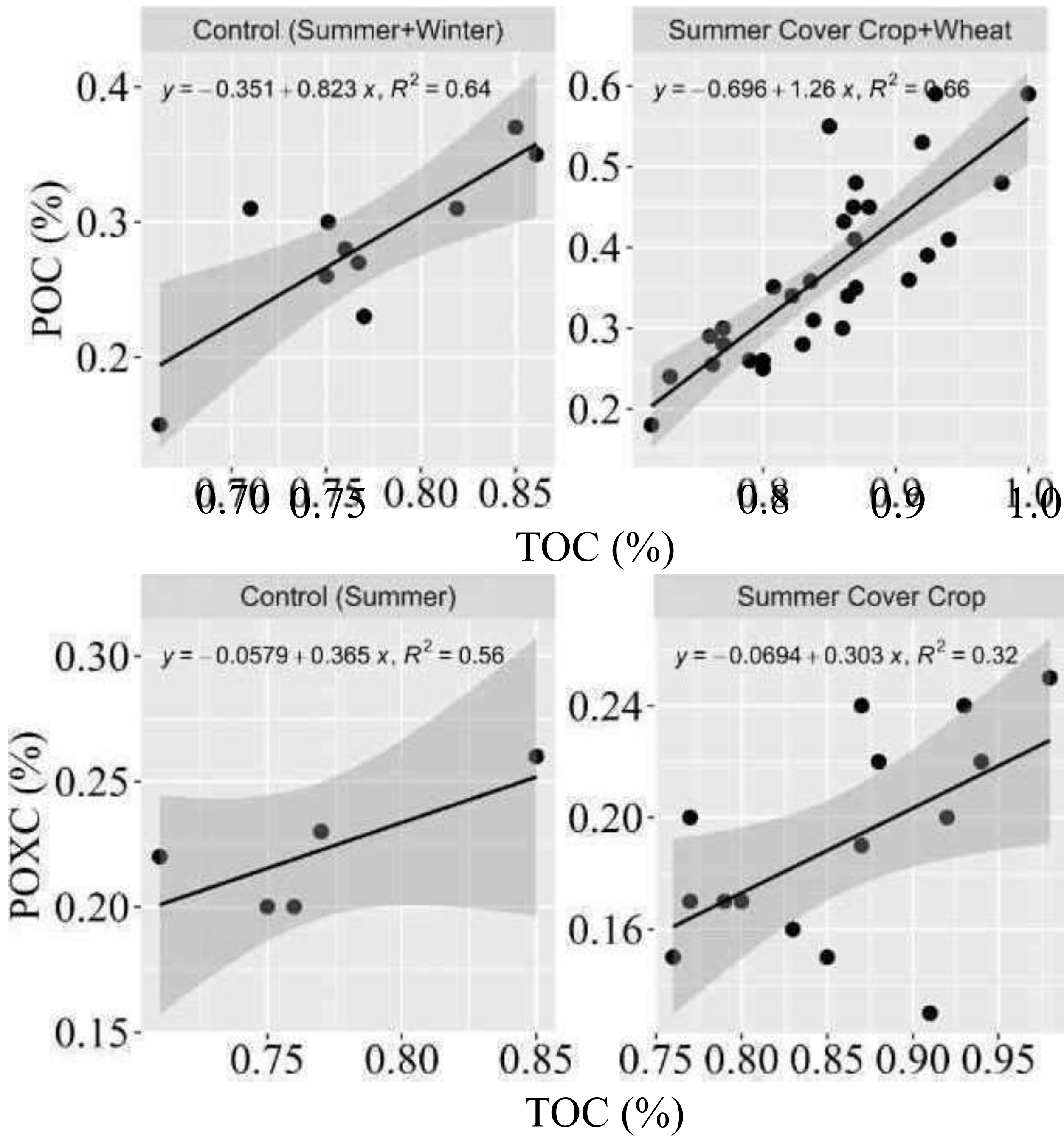

Fig 7. The relationship between total organic carbon and particulate organic carbon (POC) and permanganate oxidizable carbon (POXC). Top left: TOC and POC in summer and winter control plots; Bottom Left: TOC and POXC measured in summer control plots; Top right: TOC and POC in summer and winter cover crop plots; Bottom right: POXC and TOC in summer cover crop plots. The grey shadow area represents a 95% confidence interval.

