Investigating links between soil health and innovative cropping systems

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Acknowledgements

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Disclaimer

Cover photos

Top left: Biological oat crop spring 2016

Top right: High input canola crop spring 2016

Middle left: Pro-Trakker canola spring 2017

Middle right: Chicken manure recycling barley spring 2015

Bottom left: Summer cropping barley spring 2015

Bottom right: Field day with local farmers showcasing project at chicken manure site winter 2016

Executive Summary

The Gillamii Centre's project 'Investigating links between soil health and innovative cropping systems' undertook five case studies looking at a range of physical, chemical and biological soil health measures and fertiliser inputs relative to yield and soil health trends in five innovative cropping systems. All sites were located in a broad-acre cropping context in the environs of Cranbrook, Western Australia. The cropping systems studied in this project include:

- Biological: includes a mix of relatively low synthetic and high biological inputs compared to conventional practice, aiming to stimulate soil biological activity in three year cropping phase;
- Summer cropping: variable summer cropping rotations to reduce water table for following winter crop – sunflowers grown in summer 2014/2015 prior to first year of project and volunteer recruitment summer weeds/summer crop species observed during the summer months in following years;
- Pro-Trakker seeding equipment: commenced year after year same furrow precision seeding technology at commencement of project;
- Chicken manure recycling: spreading 4 m^3/ha partially composted aged broiler chicken bedding when going back into three year cropping phase; and
- High input: conventional cropping system with generally high levels of nitrogen and phosphorus fertiliser inputs compared to other systems.

Biological cropping systems in south Western Australia are poorly understood and pose an important challenge in the face of inherently low soil organic carbon levels found in dryland cropping soils and less predictable weather patterns associated with climate change. All cropping systems studied are farmer initiated and managed without interference from the project.

The results in this project reinforce the strong link of interactions among the chemical, biological and physical soil processes in maintaining healthy soil. Overall, the most significant indicators of yield were available Cu, available P (Olsen) (ppm) and total N inputs. The Phosphorus Wise test from Microbiology Laboratories Australia demonstrated there is major binding of P in all soils tested and there appears to be a link between P fertiliser availability and microbially-mediated P release from total P content.

The Chicken manure recycling system had the greatest distinction of soil health indicators overall, with the most positive yield residuals on N and P fertiliser inputs (highest yield for N & P inputs) in all years, highest percentage of soil organic matter, t/ha soil organic carbon (SOC), plant available water, total fungi (mg/kg), total bacteria (mg/kg), cation exchange capacity, pH, spring microbial activity indicator and mycorrhizal fungi (mg/kg). Interestingly, this system is on forest gravels and has far greater aluminium and iron (mg/kg) than other sites and the highest total P (mg/kg).

The Pro-Trakker system showed progress over time in a few key areas, with increased yield efficiency in relation to N and P inputs (2016 and 2017), and a significant increase in spring microbial activity (2017). The Biological system had the lowest yield – possibly explained by having the lowest available Cu (ppm), available P (Olsen) (ppm) and total N inputs, as well as low available Ca – although it has the deepest A horizon. All other systems had similar (lower) A horizon depths to each other. The biological system also had the greatest loss of organic matter and soil organic carbon percent in every year of the four years measured 2015-2018.

The Summer cropping and High input systems appeared overall to have a relatively stable soil health trajectory, with generally no major changes in soil health indicators over time. The High input system generally grew lots of biomass which in turn appeared to be maintaining biological activity in the soil. The threat of declining available Ca (ppm) and pH due to high inputs of N were countered by regular high inputs of lime in this system.

When comparing soil organic carbon percent (SOC) levels between 2015 and 2018, all cropping systems studied showed some decline at 0-10 cm and 10-30 cm depths with the exception of the Summer cropping system which showed a slight increase in 10-30 cm depth in 2018. When looking at the annual trend of SOC for the four years 2015-2018, the most profound reductions, on an annual basis, appeared evident in the Chicken manure and Biological systems (0-10 cm) which were the only non-continuous cropping systems, both of which went from a pasture phase into a cropping phase at the commencement of this project. No clear differences in management could be discerned to account for the most profound reduction in difference of SOC in phase cropping compared to continuous cropping. The short period of the project is acknowledged and ongoing measurement is needed to make trend analysis more robust. It is nevertheless concerning to see the general trend of reducing SOC – arguably the most critical indicator of soil health and sustainability.

1. Introduction

The Gillamii Centre (Gillamii) project titled: 'Investigating links between soil health and innovative cropping systems' aimed to identify soil health trends and significant measures or indicators of soil health – correlated with yield and fertiliser inputs – in five innovative cropping systems located in or close to the service area of the Gillamii. The Gillamii is a community based sub-regional catchment natural resource management and grower group based in Cranbrook, Western Australia. The Gillamii services the mid-upper Frankland-Gordon River and part of the North Stirling's Basin and Kent River Catchments. The project sampling period was February 2015 to January 2018.

Condition classifications for key issues affecting soil health were broadly mapped for Western Australian natural resource management (NRM) regions by the Department of Agriculture and Food (WA) (DAFWA) (2013). Condition and trend classifications are determined by the severity, trend and risk factors, taking into account climate, land characteristics and land management practices in relation to different land uses. Condition and trend classifications were described as: very poor, poor, fair, good and very good (DAFWA, 2013). Maps from the DAFWA (2013) study for the South Coast NRM region are shown in the South Coast Snapshot (South Coast NRM Inc, 2016) (Snapshot). Classifications for each of the key issues extrapolated from the Snapshot in the project study area are summarised as follows:

- water repellence – poor
- soil carbon abundance – moderate to high
- wind erosion hazard – moderate
- salinity risk – moderate
- dominant groundwater trend 2007-2012 – variable to mostly stable
- Soil acidity – very poor to poor.

The threats listed above when manifested adversely in the field, could be considered symptoms of unhealthy soil. This project aimed to explore further in order to build an understanding of the processes that drive soil health. Cropping systems selected occur along the continuum from conventional to biological (not organic) with the aim of understanding constraints to biological cropping systems that are in their infancy.

Project aims align with the vision and mission of the Gillamii Centre which are 'a productive and resilient agricultural landscape' and 'to lead, inspire and support productive agriculture, rural communities and healthy natural ecosystems' (Gillamii Strategic Plan, 2015). A broad range of biological, physical and chemical soil health indicators in context with soluble fertiliser (N, P and K) inputs were analysed to find indicators that showed significant correlation with crop yields from within and among the five different cropping systems. The project also looked to identify patterns and processes occurring in relation to soil health in light of variable seasonal conditions in the different cropping systems and implications for productivity and sustainability. The five properties included in the project are located in or close to the Gillamii catchment area (Figure 1). Cropping systems or treatments are paddock-scale, farmer-initiated and controlled.

Following are a few examples from the literature of definitions of healthy soil that have a common thread of sustainable productivity and production of nutritious food being based on biologically active soils and healthy ecosystems: 'The continued capacity of soil to function as a vital living system, within ecosystems and land-use boundaries, to sustain biological productivity, promote quality of air and water environments, and maintain plant, animal and human health' (Charman & Murphy, 1991); and '…is able to sustain biological activity, maintain environmental quality, and promote plant and animal health' (Masters, 2017).

The process of soil building is fundamental to soil health and relies on the maintenance of soil cover, active root growth and high levels of microbial activity (Jones, 2008). The conversion of organic matter to humus is the basis on which the soil building through the interactions described by Jones occurs. Humus is the end result of the carbon cycle interacting with the mineral cycle (in the presence of warmth and moisture) to produce a compost (known as humus) which holds nutrients in a plant available form. The carbon structure within the humus is recalcitrant to microbial activity (meaning it is inaccessible to further breakdown by microbes) and lasts for 20-50 years in the soil (pers. comm. A. Luebke, 2017).

Most Australian soils are ancient and highly weathered, making them inherently deficient in biologically available carbon. Soil biological function is regulated mainly by the amount of available soil organic carbon which is required by the majority of soil microbes as a source of energy. The low soil organic carbon levels found in Southern and Western Australian dryland cropping soils is a primary constraint on microbial activity (Gupta & Roget, 2004). While acknowledging that sandy Western Australian soils commonly have a cation exchange capacity (CEC) (or nutrient holding capacity) well below 10 meq per 100 g of soil, the relationship between the CEC of the mineral fraction of soil and humus can be appreciated. For example, McMahon et al (2002, p. 154) highlighted the role of humus in improving soil health as follows:

> Humus helps improve soil structure, imparts the dark colour to the soil mineral fraction and increases the soil's water-holding capacity and cation exchange capabilities. For example, the cation exchange capacity of a mineral soil ranges from about 10-100 meq per 100 g, while the capacity of humus ranges from about 100 to 300 meq per 100 g.

The literature cited above supports the understanding that healthy biological soil processes that build soil organic carbon including humus are paramount in enhancing soil health. However, the way in which management practices affect soil biological fertility is less understood than physical and chemical soil fertility (Carson, 2017; Murphy et al, 2004). It logically follows that understanding how to transition from a purely conventional cropping system to a biological cropping system is also poorly understood and is a necessary challenge to be overcome in the context of sustainability, with climate change adding additional urgency to this imperative. It is recognised that the soil health issue is highly complex and that the results in this project must be kept in context of the site conditions, agronomic methods and inputs that were studied.

It is hoped that the holistic approach taken in this project of looking at the inter-related physical, chemical and biological characteristics of soil in relation to yield and fertiliser inputs under a range of management regimes will enhance understanding of how to transition to a more biological cropping system.

1.1 Location of sites

Sites are located on five different properties, each representing a different cropping system. The properties are located in/near the mid-upper portion of the Frankland-Gordon River catchment sub-region (Figure 1). The only site not located in this catchment is the summer cropping site which is located in the Oyster Harbour Catchment, west south-west of the Stirling Range National Park.

Figure 1: Location of five different cropping system survey sites marked by yellow icon

1.2 Climate

The climate is Mediterranean, generally featuring cool, wet winters and warm to hot, dry summers. Mean annual rainfall for the properties involved in the study range from 450-500 mm. The three northerly sites (Biological, High input and Pro-Trakker) are all within approximately 10 km of each other and receive on average 450 mm annual rainfall. The two southerly sites (summer cropping and chicken manure recycling) receive on average 450-500 mm (pers. comm. farmers involved in trial). Long term rainfall statistics (1891-2017) for Cranbrook from the most central weather station to all sites) from the Bureau of Meteorology (2017) are shown in Table 1.

Mount Barker has the nearest long term temperature statistics to Cranbrook and Kendenup, where the lowest mean maximum temperature of 14°C is recorded in July and lowest mean minimum is 6°C recorded in July and August. The highest average temperature is recorded in January (26°C) and the highest mean minimum recorded in February (13°C) (BOM, 2017).

Table 1: Rainfall statistics for Cranbrook 1891-2016 (Source: BOM 2017)

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	16.4	16.3	24.1	34.6	58.3	70.8	75.9	64.8	52.0	43.1	27.0	18.1	501.4
Lowest	0.0	0.0	0.0	0.5	12.2	5.0	24.4	19.0	6.4	1.3	0.0	0.0	298.8
5th %ile	0.0	0.0	1.2	4.2	19.6	30.2	32.1	30.8	19.2	11.8	3.5	1.0	348.3
10th %ile	0.0	0.6	3.2	8.4	24.2	36.3	44.8	36.7	23.5	17.8	6.5	2.9	379.9
Median	7.1	7.9	13.3	25.3	53.6	64.8	73.2	62.1	49.8	36.2	20.5	13.4	497.5
Highest	189.0	190.2	106.7	161.2	189.4	181.0	151.5	155.5	127.2	113.7	107.1	88.2	744.8

1.3 Geology

The catchment of the Frankland-Gordon River is underlain with the southern margin of the Yilgarn Craton which consists of basement rocks of Archaean age (>2500 million years ago) (RAP & SCRIPT). Basement rocks in the study area of the Frankland-Gordon River catchment are generally igneous and metamorphic (Overheu, 2004). An east-west series of dolerite dykes has intruded into the Archaean rocks to the north of the contact between the Yilgarn Craton with the Albany-Fraser Oregon. The Albany-Fraser Oregon is composed of Proterozoic age (1200 to 1800 million years ago) gneissic and granitic rocks and underlays most of the Oyster Harbour Catchment. Slumping of the south coast after Antarctica began to separate from Australia about 100 million years ago, caused the sea to cover the low-lying parts of the area to the east of the Gordon River, when the Stirling Range and Porongurups were islands. Silt and spongolite (Pallinup Siltstone) were deposited under the sea and swampy sediments (Werrilup Formation) were deposited in low lying areas (RAP & SCRIPT, 1996). Later, during the tertiary period (about 30 million years ago) , uplift and warping associated with the down-warps of the southern edge raised the land and caused faulting and shearing of the basement rocks, the rejuvenation of drainage lines and the formation of new surfaces along the ancient river systems (Mulcahy, 1960). Former seabeds became sandplains and stagnant flats. Lateritisation occurred in the Tertiary. The rivers have removed some of the laterite (RAP & SCRIPT, 1996).

