Crop residue contributions to phosphorus pools in agricultural soils: A review
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Paul Damon, Bill Bowden, Terry J. Rose, Zed Rengel

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1   # Title

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3

4   # Authors

5   *Paul M Damon[a*], Bill Bowden[b], Terry Rose [c,d], Zed Rengel[a]*

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7   [a] School of Earth and Environment, and The UWA Institute of Agriculture, The University of Western

8   Australia, 35 Stirling Highway, Crawley Western Australia 6009, Australia

9   [b] Hovea, WA 6071

10   [c] Southern Cross Plant Science, Southern Cross University, Military Road East Lismore NSW 2480

11   [d] Southern Cross GeoScience, Southern Cross University, Military Road East Lismore NSW 2480

12   [*] Corresponding author, e-mail: paul.damon@uwa.edu.au

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16   # Keywords

17   Organic matter, microbial phosphorus, mineralisation, phosphate, soil phosphorus pools

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1. Summary

The phosphorus (P) content of crop residues and its availability to a subsequent crop can range from agronomically insignificant, to quantities in excess of crop P requirement. However, the contribution of crop residues to the P nutrition of subsequent crops has not been widely recognised, and simple predictive tools are lacking. By reviewing the published literature in which quantitative measurements of P transformations from plant residues applied to soil have been reported, we have evaluated the contribution of crop residue-derived P to the P nutrition of subsequent crops, assessed the key factors involved and summarised the knowledge as an empirical model. The contribution of crop residues to P availability is likely to be significant only under conditions where large amounts of crop residues of relatively high P concentration are applied to soil. Crop residues with low P concentration, such as cereal stubble (eg. due to re-translocation of a large proportion of stubble P into grain), will not make an agronomically significant contribution to soil P availability, but may reduce P availability due to assimilation in the microbial biomass. However, a productive green manure crop may release sufficient P to meet the requirements of a subsequent cash crop. The release of P from crop residues is significantly reduced in systems where the P-status of crops and soils is low, which reinforces the reliance on external P inputs for sustained crop productivity. The large variability in the potential contributions of plant residues to the P nutrition of subsequent crops suggests that there is a strong need to integrate model predictions of organically-cycled P with current fertiliser management strategies.

2. Introduction

Optimising phosphorus (P) use efficiency will deliver agronomic, economic and environmental benefits as agricultural production systems adjust to meet future global food production targets (Heffer and Prud'homme, 2013). Such optimisation will rely on adequate knowledge of the dynamics of soil P pools

46   to enable accurate predictions of the required external P inputs to achieve optimum growth of

47   subsequent crops. While our understanding of soil inorganic phosphate (Pi) pools is relatively

48   comprehensive, the value of P returned to the soil in crop residues has not been fully resolved.

49   Agronomically significant amounts of P can be present in crop residues and the microbial biomass

50   associated with their decomposition, and the potential contribution of this pool to the P nutrition of

51   cropping systems is significant (*eg.* Chauhan *et al.,* 1979; Dalal, 1979; White and Ayoub, 1983; Thibaud

52   *et al*., 1988; Umrit and Friesen, 1994; Kwabiah *et al*., 2003a; Nachimuthu *et al.*, 2009). The main factors

53   influencing the amount of crop residue P, its rate of mineralisation and subsequent availability to crops

54   have been identified (Stockdale and Brookes, 2006; Guppy and McLaughlin, 2009; Simpson *et al.*, 2011);

55   but their interactions remain poorly elucidated and largely unquantified. By reviewing the published

56   literature in which quantitative measurements of P transformations from plant residues applied to soil

57   have been reported, we will evaluate the contribution of crop residue-derived P to the P nutrition of

58   subsequent crops, assess the key factors involved and summarise the knowledge as an empirical model.

59

60   The dynamics of organically-derived nitrogen (N) and carbon (C) in agricultural soils has been extensively

61   described, and a wide range of predictive tools have been developed. These have proved a valuable

62   asset for landholders, agronomists and policy makers by providing good estimates of the impacts of

63   agronomic management options on the dynamics of both C (*eg.* Parton *et al.*, 1988; Coleman and

64   Jenkinson, 1999; Grace *et al.*, 2006) and N (see Herridge *et al.*, 2008) in agricultural soils. Considering

65   our extensive knowledge of the N cycle in agricultural systems, and the benefits (economic, social and

66   environmental) that have been obtained by our ability to predict and manipulate it, similar knowledge

67   of the organic P cycle could also yield significant benefits. Yet, although the principal driving factors of

68   organic P cycling have long been recognised and modelled (Cole *et al.*, 1977), models have not proven

69   to be universally applicable (Gijsman *et al.*, 1996; Schnepf *et al.*, 2011). Several models have

70   demonstrated a capacity to incorporate P release from crop residues and manures into projected crop

71   growth and yield, notably The Agricultural Production Systems Simulation (APSIM) (Keating *et al.*, 2003),

72 Century (Parton *et al.,* 1988) and CERES-Wheat (Ritchie *et al.,* 1988; Godwin *et al.,* 1989; Singh *et al.,*

73 1991; Daroub *et al*., 2003) modelling frameworks. However, these models require detailed climate and

74 site information that may not be available, and are specialised tools that cannot be operated by the

75 layperson. The contribution of crop residue P to the nutrition of subsequent crops has not been widely

76 recognised, and there is currently no decision support system (DSS) that can predict it from a simple,

77 readily-available set of variables.