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previous cover crop treatments compared to the control (Fig 7)- Meanwhile. resultsshowed that POXC and TOC in summer hada relationship in control plots. However, the relationship between POXC and TOC was not strongly correlated in cover crop plots (Fig 7). Overall. the relationships between TOC and two labile OC fractions weredifferent in cover crop plots and control plots, with TOCaccumuIation being more sensitiveto the increase ofPOC esFcia_Ily underthe impact ofcovercropmanagement (i.e.the prernCe ofcover crop and how longtill termination).

3.7 Yield affected by soil water at wheat planting

Soil at thesowing time ofcash Cropsis criticalto seed establishment and biomass pro' duction. Soil water at surface layers O— 15cm. IS—30cm and 30—15cm and soil profile water (O—150cm) thewheatabove-ground drybiomass at both grain filling and early maturity stages (Fig 8). Results also showed that the surfice layer O—15cm stored soil water at wheat «ywing had a greater effect on yield, compared to the soil water in the whole profile (Fig g)_ Wheat planted on earlytermination plotshad the highest yield. while for those planted on late termination, the yieldwas the lowest. Fig 8 shows that Cover cropping practice through the termination dates impacted soil wateravailabilityatthe plantingofwintercrop. which the crop's above-ground biomass accumulation and yield.

4. Discussion

Incorpration ofcovercropping into a crop—ßllow has practised as ameansto manageground cover, organic matter, stored soil water. qualityand health. In this research, the legacyimpact ofAlmmer cover crops on soil water acroß soil profile was explored and our results demonstrated the effectiveness ofreplacing summer cover crop with fillow. ANOVA test showed the significant oftreatments stored water, TOC, POC, Wheatbiomass, yield and grain size-

For the examined season, the earlytermination OfQlmmercover crop rsulted in a' 2%, 4% 'and I% increase in soil water at planting time at depths of0—15cm, and 30—45cm, resik•ctively, and subsequently led to a 2% increasein Wheat compared to the control- Addi• tionally. this treatment increasedTOC and POC levels by7% and respectively (Table 4). '1%e summer cover crop was to enhancesoil biology as evidenced by an increase in AMF concentrations in both A and B groups (Fig 3C and 3F). Managing summer cover crop could H'tentially increasesoil Water storage during the growing *ason ofthe winter cash crop, which could be crucial for sensitive phenology stages (Fig 5). While an underlyingcorrelation wasobserved between soil Water, biornass and yield (Fig 6), the com• bined changes in soil water and organic carbon resulted in an increased yield (12%)and improved quality, such as a increase in grain protein (5%) in the early•terminated cover croptreatment (Table4).

4.1 Cover cropping affects soil-waterrelations

Inthe current Äudy sea.u»n, soil watercontent was by including summer Cover crops and by the timing oftermination with greater differences observed in thetop layers (0—15cm, 15–30cm and 30-45cm) thanin the whole soil profile (O—150cm) (Fig 4)- Regardless of the soil water loss due to plant water uæ, the evidence from trials suæests that the inclusion ofcover crops with optimal termination and residue retention creates a beneficial legacy within the soil profile. The earlytermination wasable to retain more •oil water compared to the other scenarios(Fig 5) while enhancing chemical and biological indicators i-e,, TOC. POG AMF sequence concentration (Fig3)-"Ihis finding provides evidence that cover crop with optimal termination could maximise the soil waterstorage for a dryland cropping system in the Northern Grain iklt region ofAustralia_ These resultsapply to our study site for a seay»n with relatively low rainfill but the effect ofcover crop management on soil water storage could be different depending on climate variability,soil condition and management 1351. However, thisstudy providessufficient evidencethatcover crop managementandits impæt on health played a