Poor drainage after the uplift, especially in the Gordon and upper Kent Rivers has resulted in rain-borne salt accumulating in deep soil profiles. Poor drainage is strongly influenced by the broad and often stagnant flats found mostly around the main drainage channels and rivers where the mainly heavy clay regolith hinders movement of ground water (Ferdowsian, 2004). Lakes and dune systems were formed during very dry periods in recent geological times (approximately 2 million years ago). Wind eroded the depressions and dry lakebeds, forming the crescent-shaped sand dunes (lunettes) associated with the lakes. At the same time, fine sand from the Gordon River was blown away and deposited – to form the elongated dunes that exist in the northern parts of the Gordon River (Ferdowsian, 2002).

2. Method

Potential target cropping systems were discussed and agreed upon by the Gillamii Management Committee. Permission was granted from the relevant landholders involved. Cropping systems were selected to represent a range of different broad acre approaches within similar rainfall zones. It was not considered necessary for all soil types for the different systems to be the same as the area of interest was primarily the trends of soil health within each site. The aim was to gain an understanding of soil health in the different systems and look for any patterns that emerge from each cropping system in context of the climatic conditions and soil types during the period of the project. The summer cropping system site was selected even though it occurs outside of the Gillamii catchment area because of anecdotal impressive results that had been achieved under this system in one year, in particular, where an eight tonne wheat crop had followed a sunflower crop (pers. comm. with principal grower from the property concerned, 2014).

2.1 Cropping systems and agronomy

The cropping systems and aims of each studied in this project include:

- Biological: brown gravelly sandy loam over gravelly clay soil, includes a mix of synthetic and biological inputs aiming to stimulate soil biological activity and enhance synergistic relationships with crop plants;

- Summer cropping: deep sandy soil, summer cropping rotations to feed and build populations of beneficial soil micro-organisms ready for the following winter crop and reduce the water table in susceptible areas;
- Pro-Trakker seeding equipment: shallow brown gravelly loam over gravelly clay, year after year same furrow precision seeding technology to mitigate non-wetting soils and associated benefits of reduced soil disturbance;
- Chicken manure recycling: gravelly loam over sandy gravel soil, spreading 2 to 4 year old partially composted aged broiler chicken bedding spread over cropping site at 4 m^3/ha when going back into three year crop rotation, recycling nutrients and organic matter back into the system; and
- High input: shallow gravelly loam over gravelly clay soil, conventional cropping with generally high levels of nitrogen and phosphorus fertiliser inputs aimed to optimise yields.

Seeding systems and inputs (N and P fertiliser) are summarised in Table 2.

Table 2: Agronomic management, N and P inputs, growing season rainfall and annual rainfall for each cropping system 2015-2017

Cropping system	Year	Agronomic management	Units N inputs	Units P inputs	Rainfall April to October*	Rainfall annual
Biological (Bio)	2015	Canola from pasture	25.2	6.9	320	410
	2016	Oats: stubble retained	39.47	10.2	391	640
	2017	Lupins: stubble mulched autumn after autumn soil sampling	11.27	14.76	318	471
High input (HI)	2015	Barley	112.6	18.2	320	410
	2016	Canola	200	30	391	640
	2017	Wheat	95	21.9	318	471
Pro-Trakker (PT)	2015	Wheat	74.6	13.7	320	410
	2016	Barley	83	18	391	640
	2017	Canola	90	14	318	471
Chicken manure (CM)	2015	Barley from pasture Aged semi-composted broiler chicken manure broadcast in summer/autumn 2015 at 4 cubic m/ha	51.2	15.7	379	482
	2016	Canola	49.4	14.4	501	698
	2017	Wheat	53.44	14.4	378	550
Summer cropping (SC)	2015	Barley	42.3	11.4	379	482
	2016	Oats	44.5	15.96	501	698
	2017	Canola	40.3	18.24	378	550

*Rainfall records for Bio, HI and PT recorded at Biological site which is close to the HI and PT; CM and SC at Kendenup BOM station (2017)
** Plants showing signs of drought stress (wilting) when sampled
†Only measured at commencement and completion of project

Detail of each cropping system is as follows:

Biological: Coulters and K-hart discs, liquid inject plus 2 shoots seed and fertiliser – one on coulters and one on discs, stubble retained 2015 and 2016 and stubble mulched with speed tiller in dry conditions May 2017 which appeared to make the topsoil more non-wetting. Liquid calcium (5.2%) applied with liquid inject system at seeding time 2017. No other lime applied to this paddock since before 2010. Biological inputs are shown in Table 3.

Table 3: Biological inputs added to Biological cropping system

Year	Liquid biological inputs/ha	Granular biological inputs
2015	**At seeding time:** 90 L Compost extract 0.1 L Biological stimulant (Vitazyme) 5 L Black urea 3 L Liquid fish (fortified with P) 1 L Molasses Foliar: 50 L Compost extract 30 L Black urea 3.7 L Liquid fish (fortified with P) 1 L Fulvic Liquid trace elements	5 kg humates
2016	**At seeding time:** 75 L Compost extract 0.1 L Biological stimulant (Vitazyme) 20 L Black urea 5 L Liquid fish **Foliar:** 10 L Black urea 7.4 L Liquid fish (fortified with P) 0.2 kg Kelp concentrate 1.1 L Fulvic Liquid trace elements	5kg humates
2017	**At seeding time:** 0.1L Vitazyme 10 L Furrow Primer (5.2% calcium with molasses) **Foliar:** 5 L Humical (8% calcium, humic and fulvic acid) with liquid trace elements	15 kg humates

High input: Deep banding system (DBS) with 8" blades single shoot seed & fertiliser. P applied with seed, N mixture of methods including with seed, broadcast and foliar, with multiple foliar applications when season favourable. Stubbles retained, lime applied every 4 years at 3T/ha.

Pro-Trakker: Flexicoil air seeder, tractor has pro-Trakker guidance resulting in dead straight rows. P applied with seed, N mixture of methods including with seed, broadcast and foliar, with multiple foliar applications when season favourable. Stubble rows windrowed and burnt, lime applied 1T/ha 2014.

Chicken manure recycling: Case Shearer combine with knife points 225 mm trash culti drill, stubbles retained, and 0.5-1 T/ha applied 2015. P fertiliser applied with seed 2015 and 2016 and also broadcast in 2016. N applied with seed and broadcast.

Summer cropping: Single disc 10" spacing, 2 T/ha lime applied 2013. P applied with seed, N mixture of methods including with seed, broadcast and foliar, with multiple foliar applications when season favourable.

2.2 Monitoring program

Sampling was undertaken in a real-world situation where the farmer carries out his normal cropping practice. Five different properties were chosen to represent five different cropping systems. At the commencement of the project in March 2015, three sampling sites were randomly selected within the paddock chosen by the farmer to represent similar soil types, and marked with GPS coordinates between 50-150 m apart (Figures 2-6), at each of the five properties.

Figure 2: Location of GPS coordinates in Biological cropping system

Figure 3: Location of GPS coordinates in High Input system

Figure 4: Location of GPS coordinates in Pro-Trakker system

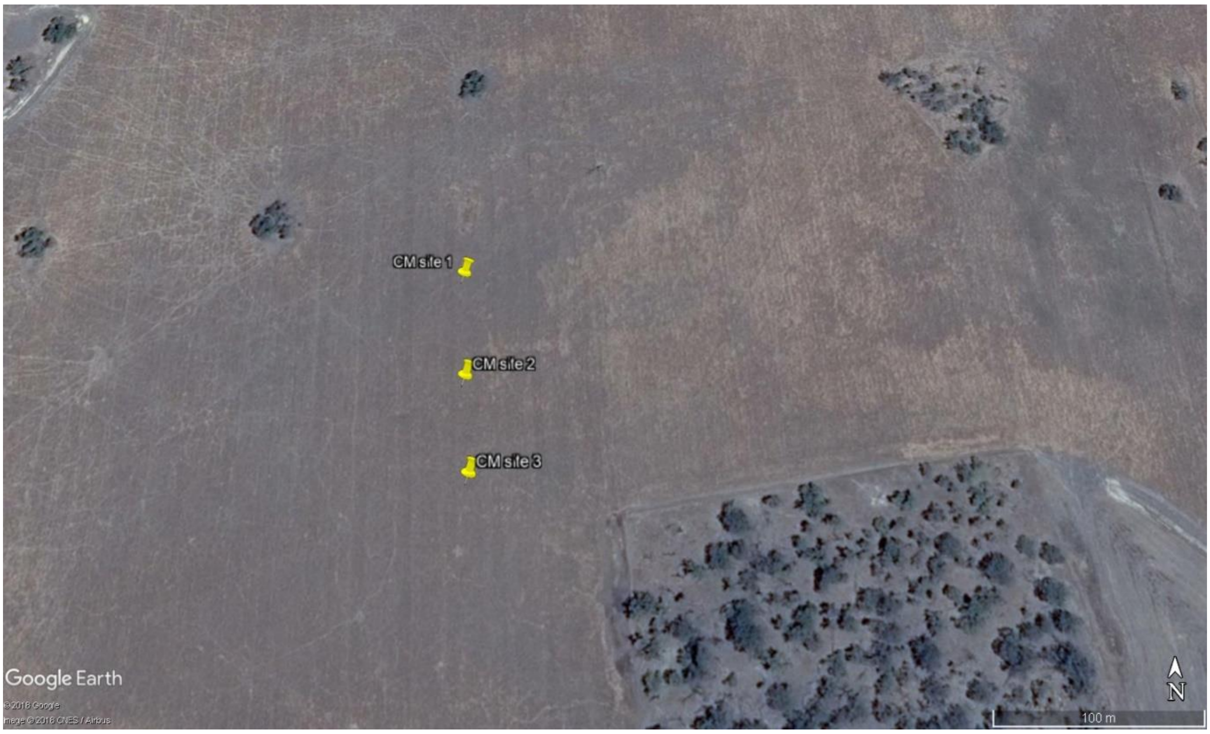

Figure 5: Location of GPS coordinates in Chicken manure recycling system

Figure 6: Location of GPS coordinates in Summer cropping system

2.3 Soil sampling and soil tests

Soil sampling was carried out at all sites on the same day, in late summer to early autumn, when the soil was dry and again in spring around late September. Soil samples for each replicate were taken from 20 core samples within a 20 m radius of the GPS coordinate recorded for each sampling site, and mixed in a bucket for chemical, biological and physical soil tests. The required soil sample size for each laboratory was then weighed out from the mixed sample for each site. Samples taken for microbial-related measures were kept on ice bricks while in the field and then frozen until posting on a Monday with freezer packs, wrapped in thick wads of newspaper. Soil tests were carried out on a mix of chemical, physical and biological measures as follows.

2.3.1 Chemical soil tests

Samples for basic soil tests and total N were sent to SWEP Analytical Laboratories (SWEP). All samples taken seasonally and at the beginning and end of project were carried out at all sites on the same day. Sampling was undertaken at 0-10 cm depth annually in January to March, and at 10-30 cm depths, at commencement and completion of the project. Basic soil tests include: pH (1:5 water and 1:5 0.01M $CaCl_2$), EC (µS.cm), total soluble salt, available elements in ppm: Ca, Mg, Na, N, P, K, S, Cu, Zn, Fe, Mn, Co, Mo, B, exchangeable Ca, Mg, Na, K, H and adjusted H (meq/100g of soil), CEC, adjusted CEC, exchangeable sodium percentage, calcium/magnesium ratio and base saturation percentage; organic matter percent (modified Walkley & Black, 6A1) and total organic carbon percent. In addition, total N was included to enable the calculation of the carbon to nitrogen (C:N) ratio.

Tests before the beginning of the soil monitoring program on samples collected from 0-10 cm depth included soil water holding capacity (plant-available water), water-extractable organic nitrogen (WEON) and water-extractable organic nitrogen (WEOC). Haney et al. (2012) found that water-extractable C:N ratio was a much more sensitive measure than soil organic C:N of the soil substrate which drives soil microbial activity. Tests taken at the end of the experiments in January, 2018 were for Morgan 1 (soluble K, Ca, Mg, P), total N, total Ca, Mg, K, Na, S, P, and trace elements Zn, Mn, Fe, Cu, B, Si, Al, Mo, Co, and Se (mg/kg) by Environmental Analysis Laboratory.

