Nutrient Release to Vetch in Cotton Systems

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A NR 490 project report submitted in partial fulfilment of the requirements for the Bachelor of Natural Resources (Honors) at the University of New England.

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Table of Contents

Chapter 4 Results

Chapter 5 Discussion

Chapter 6 Conclusion

Appendix The trial set up at the Australian Cotton Research Institute where the soil was taken for this experiment.

Reference List

List of Tables

soil used was a Vertosol and the rotations are continuous cotton, cotton-wheat or cotton-wheat-vetch.

List of Figures

Abstract

Legumes increase soil mineral N content, improve soil structure, increase infiltration, enhance water stable aggregates, aid decomposition of high C: N material and increase biological activity (Rochester & Peoples, 2005). As a result vetch has been used in cotton rotations to enhance these factors, as well as break disease cycles in cotton production and cycle nutrients important for plant growth and yield. This report aims to review the validity in these claims and discuss the importance of P in cropping systems and the processes that occur within the soil.

Soil was collected from the Australian Cotton Research Institute (ACRI), Narrabri, from three treatments within the long term rotation trial, 1) cotton – winter fallow – cotton plot (C-C) (Figure 1); 2) summer and winter fallow – cotton – wheat; wheat stubble incorporated plot (C-W) (Figure 2), and; 3) summer and winter fallow – cotton – wheat – summer fallow – vetch; wheat stubble retained as standing stubble plot (C-W-V). A pot trial was set up and three species of vetch were grown and harvested (Rasina (*Vicia sativa* cv. *Rasina)*, Popany (*Vicia villosa* subsp. *banghalensis)* and Namoi Woolypod (*Vicia villosa* ssp. *dasycarpa* cv. Namoi*)*). Soil and plant matter analyses were performed on the harvested material in the laboratory to determine P and N uptake.

This pot trial found that labile P increases with the incorporation of stubble into the soil. It was found that that incorporating stubble into a cotton-wheat-vetch system had close to the same benefit as the addition of P in regards to dry matter production. Nodulation was found to increase with the addition of P, and Woolypod had the ability to fix the greatest amount of N based on the pink colour of the nodules. Each species of vetch had different growth patterns, however most species responded positively to a temperate range of temperatures and grew the best under these conditions.

1.0 Literature Review: Vetch growth in cotton rotations: the role of phosphorus in yield variation

Legumes increase soil mineral N content, improve soil structure, increase infiltration, enhance water stable aggregates, aid decomposition of high C: N material and increase biological activity (Rochester & Peoples, 2005). As a result vetch has been used in cotton rotations to enhance these factors, as well as break disease cycles in cotton production and cycle nutrients important for plant growth and yield. This report aims to review the validity in these claims and discuss the importance of P in cropping systems and the processes that occur within the soil.

1.1 Vetch rotations in cropping systems

Generally speaking legumes increase soil mineral N content, improve soil structure, increase infiltration, enhance water stable aggregates, aid decomposition of high C: N material and increase biological activity (Rochester & Peoples, 2005). Vetch is a vigorous forage legume that grows in winter due to its frost tolerance (Rochester & Peoples, 2005). The seeds on vetch are quite large when compared to other legume species and they mature in late spring (Evans et al., 2003 [2]). It is also drought and disease tolerant and can be beneficial to integrated pest management as it attracts useful insects (Rochester & Peoples, 2005). Typically it is viny in growth structure with weak to moderate stem strength (Siddique & Loss, 1996). Vetch is a useful break crop because it does not have a high level of regrowth post forage harvesting (Evans et al., 2003 [2]).

Vetch has the ability to improve soil fertility for the following crops and through their ability to adapt to different environments can be used as grain legume (Siddique & Loss, 1996). This will add to its already long list of uses including fodder production, hay and green manure (Siddique & Loss, 1996). Vetch can produce large amounts of dry matter without irrigation and accumulate a greater amount of biomass and N than many other legume varieties (Rochester & Peoples, 2005). This may be because it has been found to be able to withstand severe water stress better than other legumes (Rochester & Peoples, 2005). Vetch has been found to not use soil mineral N as much as many other legume species and sowing timing can determine dry matter yield and nitrogen fixation capabilities (Rochester & Peoples, 2005). The best time for sowing is before mid May (Rochester). Large amounts of N fertiliser can reduce the yield of vetch (Rochester). Vetch often has a low harvest index and dry matter production, but there is a high N content in the straw (White et al., 1994). Due to this if vetch stubbles is retained it can return N to the soil (White et al., 1994).

Popany is a derivative of the vetches that were introduced to Western Australia in 1945 (Siddique & Loss, 1996). It has been found that Popany can adapt to a variety of soil types with differing pH values from 5.0 to 8.0, however it is best suited to climates that receive more than 500 mm of rainfall annually (Siddique & Loss, 1996). Popany has a weak growth rate and delayed phenology and this often results in the production of less dry matter near flowering and seed yield (Siddique & Loss, 1996). Popany is most suited to grazing and hay production because it flowers late, produces low seed yields and low harvest index (Siddique & Loss, 1996). Pod shattering is high in Popany, and they can be hard seeded resulting in germination in subsequent plots (Siddique & Loss, 1996).

Woolypod is considered to be a very productive species (Rochester & Peoples, 2005). It is a very common species that is utilised on the North West Slopes and Plains because of its ability to produce at high altitudes and high annual rainfall (Lodge et al., 1993). It has been suggested that Woolypod vetch is the most effective vetch species at contributing N to the soil through nitrogen fixation (Rochester & Peoples, 2005). Woolypod tends to germinate within a small temperature range within seven days of planting (Young wt al., 1970). 5 and 0.5ºC produces the greatest germination rates, and maintaining regular temperature results also aided it (Young et al., 1970). Shoot and root elongation rates are high in this species when compared to other legumes (Young et al., 1970). However yield is reduced over time but this allows for recruitment and also makes it an ideal species for using in a cropping rotation system (Lodge et al., 1993).

1.1.1 Nitrogen fixation

Soil nitrogen is a direct result of the rate of mineralisation by microbes in the soil (O'Leary & Connor, 1997). Vetch has increasingly added to the sustainability of many cropping systems (White et al., 1994). This has resulted from research that has found that crops produce better after a green manure legume than a grain legume (Evans et al., 2003). Vetch has been used in cotton production because it increases Nitrogen (N) fertility for the following cotton crop due to their efficiency as N fixers and their accumulation of large amounts of N during growth (Rochester & Peoples, 2005). Due to this vetch increases cropping yield potential significantly when compared to a non – legume system and increase productivity through a reduction in N fertiliser (Rochester & Peoples, 2005). Vetch is not grown for grain and therefore N is not lost through the harvesting process (Evans et al., 2003). N fertiliser and stocking rate do not tend to impact on the accumulation of N (White et al., 1994). N fertiliser was actually found to decrease yield, however it does increase the production of dry shoot matter (White et al., 1994).

Vetch is used in cropping because it is not harvested which often results in 50 – 60% of above ground N being removed, compared to 0% for the green manure crops such as vetch (Evans et al., 2003 [2]). The prostrate growth habitat of vetch results in a low harvesting efficiency and 25 – 30% of growth above ground remains afterwards (Evans et al., 2003 [2]). Legumes can provide N through N fixation in amounts ranging from 70 to 110 kg N/ha, depending on how many years the crop has been in place (Evans et al., 2003 [2]). More soil N is used by legumes in a subsequent year of cropping (72 kg N/ha) when compared to the initial year of cropping (20 kg N/ha) (Evans et al., 2003 [2]). Vetch can increase total mineral N from 117 to 131 kg N/ha and this is a significant increase compared to other crops, particularly grain crops (Evans et al., 2003 [2]). Vetch yields mineral N through the soil profile to 100 cm down better than many other legumes and grain crops (Evans et al., 2003 [2]). This yield at a great depth may be because of leaching of mineral N (Evans et al., 2003 [2]).

1.1.2 Disease and Pest Management

Weeds can be the most limiting factor when producing a crop (Elmore, 1996). Controlling weeds has been found to be the most difficult in no tillage operations, particularly when used with winter cover crops (Larson et al., 2001). Utilising a vetch break in cropping rotations breaks the life cycles of many pests and can reduce the incidence of disease (Evans et al., 2003). This can also provide competition to the weed seeds that are dormant in the soil (Buhler et al., 2000). Traditionally cultivation was used for weed control so with a decrease in cultivation herbicides are becoming more frequently utilised to fulfil this purpose (Doyle, 1983). Weed control is most effective when implemented through an integrated management system that can include crop rotation, grazing management, herbicides and strategic cultivation or mechanical management (Doyle, 1983). Integrates pest management is defined as ‘an integrative approach to management that is based on an understanding of pest population biology and its interaction with crop yield and economic returns, regardless of the pest complex’ (Buhler et al., 2000). All weed control systems should be holistic in nature and must be environmentally, economically and socially acceptable in order to become effective and widely used (Elmore, 1996). The main difference between the impact of insects and weeds on crop production is that insects reduce production through consumption of plant matter whereas weeds reduce production through resource competition (Buhler et al., 2000).