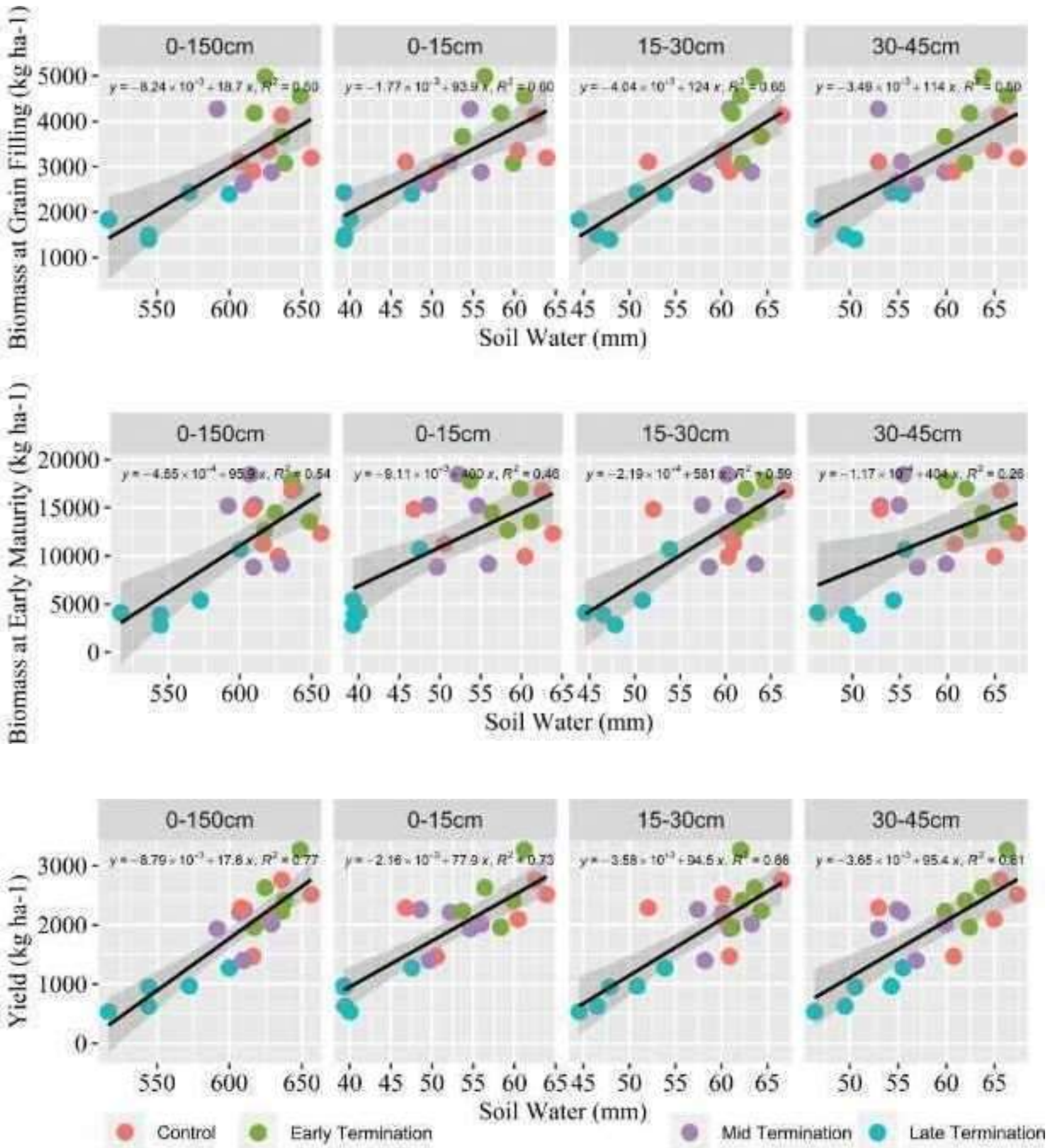

Fig 8. Relationship between soil water at top layers and whole profile at planting time and wheat yield and biomass accumulation at grain filling and early maturity stages. The grey shadow area represents a 95% confidence interval.

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substantial role in soil storageand yield. Earlytermination hadsimilarsoil Water content at wheat with the control. but enhancements in soil health indicators OC and microbial activity) played a role in the increase in yield and grain quality that weas observedOverall, the evidence from trials suæests that the inclusion ofcover crop with optimal tenni• nation and residue retentioncan be effective in retainingsoil water whilecontributing to improvai soil biological health (

increased organic matterand microbial activities) and yield production ofthefollowing •e.inter crop.