2.3.2 Biological soil tests

One-off tests taken at 0-10 cm depth only included Microbiology Laboratories Australia (MLA) tests: Nitrogen Wise (NWSE) which measures labile N, N_2 fixation by soil bacteria (not Rhizobium) from atmospheric N_2 over time and under a simulated crop, N_2 fixation and NH_4 to NO_3 conversion rate (the % of ammonium N (NH_4) converted to nitrate N (NO_3) by microbial action after one week) were undertaken at the commencement of the project in April, 2015. Phosphorus Wise (PWSE) measures Plant-available P (Olsen) and Total P (Wutshcer & Perkins), net P release (the net increase in plant-available P due to solubilisation by microbes above any solubilised P that became locked up again), P fertiliser availability (the % of soluble fertiliser P added in that remains available after one week in simulated perfect cropping environment), and P release from Total P (the % of plant available P mineralised from total P per week).

Biannual tests in autumn and spring: MLA: Microbiology activity wise plus (MAWS) – measures microbial CO_2 respiration and soil microbial biomass. Annual tests in spring only: MWSE includes a broad range of measures relating to microbial diversity, including: biomass (mg/kg) of total microorganisms, total bacteria, total fungi, and key microbial groups of bacteria and fungi; key indicators including microbial diversity, fungi:bacteria ratio and bacterial stress (Phospholipid fatty acid method); and nutrient concentrations (mg/kg) (N, P, K, S, Ca, Mg, C) held in microbes, and soil indicators including nutrient solubilisation rate, nutrient cycling rate, disease resistance, drought resistance, nutrient accessibility, and residue breakdown rate.

Sap tests undertaken annually in spring include brix, pH, EC (2016, 2017), K, N (2017 only)

2.3.3 Physical tests

Physical field tests undertaken annually in spring include: penetrometer depth, A horizon depth, soil moisture (2017 only). Physical soil tests were sampled to a depth of 0-10 cm, carried out by SWEP Analytical Laboratory include plant available water (at commencement of project only, prior to seeding in 2015) which is a measure of the water holding capacity (field capacity %) minus permanent wilting point %, and total organic carbon; and by Golden Embassy percent <53 µM wet sieve test (2015 only) and specific gravity (before only). Bulk density is considered to be inaccurate when over 10% of the soil is gravel (Hunt & Gilkes, 1992). As all sites were over 10% by weight gravel (SWEP Analytical Laboratories, 2015), bulk density was unable to be determined and the figure of 1.3 g/cm^3 was applied to derive the total organic carbon T/ha figure using the method described by Pluske, Murphy & Sheppard (2017).

2.4 Farmer data

After harvest, yield data (tonnes/ha) for the sampling area and fertiliser inputs (units N, P and K/ha), as well as liming products and biological inputs for the season were gathered from the principal farmer at each property. Yield data was standardised for different crops to wheat yield equivalents (WYE). Yield standardisation to make different crops comparable follows rule of thumb that oats yield is 25% higher than wheat, barley 15% higher and canola and lupins are half.

2.5 Data analyses

Statistical analyses were performed by the Centre of Excellence in Natural Resource Management, University of Western Australia, Albany. The following methods were used for statistical analysis. Changes in values of soil attributes were visually assessed through boxplots for all years, with subsequent paired t-tests utilised to identify significant differences over time for each soil attribute. Tests were conducted on both the full data for the soil attribute (global test) and for each cropping system individually. T-tests were performed with appropriate adjustments for unequal variances if necessary. As there were only three measures of each treatment in each time, caution needs to be taken when considering the significance of the t-test results. The correlations of each soil attribute on yield (wheat yield equivalent) were assessed through robust regression as this method accounts for outliers and heterogeneity of variance in the data. Multivariate analyses were performed to identify concurrent changes in eight key soil attributes that were selected to represent chemical, biological and physical soil health parameters – including pH, total fungi, total bacteria, CEC, organic matter, spring and autumn microbial activity and depth of A horizon – among treatments and between years. This was assessed visually through principal components analysis (PCA), and tested though permutational analysis of variance (PERMANOVA). All analyses were performed in the R statistical environment v 3.4.0 (R Core Team 2017) using the "vegan" (Oksanen et al. 2017), "RVAideMemoire" (Hervé 2016), "MASS" (Venables and Ripley 2002), and "sfsmisc" (Maechler 2016) packages.

3. Results

Results of spring microbial biomass, pH $CaCl_2$ 0-10 cm and 10-30 cm depth, brix levels taken in spring and yield (WYE) for each cropping system 2015-2017 are shown in Table 4.

Table 4: Spring microbial biomass, pH ($CaCl_2$) 0-10 cm and 10-30 cm depth, brix levels taken in spring and yield (WYE) for each cropping system 2015-2017

Cropping system	Microbial biomass C Mg/kg (spring)	pH $CaCl_2$ 0-10cm	pH $CaCl_2$ 10-30cm†	Brix Spring	Yield (WYE T/ha)
Biological (Bio)	755	4.9	5	3.8	1.8
	162	4.7	N/A	24.6	2.2
	234	4.8	5.2	10	2
High input (HI)	901	4.6	4.5	8.8	3.7
	128	4.7	N/A	9.3	3.9
	308	4.7	4.5	23*	4
Pro-Trakker (PT)	697	4.8	5	4.5	3
	80	5.3	N/A	16	3.1
	328	5.2	5.3	8.5	4
Chicken manure (CM)	1090	5	5.6	9.5	3.4
	288	5.3	N/A	9	4.6
	440	5.5	5.6	16.3*	3.3
Summer cropping (SC)	763	4.9	4.9	9.6	2.4
	185	5.4	N/A	15	2.1
	253	5.2	5.4	8.8	2.8

*Plants showing signs of drought stress (wilting) when sampled

†Only measured at commencement and completion of project

3.1 Statistics

A summary of the p-values showing change in each indicator over time for each cropping system and overall (not relating to yield) is shown in Table 5. To keep the results robust, p values showing the amount of change over time in each cropping system and overall have been adjusted (as comparing 2016 to 2015 and 2017) rather than comparing two groups of three values (i.e. Biological 1,2,3 from 2016 against Biological 1,2,3 from 2017). An overall summary of all chemical, physical and biological indicators positively or negatively correlated with increased yield (WYE) overall are shown in Table 6. The biggest predictors (highest significance) of increased yield from all measures tested were firstly available copper ppm (SWEP) closely followed by available phosphorus ppm (SWEP Olsen extractable, 9C2a) and thirdly total nitrogen inputs (soluble N) inputs.

Table 5: Summary of box plot p-values of change in each indicator over time and overall (not relating to yield (Source statistical data: Centre for Excellence in Natural Resource Management, UWA, Albany campus)

Measure	Cropping system	2015 vs 2016	2015 vs 2017	2016 vs 2017
CEC	overall	0.138	0.331	0.138
	biological	0.488	0.42	0.068
	chicken manure	0.959	0.429	0.959
	high input	0.115	0.069	0.069
	pro trakker	0.804	0.482	0.295
	summer cropping	0.437	0.725	0.725
pH water	overall	0.01	0.01	0.497
	biological	0.676	0.676	0.676
	chicken manure	0.113	0.113	0.313
	high input	0.172	1	1
	pro trakker	0.04	0.027	0.411
	summer cropping	0.318	0.318	0.318
Horizon depth	overall	0.462	0.967	0.35
	biological	0.859	0.859	NaN
	chicken manure	0.551	0.551	0.551
	high input	0.766	0.766	0.551
	pro trakker	1	1	1
	summer cropping	0.015	0.156	0.25
Organic matter	overall	0.684	0.469	0.273
	biological	0.09	0.246	0.246
	chicken manure	1	1	1
	high input	0.885	0.553	0.885
	pro trakker	1	1	1
	summer cropping	1	1	1
Spring microbial activity	overall	0.001	0.001	< 0.001
	biological	0.486	0.459	0.486
	chicken manure	0.777	0.309	0.065
	high input	0.049	0.054	0.006
	pro trakker	0.036	0.061	0.026
	summer cropping	0.034	0.034	0.034
Total fungi	overall	0.497	0.139	0.497
	biological	1	1	1
	chicken manure	0.789	0.706	0.789
	high input	0.402	0.314	0.165
	pro trakker	0.226	0.91	0.91
	summer cropping	0.397	0.106	0.331
Total bacteria	overall	0.488	0.002	0.487
	biological	0.688	0.035	0.326
	chicken manure	0.806	0.275	0.806
	high input	0.433	0.378	0.433
	pro trakker	0.065	0.413	0.454
	summer cropping	0.802	0.036	0.494

Table 6: Chemical, physical and biological data positively or negatively correlated with increased yield
(Source statistical data: Centre for Excellence in Natural Resource Management, UWA, Albany campus)

Chemical data positively correlated with yield (WYE* t/ha)	**p-value**	**rho (correlation value)**
Av. Cu ppm	0.00000000002286	0.8064451
Av. P ppm	0.00000000005447	0.7975719
Total units N inputs	0.0000000002459	0.7810548
Av. Zn ppm	0.000000034	0.7151427
Av. Ca ppm	0.00000688	0.66152447
Ca/Mg ratio	0.0008205	0.5780896
Water Extractable Organic Nitrogen	0.02486	0.57253
TSS ppm	0.0004486	0.5015381
EC µS/cm	0.0004486	0.5015381
Ex Ca me/100g	0.0004856	0.4989282
Av. S ppm	0.002893	0.4340386
Total P inputs	0.003704	0.4239714
Av. N ppm	0.005218	0.409489
C:N ratio	0.01582	0.3578001
Ex Ca %	0.017	0.3541494
Av. Co ppm	0.03184	0.3204914
Total N	0.03307	0.3183467
Ex H me/100g	0.03866	0.3093508
Av. Mo ppm	0.0421	0.304323
Adj CEC me/100g	0.04671	0.2980985
Chemical data negatively correlated with yield (WYE*)	**p-value**	**rho**
A horizon depth	2.26E-06	-0.6394651
Ex Mg %	0.002027	-0.4480291
Ex Na me/100g	0.01264	-0.3689055
Ex Na %	2.38E-05	-0.5856263
Av. Na ppm	0.0008513	-0.4789513
Physical data positively correlated with yield (WYE* t/ha)	**p-value**	**rho**
TOC %	0.003489	0.4254294
OM %	0.003575	0.4254294
Biological data positively correlated with yield (WYE* t/ha)	**p-value**	**rho**
Total fungi	0.0003067	0.5137611
Total bacteria	0.003056	0.4318301
Spring microbial activitiy	0.001758	0.4534509

*WYE = wheat yield equivalents

Statistical results (box plots) of a range of indicators of soil health and associated plots showing whether there is any correlation with wheat yield equivalents (yield) (t/ha) are shown for the following indicators: total bacteria (mg/kg) (Figure 7), total fungi (mg/kg) (Figure 8), spring microbial activity indicator (Figure 9), organic matter (%) (Figure 10), horizon depth (mm) (Figure 11), cation exchange capacity (meq/100g of soil) (CEC) (Figure 12), pH (water) (Figure 13) and plant available water (%) (Figure 14). Plots showing correlation with yield (without box plots) are also shown for: total organic carbon (t/ha) (Figure 15), available calcium (ppm), available phosphorus (Olsen) (ppm) (Figure 16); and showing residuals for total units nitrogen and phosphorus inputs (Figure 17). Plots showing multivariate results for 2015 and 2016 for all sites and key indicators of soil health including A horizon depth, autumn and spring microbial activity indicators, CEC, organic matter, total fungi and total bacteria and pH (water); as well as multivariate results for the three years 2015-2017 showing all except the autumn microbial activity and CEC) (Figure 18).