Care must be taken to ensure weeds to not become resistant to herbicides (Elmore, 1996). Weeds are proficient in adapting to different climates and environments through their capacity for morphological change (Buhler et al., 2000). To ensure this does not occur manager education is required to be aware of resistance, ensure crop rotations are utilised, utilise new herbicides as they become available, and take part in government weed initiatives (Elmore, 1996). One of the problems associated with weeds is the lack of knowledge of species in a crop. This leads to incorrect herbicides or herbicide concentrations being used (Elmore, 1996). While tillage has been used in the past as a weed control it has become increasingly prevalent to utilise herbicides that are suitable and convert to no tillage systems to reduce land degradation (Elmore, 1996). This system will make production more efficient and increase the profit margin for producers (Buhler et al., 2000). Management of weeds is the best way to control reproduction, emergence and inter species competition (Buhler et al., 2000).

Timing of sowing is key for vetch because if planted too late the effects of increased rainfall through spring can lead to disease and reduced N concentrations in the stubble (Evans et al., 2003). Other diseases such as Yellow leaf spot (*Pyrenophora tritici – repentis)* and Take all (*Gaeumannomyces graminis* var. tritici) can infect stubble and be passed on to the following crop, causing stunted growth and reduced yields. Break crops must be carefully chosen so these diseases do not cause problems (Doyle, 1983).

1.1.3 Soil Health

The main attributes of soil fertility are 'available soil nitrogen, other macro and micro plant nutrients, relative position and slope of the terrain and soil organic matter content' (Islam et al., 2004). Over time changes in tillage soil water content and temperature impact on processes within the nitrogen cycle, including mineralisation, immobilisation, denitrification and leaching (O'Leary & Connor, 1997). Nitrogen is immobilised and denitrified at the same time which makes these factors difficult to measure (O'Leary & Connor, 1997). Soil mineral nitrogen content is reduced when stubble is retained for the following crop (O'Leary & Connor, 1997).

The net effect of the fixation of N on soil N balance on the soil when green manuring occurs is larger than in other systems (Evans et al., 2003). Initially nitrogen is bound in the retained stubble and than in the decomposing micro-organisms. It re – enters the soil with the death of the micro-organisms and becomes available for the following crop (Doyle, 1983). Soil pH can be lowered with the retention of stubble due to the increase in certain nutrients that have an effect on the availability of others (Graham et al., 2002).

The majority of N is located in vetch shoots so if they are removed so too is the N (Evans et al., 2003). Other stubble residues are inferior to vetch when used for green manure (Evans et al., 2003 [2]). This is a result of a large residue amount and residue N concentration that leads to a significantly large amount of total N in the residual stubble (Evans et al., 2003 [2]). However vetch does not produce the same amount of total N when it is cropped continuously, dropping to 141 kg N/ha (Evans et al., 2003 [2]). The C: N ratio of plants based materials when incorporated into the soil can be compared to the C: N ratio of soil microbial biomass. The greater the difference in ratios the slower the accumulation of mineral N into the soil is (Evans et al., 2003 [2]). Vetch stubble has a C: N ratio of 16 and soil microbial biomass has a C: N ration between 5 and 15 which means that vetch allows for fast accumulation of mineral N (Evans et al., 2003 [2]). This is very good when compared to ratios of other crops, fore example wheat has a C: N ration of more than 100 (Evans et al., 2003 [2]).

Reducing the amount of tillage is useful in areas that require soil water to be conserved during a fallow period (Doyle, 1983). Moisture is retained through the increase in ground cover and because herbicides are utilised in minimum tillage situations to remove weeds, and therefore the competition for water (Doyle, 1983). Retaining stubble improves soil aggregate stability, chemical, physical and biological fertility, accumulates organic matter, reduces weed infestations and can ensure yields when water is scarce (Graham et al., 2002). Through managing stubble soil erosion can be reduced, particularly in areas where soil is left bare for ley periods (Doyle, 1983). The reduction in erosion occurs because stubble reduces wind velocity at the soil surface, reduces droplet impact and reduces runoff velocity resulting in water retention in the soil (Doyle, 1983). Cultivation and burning in the long term result in a decrease in soil organic matter. This impacts on soil structure through the loss in aggregate binding materials and soil aggregates are the basis of soil structure. Stubble retention and decreasing cultivation have been found to increase soil organic matter and therefore aid the maintenance of soil structure (Doyle, 1983).

1.2 Cotton Rotations

Cotton in northern NSW is now irrigated to a level of 75% (Cooper, 1999). There are three main cotton growing areas in NSW, being the Macquarie, Namoi and Gwydir Valleys. Area sown to cotton in each of these regions is 30039, 50436, and 96067 hectares respectively (Cooper, 1999). Crop rotations have been introduced into intensive cotton systems in order to inhibit the increasing soil structure decline (Cooper, 1999). In each valley over half of the properties use crop rotations, with over

80% of the Namoi and Gwydir Valley properties utilising crop rotations (Cooper, 1999). In these areas the most common rotation crop was wheat followed by soybeans, and was determined by its ability to reduce disease in the following crop, better soil structure and increase soil organic matter (Cooper, 1999). Wheat is consistently used because it does not require irrigation and these Valleys are suffering from water restrictions however safflower has a better ability to improve soil structure (Cooper, 1999).

Winter growing crop species, particularly winter cereal species, are the most common cotton rotation crops utilised in NSW because they are directly applicable to the summer growing cotton (Cooper, 1999). Cotton producers have increasingly planted cotton after wheat instead of after a fallow period or on previously uncropped land (Cooper, 1999). Legume break crops, including vetch, have allowed mangers to introduce longer phase lengths in cropping in pasture – ley crop rotations or continuous cropping (Evans et al., 2003). Legume – cotton rotations have become more common on properties with smaller areas (Cooper, 1999). In the Macquarie, Namoi and Gwydir Valleys 74% of cotton producers used wheat as their crop rotation and 12.5% used legume rotations (Cooper, 1999). Soybeans have been commonly used as a crop rotation with cotton but it does not protect the following cotton crop against disease because it acts as a host for diseases and weeds that also affect cotton and is therefore not as useful as wheat or legumes when used in crop rotations (Cooper, 1999).

Crop rotations vary depending on location, education, cost, resource availability and species suitability. Common rotations in northern NSW include intensive tillage with continuous cotton, minimum tillage with continuous cotton and cotton – winter wheat – summer bare fallow (Hulugalle et al., 1997). There is a growing trend towards grain crops rather than legume crops as a rotation with cotton due to its ability to produce some capital benefit (O'Leary & Connor, 1997). Intensive tillage leaves little residue on the soil surface which results in soil erosion and nutrient runoff (Larson et al., 2001). The cotton – wheat – fallow rotations are characterised by a lower pH and exchangeable sodium (Na) that continuous cotton rotations. Intensive tillage with continuous cotton rotations are characterised by having low organic C and high plastic limit, geometric mean diameter of soil aggregates after puddling and drying, pH, exchangeable magnesium (Mg) and Na, and exchangeable sodium percentage (ESP) when compared to minimum tillage continuous cotton (Hulugalle et al., 1997). The amount of organic C is the main reason for these differences. Organic C decreases in intensive tillage with continuous cotton due to the high rate of decomposition by microbes (Hulugalle et al., 1997). The high values of exchangeable Na and ESP in intensive tillage Vertosols can occur because of the inversion of the sodic subsoil during cultivation (Hulugalle & Entwistle, 1996). The continual effects of intensive tillage are clear through compaction and soil structure decline (Hulugalle et al., 1997). A cotton – wheat – fallow rotation will increase soil strength compared to continuous cotton (Hulugalle et al., 1997). However, while in the short term minimum tillage can reduce compaction, studies have found that in the long term compaction occurs under minimum tillage at a faster rate than what occurs under intensive tillage (Hulugalle & Entwistle, 1996). This may be a result of cultivation improving subsoil compaction (Hulugalle & Entwistle, 1996). Water penetration through macropores is greater in cotton – wheat – fallow rotations than continuous cotton rotations which could be due to a greater number of root channels and fauna burrows (Hulugalle et al., 1997). This also allows for greater extraction at depth in minimum tilled soils because root systems can infiltrate deeper pore spaces (Hulugalle & Entwistle, 1996). However there was less profile water content in the minimum tillage cotton – wheat – fallow rotations during cycles of drying (Hulugalle et al., 1997). Intensive tillage can damage the soil and this results a high dispersion index as the bonds between soil particles are broken. External energy inputs exerted onto the soil through cultivation may increase a Vertosol's susceptibility to dispersion at lower ESP values than usually expected (Hulugalle & Entwistle, 1996). Cropping rotation has little impact on mineral associated organic matter and plastic limit (Hulugalle & Entwistle, 1996). Vegetative growth and cotton lint yield has been found to increase in cotton – wheat – fallow rotations, while maturity ratio, fineness and micronaire are decreased (Hulugalle & Entwistle, 1996). Importantly the cotton lint fineness did not result in a lack of fibre strength (Hulugalle & Entwistle, 1996).

The lint yield for intensive tillage with continuous cotton, minimum tillage with continuous cotton and minimum tillage with cotton – wheat – fallow rotations was \$3541, \$3732, and \$4100 respectively in a 1992-1993 (Hulugalle & Entwistle, 1996). This pattern was followed in the following cropping season and concluded that a higher value lint was produced when grown in a minimum tillage cotton – wheat – fallow rotation (Hulugalle & Entwistle, 1996).

Cotton wheat rotations that utilise minimum tillage have the greatest carbon sequestration (Hulugalle, 2000). Intensive tillage and cotton monocultures did not sequester as much carbon due to a decrease in soil organic carbon (Hulugalle, 2000).