78

79 Plant uptake of residue-derived P has predominantly been evaluated using isotope labelling and isotopic

80 dilution methodologies. Residues labelled with ^{32}P or ^{33}P isotopes have been applied to soil, enabling the

81 differentiation of residue-derived P, native soil P and mineral fertiliser P through the plant-soil system

82 (eg McLaughlin and Alston, 1986). Such studies have typically been conducted over a short term (1-2

83 months), according to the half-life of the available P isotopes, with the amounts of residue-derived P

84 recovered in plants generally being 5 % to 10 % of the total P content of the residues (Blair and Boland

85 1987; Nachimuthu *et al.*, 2009), 20 to 30% (Umrit and Friesen, 1994) and as high as 40% (Dalal, 1979).

86 Similarly, a large proportion of crop residue P is generally recovered from soil as inorganic P (Pi) in plant-

87 available and sorbed pools (Chauhan *et al.*, 1979; White and Ayoub, 1983; Kwabiah *et al*., 2003a) in

88 proportions similar to those observed when P is applied as mineral P fertiliser (Friesen and Blair, 1988;

89 Cong and Merckx, 2005).

90

91 Where P pools and mineralisation were measured over a period of decades, rotation management has

92 been shown to have a significant effect on the dynamics and partitioning of soil P. In the context of a

93 pasture/cereal cropping rotation, Bünemann *et al.* (2006) measured accumulation of P in the organic

94 fraction during a wheat/pasture rotation at ~2 kg ha^{-1} year^{-1} (a trend previously reported by McLaughlin

95 *et al.*, 1988), but no accumulation under continuous cropping. Soil organic matter has been shown to

96 increase under legume pasture phases, with subsequent release of nutrients through mineralisation of

97   the organic matter during cropping phases (*cf*. Simpson *et al.*, 2011). Although the accumulation of soil

98   N is usually the focus of pasture phases, there is also the potential for pasture or green manure phases

99   to augment soil P availability in the subsequent cropping phase (Horst *et al.*, 2001). Interestingly, pulse

100 crops including chickpea, white lupin, and faba bean have been shown to enhance the P nutrition of

101 subsequent cereal crops even when legume residues have been removed from the soil (Nuruzzaman *et*

102 *al.*, *2005;* Rose *et al.*, 2010), and some legume genotypes improve the P nutrition of subsequent cereals

103 more than others (Rose *et al.*, 2010b). However, the mechanism(s) responsible for this are not clear, the

104 impact of the time lapse between legume harvest and subsequent cereal sowing on potential P benefits

105 is unresolved, and there are currently insufficient data to incorporate such mechanisms into predictive

106 models for P turnover.

107

108 Although the processes determining the cycling of P in soils are indisputably complex, several key factors

109 have consistently been demonstrated to govern the mineralisation and availability of crop residue-

110 derived P. These main factors can be broadly grouped as the quality of the crop residues, the activity of

111 the soil microbial biomass, and the subsequent sorption reactions of mineralised P in soil (summarised

112 in Figure 1 as a conceptual model). We characterise the process of P release from crop residues based

113 on four key P pools; namely the inorganic and organic P components of crop residues, P assimilated in

114 the microbial biomass and Pi associated with the soil. The key processes of P transfer between these

115 pools are represented by five vectors: the rate of release of the inorganic and organic P fractions from

116 residues (k_{Pi} and k_{Po}) and the microbial biomass pool (k_{Pm}), the assimilation of Pi by the microbial

117 biomass as it proliferates after the addition of crop residues (M_{Pm}), and the uptake of native soil Pi by

118 the stimulated microbial biomass (M_{Pi}) when Pi released from crop residues is less than M_{Pm}.

119

120 **Figure 1:** A schematic representation of the conceptual pools and vectors as described and quantified.

121 'Residue Pi' represents water-soluble phosphate and 'Residue Po' represents the organically bound

122 component of P in 'Crop Residues'. 'Soil Pi' represents all Pi that is associated with the mineral

123 component of soil that is potentially exchangeable with the soil solution. 'k_{Pi}' and 'k_{Po}' represent the

124 decay constants for the rate of release of 'Residue Pi' and 'Residue Po', respectively. 'M_{Pm}' represents

125 the amount of Pi assimilated by the 'Microbial Biomass' as it proliferates in response to the availability

126 of C substrate from 'Crop Residues', whereas 'M_{Pi}' represents the uptake of 'Soil Pi' by the stimulated

127 'Microbial Biomass' where P released from crop residues is less than 'M_{Pm}'. 'k_{Pm}' represents the decay

128 constant for the rate of release of Pi from the 'Microbial Biomass' as it decays in response to diminishing

129 availability of C substrate from 'Crop Residues'.