Horizontal lines or bands in the box plots on the left indicate desirable values/range. In plots on the right, lines indicate significant regressions ($p<0.05$), correlated with increased wheat yield equivalents (WYE or yield), where the code for lines is:

Solid = overall (all data points)
- Dashed = 2015
- Dotted = 2016
- Dotdash = 2017

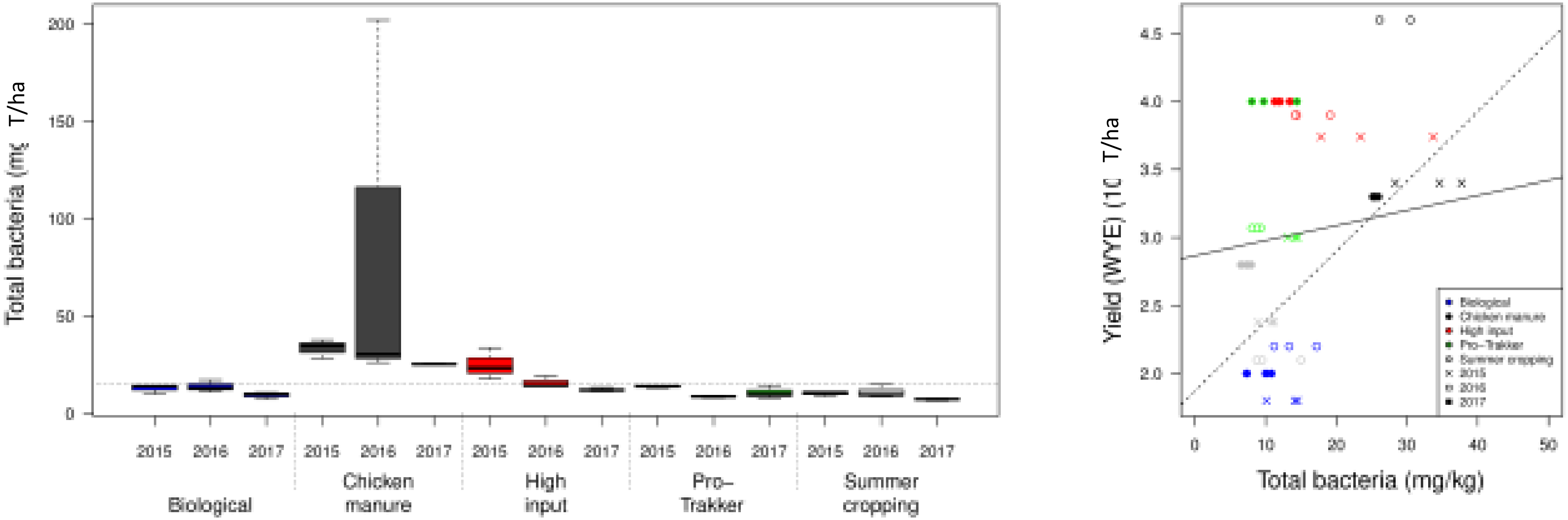

Figure 7: Total bacteria box plots (left) and showing significant (p=<0.05) correlation (p=0.008) with increased yield (t/ha) in 2015 and overall (p=0.003056)(right).

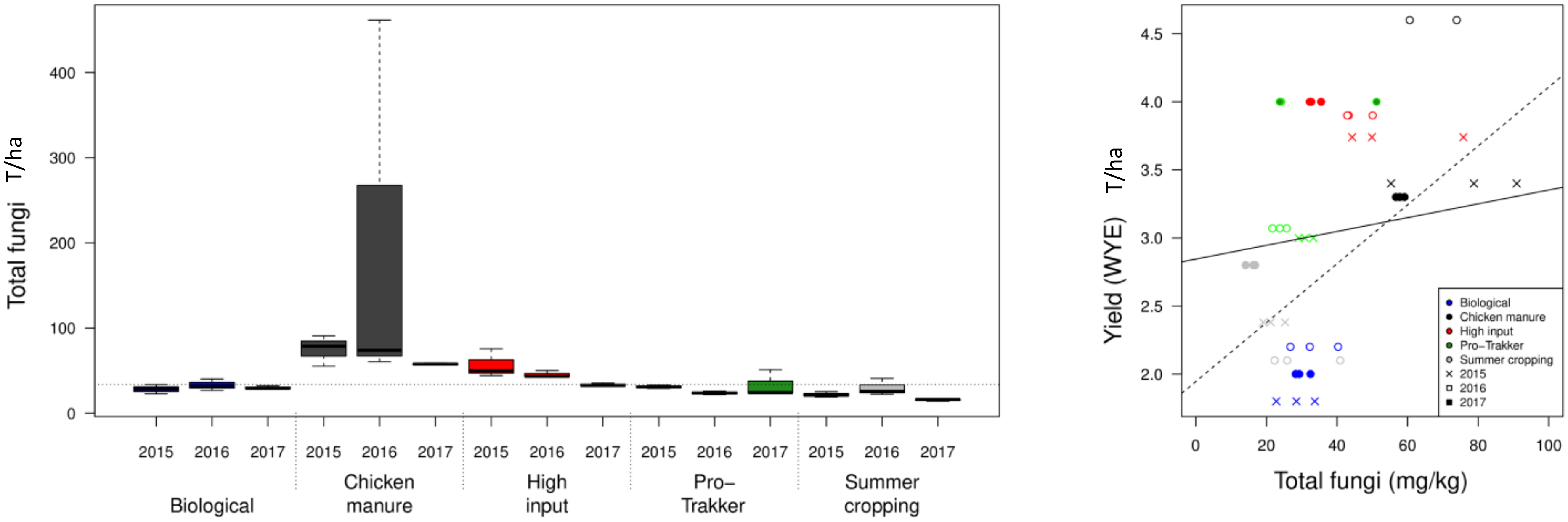

Figure 8: Total fungi box plots (left) and correlation with yield (t/ha) (right), showing significant correlation (p<0.05) with increased yield in 2015 (p=0.0101) and overall (p=0.0003067)

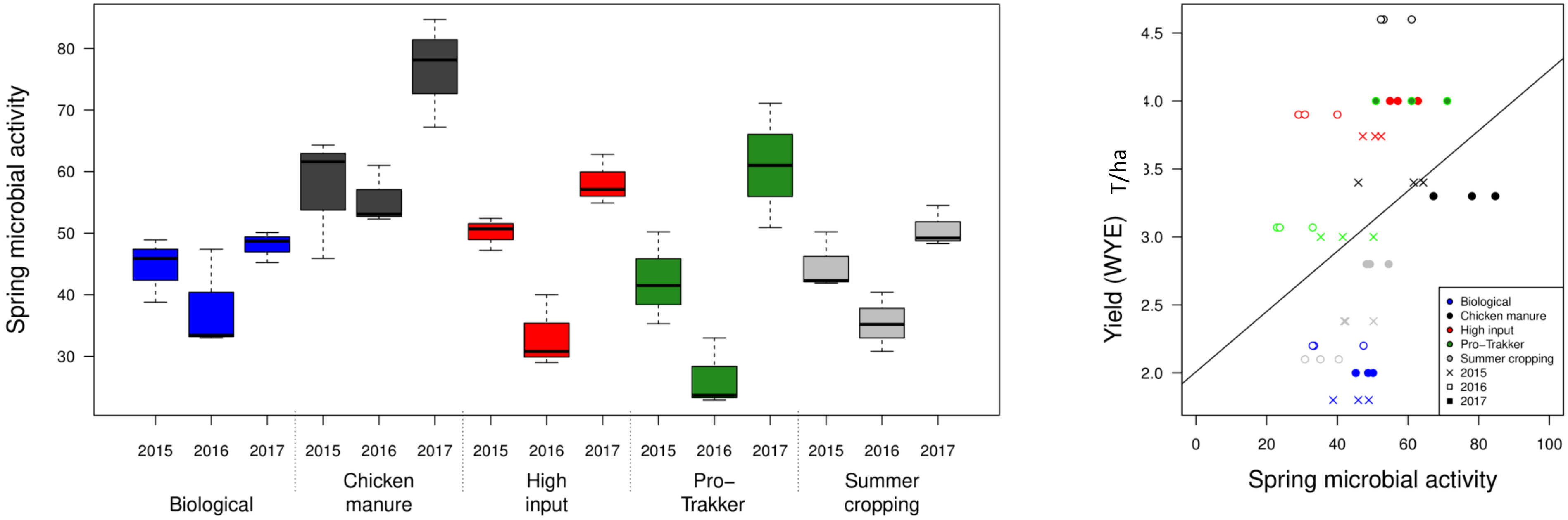

Figure 9: Spring microbial activity box plots (left), showing significant correlation ($p<0.05$) with increased yield (t/ha) overall ($p=0.001785$) (right)

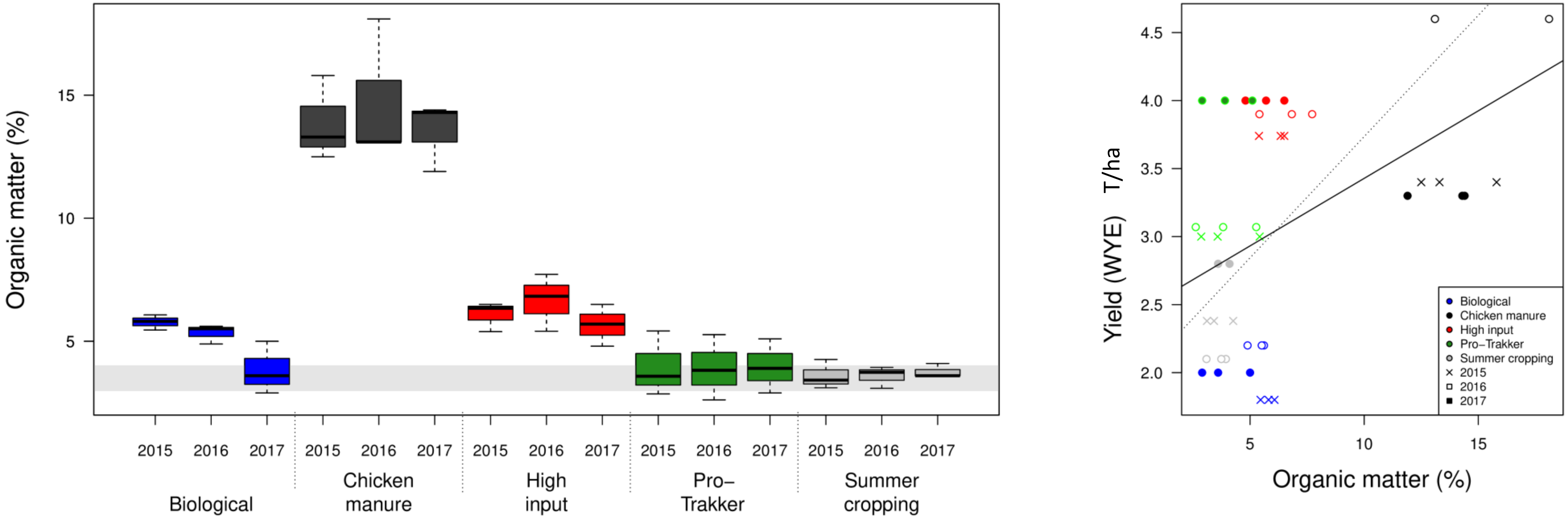

Figure 10: Organic matter (%) box plots (left), showing significant correlation (p<0.05) with increased yield (t/ha) overall (p=0.003489) (right)

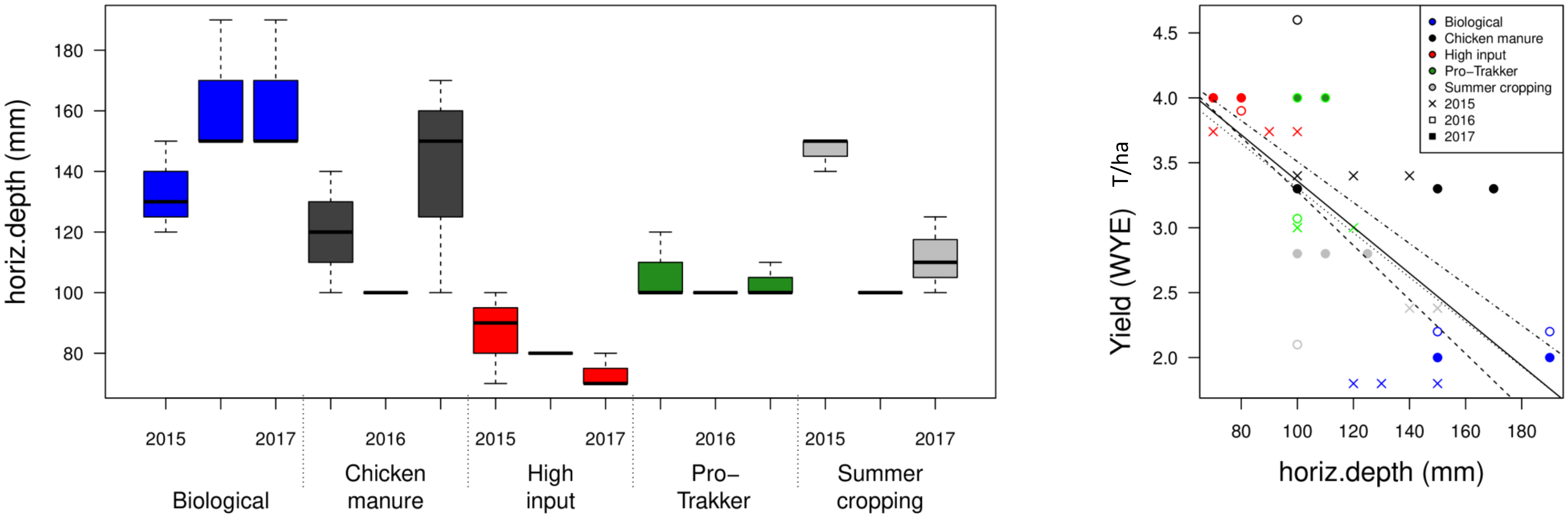

Figure 11: A Horizon depth (mm) box plots (left), showing negative correlation (p<0.05) with yield (t/ha) in all years (2015 p = 0.002, 2016 p = 0.013, and overall (2015-2017) (p=2.261e-06) (right)