1.2.1 Vetch and Cotton Production

No till cropping in cotton has significantly larger yields that conventional tillage systems (White & Worsham, 1990). However introducing a winter crop tends to increase capital outlays through cover establishment, cover death and fertiliser changes (Larson et al., 2001). Legumes provide nitrogen to the next crop and reduce N fertiliser requirements (Larson et al., 2001). Vetch is most useful when sown for green manure purposes rather than for grain, and its benefits can be seen through more than one cropping season in regards to yield (Evans et al., 2003). There is a strong correlation between the biomass of a legume and the N benefit it can provide through fixation (Heenen et a., 1998). Utilising vetch in the cropping rotations increases productivity and profitability because yields are greater and N fertiliser rates are less than systems that do not utilise legumes (Rochester). The use of vetch in a cotton production system saves on N fertiliser use and can increase yield production through the improvement in soil condition (Rochester). Studies have shown that hairy vetch winter crops followed by cotton, when grown without N fertiliser, is risk efficient (Larson et al., 2001). Vetch increases the amount of organic matter that is available for the next cotton crop and can aid the uptake of nutrients in the following cotton crop (Rochester). Common nutrient increases are N, P, K, Zn and Cu, and Na is often decreased (Rochester). Vetch improves soil structure and reduced soil strength which ensures the cotton roots can penetrate beyond the soil surface (Rochester). Soil structure is improved through the exudation of organic acids that dissolve lime and gypsum in the soil (Rochester). Vetch also improves water holding capacity and water infiltration (Rochester). However soil water content is often reduced under vetch and if crops are planted into living matter they can interfere with crop growth (White & Worsham, 1990). However at depth residues high in nitrogen from mineralisation is useful to a following crop for development and non tillage systems enhance nitrogen lower in the soil profile (O'Leary & Connor, 1997). Retaining legume stubble may have some negative impacts on cotton production. Climate pressures mixed with no tillage and stubble retention have been shown to reduce germination, decrease the rate of plant growth, decrease N uptake and lower soil water levels (Larson et al., 2001). No tillage has also been found to stratify soil nutrients at the soil surface which reduces their availability to plants (Larson et al., 2001). Research has found that minimum tillage is therefore often more useful for soil nutrients.

Early sowing of crops can be beneficial in ensuring soil N mineralisation is captured instead of being leached through the soil profile (Heenen et a., 1998). Vetch is not a particularly tall legume and so lodging is not as great a problem as what it is with other crops such as wheat (Heenen et a., 1998). Nitrogen is released from legume stubble through decomposition but this may not correlate to the period of time that N is at greatest need by the growing crop (Larson et al., 2001). Cotton grown after vetch can have a very variable lint yield compared to other winter crops grown in cotton rotations, including wheat which produced the least variable lint yield (Larson et al., 2001). Factors that can influence this variability include N fertiliser application, tillage type, time, climate and pest management (Larson et al., 2001). Weeds respond positively to increased soil N from vetch growth and so this factor is one of the major reasons for high variability in yield, along with the increase in pest numbers due to increase in plant matter quality (Larson et al., 2001). Long term research has found that variability in yield decreased with time suggesting soil quality improvements when vetch rotations are utilised (Larson et al., 2001). To aid reducing variability in yield it is suggested that N fertiliser is not applied (Larson et al., 2001). When cotton is planted following vetch the largest profit maximising yields can be produced (Larson et al., 2001).

1.3 Vertosol Cropping Systems

Vertosols are the dominant soil type in low rainfall areas of northern NSW (Norrish et al., 2001). Over the last ten years minimum tillage and crop rotations have become more common in cotton crops n eastern Australian Vertosols (Hulugalle et al., 1997). This is a result of research that has found these new systems reduce soil erosion and degradation, improve energy conservation and improve the conservation of water (Hulugalle et al., 1997). Soil compaction was reduced and soil N was increased under crop rotation (Hulugalle et al., 1997). Minimum tillage has ensured soil fauna diversity and structure is maintained, particularly in semi arid dryland Vertosols (Hulugalle et al., 1997). Positive impacts of retaining stubble are usually associated with dry conditions (O'Leary & Connor, 1997). This is apparent when water is available under dry conditions when in other rotations this is not the case (Hulugalle & Entwistle, 1996). Beds are utilised on Vertosols to reduce erosion and run off, particularly on slopes. If these beds are well structured they can facilitate nutrient uptake at a fast rate when required (Hulugalle & Entwistle, 1996).

Current research has found that diffuse reflectance spectroscopy in the ultra violet, near infrared and visible spectrums can be used to quickly determine soil pH, organic carbon, air – dry gravimetric water content, clay, cation exchange capacity (CEC), exchangeable calcium (Ca) and magnesium (Mg) and occasionally field soil organic matter (Islam et al., 2004). This has lead to the possibility that calibration can occur in time based on soil fertility parameters (Islam et al., 2004).

1.3.1 Physical Soil Properties

The Vertosol located at the Australian Cotton Research Institute (ACRI) had a varied texture. To 30 cm the clay content was 53% and the sand content was 26%; between 30 and 60 cm the clay content was 60% and sand content was 22% (Hulugalle et al., 1997). The sub surface soil suffers from a high level of compaction (Hulugalle et al., 1997). The soil clod bulk density average with 20% water content to a depth of 15 cm is 1.1 Mg/m^3 and 1.8 Mg/m^3 from 15 – 60 cm (Hulugalle et al., 1997). Intensive tillage with a continuous cotton rotation has the greatest dispersion as a result of the inter particle bonds being stressed compared to minimum tillage cotton – wheat – fallow rotations (Hulugalle et al., 1997). Intensive tillage has also shattered the soil particles and now the soil has low strength (Hulugalle et al., 1997). An increase in soil compaction and soil strength reduces the ability of cotton to extract water (Hulugalle et al., 1997). Soil fertility on irrigated Vertosols can be managed through maximising rotation crops because they can include fibrous and deep rooted crops that will increase pores that the following crops can utilise and that water can infiltrate the soil deep into the profile (Hulugalle et al., 1997).

Vertosols are soils that never stop draining (Hochman et al., 2001). The highest level of soil water stored in the soil that is available for plant growth is called the plant available water capacity (PAWC) (Hochman et al., 2001). PAWC is affected by soil texture, soil structure, clay mineralogy, salinity, sodicity, soil acidity, nutrient deficiencies, and the impacts of soil biota (Hochman et al., 2001). PAWC decreases going down the soil profile due to the shrink- swell properties common to Vertosols and black Vertosols hold more water than Grey Vertosols (Hochman et al., 2001). Research conducted in laboratories has found that the PAWC in these tests were lower than estimates in the field. This has been predicted to be a result of the Vertosol's ability to expand which could not be seen in the laboratory (Murphy & Lodge, 2001). Vertosols are characterised by large total pore spaces that give them the potential to hold large amounts of water compared to other soil types, but they also rely on a large amount of water to become saturated (Murphy & Lodge, 2001).

1.3.2 Chemical Soil Properties

The soil that the vetch was grown in was from the Australian Cotton Research Institute (ACRI) in Narrabri NSW. It is a 'fertile alkaline dark greyish brown cracking medium clay' (Rochester & Peoples, 2005). The parent materials of this soil are igneous including basalt and diorite (Murphy et al., 2007). The clay profile is uniform and the colour spectrum includes grey, brown and black (Murphy et al., 2007). The surface soil of Vertosols are self mulching and alkaline at depth. The soil aggregates are sticky when wet but become loose when dry, forming large cracks in the soil (Murphy et al., 2007).

Inositol phosphates have a high charge density which allows for rapid adsorption onto soil minerals (Stewart & Tiessen, 1987). They also have extensive interactions with sesquioxides which protect inositols from becoming degraded (Stewart & Tiessen, 1987). This soil has a calcium carbonate concentration of 0.5% up to a depth of 30 cm and 0.2% between 30 and 60 cm (Hulugalle et al., 1997).

Near infrared can respond to the bonding energies of hydrogen and therefore determine the levels of inorganic salts in the soil (Islam et al., 2004). Reflectance was found to be able to predict cation exchange capacity (CEC), pH, electrical conductivity (EC), organic carbon, total N, exchangeable calcium (Ca), magnesium (Mg), Sodium (Na), Ca: Mg ratio, exchangeable sodium percentage (ESP) and some micronutrients to accuracy levels acceptable for most experiments (Islam et al., 2004). This is particularly so because of the speed this process can analyse data (Islam et al., 2004).

1.4 Phosphorous in Vertosol Cropping Systems

Soil organic P is quite dynamic however only a small amount of the soil organic matter is biologically active at any one time (Stewart & Tiessen, 1987). Immobilisation and mineralisation of soil organic P occur at the same time making net changes difficult to measure (Stewart & Tiessen, 1987). Physical, chemical and biological properties determine the immobilisation, mineralisation and redistribution of P in the soil (Stewart & Tiessen, 1987). This can be through P sorption on colloid surfaces and uptake from microbes, mycorrhiza or plants (Stewart & Tiessen, 1987). Phosphate ions enter the labile pool through the dissolving of primary P minerals. Some of this labile pool is precipitated as secondary P minerals and slowly changes into unavailable forms as the soil becomes more weathered (Stewart & Tiessen, 1987). Organic P mineralisation is directly correlated with soil pH. P is released into the soil at high pH. Liming of acid soils increases the pH, increases microbial activity and therefore increases organic P mineralisation (Stewart & Tiessen, 1987).