4.2 Available soil water at planting as a driver Ofwheat biomass and yield

Winterwheat biomass and yield associatedwith summerCoverCrevwere attributed to avail• •able soil *rater at sowing time, evidenced by its correlation with Wheat above-ground biomass •at the grain filling and early maturity stage (Fig 8). Wheat biomass during grain filling and early maturity resm»nse to stored soil water at sowingtime was negativelyaffected by themid and late termination ofcover crop (Fig 8). due to inadequate soil water at sowing contributed toa reduction/delay in crop establishment and biomass production. Despite the increase in soil OC and microbial activity, the cause ofsuch reduction in wheat biomassand yield was associated With the incorByration oflonger summer cover crop treatments i.e,, mid and late termination. The summer cover crop was terminated and then left standing, which allowed the soil surfice to have ground cover even afterthe termination. However, mid and late• terminatedplots had greater above-ground biomas and hence crop residue after termination. A physical barrier ofthe heavy/dense cover crop residue may lead to an unhvourable/adverse impact on Wheat emergence by obstructing light penetration and releasing phytotoxic chemi• cals from the residue. 'Ihis phenomenon Ofcr0p residueinhibiting plantemergencewas also revx»rted in other studies 1106, IU71.

As showm in Fig S, Summer cover Crop treatments (Leo earlytermination) could provide soilWater similar to summer control at the grain filling stage while "cilitating soil biological activities- Soil water availability iscritical to wheat root growth and above-ground biomass accumulation, especially for crops during the grain filling st+ as wheat hasa higher water uptake rate at this Stage 1108 Biomassat maturity can affect thefinal grain production ofwheat I I Furthermore, dryland wheatgrowth, grainyield and qualityare highly delRn• dent on the amount ofsoil water storage atthe planting, flowering. and grain•filling stages 1110—1121. Field data a typical Australian dryland cropping system Where the avail• ability ofsoil water storage and water efficiencyare limited 1 1 131. The previous research studies stated that lower soil water availability at planting can lead to a decrease in wheatyield as affected by the incorporation ofcover crops. 1114, 1151, here the finding ofthis studyfurther highlights the importance ofcover crop management andshortening ofsummer hllow (also called short 6110%').

Greater wheat biomassproduction early termination ofcover crop contributed to higher water use efficiency ofwinter crop, and consequentlygreater yield production (Table 6). This was dueto the combined effect ofincreased soil Water at sowinbsoil OC and micrc%ial activities. as discussed in 4.1. With increasing concern aboutclimate change and droughts, the availability ofwater reM»urces is becoming crucial to dryland cropping systems and system WUE which is often used as a target for soil management 11151. •lhis study indi• Cates that managing soils through proper cover crop managernent can improve WUE and potentially crop biomass and yield. Cover crop management can be practised for improving prexiuctivityvia enhanced soil water storage and WUEwhich can helpKd in the chal• lenges ofclimate and droughtevents

4.3 Cover crop affecting soil organic carbon

Soil to summer cover crop, specifically soil TOC POC and POXCwere different under cover crop treatments and hillow. In summer. the greatest soil TOC at cover crop termi• nation was

Observed in the soil sur%ce layer (0—1(km) ofthe late termination plots and was significantlygreaterthan the TOC in control by 17% (Table 4),which could an outcomeof developed root systems in soils and enhanced biological activities observed by an increase in AMF DNA SC (Table 4). Soil POC content at cover crop termination differed arnong treat• ments, With themost significant difference(also the greatest) observed in late termination plots, it was likewise associated With increased soil AMY activities (Table4). Soil POC constitutes hotsm»ts for microbial activities and has been used asan indicator ofsoil biological activ ity With enhanced soil AMP growth andactivitiesin the late termination plots, AMF was able to åcilitate fresh residue decomposition and increase POCavaiIabiIity 1541. Soil POC was considered a indicator for changes in soil quality 1117— 1191 showed that variation in POC Can account 69—94% of the changes in TOC dueto land use and management_ Various other studies have reported similar findings regarding cover crops Of species improving soil TOCand POC contents 1118, 120L Across all treatments, TOC and POC were correlated to each other (Fig 7) suggesting: I)cover crop management had a consistent effect on improving both TOC and POC availability compared to the control; 2) an increase in POCcontentcontributed to increaQ in TOC pool.