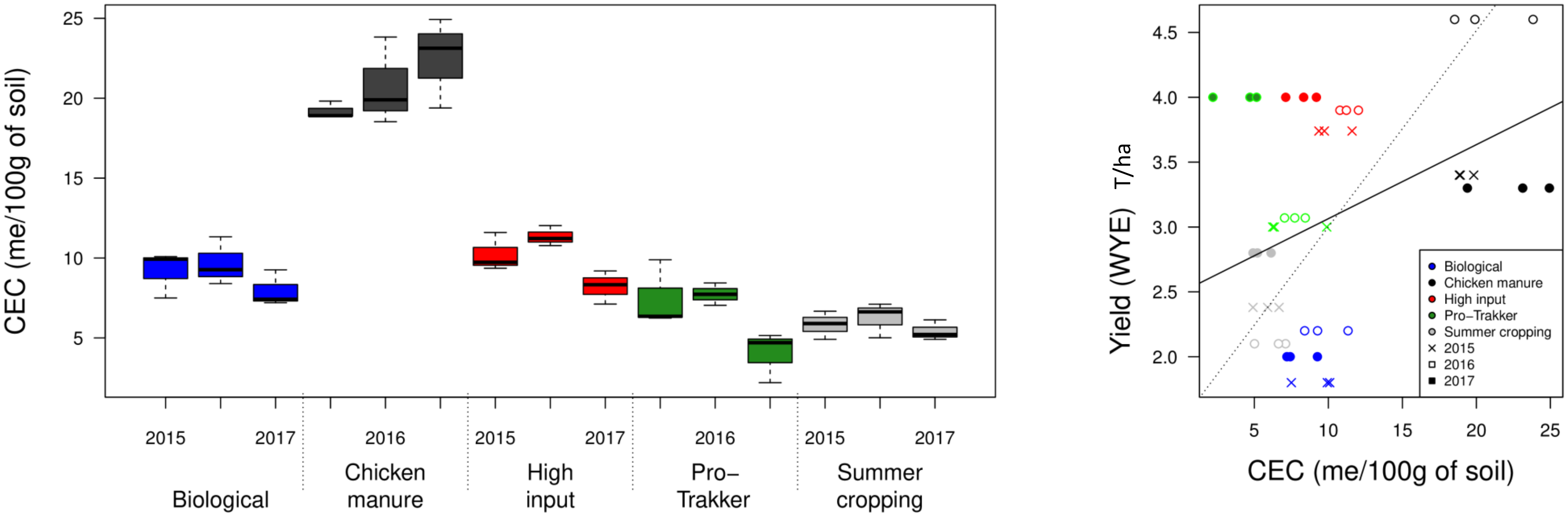

Figure 12: CEC (me/100g of soil) box plots (left), showing significant correlation ($p < 0.05$) with increased yield (t/ha) in 2016 ($p = < 0.001$) only (right)only. Adjusted CEC did show a significant correlation with yield overall ($p = 0.04671$) (Table 6)

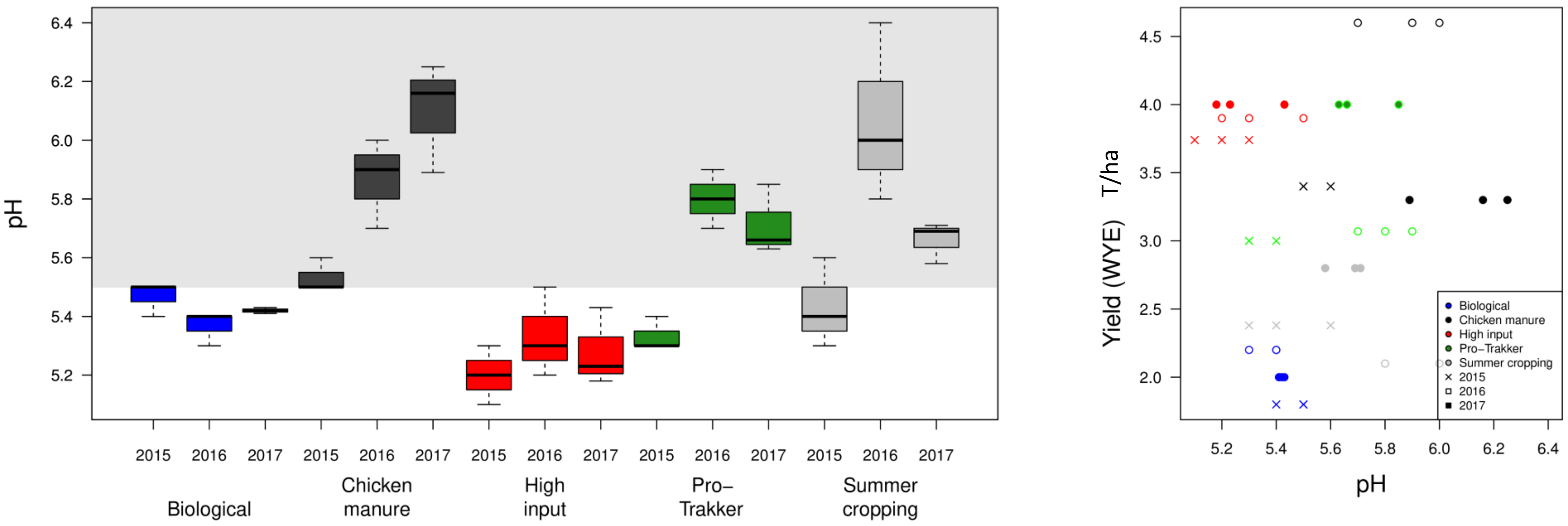

Figure 13: Soil pH (water) box plots (left), showing no significant correlation with increased yield (t/ha) (right)

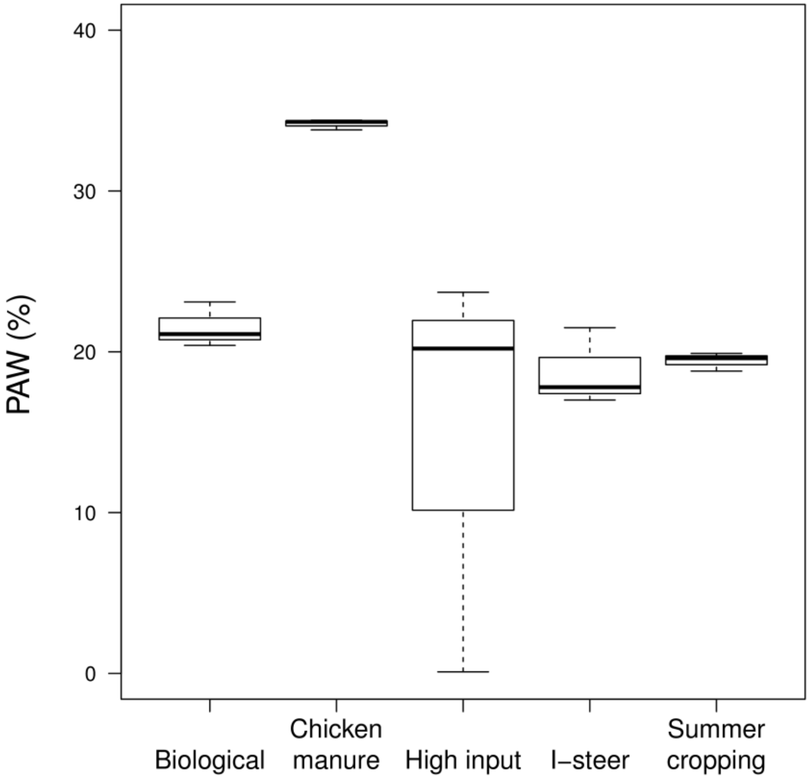

Figure 14: Comparison of plant available water (PAW) among treatments (left) with no significant effect of PAW upon yield (t/ha) (right).

Plant available water (PAW) sampling undertaken only in 2015 was found to differ among treatments at an alpha level of 0.10 (P= 0.070), with that for the Chicken manure cropping site being significantly ($p<0.05$) greater than other treatments. No significant relationship between PAW and yield was detected (p= 0.862).

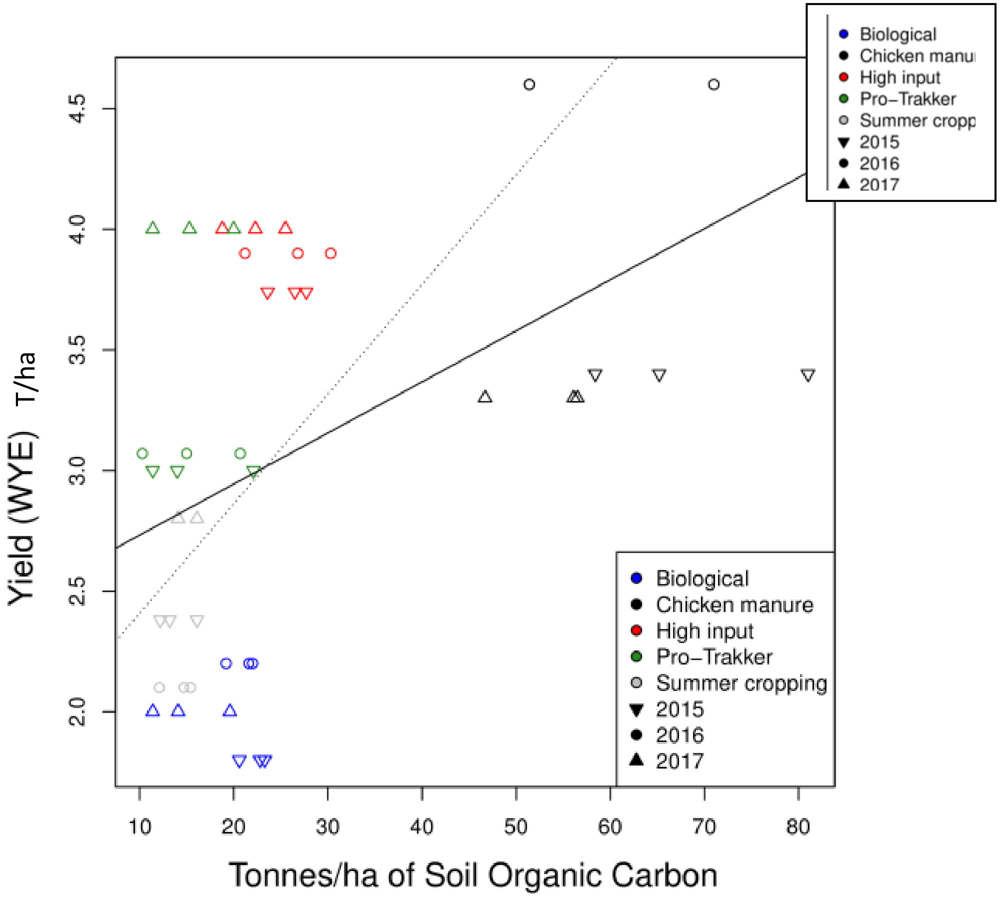

Figure 15: Tonnes Soil Organic Carbon/ha was found to have a significant ($p<0.05$) influence on increased yield (t/ha) in 2016 overall ($p = 0.003489$).