When soil organic P is stabilised it re – enters the P transformation cycle during the biological mineralisation of organic matter in soil (Stewart & Tiessen, 1987). Carbon is lost in this process as carbon dioxide because of the energy requirements of the decomposing organisms (Stewart & Tiessen, 1987). Extracellular enzymes can be released in response to low labile P availability or be present in the soil. These enzymes hydrolyse P esters through biochemical mineralisation (Stewart & Tiessen, 1987). However hydrolysis by enzymes can be stopped by phosphate interactions with sesquioxides or soil organic matter (Stewart & Tiessen, 1987). Phosphates are stabilised when associated with organic matter or through organism excretion in response to low labile P availability (Stewart & Tiessen, 1987). As a result of higher organism activity in the rhizosphere phosphatase activity is also greater here (Stewart & Tiessen, 1987). Plant roots are P sinks and they lower the concentration of labile P in the soil solution. This promotes biochemical mineralisation and results in increasing the turnover of P (Stewart & Tiessen, 1987). Biological mineralisation is a non-differential process, with major nutrient losses such as C, N and organic P all being lost at similar percentages in soil organic matter (Stewart & Tiessen, 1987). The mineralisation of organic matter is usually fast enough to avoid entering P limiting conditions and therefore ensuring P is available for crop export (Stewart & Tiessen, 1987).

Soil organic P's main active component is biomass P. It is taken up by predators or saprophytes and is than incorporated into the new consumer biomass (Stewart & Tiessen, 1987). This process is the fastest process in the soil organic P cycle. While this is occurring C and N are also changed rapidly. Soil organisms take up organic P through secretions into the soil environment, and plants take up organic P after hydrolysis (Stewart & Tiessen, 1987). Soil organic P becomes fixed in soil organic matter as a result of moiety or phosphate group and mineral interactions (Stewart & Tiessen, 1987). It is located in the side chain of organic matter which tends to be the most reactive (Stewart & Tiessen, 1987). When soil organic P becomes stable it can collect in the following forms: either chemically resistant or aggregate protected (Stewart & Tiessen, 1987). A third of soil organic P is combined with humic and fulvic acids or metal complexes (Stewart & Tiessen, 1987).

There are a variety of extraction methods that are available to fractionate organic P. Fractionation occurs based on the stability of organic P in regards to specific reactants and P pools. When organic P is extracted with bicarbonate it fills the pool of highly labile P which is related to plant available P (Stewart & Tiessen, 1987). Extracting organic P in low labile P soils using NaOH found that this source was used for microbial uptake (Stewart & Tiessen, 1987). A large portion of soil organic P is associated with fulvic acid. This is labile and is a component of organic materials and plant litter (Stewart & Tiessen, 1987).

Soil type has an influence on the mineral composition of plant tissue (Salardini). P concentration in shoots, roots and flowers increases with the application of P (Salardini). P applications increase Ca and Mg concentrations in plant shoots, but decrease K concentrations (Salardini). Rainfall variation and soil water content influences the 'yield response to P fertiliser, the 'critical range' of extractable soil P, the relative effectiveness of fertiliser P, and the reliability of predicting P fertiliser requirement' (Norrish et al., 2001). High rainfall results in high critical concentrations of extractable soil P and good soil water content improve root growth while enhancing the plant's ability to uptake available soil P (Norrish et al., 2001). This leads to a low critical extractable P concentration (Norrish et al., 2001). Research has found that crops take a large fraction of the P they utilise from deep in the profile, to 80 cm (Norrish et al., 2001). This is particularly the case in periods of drought. Plants do not uptake soil P or fertiliser P from the surface due to a low water content (Norrish et al., 2001). To ensure a satisfactory amount of plant growth and yield P must be adequately supplied from the early stages of crop development (Norrish et al., 2001). Water at the stem elongation stage is also particularly important in ensuring plants uptake soil P and fertiliser P (Norrish et al., 2001). Root growth depth and crop water use will not respond to P fertiliser is reduced if subsoil conditions such as sodicity or salinity are prevalent (Norrish et al., 2001). Studies on hybrids have found that they have a minimal yield response to P on Vertosols (Salardini). Soil P fixation has an impact on P uptake (Salardini).

Inorganic P fertilisation has lead to the accumulation of organic P in soils (Stewart & Tiessen, 1987). The rate of mineralisation of organic P is however dependent on temperature. Studies have found that 12% of total P is lost when continuous cultivation occurs on a soil and that in the top 15 cm of soil 50% of total P is exported, leading to the conclusion that plants utilise P that is available from lower down the soil profile (Stewart & Tiessen, 1987). Organic P is not as easily lost from the soil through leaching or volatilisation as other nutrients. Laboratory experiments have shown that 33% of C, 32% of N and 24% of organic P is lost from the soil (Stewart & Tiessen, 1987). Cultivation also results in the reduction in mineralisation of organic matter, particularly based on the chemical nature of organic materials; accessibility of organic materials, microbial population activity and structure, and the presences of free soil enzymes (Stewart & Tiessen, 1987). The P balance shifts towards less available phosphates when soil organic matter stability is disrupted by cultivation and crop harvesting reduces total P amounts (Stewart & Tiessen, 1987).

Cropping systems and natives grassland systems have different P needs. Cropping systems favour inorganic P precipitation and the reduction in P availability. Native grassland systems recycle P closely in organic forms prefer the maintenance of a high level of P availability (Stewart & Tiessen, 1987). Soil texture and different minerals affect P mineralisation and the relative amounts of inorganic and organic P. Mineralisation of organic P is induced by carbonates and calcium salts and these results in an increase in inorganic P (Stewart & Tiessen, 1987). When soils are rich in carbonate the reaction between phosphate and calcium results in low P solubility (Stewart & Tiessen, 1987). P availability for plants is determined by labile and surface forms of phosphate (Stewart & Tiessen, 1987). The above mentioned processes suggest that calcareous soil minerals compete with plants for available P (Stewart & Tiessen, 1987).

1.4.1 Phosphorous Fractions

1.4.1.1 Organic Cycling of Phosphorus

Stubble Retention

There is a world wide trend towards crop stubble retention as opposed to traditional methods such as burning because it returns organic matter and nutrients to the soil, particularly Ca, K, and P (Graham et al., 2002). Stubble retention can be in the form of incorporation, surface mulching or seeding into stubble residues that have been undisturbed and results in structural works being required to a lesser extent (Doyle, 1983). Research has found that available P and extractable P increase and organic P accumulates when stubble is retained (Graham et al., 2002). However studies suggest that phosphorous uptake has been reduced because it has accumulated in the soil surface and often plants utilise phosphorous in lower soil horizons (Doyle, 1983). It may also occur because root growth becomes restricted in seed beds that have not been cultivated (Doyle, 1983). Nutrients can become tied up in stubble while it decays which reduced availability to the growing crop (Larson et al., 2001).

1.4.1.2 Microbial Phosphorous Cycling

Soil microbes are important in ecosystems for nutrient cycling, organic matter decomposition, nutrient availability, pesticide and contaminant decomposition, soil structure and aiding plant growth and health (Wakelin et al., 2007). Management strategies that change the soil's chemical and physical properties can change the structure of microbial communities (Wakelin et al., 2007). For example, stubble retention or nitrogen application can have a significant impact on microbial communities and their structure (Wakelin et al., 2007). These factors increase fungal communities but have less impact on bacteria communities (Wakelin et al., 2007). Changing management practices that impact on microbial communities has a direct impact in the various ecosystem processes that microbes are involved with, including nutrient cycling (Wakelin et al., 2007). Stubble retention provides organic matter for microbes and results in nutrients, including P, becoming available for following crops (Wakelin et al., 2007). Low soil temperature, change in available soil moisture, soil atmosphere and energy supply all have a negative effect on microbial density and activity in soil (Stewart & Tiessen, 1987).

Residue and cultivation management influence microbe numbers and their distribution in the soil (Stewart & Tiessen, 1987). Microbial P is determined through the change in the organic and labile P amounts. This can be measured through a chloroform treatment that is followed b specific extraction agent removal (Stewart & Tiessen, 1987). Nucleic acids form greater than 60%, acid soluble P esters form 20%, and phospholipids form 5% of microbial intracellular P (Stewart & Tiessen, 1987). Nucleotide amounts are determined by the cell growth stage or activity, whereas phospholipids are located in the cell membranes and remain relatively constant (Stewart & Tiessen, 1987).

Microbial decomposition of organic matter leads to the production of organic acids which lower the soil pH (Hulugalle et al., 1997). This results in the release of hydrogen ions and decreases the exchangeable Na and Mg and ESP (Hulugalle et al., 1997). These characteristics are common to minimum tillage rotations. Cation concentration, pH and pollutant inhibition help determine the transport of labile P into microbial cells (Stewart & Tiessen, 1987). This is also dependent on energy.

Soil micro and mesofauna impact on substrate decomposition and P mineralisation (Stewart & Tiessen, 1987). The trophic structure of microbes is affected by soil texture and habitable pore space and this determines the organism size classes (Stewart & Tiessen, 1987). This trophic structure impacts on energy and nutrient flows in terrestrial ecosystems (Stewart & Tiessen, 1987). Smaller organism have the ability to make nutrients available to larger organisms because they move through spaces that are too small for these organisms (Stewart & Tiessen, 1987). Bacteria usually only utilise P in amounts they require to fulfil their metabolism (Stratful et al., 1999). The optimum pH for bacteria to uptake P aerobically is between 7 and 8 (Stratful et al., 1999). Bacterial grazers including protozoa and nematodes increase system activity and return nutrients to the soil solution. This can be determined by carbon dioxide output and P mineralisation (Stewart & Tiessen, 1987). Earthworms enrich the surface of the soil with P, increase the exchangeable labile P levels and increase mineralisation rates of easily extractable organic P (Stewart & Tiessen, 1987). Termites are a major decomposer of soil organic matter and enhance nutrient cycling in tropical ecosystems (Stewart & Tiessen, 1987). IN pastures large herbivores are involved in grazing plant materials and P and other nutrient recycling (Stewart & Tiessen, 1987). Growing plant roots also have an impact on the release of P from plant litter, increasing the rate of release (Stewart & Tiessen, 1987).