Differentfrom soil TOC and POG results showed that POXC at covercrop termination was the greatest in the control plots. K-»llowed by late, mid and early plots, but the differences among treatments and control were not significant- "Ihis suggests that cover crop man+ment did notsignificantly affect POXC content over the short term and control plots had a simpler system where POXC was not decomposed/utilixd by soil microorganisms as %ster •as the soils in cover crop plots 1121— 1231. Some studies re'x»rted that POXC was sensitive to management practices and could be used as an early indicator ofimproved soil organic matter management 1M, 124, 125 but cover crop treatments sometimes can have little on POXC due to low content ofsoil organic matter 11261. POC and POXC are the measure, ments oflabile organic carbon, the POC method was found to be more sensitive to rapid gain in OC as a result ofmanagementor land-use change, while POXC was filund to nu»re sensitive to soil lignin content (a stable component ofSOM), instead ofrapid gains in OC 11271. Based on our results, soil POC was more correlated with changes in TOC while less correlation was found between POXC and IOC. (Fig 7). "Illis may suggest POC in our experiments was xnsitive to the changes in TOC due to cover crop incorporation. While. as POXC was ænsi• tive to changes in soil lignin comyx»unds which were sourced from sul%ce residuedecomposi• don_ Our findingalso suggests that: I) POXC was particularly insensitive to the changesin TOC likely because thetrial site had crop residue retained from the previous years and the crop residue has not been decomB)Sed at the time ofearly or mid termination and hence there was little lignin input in these two treatment plots 2) late termination treatment allowed more timefor the residue to decompose (including the wheat qubble from the previous year •and fallen litter from the«overcrop), and consequently hadquire lignin input and stimulated POXC accumulation.

Soil OC comB»nents measuredatthe end ofthé winter æason showed that wheat planted On mid termination plots had an advantage in storing more TOC and POC by I % and 52% compared to the control but disadvantaged yield by compared to the control (Table 4). Thiswas likely a result ofa better soil water-microbial environment to handle residiR retained •and into thesoil compared to the other plots. Overall, results ofthis study showed that the short-term cover cropping in summer promoted a rapid gain in soil IOC and POC_

Based on existing studies, the positive relationship between soil OC and crop yield beginsto level offwhen soil OC content reaches approximately 2% 128, 1291. However. no Bitential correlation between soil OC and yield was observed in trial•s soils asOC content Was below 1%,whichmay not be the solefactor driving thegrain yield-

4.4 Cover cropping affects arbuscular mycorrhizal fungi groups differently The results showed different DNA sequence concentration ofsoil AMF Group A and Bat tere mination time. and their re+»nse to fillow and cover crop treatmentsvaried (Fig 7). Thiswas' consistent With the study of 11301 that reported AMF species had different root colonimtion rates depending on the AMY åmily (taxonomic variation). •IT-te responQ to AMY coloniNtion differsin host plant species. root growth and the space available for development | 1311. Each group's species may have asimilar response to the changes in environmental factors such as&ariation in soil properties and host plant biomaß | 132, 1331 which can occur under cover cropping. '[he preænce or absence ofAA-IF colonisation is also related to soil water conditions which in our trialsin vertosols, soil fluctuates seasonally to favour or hinderthe AMP associations with the host plants 11341.With greater AMP Group A DNA sequence concentration found in late termination soil compared to the control. it Was likely because late termination plots had greater sorghum root biomass, which allowed a higher chance AMF Group A to coloniæ and establish 1621. The greatest AMF Group B DNA concentration was found in early termination plots compared to the control, and the lowest was found in latetermination plots The decreasing pattern ofAMY Group B DNA sequence concentration from the time ofearly termination towards late termination was 'Xjssibly related to soil Water availability in the rhizosphere mne I t35, 1361. In addition, previous works s%ested that intense competition among AMF over root space could lead to competitive dominancein the«oloni• zation of AMFspecies by excluding others 1137. 1381.