130

131 We present herein a quantitative summary of the available literature resources, with respect to the rate

132 and magnitude of P transfer from crop residues to the plant available soil pools, and the major

133 environmental and management factors involved. We discuss how the pools and vectors represented in

134 Figure 1 describe the major processes governing the transfer of crop residue P to plant available soil P,

135 and quantify them. This knowledge is then integrated as a simple empirical model of the response of soil

136 P availability to various crop residue scenarios. We draw as broadly as practicable on the published

137 literature, to represent averaged values that can be expected across a diversity of conditions, thereby

138 summarising key areas of scientific consensus, and processes that are as yet poorly elucidated. As the

139 sum of existing knowledge and in the interest of robustness and simplicity, the release of P from crop

140 residues is described according to major processes illustrated in Figure 1; they have been quantified

141 widely. The numerous interacting factors that have yet to be completely elucidated (*eg.* tillage effects, P

142 sorption in soil, pH of soil) are not accounted for, but their potential relevance is discussed. Likewise, the

143 interaction of growing plants with residue P during its release from crop residues is not addressed, as

144 this level of understanding has not been reported in the literature yet. We propose that the model be

145 used as a template for i) targeted elucidation of the mechanisms controlling the mineralisation and fate

146 of organic matter-associated P, and ii) the development of more refined predictive models that

147   integrate the P contributions from various crop residue handling scenarios into decision support systems

148   for P fertiliser management.

149

3. Amount and fractions of P in crop residues

151

152   The amount and forms of P in residues have a large bearing on the immediate bioavailability of P in the

153   residue material and on the subsequent reactions of P with soil constituents. The P characteristics of

154   crop residues are highly dependent on environmental and soil conditions and on the physiological age of

155   the crop from which they are derived. The P concentration of applied residues is the principal factor

156   determining whether P will be mineralised in the short term as a result of residue decomposition.

157   Generally, P will be mineralised if the P concentration in residues is greater than 3 mg g^{-1} or immobilised

158   if it is less than 3 mg g^{-1}, although reported threshold values range from 2 to 3 mg g^{-1} (eg Fuller *et al.*,

159   1956; White and Ayoub, 1983; Friesen and Blair, 1988; Umrit and Friesen, 1994; Iyamuremye *et al.*,

160   1996; Kwabiah *et al.*, 2003a; Iqbal, 2009). Immobilisation of soil P occurs when the total P content of the

161   residue is insufficient to meet the P requirement of the microbial biomass as it proliferates in response

162   to the new C substrate; the relevant issues will be discussed in detail in a following section.

163

164   The forms of P in crop residues as they influence the dynamics of P release can be characterised as

165   soluble Pi, which is rapidly leached within days and an insoluble organic phosphorus (Po) component,

166   which decays at a rate several orders of magnitude slower (Figure 1). Water-soluble Pi typically

167   constitutes from 40 to 60 % (average 50 %) of the total P content in mature crop residues at grain

168   harvest (Chang, 1939; Kaila, 1949; Birch, 1961; Jones and Bromfield, 1969; Kwabiah *et al.*, 2003b; Noack

169   *et al.*, 2012) and from 60 to 80 % (average 70 %) of total P content in green crop residues during the

170   vegetative stage (Jones and Bromfield, 1969; Bromfield and Jones, 1972; White and Ayoub, 1983;

171   Friesen and Blair, 1988; Ha *et al.*, 2008). The root component of crop residues can be assumed to have

7

172   comparable P release (per unit of biomass) to the shoot component (Martin and Cunningham, 1973,

173   Thibaud *et al.*, 1988).

174

175   During plant growth the concentration of P in the cytoplasm is tightly regulated (Schachtman *et al.*,

176   1998), and P in excess of these requirements is stored primarily in the vacuole as Pi (Shane *et al.*, 2004).

177   Data from studies with tobacco suggest that the proportion of Pi can range from 20 % of total P in leaves

178   at low P availability to 50 % at high P availability (Kakie, 1969). Cytoplasmic Pi (often referred to as

179   metabolically-active Pi) is typically around 0.1-0.8 mg P g^{-1} dry matter (Veneklaas *et al.*, 2012); this Pi, as

180   well as that stored in the vacuole, is water-soluble and should be readily available for plant/microbial

181   uptake (or sorption in soil) upon return to the soil. The amount of P in vacuoles therefore has a

182   significant impact on the short to medium-term release of P from residues. While it is generally

183   accepted that the Pi concentration in tissues is a reflection of the P supply from the growth medium

184   (White and Hammond, 2008), the range of variation that can be encountered in typical crop species

185   grown and the key factors affecting speciation need elucidation.