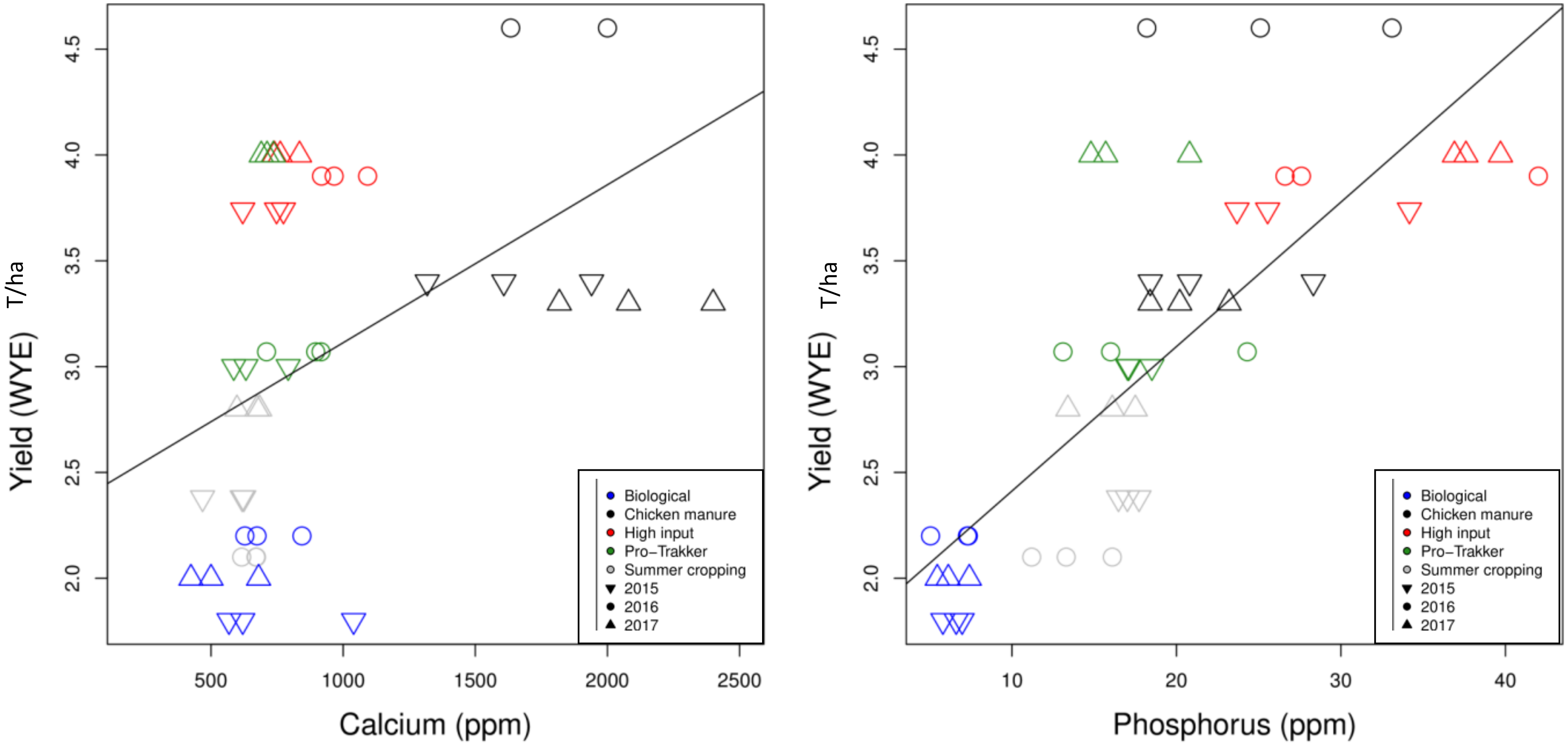

Figure 16: Overall relationship between available calcium (ppm) (left) and available phosphorus (ppm) (Olsen) (right) and yield (t/ha), showing significant correlation between both indicators overall (Available Ca: p = 6.88E-06, rho = 0.66152447, Available P: p = 5.45e-114, rho = 0.795719).

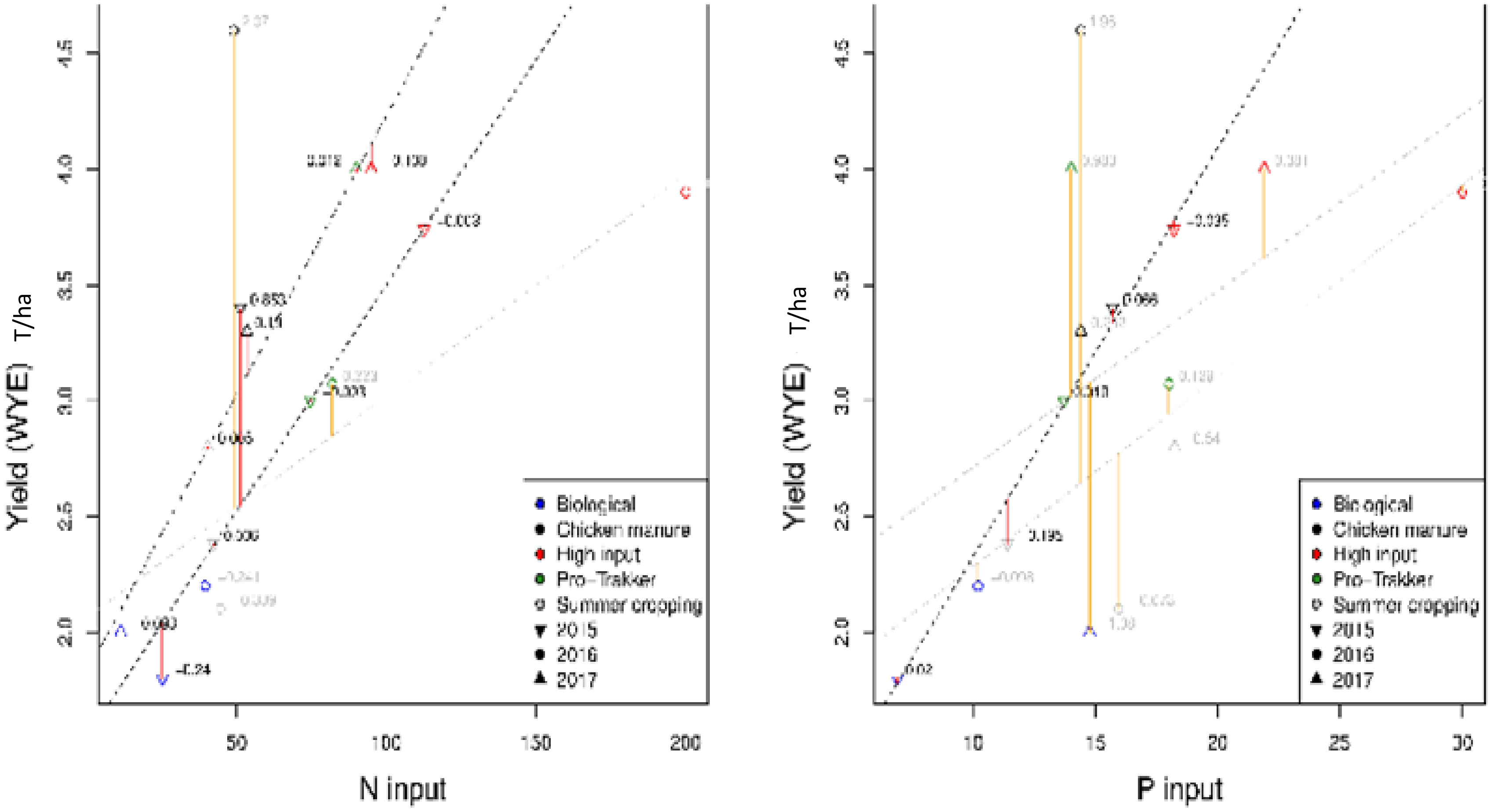

Figure 17: Total units N (left) and P (right) inputs, showing years where there was a significant correlation with yield (t/ha) in bold. Positive residuals (indicating greater yield for input of N or P) for all years are shown by lines pointing upwards from the trend line. A significant correlation with increased yield for N inputs was shown in 2015 and 2017, and overall (p = 246e-10, rho = 0.7810548,) for P inputs in 2015 and overall (p = 5.45e-11, rho = 0.7975719)

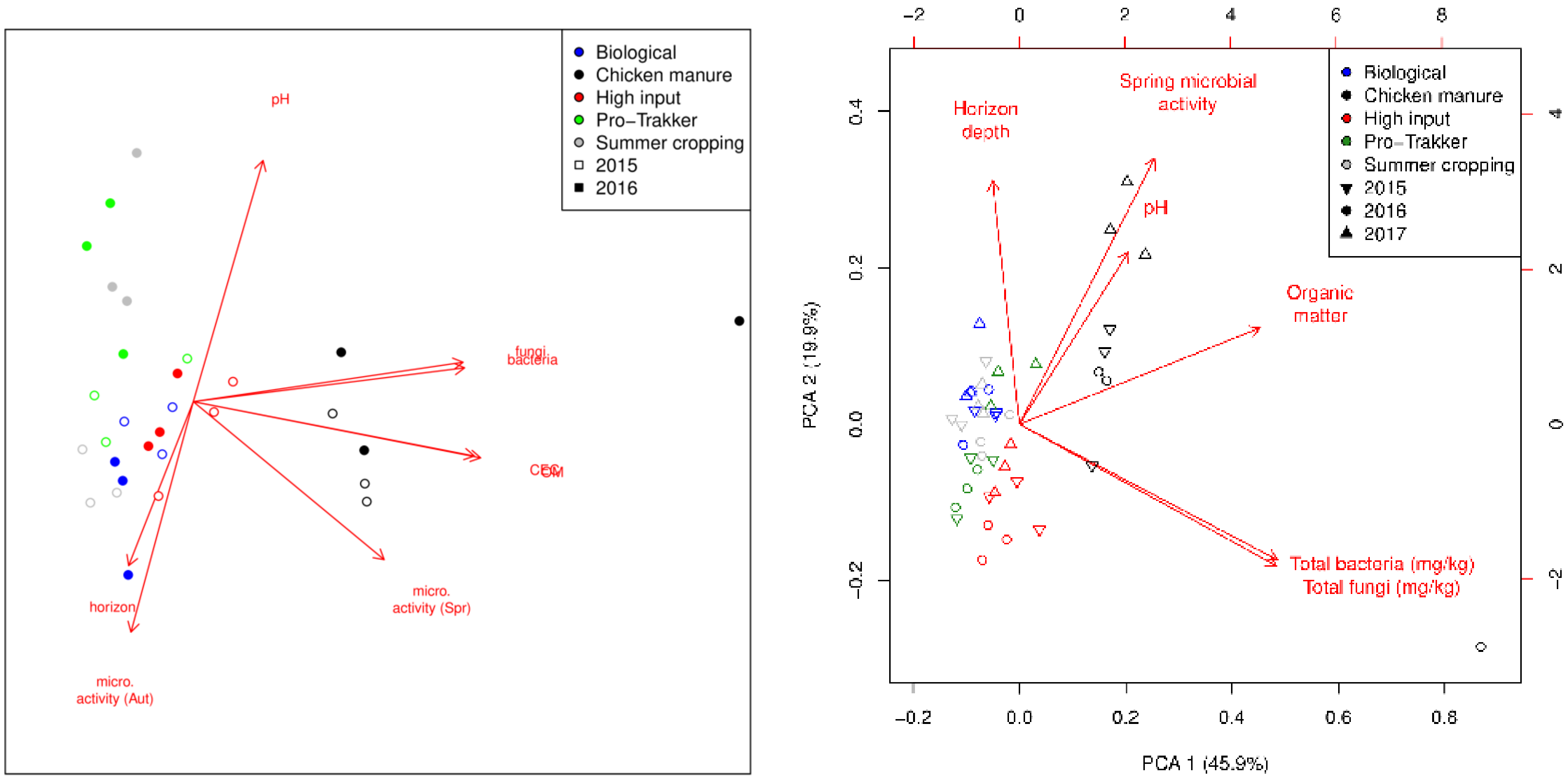

Figure 18 Multivariate results: The PCA ordination performed on the first two years of data (left) indicates the greatest distinction among treatments was increase fungi, bacteria, cation exchange capacity, organic matter, and spring microbial activity in the 'Chicken manure" treatment. The PCA ordination performed after three years of data (right) has fewer indicators included, and still shows the chicken manure site having the greatest distinction overall.

3.1.2 Soil organic carbon percent levels in each cropping system

Soil carbon condition grades (0-10cm soil depth) of over 4% represent very high, 2-4% high, 1-2% moderate and 0.5-1% low, less than 0.5% very low (Griffin et al, 2013). Soil organic carbon % (SOC) levels in the different cropping systems are mostly in the high category, and the chicken manure system is very high (Table 3).