43 limitations and recommendations

Overall, this studywas subject to potential limitations Findings ofthis study were based on the trials within a I•yearwindow, although with sufficient replications and two examined æax»ns that had arelatively typical rainfall (Fig),a longer term observation might be needed Our onfarm cropping system research aimed to explore the plant•soil-water relations with implications ofsummer cover crop practice over the growing ofcover cropand cash crop. This has certain significantvalues to future field studies in the eastern region ofthewheat beltas soil Water at plantingplays a critical role in crop establishment and yield prrx\uction. The changes of POC (which is resm'nsiv•eto åort•term management change) did capture the impact ofsummer cover crop and suæested an improvement ofsoil quality related to SOM and microbial activities. •I%erefore. it is recommended that summer cover crop incorporation could help to promotesoil health (organic carbon accumulation and microbial activities) through residue retention. '[his study also showedthe importanceofthe timing ofcover crop termination, forits impacton soilwater storage. For futurestudies. it is crucial to consider a number of fac- t'NS priorto implementing cover Crop practices I) decision on planting and termination of cover crops should be carefully planned; 2) considering the impacts ofcover cropping because it may not necessarily achieve all the benefits (adequate soil water preservation.yield increase. carbon accumulation, microbial health enhancement) that can be by manyßctors such •as condition, growing ray-»n, climate, management and investmentdecisions; 3) consideringthe B*ential impact ofcover cropping on soil nitrogen retention and their regulation effectsOn nitrogen cycling procesRs. For assessing long-term effect of covercropping practice. it is also recommended to apply validated biophysical modellingto investigate the interactions between soil-crop under the ofclimate variability and management

5. Conclusion

The implementation ofsummer cover Cropwith earlytermination improvedsOil biological health and increased soil water contentatwheatsowingtime.which collectivelyenhanced wheat yield and grain protein content- This study also highlights theiniprtance of timely termination and residue retention. CA»ver crop with late termination had some drawbacks such as depletingsoil water during the growing and consequently affected soil water availability at wheat sowing time. Although there wasevident advantage in soil OC addi• tion and AMP growth under late termination treatment, the loss ofsoil water at sowing time Was detrimental, which led toa significant decline in Wheat biomass and yield production. There was a 4% in surface Y)il water at winter wheat sowing time under optimum Almmer cover crop, but the effectives were not proportional in yield increase i.e,, which suFsts thatyield increase could be benefited from enhancement in soil health i.e., soil OC and B'tentially microbial activities.Overall. summer cover crop practice showed great poten tial to increase soil health and crop productivity in dryland agricultural systems. Cover crop can beused to manage soil water and soil health, although further research is needed to con• sider the climatevariability and management regime thatWill maximix the H)tential and effectiveness ofcover crop practice

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Author Contributions

Conceptualization:HanluZhang, Afshin Ghahramani.

Data curatü»n: Hanlu ZhangyAEhin Ghahramani, Aram Ali AndrewErbacher,

Amnal analysisHanlu Zhane

Fundingacquisition: Ghahr.mani.

Investigation: Hanlu Zhang.

Methodology: Hanlu Zhang, GhahramanL

Project administration: Afshin GhahramanL

Supervision: Afhin Ghahramani,

NS'riting —original draft: Hanlu Zhang, Aßhin Ghahramanie

NS•'riting —review &editing: Hanlu Zhanb AEhin Ghahramani, AramAli,Andrew Erbacher.

References

1. Hensley M, Bennie AT, Rensburg LD, Botha JJ. Review of 'plant available water' aspects of water use efficiency under irrigated and dryland conditions. Water SA. 2011; 37(5):771–80. https://doi.org/10.4314/wsa.v37i5.14
2. Dreccer MF, Fainges J, Whish J, Ogbonnaya FC, Sadras VO. Comparison of sensitive stages of wheat, barley, canola, chickpea and field pea to temperature and water stress across Australia. Agr Forest Meteorol. 2018; 248:275–94.
3. Asoodar MA, Bakhshandeh AM, Afrasiabi H, Shafeinia A. Effects of press wheel weight and soil moisture at sowing on grain yield. J Agron. 2006; 5(20):278–83.
4. Bell L, Kirkegaard J, Whish J, Swan T, Dunn M, Brooke G, et al. Managing crop differences in soil water extraction and legacy impacts within a farming system. GRDC Update. 2021.
5. Verburg K, Thomas M, Cocks B, Austin J, Glover M, Stockmann U, et al. Using existing soil and landscape data sources to estimate plant available water capacity (PAWC) for decision-making and crop