186

187   During grain maturation, P is transferred from vegetative plant parts to developing grains where it is

188   stored primarily as phytate (Marschner, 2012). In wheat, 80-90% of total plant P content can be

189   translocated to grain during maturation and subsequently exported with the harvested product (Batten

190   and Khan, 1987), so that total P concentrations in mature residues can be an order of magnitude lower

191   than those in green residues. However, the partitioning of P between grain and straw/roots at maturity

192   is highly dependent on crop species, genotype and environment. For example, the P harvest index (PHI,

193   or proportion of aboveground plant P located in the grain at maturity) of wheat can range from 30-90%

194   depending on genotype and environment (Batten, 1992). In contrast, most studies consistently report

195   that canola has a PHI of 70-80 % (Jackson, 2000; Rose *et al.*, 2007, 2008), but this narrow range may be

196 more of a reflection of limited published data, as opposed to lack of variation in PHI across genotypes

197 and environments.

198

199 Regardless of whether variation in PHI arises due to species or genotype differences, the key question is

200 how these differences impact on the speciation of P in the residue, i.e. does a greater proportion of P

201 retained in straw mean an increased proportion of Pi in the straw? Unfortunately, the speciation of P

202 compounds in crop residues remains poorly documented. Noack *et al.* (2012) recently demonstrated a

203 large variability in the amount of P residing as Pi in mature crop residues across crop species, but

204 examining the effect of genotype, soil fertility, seasonal conditions, or crop management on P speciation

205 was beyond the scope of that study. The effect of crop management strategies that interrupt the

206 translocation of P into the exported product, such as swathing or chemically desiccating an

207 indeterminate canola crop vs direct harvesting a determinate canola crop may have a large bearing on P

208 cycling. Seasonal events such as frosting and terminal drought, which reduce grain yields, may also

209 result in a substantial increase in the amount of P retained in residues. Given a relatively high proportion

210 of Pi in residues of a range of crops compared with the high proportion of phytate in seeds (Noack *et al.*

211 2012), efforts to restrict the loading of P into grains (Rose *et al.* 2010c; Richardson *et al.* 2011; Rose and

212 Wissuwa 2012; Veneklaas *et al.* 2012) may have substantial implications for P mineralised in crop

213 residues. In contrast, it is difficult to predict the impact of soil P fertility on the amount and forms of P in

214 residues. Even though high-P supply to plants increases tissue P concentrations in vegetative biomass

215 (White and Hammond 2008), such high P supply also tends to increase yields, which, in turn, increases

216 the amount of P located in seeds at maturity. Presumably, once yield potential is achieved there comes

217 a point where any P taken up beyond maximum yields (luxury P) leads to higher inorganic P in straw as

218 well as higher seed P (see Rose *et al*. 2008), but there is presently little information available on the

219 impact of P supply on P speciation and the distribution of the P in crop residues.

220

221   Table 1 summarises the average biomass and P content of common crop residues that can be expected

222   under low, medium and high productivity situations in the southern Australian grain cropping regions.

223   The values presented are referenced from survey data for multiple sites and seasons where available,

224   and values representing consensus in the literature where survey data was unavailable. The data

225   represent the southern Australian cereal cropping regions, but may be applicable to other dryland

226   cropping regions, particularly where highly weathered soils predominate. The data confirm that the

227   most influential factor with respect to the quantity and speciation of P in crop residues is the

228   developmental stage of the crop, exemplified by the differences in P between mature crop residues

229   remaining after grain harvest (less than 1 kg P ha^{-1} in a low-yielding wheat crop residues) and those

230   residues utilised at the vegetative growth stage (more than 30 kg P ha^{-1} in a productive green manure

231   crop).

232

233   ## 4. Microbial biomass P

234   The soil microbial biomass has two main roles in the dynamics of crop residue P in soil; i) the principal

235   driver for the transformation of organically-bound phosphorus to plant-available phosphate, and ii) the

236   accumulator of a significant pool of P. The notable effect of crop residues on soil P dynamics, when

237   compared to mineral fertiliser, is their stimulation of the soil microbial biomass with subsequent uptake

238   and immobilisation of P (and other minerals) in this biomass. Upon the addition of crop residues, the

239   microbial biomass is generally the predominant soil P pool that is influenced in the short term,

240   regardless of the characteristics of either the crop residues or the soil (eg Chauhan *et al.*, 1979, White

241   and Ayoub 1983; McLaughlin and Alston 1986). In comparison, application of mineral P fertiliser causes

242   little (McLaughlin and Alston 1986; Marschner *et al.* 2006), or no increase (Chauhan *et al.*, 1979) in the

243   amount of P in the microbial biomass.

244

245   The size of the microbial biomass in soil is stimulated rapidly upon addition of crop residues. The

246   magnitude of the increase in microbial biomass is proportional to the amount of C in residues, since C-

247   substrate availability is the primary factor limiting microbial activity in agricultural soils (eg. Van Veen *et*

248   *al.*, 1984; Bünemann *et al.*, 2004a). The magnitude of microbial biomass proliferation may respond to

249   other characteristics of the crop residues that are related to age, species and environmental factors;

250   however, these factors have not been thoroughly elucidated. The C concentration in crop residues is

251   typically 450 mg g^{-1} (45 %) (Baldock, 2009), on average, and we will assume this value represents all crop

252   residues considered herein.