Table 3: **Lowest and highest recorded mean soil organic carbon (%) for each cropping system measured annually for the 4 year period of the project, and indicative soil organic carbon grade**

Cropping system	**Range (average/site) of Soil organic carbon* (%) (0-10cm) recorded annually 2015-2018**	**Grade****
Biological	2.11-3.35	High
High input	3.29-3.5	High
Pro-Trakker	2.29-3.77	High
Chicken manure	7.35-8.56	Very high
Summer cropping	1.95-2.18	Moderate to high

*Soil organic carbon calculated as 58% of organic matter (modified Walkley & Black (WB) 6A1)

**Grades are based on Griffin, Hoyle and Murphy (2013) which is WB multiplied by a factor of 1.3. The authors are unaware of whether the modified method used by SWEP is directly comparable with the method applied by Griffin et al and therefore grades are indicative only

4. Discussion

This project has undertaken case studies on five farmer-initiated cropping systems for the purpose of identifying current trends of soil health in a range of cropping systems and soil types. It wasn't within the scope of this project to include an economic analysis or to measure the food quality or nutrient density of produce of/from the different cropping systems. It is acknowledged that these are also important considerations in looking holistically at the cropping systems overall.

The soil measurements most strongly correlated with the highest wheat yield were available Cu (ppm), available P (ppm) (Olsen) and total inputs of N in the context of the cropping systems studied in this project. Not surprisingly, the lowest yield shown in the biological system was associated with the lowest available Cu (ppm) (Figure 19), available P (ppm) and total N inputs. Positive residuals of total units N and P inputs (Figure 17) for all three years of the project were only recorded in the chicken manure system. Positive residuals indicate greater yield for a given amount of inputs in relation to other systems. The Pro-Trakker system had a positive residual for P input in 2016 and 2017, and the High Input system had a positive residual of P inputs in 2015 only.

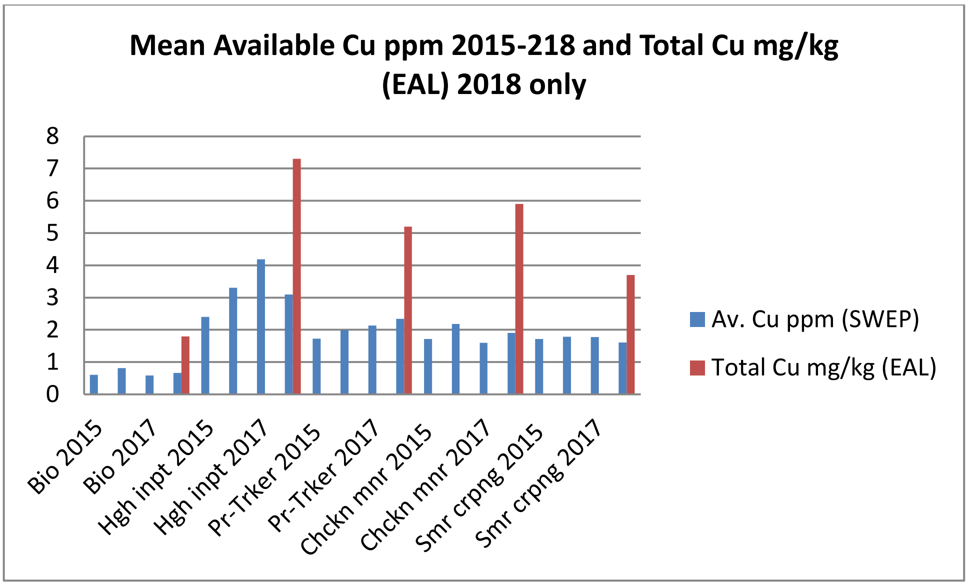

Figure 19: Mean of three sampling sites at each cropping system 2015-2018 Available Cu (ppm) and relationship with : mean of three sampling sites at each cropping system Total Cu (mg/kg) 2018 only at each cropping system, showing particularly low levels at the Biological system

A high lock up rate of fertiliser-applied soluble P was found by Microbiology Laboratories Australia's (MLA) Phosphorus Wise (PWSE) test undertaken in autumn 2016 (See Methods 2.2). Out of the 15 samples, only one was found to have intermediate lock up of soluble P, while all others had high lock up rates. A strong relationship between P fertiliser availability and microbially-mediated P release from Total P (%) (MLA) (Figure 20) shows that, where there is no fertiliser P remaining after 7 days, there is also no microbially-released P from Total P. These findings indicate there is insufficient soil biological activity to prevent the vast majority of the applied P being quickly locked up in a 'non-plant available' form (pers. comm. Dr A. Martin, MLA).

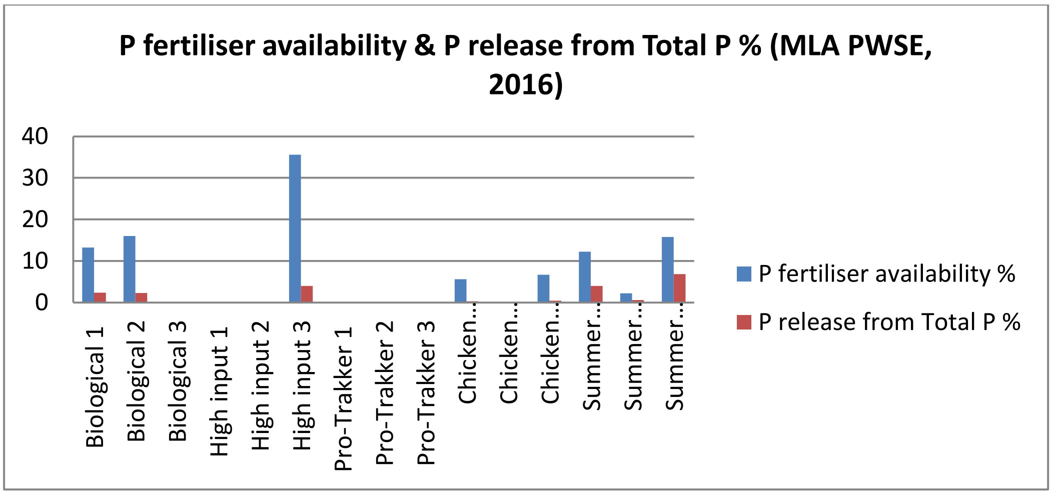

Figure 20: Relationship between P fertiliser availability and microbially-mediated P release from Total P (%) for each sampling site at each cropping system in 2016

Phosphorus availability can be increased by processes relating to organic matter levels and restricted by iron and aluminium oxides found naturally in acid soils (Department of Agriculture and Fisheries, Prince Edward Island, Canada, 2017). The chicken manure site had the highest Total P and the highest iron and aluminium (on forest gravel soil) of all cropping systems soils studied (Figure 21). The chicken manure site also had the highest organic matter percent and mycorrhizal fungi (mg/kg) compared to other sites (Figure 22), pH around 6 (water) in 2017 (Figure 13) and the most efficient use of fertiliser P as shown by the positive residuals of yield in relation to P inputs (Figure 17). Further study is required to tease out roles of the soil itself and the chicken manure in contributing to these properties.

It is speculated that the positive residual of increased yield in relation to soluble P inputs at the chicken manure site in the face of having the highest levels of iron and aluminium may be due to buffering by the high organic matter levels and associated mycorrhizal fungi numbers (Figure 22) and least acid soils, with highest Total P.

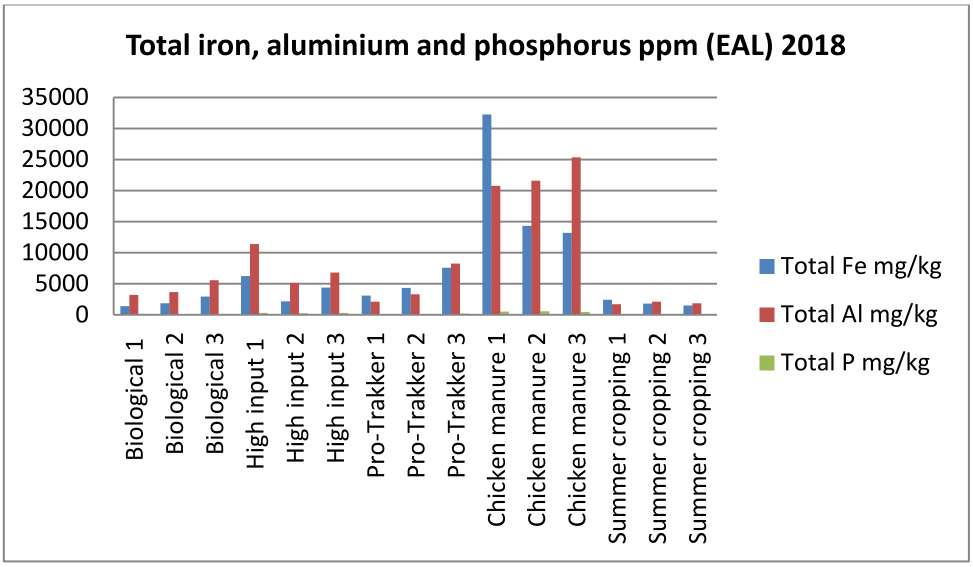

Figure 21: Relationship between levels of Total iron, Total aluminium and Total phosphorus at each sampling site within each of the different cropping systems

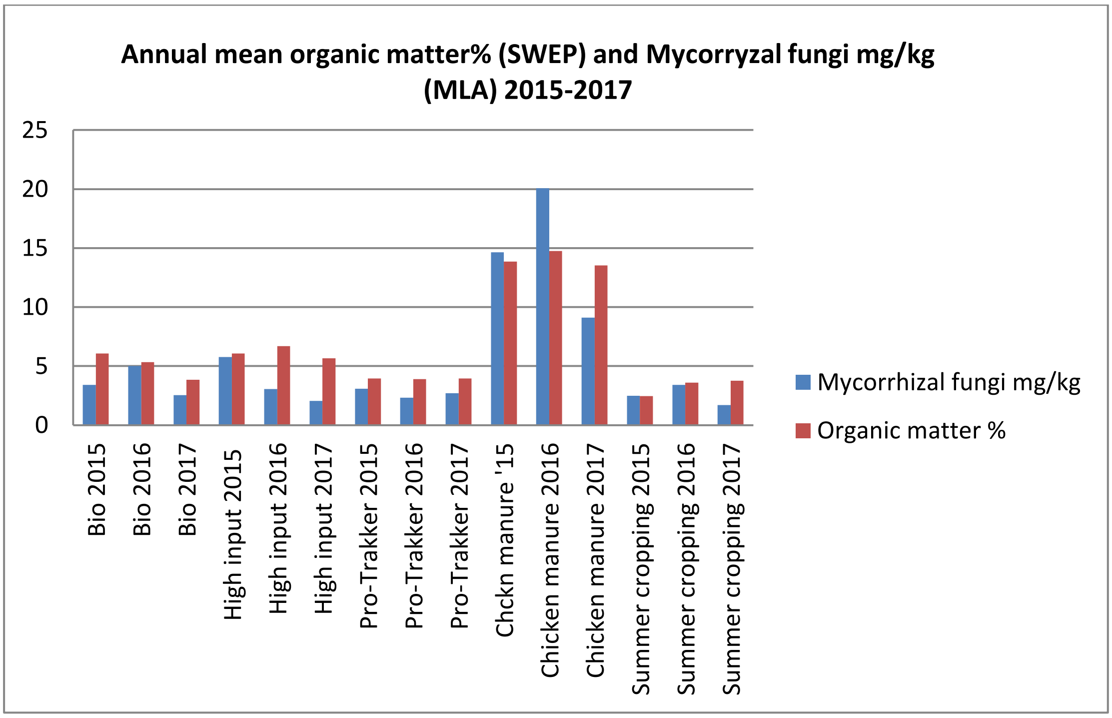

Figure 22: Relationship between mean annual organic matter % and Mycorrhyzal fungi mg/kg for each cropping system 2015-2017

The autumn 2015 NWSE (Nitrogen Wise) test (MLA) showed free living nitrogen fixing bacteria (mg/kg) to range from poor to fair, and ammonium N (NH_4) conversion rates to plant available nitrate (NO_3) to be generally good overall. Levels of nitrogen fixing bacteria are understood to be suppressed when synthetic fertiliser N is applied at above threshold levels (Jones, 2014). The bacteria involved in nitrogen fixation are different to the bacteria involved in transforming the non-synthetic nitrogen to a plant available form (pers comm. Dr M. Manjarrez, MLA) – an example of the importance of microbial diversity in optimising efficiency of nitrogen applications. The highest positive residuals of applied synthetic N in relation to yield at the chicken manure site (Figure 17), appear to be supported by the highest levels of nitrogen fixation from atmospheric N by free-living nitrogen fixing bacteria which is also highest at the chicken manure site (Figure 23). Free-living N_2 fixation is promoted by carbon inputs which would have been substantial in the chicken bedding. There is a balance between having sufficient N to enhance decomposition of the straw, but not so much N that N_2 fixation is inhibited (pers comm. Dr M. Roper, April 2018).