GFWC; AV 4. AvaA& fran:
•at-al-CO
•ark C , LM, 9øwart A, , M. Eltoas ot past and t*xna— Mid Bd Fend
7. Varp G/ S, J , untotto C, G, Basanta M, Lovera E, al. Fü and
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16. Fay D, Apria-ti R, Yuwt DYP , Chu D, Famw Wver crops and dyname
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17. H, JD, A), Tatarko J , Stuvor TW a sernarUj Efta:ts on .
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18. Kkßo NL Currie ('E crop ASABE m, 52
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27. Garba Il, LW, WiAarns A. Cover legacy noæts and on "eus a Agrm
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34, Л, M_ tnro ta“ow M
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40, Т*ЮдJE, ВЮ. Grat›r ЕК В“мтаг Тю аЬи'Шгхе,
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42. MSA M O, EI P, M д-
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44, Uras ST. Cao a Iest to ю
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Wang CИ, Wu Щ АПМу MS , PM'sm D, 2,
soii systams_ SB Agrk:_ 2016', 73:53542
46. Rj. mattor as Mcator 0' фаЫу Zeakmd_ so• ва ат;
47. DenM K. SixJ. H, Frey SD , t»tweon wn:kx H, of cydes шт
ВЮ ВЮВ-ЮТ_ _ dy'nn«
Murphy BW_ «—c m(ter м:• Res_ 2015;

49. %wts WJ, Рж*цвку УА, & .•aEr MM, H. Effet1
03; 1 Щ
МТамту В, КИВ•аПшу АВ. 2018:
Еш JSN
51. L\ng У, Ниагщ Н, l_ ZQ, WH. E— 0' шт

mdsn•re dynu-r—_ 477: Тгмв РиНЮаЫв [M; T 4 ,, p. 481—4.
SB, J %robal in .
2012; PMIO: 22772903
ME turW: h•rways tor aruf rurioNs arki VB.
54. Wai Vosåtka M, Ca B, Dom , Lu C, Xu J, rdoot attxnÄAar my-corrNza turO
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57. Wg MC , SF. Ev•inør VT. Tho rob myconhizal
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N. C, MA, S. Khm , M. etal. ot attn=uhr in gAant growth in abiotic Frmt
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61. Kin N, MC , Guan K. Vilhmil cov« amont
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'tuzas_ a ot crcv J ECOL 17; 17W93.

Moru EM, Avkj •nana C, TurriniA, G, BårtAi P. Fust a mvol

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I. M. C. activay

cover a sunmwor Si:A 2016:

EE. WU*hgs K, McDmOI MD, GP. GraMy AS. Covercrop to a no-W torwrgy crc»ging systan_ GCB 2017 9(7): 12S2• ST, ME. ME. «atms pr«isctbn "th fgwor nputs. Agr Ecosyst Envüon. B:

67. Augé RM. Water symÄ

68. AD, Kaspar TC, Archam_As SV, DB, Sauer TJ, Parkin 1B, Sod with tho Ong-tom of a rye covet crop. Water

H, Mkta WA, Presky DR, Ciaasson MM _ ot cowr nou f« '*wsical prowrtios_ SSSAJ _ 2011 ;

70. SI , NV. Otteas Envfon Sci. 201 S: 29•_ 134

71, V , J , J msan LS, K,

agotTAü: N , P S Agr Emsyst Environ.

72. HunW MC, Snot' ME. LW , OA. for 2017; I;

U GD , Hayas , W. Satüal GA, Ihar BSIThw tho pecajctivity of sys, terns P-ßu_re Sci 20t4;7; t OMB-ttxji.