253

254   Phosphorus from the crop residue substrate and from soil P pools is taken up by the proliferating

255   microbial biomass. Microbial biomass P responds rapidly to the addition of C substrate to soil, reaching a

256   maximum within days of substrate addition (Chauhan *et al.*, 1979; White and Ayoub, 1983). In the short

257   term, net mineralisation will occur if the amount of soluble P in residues is in excess of that taken up by

258   the microbial biomass. However, residue P content is often insufficient to meet the requirements of the

259   growing microbial biomass, under which circumstances the microbial biomass will take up Pi from the

260   solution and exchangeable pools in soil; leading to net immobilisation of soil Pi. Hence, the importance

261   of crop residue characteristics in determining the dynamics of P release is due to the interaction

262   between the crop residues and the microbial biomass.

263

264   Phosphorus is taken up by the proliferating microbial biomass to meet its growth and metabolic

265   requirements according to relatively flexible ratio of C:P within the microbial biomass. The C:P ratio and

266   forms of P in the microbial biomass differ widely between microbial communities and ecosystem types,

267   and Bünemann *et al*. (2011) present a thorough review and assessment on the subject. In cereal

268   cropping soils the C:P ratio of the microbial biomass has been reported to range from 10:1 (Oehl *et al.*,

269   2004; Bünemann *et al.*, 2007) to 35:1 (Chauhan *et al.*, 1979; Butterly *et al.*, 2010). Chauhan *et al.* (1979)

270   found the C:P ratio of new microbial biomass formed after residue addition to be 20:1, compared to

271   35:1 for the resident soil microbial biomass. Parton *et al.* (1988) proposed that the C:P ratio of the

272   microbial biomass varies as a function of soil P availability. As a simplistic representation of the

273   concurrent short-term effects of microbial biomass proliferation and P uptake, we propose that the

274   proliferation of the microbial biomass and the amount of P taken up as a consequence of this

275   proliferation are in proportion to the amount of C substrate in crop residues. The amount of P taken up

276   by the microbial biomass was 1 mg P g^{-1} C applied as organic residues (M_{Pm}; Figure 1) on average for a

277   range of crop residues and soil types (Chauhan *et al.*, 1979; Kwabiah *et al.*, 2003a; Iqbal, 2009).

278   Therefore, assuming the C content of crop residues is 450 mg kg^{-1}, if the concentration of soluble Pi in

279   residues is greater than 0.45 mg P g^{-1}, k_{Pi} will exceed the demands of the microbial biomass, and M_{Pi} will

280   be zero. Where the soluble Pi content is less than 0.45 mg P g^{-1}, k_{Pi} will not meet the P requirements of

281   the microbial biomass in the short term, and Pi from soil pools will be immobilised in the microbial

282   biomass, quantified as M_{Pi} (Figure 1).

283

284   Although the C:P ratio of the microbial biomass responds to P availability in the soil and crop residue

285   substrate, the microbial biomass has a high capacity to acquire P from soil P fractions that are generally

286   not considered to be plant-available, and will be more competitive than plants for solution and

287   exchangeable P (Chauhan *et al.*, 1979; White and Ayoub, 1983; Friesen and Blair, 1988; Bünemann *et al.,*

288   2004b; Cleveland and Liptzin, 2007; Iqbal, 2009; Ehlers *et al.,* 2010; Oberson *et al.*, 2011). It has been

289   demonstrated that even for highly P-limited environments, such as tropical soils with high P sorption

290   capacity and sparse P fertiliser history, the microbial biomass dominates geochemical processes for

291   competitive uptake of applied P (Kwabiah *et al.*, 2003a; Olander and Vitousek, 2004) and is limited by C

292   and N rather than by P availability (Bünemann *et al.*, 2004a).

293

294   The microbial biomass in soil and its response to substrate addition is significantly influenced by soil pH,

295   a concept reviewed in detail by Wardle (1992). Briefly, the size of the microbial biomass typically

296   decreases with decreasing soil pH. Thompson *et al.* (1954) and Harrison (1982) both reported soil pH to

297   be a significant factor influencing rates of organic P mineralisation. The stability of soil organic P to

298   mineralization increased as soil pH decreased, so soil organic P may be more stable, and mineralisation

299   rates slower, in soils with acidic pH. Indeed mineralisation rates of C and N have been widely

300   demonstrated to be lower, and soil organic C retention to be higher, in soils at acidic pH (*eg.* Amato and

301   Ladd, 1992; Motavalli *et al.*, 1995; Li *et al.*, 2007). However, empirical data to quantify the influence of

302   soil pH on mineralisation rates is poorly developed for both C and for P.