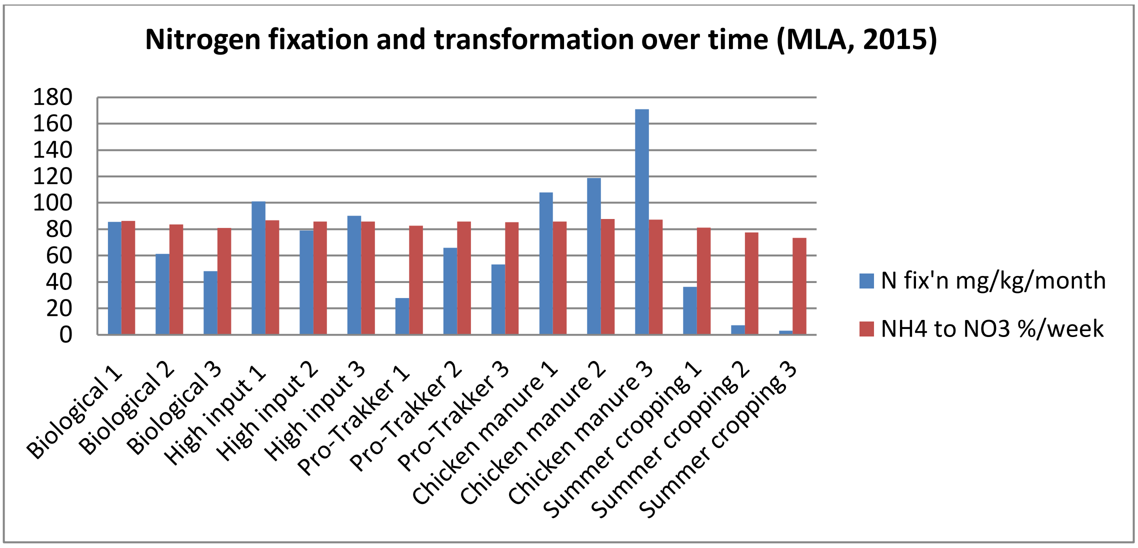

Figure 23: Levels of nitrogen fixation from free living nitrogen fixing bacteria mostly from atmospheric N and nitrogen transforming bacteria at all three replicated cropping system sites sampled in April, 2015 (MLA), showing similar levels of NH_4 conversion to NO_3 %/week and variable N fixation across systems, with the highest levels at the chicken manure site.

Available Calcium (ppm) was found to have a significant ($p = 0.003575$) effect upon yield overall (Figure 16). This relationship appears to be applicable to the Chicken manure, Pro-Trakker, and Summer cropping treatments. Large differences can be seen in yield values of the Biological and High input treatments, despite slight changes in their Available Calcium measurements. The Biological system is relying on synergy between microbes and plants to increase productivity. Most microbial processes are reduced in acidic soil because growth and reproduction of soil microbes are reduced – in turn affecting the rate of breakdown of organic matter and cycling of nutrients (Gazey & Davies, 2009). It is therefore suggested that low available calcium levels on the Biological system is likely to be a factor impacting the production of biomass and ultimately yield in this system.

The important role played by soil biology in maintaining productivity and sustainability is demonstrated by the following biological indicators being correlated with increased yield overall: total bacteria (Figure 7) and total fungi (mg/kg) (Figure 8), spring microbial activity (Figure 9), organic matter (%) (Figure 10), and soil organic carbon t/ha (Figure 15). It is interesting to note the pattern of significant relationship with yield of total fungi and total bacteria in 2015 and 2017 which were seasons marked by fluctuations of wet and dry periods throughout the growing season while 2016 was a season of above average rainfall (Table 5), with relatively even moisture throughout. Conversely, spring microbial activity was significantly less in 2016 than in 2015 and 2016 in all systems, and yet was correlated with increased yield overall, but not 2015, 2016 or 2017 in isolation.

The significantly higher plant available water (Figure 14) in the chicken manure site is likely to be linked to the high soil organic matter at this site (Figure 10). The lack of correlation between plant available water and increased yield needs to be treated with caution because all other systems had similar organic matter levels and plant available water to each other. The soil carbon fraction of soil organic matter is known to hold significant volumes of water like a sponge. A one percent increase in soil organic carbon equates to approximately 2% increase in water holding capacity (Department of Primary Industries and Regional Development, 2017). Figure 24 shows photograph of top soil in January 2018 with 'matchhead' macro-aggregates and well aerated soil associated with high levels of soil organic matter and soil organic carbon at the Chicken manure site.

Figure 24: Soil sample from Chicken manure site in January 2018 showing matchhead soil macro-aggregates and well aerated soil

Soil organic carbon percent (SOC) levels were calculated as 58% of soil organic matter % (Figures 25 and 26). Graphed comparisons of the annual mean of replicates taken in autumn of each year (0-10cm) show variation over the period of the project (Figure 25) in each cropping system, as well as between the beginning and end of the project (0-10 cm and 10-30 cm) (Figure 26). SOC levels are mostly in the high category (Biological, High input and Pro-Trakker), the Chicken manure system is very high in the 0-10 cm soil depth (Table 3, Figure 25) and the deep sand Summer cropping site which has the lowest SOC is moderate to high (SOC condition grades sourced from DAFWA, 2013, p. 80). An impediment to building humus may be the lack of clay that assists in aggregation (Wagner et al, 2007). Although there is a general trend of reducing SOC overall in both 0-10 cm and 10-30 cm depths, the steepest reduction appears in the Biological and Chicken manure sites – both cropping systems that involve three year cropping/pasture rotations only (Figure 26). The Summer cropping system is the only one with an (slight) increase in 10-30 cm depth subsoil SOC%.

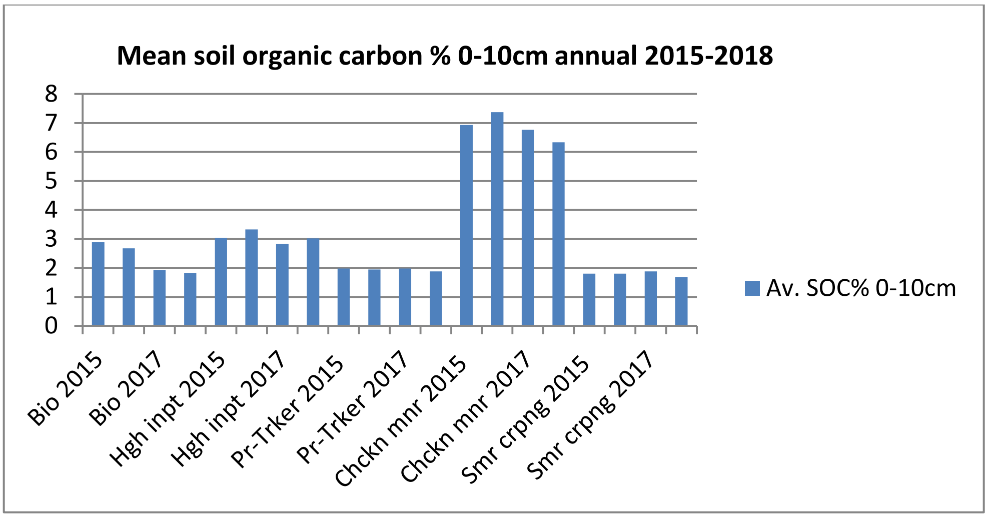

Figure 25: **Soil organic carbon (%) levels from samples taken summer/autumn taken 2015-2018 (0-10cm depth) at each cropping system with replicates averaged (based on 50% conversion rate from organic matter % where soil sample has been put through a 0.75 mm sieve (SWEP)).**

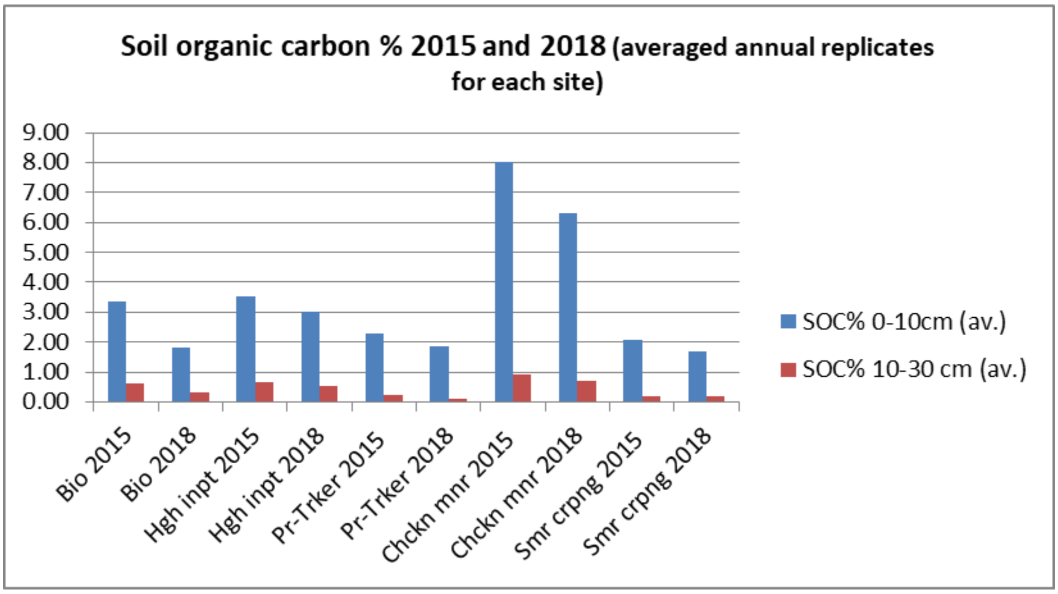

Figure 26: **Soil organic carbon (%) comparisons between commencement and completion of project (2015 and 2018) for 0-10 cm and 10-30 cm soil depths.**

The Biological system had the deepest A horizon (measured annually in spring) but the lowest yield. This system has featured increased N and P inputs since the first year of the project, but is still performing poorly from a yield perspective in comparison to other systems. It appears that constraints to production such as low available calcium, phosphorus (Figure 16) and copper (Figure 19) in particular need to be addressed in order to improve productivity in this system. Supporting the biology with biological inputs without ensuring sufficient nutrition isn't going to work because the microbes feed before the plant and will keep what they need for themselves if in short supply.   The trend of decreasing soil organic carbon percent generally and most markedly in biological and then the chicken manure systems – the only non-continuous cropping sites – during the cropping phase was observed. It is difficult to identify differences in management that might have contributed to the non-cropping sites with the greatest reduction in soil organic carbon percent during the cropping phase compared to the sites that were continuous cropping as stubbles were retained in all cases and all were using a minimum till cropping system.

The summer crop (sunflowers) (in the Summer cropping system) was only grown in the paddock being studied in the summer prior to the commencement of the project, and was a fairly sparse crop. It was also noted that reasonable recruitment during the summer months of a range of summer weeds/summer crop species in other years which were not sprayed out may have contributed to maintenance of soil health at this deep sand site. This site was the only one that didn't show a reduction in soil organic carbon (percent) in the 10-30 cm depth over the period of the project.

The Pro-Trakker system was only commenced in the first year of the project and therefore was too early to see impacts in the dry 2015 winter and early cut off in spring, and is showing some positive signs of improvement such as positive residuals on phosphorus input in 2016 and 2017 and a significant improvement of spring microbial activity in 2017.

The high input conventional system soils are biologically active. It appears that the high inputs are driving strong plant growth, which in turn is supporting the soil biology. It appears that soil pH (while sub-optimal) and available calcium levels are being maintained with regular high lime inputs of 3 t/ha every 4 years. Other cropping systems had far lower lime applications (see 2.1 Cropping systems and agronomy). This system appears to be currently maintaining a stable trend overall from a soil health point of view.

5. Conclusion

This project used yield (wheat yield equivalents) as a surrogate or indicator for crop plant health and vigour, and related soil chemical, physical and biological measures to track soil health trends and patterns for the 2015 to 2017 winter cropping seasons in five different cropping systems. Statistical analyses performed in this project have uncovered a number of significant correlations between chemical and biological measurements of soil with increased yield. The results in this project reinforce the strong link of interactions between the chemical, biological and physical soil processes in maintaining healthy soil.

The biological aspect of the soil health story is highly complex and interwoven with physical and chemical attributes. The resilience and sustainability of soil health is driven by adequate levels of soil organic carbon (SOC). The chicken manure system in this project had the greatest distinction among soil heath measures overall, including very high levels of SOC. Part of the challenge of plant nutrition in a soil health context is how to supply more of the necessary units of N and P in an organic and/or available form that the relevant microbes can better harness to convert into plant available (inorganic) form while building SOC and healthier soil. This may be a key part of the success story for the chicken manure recycling cropping system.

5. References

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