Soil invertebrates make up a small amount of total soil biomass but their role in the transformation of P is much more important (Stewart & Tiessen, 1987). A large variety of invertebrates live in Vertosols, and their abundance and diversity is determined firstly by the microclimate of the soil profile, particularly at the surface and to a lesser extent, pesticide use and the cropping system (Hulugalle et al., 1997). The groups with the greatest abundance are Collembola, ants, beetles, mites and grasshoppers (Hulugalle et al., 1997). Earwigs and spiders are both widespread but have a lower abundance than the other invertebrate species (Hulugalle et al., 1997). Little differences in invertebrate activity occur between different crop rotations but ant species increase under minimum tillage rotations when compared to intensive tillage rotations (Hulugalle et al., 1997). This trend is the same for Collembola, who also have higher abundances in the cotton – wheat – fallow rotation compared to continuous cotton rotations (Hulugalle et al., 1997). The only species that shows resilience to all tillage rotations, temperatures and cropping systems are mites (Hulugalle et al., 1997).

1.4.2 Fertiliser

Fertiliser application can decrease soil aggregate stability due to the introduction of exchangeable cations (Graham et al., 2002). Fertiliser inputs can also reduce the pH of the soil, which is a negative or positive effect depending on the soil type (Graham et al., 2002). The higher the N fertiliser rate, the greater the pH decline. This can impact on crop yield if lime is not used (Larson et al., 2001). Liming is often used to lower the pH of a soil, but it has minimal effect on N supply (Heenen et a., 1998). This leads to an increase in the mineralisation of soil organic N (Heenen et a., 1998). With the decrease of pH the availability of molybdenum increase and this is beneficial to plants as it improves assimilation of N into the plant (Heenen et a., 1998). N fertiliser can increase total soil N, mineral N, N uptake, and grain protein and yield (Heenen et a., 1998). Minimum tillage tends to require less N fertiliser application than intensive tillage operations. This means that the soil pH remains more stable in minimum tillage operations because the increase in nitrate N through fertiliser application is not applicable in this situation ((Hulugalle & Entwistle, 1996). While N fertiliser can maximise production it can also result in a higher incidence of disease and increased soil acidification (Heenan et al., 1998). Fertiliser P can result in the accumulation of organic P in the long term (Graham et al., 2002). Stratification and other problems associated with soil acidity can occur when encompassed with high N fertiliser levels (Larson et al., 2001). N fertiliser application is often redundant after vetch growth in cotton – vetch rotations because cotton yield is not affected by it (Larson et al., 2001).

2.0 Introduction and Aims

Australia's cotton industry has modified itself over the years. Of particular interest are the changes in cropping rotations and tillage intensities. Minimum tillage is becoming more common due to the research conducted showing it reduces the impact on soil structure and soil organisms. In association with minimum tillage is the increasing use of crop rotations. Crop rotations have been utilised in cotton systems because they remove/reduce the need for a fallow period, break disease cycles, and depending on the species, increase nutrients, particularly nitrogen (N), and can ensure water is retained in the soil. Common rotation crops that have been used in cotton systems include wheat, legumes, safflower and soybeans. Wheat is the crop used to the greatest extent, however legumes are being used increasingly as their positive impacts are becoming better understood.

Nutrients are an important factor in plant growth and their cycling is often associated with the microbial biomass of the soil (Chen et al., 2003). Vetch has been increasingly used in cotton cropping systems because of its ability to fix N and provide this nutrient for the following crop. Phosphorous (P) is the other major nutrient required for plant growth and development. Soil P cycling and availability is controlled by the biological processes of mineralisation and immobilisation and the chemical processes of adsorption, desorption, dissolution and precipitation (Chen et al., 2003). As P is a constituent of plant material it remains in the residual material that remains after harvest. As a result stubble can be a source of P for the following crop, and provides the extra benefit of groundcover while a fallow period is used. Soil organisms decompose the stubble and release the P that has accumulated in the stubble.

There are many aims of this experiment. Firstly, it hopes to determine if surface cover in the form of stubble increased surface labile P pools and therefore increasing dry matter production of plants. Secondly it hopes to determine if the increase of N through the use of vetch increases plant growth and development, and hence P uptake. Thirdly, to determine if vetch can access P pools from subsoil P reserves that cereals and cotton cannot and cycle it to the surface. Lastly it hoped to determine the reason for increased growth and P uptake of crops and green manures where vetch was in the rotation. This will involve examining the availability and response to P of vetch in soils associated with different long-term rotations.

3.0 Materials and Methods

3.1 Soil collection

Soil was collected from the Australian Cotton Research Institute (ACRI), Myall Vale, Narrabri, NSW, (30º18'23.13"S 149º46'20.89"E), elevation 209 metres. Soil was collected in March from three treatments within the long term rotation trial, 1) cotton – winter fallow – cotton plot (C-C) (Figure 1); 2) summer and winter fallow – cotton – wheat; wheat stubble incorporated plot (C-W) (Figure 2), and; 3) summer and winter fallow – cotton – wheat – summer fallow – vetch; wheat stubble retained as standing stubble plot (C-W-V) (Figure 3). Approximately 40 kg of surface soil (0-10 cm) was collected from between cotton or wheat plants in the hills of each of 4 replicated trial plots from at least 10 different sampling sites within each 165 m^2 plot. Wheat stubble from each C-W-V plot was also collected. All samples were transported to the Glasshouse Complex at the University of New England (UNE), Armidale, NSW, dried, ground and passed through a 0.5 cm sieve. The trial was set up in the 90's, and a layout for the trial can be located in Appendix 1.

Figure 1. The long term cotton – winter fallow – cotton plot (C-C) located at the Australian Cotton Research Institute, Narrabri, NSW in March 2009.

Figure 2. The long term summer and winter fallow – cotton – wheat; wheat stubble incorporated plot (C-W) located at the Australian Cotton Research Institute, Narrabri, NSW in March 2009.

Figure 3. The long term summer and winter fallow – cotton – wheat – summer fallow – vetch; wheat stubble retained as standing stubble plot (C-W-V) located at the Australian Cotton Research Institute, Narrabri, NSW in March 2009.

3.2 Pot Trial

3.2.1 Establishment

72 pots were set up with a plastic liner to ensure water was not lost through drainage. The field capacity of the soil was determined through completely soaking the soil and weighed after soaking overnight. This soil was found to have a field capacity of 13.75% (110mL/800g). 800 grams of soil was placed in each pot, ensuring a complete mix of matrixes. The pots were labelled based on the treatment plot and the replication number. Sub samples of each bin were collected for analysis by repeated splitting. Superphosphate was added to each pot at the equivalent of 150 kg P/ha. Stubble was chopped to 2 cm increments and 4 grams were added to the C-W-V treatments. 10 mL of basal treatments were added to every pot via syringe. The basal was N, K, S, Ca, Mg, and Zn and two solutions were made. The first was 29400 mg. Na2SO4 in 1 kg, the second was 12700 mg/kg KCl, 37000 mg/kg NH4NO3, 15000 mg/kg CaCl2.2H2O, 8300 mg/kg MgCl2.6H2O and 900 mg/kg ZnCl2.2H2O in 1 L.

The vetch species used in the study were Rasina (*Vicia sativa* cv. *Rasina)*, Popany (*Vicia villosa* subsp. *banghalensis)* and Namoi Woolypod (*Vicia villosa* ssp. *dasycarpa* cv. Namoi*)*. Rasina is a relatively new species that has been designed to germinate early in temperate regions; Popany is a late maturing variety that has a more upright growth pattern and Namoi Woolypod has been demonstrated to produce large amount of vegetative growth. Each species were germinated in a tray before planting. After three-four days of growth five seedlings were planted into the soil of every pot. The soil was wetted to field capacity and the pots were placed in an allotted glasshouse bay. The moisture content was maintained throughout the growing period based on weight. On average the plants were watered every three days. The pots were regularly moved within the glasshouse to ensure random trial design.

3.2.2 Harvest

After eight weeks of growth the plants were harvested by cutting the plant approximately 1 cm above the soil surface and placing the plant material in labelled paper bags. Upon harvest they were dried and weighed in preparation for grinding analysis and analysis. The samples were ground to 2mm for complete elemental analysis and 0.5mm N analysis. The soil was washed from the roots through saturating the soil in a bucket of water. The soil was gently coerced from the roots and the root material was gently washed to remove any adhered soil. They were than placed in labelled plastic bags and kept in the refrigerator. Some root material was lost through the washing phase but it is considered that the amount was constant across all samples when comparing the samples for nodule counting. A nodule count undertaken with a microscope. The stubble taken from the C-W-V plot was also ground for analysis.