303

304   Microbial biomass P is potentially available for plant uptake. In the short term, there is potential for

305   competitive uptake by plant roots following predation by soil fauna. During transient periods of drying

306   and re-wetting of soil, desiccation and lysis of microbial cells and the subsequent transfer of microbially-

307   held P to extractable soil pools can be significant (Turner *et al.*, 2003). In the medium term, the size of

308   the microbial biomass decays at a rate similar to the decay of organic C (Oehl *et al.*, 2001; Bünemann *et*

309   *al.*; 2004a; Grace *et al.*, 2006) as the availability of C substrate decreases. The incubation studies of Oehl

310   *et al.* (2001) and Bünemann *et al.* (2004a) demonstrated that the decrease in microbial P after

311   exhaustion of C-substrate resulted in an increase in plant-available P. However, the work of Marschner

312   *et al*. (2005; 2006; 2007) indicates that crop reliance on microbial biomass-derived P may be strongly

313   influenced by soil properties and plant species, a subject that indeed warrants further investigation.

314

315   Ladd *et al.* (1995) proposed that the microbial biomass derived from residue addition could be allocated

316   into 2 pools; unprotected (due to its presumed association with crop residues) and protected (that with

317   opportunities for protection within the soil). The ratio of protected / unprotected biomass is dependent

318   on clay content and the CEC of the soil, and ranges from 0.6 (high clay soil) to 0.4 (sandy loam soil).

319   However, for the purpose of simplicity and with consideration of the limits of the published data, we will

320   adopt a single pool for the microbial biomass P, and assume that its size decays at the same rate as the

321   stable residue pool.

322

323   Martin and Cunningham (1973) reported a relatively non-significant role of the microbial biomass in P

324   transformations during the decomposition of intact wheat roots. They proposed that the use of finely-

325   ground plant residues in many studies may have misrepresented its availability to microorganisms and

326   resulted in an over-estimate of the microbial biomass response. It is likely that the rate, but not the

327   magnitude of microbial biomass proliferation may be influenced by the particle size of the substrate (*eg.*

328   Ambus and Jensen, 1997; Singh *et al.,* 2006).

329

330   The data presented are almost exclusively derived from studies where finely-ground crop residues were

331   incorporated into soil. Given the widespread adoption of no tillage cropping practices worldwide, it is

332   imperative to investigate how the assumptions translate into systems where the majority of crop

333   residues are a) largely intact and b) either standing or at the soil surface. The factors that may differ

334   between finely-ground crop residues incorporated into soil (classical tillage) and no-till systems include

335   variable moisture content at the soil surface, greater potential for separation of soluble and insoluble

336   components by leaching, reduced availability of soil nutrients for uptake by the microbial biomass

337   during decomposition and lower surface area of intact residues for decomposition. The influence of

338   tillage practices on the dynamics of mineralisation remains poorly elucidated even for C and N, which

339   have been more extensively studied than P. The simulation models APSIM, RothC (Coleman and

340   Jenkinson, 1999) and Ceres Wheat, have cultivation increase the rate that "litter" (residues) are

341   incorporated and become fresh soil organic matter, but thereafter, the rates of mineralisation are not

342   changed by cultivation. Whilst Daroub *et al.* (2000) measured no effect of tillage on the release of P

343   from plant residues applied to soil, Chauhan *et al.* (1979) found that mixing soil increased microbial

344   biomass P to a greater extent than the addition of grass residue, indicating a potential tillage effect. Due

345   to a lack of empirical data we have not quantified the effect of tillage on the release of P from crop

346   residues.

347

5. Soil phosphate fractions

349   The plant uptake of P from soil occurs predominantly in the form of Pi (HPO_4^{-2} and $H_2PO_4^-$; Bucher,

350   2007); hence, the soil Pi pool (Figure 1) represents soil P forms that are potentially available for uptake

351   by plants. The soil Pi pool (Figure 1) incorporates the net release of Pi from crop residues and is a

352   simplified representation of a complex, dynamic, and diverse system. Soluble Pi can be readily leached

353   from crop residues (Jones and Bromfield, 1969), resulting in a direct, rapid transfer from crop residue to

354   the soil Pi and microbial P pools (with the assumption that there is no new crop interacting with these

355   pools). Phosphorus that is taken up by the microbial biomass as it proliferates in response to the crop

356   residue-C substrate availability is subsequently released as the microbial biomass decays with the

357   exhaustion of C substrate (Oehl *et al.*, 2001; Bünemann *et al.*, 2004a). The size of the soil Pi pool (Figure

358   1) is the sum of Pi released from crop residues and the microbial biomass at a time point in the P

359   mineralisation process, together with Pi from fertiliser inputs and background native P in the soil.

360   Biological and geochemical processes of mineralisation, sorption and dissolution of P contribute to

361   background native soil Pi.