74. ITuup-Kristmsa• K. J. F-bot tho sy40ms Arm 6; t 10_ rncw122 PMID:

75. Bureau camato o' A" Av— 'run: h ttpJ/www tnn_gov auemalß'daw.
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77. Оагщ УР. PW, Щ W , ОаИ' НС, Ш, at aL Suat*
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79. Рд С, КЛ З, i_i' У , Н' Х, ecosysErrs_ ESRv. фтиТД
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97. Уоопи-в , Вгептш JM Смыт ам
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101. E-вшптют M, Tay R T, EBstramj M. Func1*ma' тусопЖт—Пю FOV ЕссИ, 2010;
102 OS, RE, wam
Agre%l _ I
Fremh RJ, JE Water dfeigœy whoat a M0'Mgrrangan•type water AIN J AgrÉ Rex 3*6) 743-64.
104. CD. EC. Wtwn is a rulos_ gun f974; 81
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107. KN_ Ettœts Ot and covor cm rA1rn rnaw
Xuo O , Zhu Z, Stewart BA, DA
X, S, Sim H, poi D, Wau Y_ [hy rmttor, as water in
110. GP , PV Fritz AK, MB , GA BS. Ot dra.ght and tenwrature M•at. 2012; t 0711
FPt 124S PMIO: 324807/3
cra Rov PEmtsci_
112 Ai N M _ A GrowÜL Qu*y Wat« A Pflanzen_ 202274:371-U
, A, RoNnson dB, DJ. A tod tor Erwiron %ftware_ 04 SS | 14. CA. by J. I): 121—7.
115. , MF. E.arWnm JG _ ro»onsa Ot to watx at AgrWatgr Manaw_ https•.'/doi O. 1
116. A, Kr*ic PN, M•mte AD. Zhau B. SC. MS, al. of a&pt. to in •meat tarrn to Ag Ecœwt
117. K, A, DI. C, SA, F, Ot al a tinctkmal tor NN ; PMID 34226560
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121. A, B, AO, UM, OJ- cover wheat•Wbw sy•stxn. J. 20f 9: I (4) 2f I'
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123. SW , IT. J. Cartn•v: Activa SO' Carbm_ DL, Stott DE. Mikha MM, oeitors. Soil Hoalth Series: Vouyn02 t.xy Sod Hganh 2 p. 152-75.
124. LLEas S. R. Can matter SSSAJ_ 2021
12S. S. V. so' Cartxm as an Soit in tho %rtia_ In: Sahnikov E, Ma_wner LavrÉtEtov A, F , Sod ruw Ya-k: Cham•, p.

126. Dockot H_ Ot cover
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127. JO, Swdt RS, %Gowan JA. CanpariMm Ot
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u

128. Pan G, Smith P, Pan W. The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. Agr Ecosyst Environ. 2009;1; 129(1–3):344–8.

129. Oldfield EE, Bradford MA, Wood SA. Global meta-analysis of the relationship between soil organic matter and crop yields. Soil. 2019; 5(1):15–32.

130. Hart MM, Reader RJ. Taxonomic basis for variation in the colonization strategy of arbuscular mycorrhizal fungi. New Phytol. 2002; 153(2):335–44.

131. Piotrowski JS, Denich T, Klironomos JN, Graham JM, Rillig MC. The effects of arbuscular mycorrhizas on soil aggregation depend on the interaction between plant and fungal species. New Phytol. 2004; 164(2):365–73. https://doi.org/10.1111/j.1469-8137.2004.01181.x PMID: 33873560

132. Hart MM, Reader RJ. Do arbuscular mycorrhizal fungi recover from soil disturbance differently? Trop Ecol. 2004; 45(1):97–112.

133. Maia LC, Passos JH, Silva JA, Oehl F, Assis DM. Species diversity of Glomeromycota in Brazilian biomes. Sydowia. 2020; 72:181–205. https://doi.org/10.12905/0380.sydowia72-2020-0181

134. Anderson RC, Liberta AE, Dickman LA. Interaction of vascular plants and vesicular-arbuscular mycorrhizal fungi across a soil moisture-nutrient gradient. Oecologia. 1984; 64(1):111–7. https://doi.org/10.1007/BF00377552 PMID: 28311647

135. Deepika S, Kothamasi D. Soil moisture—a regulator of arbuscular mycorrhizal fungal community assembly and symbiotic phosphorus uptake. Mycorrhiza. 2015; 25(1):67–75. https://doi.org/10.1007/s00572-014-0596-1 PMID: 25085217

136. Cavagnaro TR. Soil moisture legacy effects: impacts on soil nutrients, plants and mycorrhizal responsiveness. Soil Biol Biochem. 2016; 95:173–9.

137. Cano C, Bago A. Competition and substrate colonization strategies of three polyxenically grown arbuscular mycorrhizal fungi. Mycologia. 2017; 97(6):1201–14. https://doi.org/10.1080/15572536.2006.11832730.

138. Engelmoer DJ, Behm JE, Toby Kiers E. Intense competition between arbuscular mycorrhizal mutualists in an in vitro root microbiome negatively affects total fungal abundance. Mol Ecol. 2014; 23(6):1584–93. https://doi.org/10.1111/mec.12451 PMID: 24050702