3.2.3 Plant Analysis

The sealed chamber digest method of Anderson and Henderson (1986) was used to analyse the elemental content. A lucerne standard and blanks were utilised in this process. 0.2 g of plant material was digested with 2 mL of perchloric acid ($HClO_4$ -70%) and hydrogen peroxide (H_2O_2 -30%). The mixture was pre-digested overnight than 1mL of H_2O_2 was added before being placed in an oven for 30 minutes at 80ºC. When cool, 1mL H_2O_2 was added and digested for 1 hour. When cool again, the digested material was made to weight (25 mL) using deionised water and mixed thoroughly. Analysis was undertaken using ICPOES using appropriately matched standards.

The Carlo Erba 1500 Solid Sample Analyser coupled to a Tracer Mass Stable Isotope Analyser was used to analyse the N fraction of the plant material. The plant material was ground to 0.5mm for this process. 0.5g of sample was weighed into 5x8 mm tin cups and than loaded into the auto-sampler. Wheat flour standards were utilised in this process.

3.3 Soil Analysis

Sequential P fractionation was undertaken on the soil sample, which was ground to 0.5 mm. Inorganic P fractions (Pi) were determined by tumbling 1g air-dried ground soil for 16 hours in 30 mL of each of the following solutions: (1) H_2O, (2) 0.5 M

$NaHCO_3$ adjusted to pH 8.5, (3) 0.1 M NaOH and (4) 1 M HCl. Between each solution the samples were centrifuged and the inorganic supernatants poured into vials, capped and refrigerated.

Residual P was determined by digesting the soil residue with 3 mL concentrated $HClO_4$ at 130º C for 15 minutes, than 160º C for 10 minutes and 190º C for 30 minutes. Anti bumping chips were added pre-digestion. Once cooled, solutions were made up to 75 mL with deionised water and allowed to settle overnight.

Total P (Pt) was determined for the 0.5 M NaHCO3, 0.1 M NaOH, and 1 M HCl fractions by digestion of the respective P supernatants. Briefly, 15 mL supernatant was neutralised. 1.5 mL of 6 M HCl for NaHCO3 supernatants and 1 mL of 1 M HCl for 0.1 M NaOH supernatants. They were than heated at 100º C for 1 hour with 1 mL of 1 M H2SO4, 0.25 g K2S2O8 and anti-bumping granules. Digested solutions were neutralised and diluted to 75 mL with deionised water.

The P content of all samples before and after digestion was determined using the malachite green P determination (Motomizu et al. 1986). 250 µL of 1 M H2SO4 solution was carefully added to 3 mL of sample. It was mixed gently and effervescence allowed to occur. After 5 minutes another 250 µL of 1 M H2SO4 solution was added and mixed gently than effervescence was allowed to occur. After 5 minutes 250 µL of 1 M H2SO4 solution was added and mixed gently than effervescence was allowed to occur. After 10 minutes 1 mL of mixed reagent was added and allowed to sit for 45 minutes. The absorbance was measured on a spectrophotometer at 630 nm. The first absorbance of the unknowns was greater than the 0.5 µg/mL standard so the unknowns were diluted and the samples re-run from the beginning. A Stock A solution of 1000 µg/mL P was used to make the standards for a 10 µg/mL Stock B solution. The final concentrations used (µg/mL) were 0, 0.05, 0.1, 0.2, 0.3, 0.4 and 0.5. The 0.1 µg/mL standard was utilised 5 times to place standards between the samples. The standard curve was completed after all the unknowns.

Organic P (Po) was determined by subtracting the Pi (before digestion) from the Pt (after digestion).

3.4 Statistical analysis

The results were tabulated and a three way ANOVA analysis undertaken (Rotation, Variety, and dry weight/nodules) to determine the means and standard deviations. Least quare means were derived from this analysis. Graphs of standard curves were generated using an analysis package and Excel. The sum of labile P in the soil was determined through the addition of the water and carbonate extractions.

4.0 Results

4.1 Soil properties

Labile P (the sum of resin and bicarbonate extractable P) in the vetch rotation was 36% greater than the continuous cotton rotation (Table 1). Similarly, total P was also greater in the surface soil of the vetch rotation relative to continuous cotton and cotton-wheat rotations (Table 1). The total P concentration was 12% greater with vetch present in the system than the cotton –cotton rotation (Table 1).

Table 1. The mean sum of labile P (mg/kg) and mean total P concentration of a Vertosol (0-10 cm) after 18 years of a rotation trial with three vetch varieties, Rasina (*Vicia sativa* cv. *Rasina),* Popany (*Vicia villosa* subsp. *Banghalensis)*, and Namoi Woolypod (*Vicia villosa* ssp. *dasycarpa* cv. Namoi).

Rotation	Sum of labile P (mg/kg)	Total P concentration (mg/kg)
Cotton-cotton	47	590
Cotton - wheat	43	593
Cotton-wheat-vetch	67	671

4.2 Dry matter production

Woolypod vetch produced 21 and 11 % greater dry matter than Popany and Rasina respectively (Table 2). The application of P increased vetch dry weight by 37% ($P<0.001$) (Table 2). The cotton-wheat-vetch rotation produced 15 and 17 % more dry matter than the continuous cotton and cotton-wheat rotations respectively ($P=0.003$) (Table 2). There was no significant interaction between rotation, variety or P application in this trial.

Table 2. Vetch (Rasina (*Vicia sativa* cv. *Rasina),* Popany *(Vicia villosa* subsp. *Banghalensis)*, and Namoi Woolypod (*Vicia villosa* ssp. *dasycarpa* cv. Namoi)) dry matter production (g/pot) in a Vertosol collected from rotations with continuous cotton, cotton-wheat or cotton-wheat-vetch following eight weeks growth in a glasshouse with and without P addition. Values are the mean of 3 values with standard errors in parentheses. Significance (P<0.001) is demonstrated through the symbol $_a$.

	Continuous cotton		Cotton -wheat		Cotton-wheat-vetch	
	-P	+P	-P	+P	-P	+P
Popany	0.56 (0.02)	1.13 (0.12)	0.63 (0.06)	1.29 (0.08)	0.92 (0.09)	1.33 (0.07)
Woolypod	0.90 (0.02)	1.53 (0.12)	0.83 (0.06)	1.49 (0.08)	1.23 (0.09)	1.39 (0.07)
Rasina	0.85 (0.02)	1.41 (0.12)	0.76 (0.06)	1.22 (0.08)	1.09 (0.09)	1.55 (0.07)

Figure 4. Popany (*Vicia villosa* subsp. *Banghalensis)* grown in a Vertosol soil collected from a cotton- cotton rotation following 8 weeks of growth in a glasshouse. Left: P added, left: no P added.

Figure 5. Popany (*Vicia villosa* subsp. *Banghalensis)* grown in a Vertosol soil collected from a cotton- wheat rotation following 8 weeks of growth in a glasshouse. Left: P added, left: no P added.

Figure 6. Popany (*Vicia villosa* subsp. *Banghalensis)* grown in a Vertosol soil collected from a cotton- wheat-vetch rotation following 8 weeks of growth in a glasshouse. Left: P added, left: no P added.

4.3 Phosphorus and Nitrogen Uptake

4.3.1 Phosphorus

In the majority of treatments the addition of superphosphate resulted in a three fold increase in P uptake. The exception is the C-W-V rotation whose P uptake doubled, except for Rasina which had a P uptake four times greater when P was added. With the addition of P, the C-W-V rotation had the greatest P uptake, being approximately 22 and 18 % greater than the C-C and C-W rotations respectively.

Table 3. Vetch (Rasina (*Vicia sativa* cv. *Rasina), Popany (Vicia villosa* subsp. *Banghalensis)*, and Namoi Woolypod (*Vicia villosa* ssp. *dasycarpa* cv. Namoi)) Phosphorus uptake (µg/pot) in a Vertosol from rotations with continuous cotton, cotton-wheat or cotton-wheat-vetch following eight weeks growth in a glasshouse.

	Continuous cotton		Cotton -wheat		Cotton-wheat-vetch	
	-P	+P	-P	+P	-P	+P
Popany	135	477	175	577	320	608
Woolypod	180	598	192	659	377	699
Rasina	174	567	189	496	270	806

4.3.2 Nitrogen

The N uptake of all treatments with the addition of P was relatively similar. The difference occurs with the treatments without P, with the C-W-V rotation having an N uptake approximately 36 and 32 % greater than the C-C and C-W rotations respectively.

Table 4. Vetch (Rasina (*Vicia sativa* cv. *Rasina),*Popany *(Vicia villosa* subsp. *Banghalensis)*, and Namoi Woolypod (*Vicia villosa* ssp. *dasycarpa* cv. Namoi)) Nitrogen uptake (g/pot) in a Vertosol from rotations with continuous cotton, cotton-wheat or cotton-wheat-vetch following eight weeks growth in a glasshouse.

	Continuous cotton		Cotton -wheat		Cotton-wheat-vetch	
	-P	+P	-P	+P	-P	+P
Popany	2.17	4.43	2.44	4.62	3.96	5.54
Woolypod	3.24	6.13	3.21	6.27	5.00	6.53
Rasina	2.70	5.45	2.87	4.15	3.64	4.89

4.4 Nodule Number

Rasina had 22 and 15 % more nodules than Popany and Woolypod respectively. Plants with +P had 43% more nodules than those without (P=0.139).

When vetch is in the crop rotation nodules are present regardless of P status because there is sufficient rhizobium (Table 5). In the other crop rotations with the addition of P, when the plants are healthy there is high nodulation due to the high level of rhizobium (Table 5).