362

5.1. Forms and transformations

364   The soil Pi pool includes soil solution Pi and chemically sorbed Pi, which interact in a dynamic

365   equilibrium. The distribution of soil phosphorus between the sorbed and solution phases is dominated

366   by sorption reactions (Barrow, 1983; Barrow, 1999), while its availability to plants (and microbes) is also

367   affected by diffusion processes (Probert and Keating, 2000). Sorption reactions are highly influenced by

368 the chemistry and mineralogy of soil, and their influence on P availability is greatest in soils with high P

369 sorption capacity, such as tropical soils dominated by iron and aluminium sesquioxides. The availability

370 of Pi in soil, whether derived from mineral fertiliser or from crop residues, can be short-lived in soils

371 with high P sorption capacity. For the purpose of this exercise, we have represented soil Pi as a single

372 pool, into which all P released from crop residues is allocated and from which the microbial biomass

373 may acquire P.

374

375 Organic P compounds released into soil either directly from crop residues or after the lysis of microbial

376 cells are subject to sorption and precipitation reactions in soil, after which their potential for

377 mineralisation into Pi is greatly reduced (Celi and Barberis, 2005). Organic P compounds are readily

378 adsorbed onto iron oxides and to a lesser extent, aluminium oxides, with the amount of iron oxides

379 generally governing the capacity for Po adsorption (Anderson *et al*., 1974). As such, sorption and

380 stabilisation of Po is greatest in highly weathered, tropical soils with high P fixing capacities, hence there

381 is often an accumulation of Po in these soils (Reed *et al*., 2011). The sorption and subsequent

382 stabilisation of Po in soils remain the major processes whereby the dynamics of P release from crop

383 residues may deviate from that of C and N, for which there is a more refined understanding. However,

384 methodological problems have hindered the elucidation of the long-term fate of crop residue Po in soil,

385 notably the relatively short half-life of ^{32}P and ^{33}P isotopic tracers, and a limited capacity to characterise

386 P-containing compounds that cannot be extracted from the soil matrix.

387

388 Organic P forms can constitute up to 80 % of total P in soil (Anderson, 1980) and can be associated with

389 soil organic carbon (C), or adsorbed by soil minerals (Celi and Barberis, 2005). Stimulation of the

390 microbial biomass to mineralise soil Po is referred to as a "priming effect" and is a potential strategy for

391 matching soil Pi supply with crop demands (Simpson *et al*., 2007). Where Po is associated with organic C,

392 it can be released into soil solution by C mineralisation and subsequently hydrolysed by enzymes

393 released from the microbial biomass (Randhawa *et al*., 2005; Richardson 2007). Although the absence of

394 suitably stable P isotopes makes direct measurement of Po mineralisation difficult to measure, the

395 "priming effect" was found to be negligible where ^{14}C was used as a tracer for C mineralisation

396 (Dalenberg and Jager, 1989). Hydrolysis of sorbed Po compounds, such as inositol phosphates, by the

397 microbial biomass may be stimulated after addition of crop residues to soil, particularly where a high C:P

398 ratio of crop residues promotes the uptake of soil P by the microbial biomass. However, there is

399 evidence that assimilation of soil P by the microbial biomass occurs predominantly from the available

400 soil Pi fraction (White and Ayoub, 1983; Wu *et al*., 2007; Jalali, 2009), even in low P soils (Bünemann *et*

401 *al*., 2012). Although the "priming effect" will not be addressed in our modelling, further investigation is

402 warranted, given the potential benefits of manipulating the release of Pi from the significant pools of

403 soil Po.

404

405   5.2. *Availability to plants*

406 Sorption of Pi by soil minerals is the principal factor influencing plant availability of P mineralised from

407 crop residues (White and Ayoub, 1983; Friesen and Blair, 1988; Umrit and Friesen 1994; Jalali, 2009;

408 Jalali and Ranjbar, 2009). The availability of Pi released from crop residues is influenced by sorption

409 reactions in a similar way to Pi applied to soil as mineral fertiliser (Friesen and Blair, 1988; Cong and

410 Merckx, 2005). Iyamuremye *et al.* (1996) used the method of Hedley *et al.* (1982) to investigate the role

411 of both residue and soil characteristics on the fate of crop residue-derived P in soil. The majority of P

412 released from crop residues was recovered as chemically-sorbed Pi (NaOH-extractable) for all soils,

413 although the proportion recovered in readily available (resin and bicarbonate-extractable) pools was

414 related to the P sorption capacity of the soil. Friesen and Blair (1988) measured almost no increase in

415 the soil solution P during the mineralisation of crop residues, with almost all mineralised P sorbed to Fe

416 (NaOH-extractable) and Al minerals (NH$_4$F-extractable). Although the Al-sorbed P fraction was readily

417 depleted by plants (and the microbial biomass), the Fe-sorbed fraction was unavailable. The factors

418 governing the sorption of phosphate ions in soil are well understood, and it is evident that the P release

419   from crop residues occurs primarily as Pi; hence the existing models targeted toward fertiliser and

420   native soil P should adequately describe the reactions of crop residue P in soil.

421

422   Addition of crop residues to soil can indirectly influence the availability of P within the soil P pool by

423   altering the chemical and physical properties of the soil (Joffe, 1955). Cong and Merkx (2005) measured

424   significant changes to a suite of chemical and physical characteristics, leading to an increase in both the

425   chemical availability and diffusive supply of P following a high rate of organic matter addition to soil.