Table 5. Vetch (Rasina (*Vicia sativa* cv. *Rasina),* Popany (*Vicia villosa* subsp. *Banghalensis)*, and Namoi Woolypod (*Vicia villosa* ssp. *dasycarpa* cv. Namoi)) mean nodule numbers in a Vertosol from rotations with continuous cotton, cotton-wheat or cotton-wheat-vetch following eight weeks growth in a glasshouse.

	Continuous cotton		Cotton -wheat		Cotton-wheat-vetch	
	-P	+P	-P	+P	-P	+P
Popany	4	31	11	24	22	32
Woolypod	17	27	16	15	30	30
Rasina	11	31	21	27	39	33

Table 6.Least square means for P status x Rotation for nodules in a vetch (Rasina (*Vicia sativa* cv. *Rasina),* Popany (*Vicia villosa* subsp. *Banghalensis)*, and Namoi Woolypod (*Vicia villosa* ssp. *dasycarpa* cv. Namoi)) 8 week glasshouse pot trial. The soil used was a Vertosol and the rotations are continuous cotton, cotton-wheat or cotton-wheat-vetch.

P Status	Rotation	Mean	SEM
50	C-C	29.556	3.248
50	C-W-V	31.667	3.248
50	C-W	21.994	3.508
0	C-C	10.667	3.248
0	C-W-V	30.222	3.248
0	C-W	15.889	3.248

5.0 Discussion

5.1 Phosphorus release from stubble

Phosphorus concentrations in stubble may be significant (White, 1984). The data corresponds with the hypothesis that incorporating stubble into the soil increases the P concentration available for plant growth. This much more positive than standing stubble which tends to reduce the availability of P for uptake due to its accumulation at the soil surface (Doyle). The current study agreed with this finding, with the treatments that had stubble incorporated into the soil having a greater production of dry matter than those that did not.

A portion of the organic P in soil comes from crop residues (Lupwayi et al., 2007). While P is a common plant nutrient it has not been studied in many long term experiments and we do not fully understand the processes associated with its cycling (Bunemann et al., 2006). It can become inert in residual P fractions after fertilisation, suggesting it does not necessarily transform easily, and is not fully available for plant use (Bunemann et al., 2006). Generally speaking however, organic residues high in P decompose and release P at a faster rate and within a shorter timeframe than other residues (Baggie et al., 2004). This was evident in the pot trial as there was a significant difference in growth between pots that were treated with and not treated with the addition of P. Soil organic P can be closely linked to organic C, with the build up of C through mulching and stubble retention being closely linked with the increase in the build up of organic P. This is most common in cropping systems involving legumes, and when C and N are adequate (Bunemann et al., 2006). Vetch may add to this increase in organic P through utilising P from the subsoil and recycling it into the surface soil for the next crop.

Vetch as a green manure is a desirable species to involve in a cropping rotation because it does not lose mineral N through exporting seeds in comparison to grain legumes or some other legume pasture species (Evans et al., 2003). The application of organic residues also reduces P adsorption, ensuring that any fertiliser used in a cropping system is utilised efficiently (Andrade et al., 2002). These organic residues are a result of stubble decomposition and usually take the sites in the soil where P adsorbs (Andrade et al., 2002). More recent reviews of P and organic matter interactions in the soil have found that organic residues do increase P availability, but for a different reason. These studies have found that P increases in the soil because it is a component of the organic matter itself (Guppy et al., 2005). Aluminium toxicity can be detrimental to plants, but through increasing organic matter soluble aluminium can be temporarily removed from the system, encouraging plant growth (Andrade et al., 2002). These are positive impacts for farmers, since reducing costs and application rates is important to maintain profitability and ensure the sustainable use of the land.

There are many benefits of including vetch in a cropping system. The incorporation of vetch into a rotation coupled with the addition of P resulted in a smaller difference in vetch growth when compared to treatments without P. Vetch may also impact on N uptake through their ability to fix N. The increase in N encourages growth and development, and subsequently roots may become strong enough to reach P in the sub surface soil layers. This in Various factors including pH, clay adsorption and soil moisture content determine if P is available in the soil solution or if it is immobilised (McDowell et al., 2001). The sum of labile P was greatest with vetch in the system, which means that after a vetch crop there is a greater amount of P available to the next crop (Table 1). Labile P was also greater when fertiliser was used and stubble was retained, which is typical in many studies (Graham et al., 2002). Vetch also has the added benefits of increasing the N in the soil that is available for the next crop and subsequently improving yields (Rochester & Peoples, 2005). This was true for the pot trial, with the greatest N uptake occurring when vetch was in rotation. There was also a smaller difference in N uptake in the vetch rotation when P was added and not added (Table 4). Most of the available mineral N is located at the surface until it is leached into the subsoil (Evans et al, 2003). Both soil structure and biological activity are often improved after a rotation of vetch (Rochester & Peoples, 2005).

The release of P from stubble is a complex process (McDowell et al., 2001). Decomposition is dependent on extrinsic factors such as the weather and the moisture in the soil (White, 1984), and has been closely associated with the decomposition of litter and soil organic matter (Bunemann et al., 2006). It is also dependent on intrinsic factors such as biochemical fractions (Ruffalo & Buffo, 2003). Mobilisation of P from stubble is greater under conventional tillage conditions than zero tillage conditions

(Lupwayi et al., 2007). A large amount of P is released in the initial stage of decomposition through the action of substances such as nucleic acids (Lupwayi et al., 2007). After this point little more P is released because the immobilised forms are left. This information corresponds with the labile P data and yield of plants in the rotation that included stubble incorporation into the soil. If time permitted a second trial could have been set up to be harvested later to determine at what point the release of P stops. From past research it could be suggested to allow green manures to remain if a crop is to directly follow, say a legume, because of the fast rate of P release from green manure crops when compared to other types (Lupwayi et al., 2007). Field surveys would probably have encountered a different result because micro-organisms tend to be greater in number and diversity in the field when compared to pot trials. Micro-organisms play an important role in organic matter decomposition (Salas et al., 2003).

There have been many recorded benefits of retaining stubble, including improving soil structure and reducing erosion (Doyle). However, incorporated wheat stubble has been found to reduce soil nitrate N with no subsequent impacts on the following crop. Long term studies have found that an increase in nitrogen based fertilisers is required when utilising soil stubble (White, 1984). When stubble is incorporated into the soil the nitrogen availability becomes a function of the C:N ratio of the stubble, the amount of stubble and the environmental conditions (White, 1984). Stubble has a tendency to immobilise nitrogen (White, 1984). In this study the uptake of N did not differ greatly across soil treatments, suggesting that stubble does not increase N availability in the soil. Stubble incorporation may change the water holding capacity of the soil (White, 1984). This was evident throughout the pot trial, with the stubble incorporated pots always showing less evaporation effects than the pots without stubble incorporation.

5.2 Phosphorus use by cotton and wheat

Rotations in crops has long been know as a positive step to remove diseases and weeds, as well as improve various characteristics of the soil, for example, soil structure or water holding ability. Monocultures often lead to reduced yields in following crops due to soil degradation and the run down of nutrients in the soil. This has been seen in cotton monocultures (Hulugalle & Scott, 2008). The increased need for fertilisers and other management tasks lead to the incorporation of wheat into the cropping rotation. While this has ensured soil quality improves and profitability is maintained, the greatest benefit for the future has been seen in the use of cotton-wheat-vetch rotation. One of the many benefits of this system is the ability to withstand fluctuations in market prices of inputs such as fuel and nitrogen fertilisers (Hulugalle & Scott, 2008). Our results add to these positive impacts, as it was seen that incorporating stubble into a cotton-wheat-vetch system had close to the same benefit as the addition of P. Vetch in rotation may also benefit the following crops because it can acquire P from sub surface layers that other crops cannot, subsequently recycling the P and making it available in the surface layer of soil.

5.3 Other sources of labile P

One of the major sources of labile P is organic matter mineralisation and the activity of enzymes, or it may occur naturally in the mineral soil (Johnson et al., 2003). Labile P is removed from the soil through adsorption and precipitation reactions with iron oxide and aluminium oxide (Nwoke et al., 2003). VA mycorrhizal fungi bring P to the surface for the plants to utilise and can add labile P to the root zone for plant growth (Hayman & Mosse, 1972). Labile P can increase though the competition from organic anions for adsorption sites (Nziguheba et al., 1998). Due to the large amount of organic matter that was placed in the pots, it is probable that the vast majority of the labile P was obtained through mineralisation and decomposition of the organic matter. There was limited soil and therefore limited adsorption sites in the pots, meaning that more P would become available once the few sites were taken.

5.4 Differences in species

The temperature was altered approximately six weeks into the experiment as a result of declining growth. All vetch species tend to have greater dry matter production and quality when grown at cooler temperatures (Gurmani et al., 2006). This was particularly important for Rasina, which was bred in South Australia and grows better at cooler temperatures, however all species had increased growth after the temperature decreased in this pot trial. It is not expected that the pots with stubble incorporated in them had a significant impact on soil temperature, as past studies have found a change in soil temperature usually occurs when stubble is left as mulch on the soil surface (White, 1984). Soil temperature in pots tends to come into equilibrium with the surrounding ambient temperature because there is only a small volume of soil within the pot, and heat is lost through the sides of the pots.

Nodules are a result of rhizobia soil bacteria colonising leguminous cells and tissues through infection threads which begin when cell walls become degraded (Passardi et al., 2002). Popany vetch have resistant roots to rhizobium bacteria interaction, therefore they have greater root activity when the seeds are inoculated, with four times as many nodules in some studies (Passardi et al., 2002). There were varying nodule numbers between the species, and the colours were a mix of white and pink, with pink nodules fixing the greatest amount of N (AGRO 223, 2008). Woolypod vetch had the greatest number of pink nodules, along with many large white nodules. This suggests that Woolypod nodules fix N at a greater rate than Rasina and Popany, and should be studied further considering pink nodules often fix nitrogen better than white nodules. These findings correspond with the data that shows that N uptake is greater in Woolypod vetch (Table 4). Due to the recent use of Rasina there have been no studies on their nodulation, however from the results of this experiment Rasina had the greatest nodule number, making it a useful species choice for increasing the N content of the soil.

Rasina is a relatively new species, particularly compared to Popany (Elliott et al., 2009). While research has been it has been found that Rasina has the greatest total biomass when compared to other vetch species (Elliott et al., 2009). This corresponds with the data gained from the pot trial when vetch was in the cropping rotation with P added. A pot trial ensures that climatic conditions are not limiting, whereas this can be a problem with field trials. Elliott et al., (2009) found that Rasina had a dry matter yield 6% greater than the next greatest producing species, and 30% more dry matter yield than Popany. In out study however on average Rasina yielded a dry matter production 15% greater than Popany. This suggests that the soil was the limiting factor because pot trials are set up to ensure climate is not limiting. Past studies at Narrabri have found the Namoi Woolypod vetch produces the greatest dry matter and fixes the most N; however this study compared to Popany, not Rasina (Rochester).

These findings correspond to the pot trial results, with Woolypod vetch producing more dry matter than Popany in every rotation, with and without the addition of P. Other studies at Narrabri have also found that Woolypod vetch when compared to Popany fixes more N (Rochester & Peoples, 2005).

The results suggest there is a positive relationship between legume inclusion in a system and increases in yield (Bunemann et al., 2006). Bunemann et al (2006) found that organic P was greatest when a legume was in the rotation, and that it accumulated over time in the soil. Many studies have suggested that it may take many years for a noticeable difference in rotation types to occur, due to the use of nutrients by the crops, but after a few years the differences are quite apparent and it is positive to include a legume in the crop rotation (Bunemann et al., 2006). This made our experiment more viable because the soils were taken from a long term research site where the rotations had included vetch for many years.

5.5 Legume response to P and N

Legumes utilise a large amount of nutrients in the soil for growth and development, particularly phosphorus and potassium. If nutrients are not available in high enough amounts than nitrogen fixation does not occur to the full potential of the plant (Lauringson et al., 2004). P has an impact on many of the developmental stages of vetch, including pod and seed development and growth (Gurmani et al., 2006). The addition of P also increases nodule numbers, which corresponds with the results of this experiment where all rotations with P added had significantly greater nodule numbers (Gurmani et al., 2006). P also leads to increases in dry matter yield, but can become dependent on the form that P is applied in and the requirements of the legume type (Andrew & Robins, 1969).

There are many soils in the world that are low in P, with Australia being a commonly used example. This characteristic can make plant growth and development difficult, since P is a nutrient required in the germination phase as it is required for growth until the plant can photosynthesise. The root system of a plant usually grows in a certain formation, either fibrous or taproot depending on the species type. Legumes are typically tap rooted, and as a result have evolved to meet low P soil conditions.

Symbioses occur between legumes and mycorrhizal fungi to ensure the P needs of the plant are met (Newbery et al., 1988). The fungi attach to the roots and spread out throughout the soil, creating vast systems of mycorrhizal fungi. In essence this spread of fungi extends the legume roots and ensure the P needs of the plant are met. In legumes the mycorrhizal fungi tend to be external to the plant, and known as ectomychorrizal fungi. While in the experiment this was not an issue because P was controlled and could not be leached, as well as there were no opportunities to create vast systems, this factor would need to be considered in the field. As a result it would be advisable to inoculate the seeds before planting to ensure this symbiosis was available to the plant.

Vetches are very vigorous winter growing crops that are excellent N fixers (Rochester & Peoples, 2005). This is a typical characteristic of all legumes as much of the world's N sources are unavailable to plants. Rhizobium bacteria form a symbiotic relationship with legume roots, and are the reason why N fixation occurs. The process is anaerobic, with the least oxygen being available in pink coloured nodules. This pink colour was noted for many of the Woolypod vetch nodules, suggesting they had the greater ability to fix N. This may provide a reason why Woolypod vetch had the higher N uptake across all crop rotations and P statuses.

6.0 Conclusion

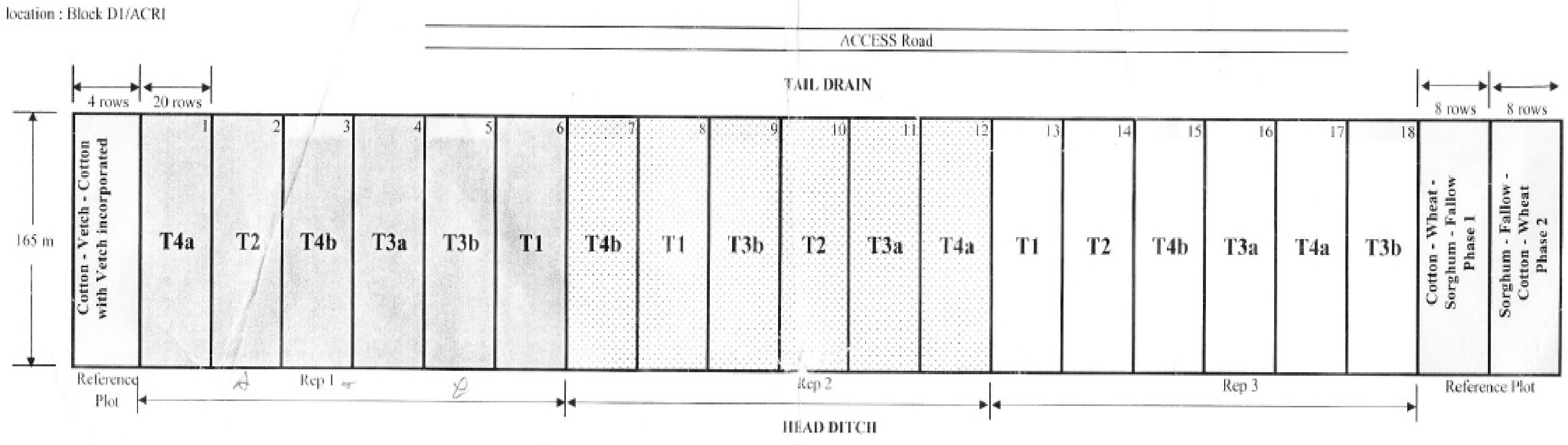
The aims of this experiment were to determine the reason for increased growth and P uptake of crops and green manures where vetch was in the rotation. This involved examining the availability and response to P of vetch in soils associated with different long-term rotations. Incorporating stubble into a cotton-wheat-vetch system had close to the same benefit as the addition of P. Labile P was greatest when vetch was in rotation and stubble was incorporated into the soil, which occurs because the decomposition of organic matter is a major source of labile P. Vetch tends to access P pools that cotton and wheat do not, meaning P becomes recycled into the surface of the soil and therefore available to future crops. Legumes in general are known to increase N in the soil through nodulation and N fixation which results in greater growth and development. It may be this increased root growth that results in an increase in P uptake. Of the three species used in the experiment Woolypod vetch had the greatest dry matter yield per pot. This pink colour was noted for many of the Woolypod vetch nodules, suggesting they had the greater ability to fix N. This may provide a reason why Woolypod vetch had the higher N uptake across all crop rotations and P statuses.

The inclusion of vetch into a cotton cropping has a variety of benefits on the cropping system and on the soil. Legumes are know for their ability to stabilise the soil, aid in maintaining soil structure, and most importantly, providing N to the following crop due to their ability to fix N. Vetch is a suitable rotation crop for cotton because it is winter growing and means soil is not left bare and vulnerable to erosion which is common when a fallow period is utilised. Wheat is another commonly used rotation crop because it provides cover and can also provide capital through harvest, and the fact that the crop does not need to be killed off like vetch does.

Plants utilise P to aid their growth and development, particularly at the initial stages. As a result some of the total soil P accumulates in plant material. Some of the P is removed through harvesting however if stubble is retained microbial decomposition can change the P in the stubble into an available form. Retaining stubble from wheat rotations and incorporating a vetch rotation can reduce the need for fertilisers in cotton cropping systems. Utilising a minimum tillage cultivation system prevents disruption to the soil and the harm that occurs to soil organisms.

Appendix 1

The trial set up at the Australian Cotton Research Institute where the soil was taken for this experiment.



Design: 3 RCB

Treatments:

T1: cotton-vetch-cotton

T2: cotton-winter-fallow-cotton

T3a: Cotton-wheat-summer and winter fallow-cotton; wheat stubble incorporated

T3b: Summer and winter fallow-cotton-wheat; wheat stubble incorporated

T4a: Cotton-wheat-summer fallow-vetch-cotton; wheat stubble retained as standing stubble

T4b: Summer and winter fallow-cotton-wheat-summer fallow-vetch; wheat stubble retained as standing stubble

NB. All treatments are minimum-tilled; vetch is sprayed out before sowing cotton

EM-38 survey is planned to identify field variability before plot establishment

All plots furrow irrigated

plot are 165 m x (1-m) 20 rows

duration of experiment: 12 years

4 m buffers between reps

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