426   They demonstrated the capacity of plant residues to increase pH, decrease extractable Al, and increase

427   the net negative charge surfaces in soil, with the net effect of increased solubility and reduced sorption

428   of Pi in soil. Greater macro-aggregation and reduced specific surface area and porosity of soil were also

429   measured, reducing P sorption and increasing P diffusion rates. A review by Guppy *et al.* (2005)

430   concluded that the application of organic matter to soils at agronomically feasible rates does not reduce

431   the sorption of P by soil, and that any increase in soil P availability could be directly attributed to P

432   released from the crop residues. However, it should be noted that the distribution of crop residues is

433   often locally concentrated after deposition by harvesting operations at rates many-fold greater than if

434   crop residues were evenly distributed (eg. Brennan et al., 2000). It is likely that soil P availability is

435   influenced by physical and chemical changes in soil following the addition of crop residues; however the

436   magnitude of these changes under diverse scenarios has not been elucidated.

437

438   ## 6. An empirical model

439

440   The mobilisation of P from crop residues added to soil typically exhibits two distinct phases, with an

441   initial rapid release of labile P in the first weeks after addition (the soluble Pi content), followed by a

442   prolonged phase of slower release of the more recalcitrant organic P species (eg Blair and Boland, 1987;

443   Friesen and Blair, 1988; Umrit and Friesen, 1994). Carbon mineralisation from crop residues has been

444   observed to follow a similar two stage pattern, and two-component exponential decay functions have

445   been widely adopted to describe the decay and nutrient loss from organic residues (eg Grace *et al.*,

446   2006, van Veen *et al.*, 1985), ascribing decay coefficients to the labile and recalcitrant fractions (eg

447   Shammas *et al.*, 2003). This approach was found to adequately describe the mobilisation of P from a

448   range of organic residues with contrasting characteristics when added to soil (Jalali and Ranjbar, 2009).

449   Equation 1 describes the exponential decay function in the model presented, whereby the rate of

450   decomposition is quantified by the decay coefficient (k).

451

452   Equation 1: Exponential decay functions and P release from individual pools

453     $P_t = P_0 \exp^{(-k \cdot t)}$

454

455   P_t = P released at time t (kg ha^{-1})

456   P_0 = initial P content (kg ha^{-1}) of the labile or recalcitrant fraction

457   k = decay constant

458   t = time after residue addition (weeks)

459

460   The soluble component of residue P has a typical residence time of about 4 weeks in residues (eg Blair

461   and Boland, 1987; Friesen and Blair, 1988 (2 weeks); Umrit and Friesen, 1994; Jalali and Ranjbar, 2009)

462   at 25 °C and optimal moisture conditions, which is well fitted by the decay constant of the SOCRATES

463   model (Grace *et al.,* 2006) for the labile component of crop residue C. We therefore allocate the decay

464   constant of 0.29 week^{-1} to vector k_{Pi} (Figure 1) at 25 °C and optimal moisture conditions.

465

466   Mineralisation of C and P has been reported to be well correlated (Cole *et al.*, 1977; Baggie *et al.*, 2004;

467   Bünemann *et al.*, 2004a); hence, the release of the stable component of crop residue P was assumed to

468   occur in parallel with the mineralisation of the stable C component. The decay constant for C

469   mineralisation in the Socrates model (Grace *et al.*, 2006) predicted a half-life of 35 weeks (at 25 °C and

470   optimal moisture) for the stable component. This figure is similar to that reported by Jalali and Ranjbar

471   (2009) for the release of the stable component of P from a range of plant residues in a soil-less system.

472   Hence, we assume the recalcitrant component of residue P will decay according to the decay constant of

473   0.02 week^{-1} at 25 °C and optimal moisture (k_{Po}; Figure 1).

474

475   The microbial biomass is a significant pool of P associated with the decomposition of crop residues in

476   soil, and the dynamics of the pool size have a significant influence on the release of P from residues

477   (Oberson and Joner, 2005; Richardson and Simpson, 2011). The accumulation of soluble residue Pi in the

478   microbial biomass after addition of crop residues to soil (M_{Pm}; Figure 1) was assumed to occur within

479   the first week after addition, at the rate of 1 mg P g^{-1} C substrate applied in crop residues, as described

480   above. The subsequent decay (or longevity) of the microbial biomass during the decomposition of crop

481   residues is largely determined by the quantity of C substrate remaining, but is influenced by the clay

482   content and cation exchange capacity (CEC) of the soil (Amato and Ladd, 1992). For simplicity in this

483   exercise, soil clay properties were not accounted for and the microbial biomass-P was assigned to decay

484   in parallel with the stable P component, since the two pools were adequately described by similar decay

485   constants in the SOCRATES model (Grace *et al.*, 2006). Therefore, k_{Pm} (Figure 1) is equal to k_{Po}, at 0.02

486   week^{-1} at 25 °C and optimal moisture conditions.

487

488   The main effects of temperature and moisture on C mineralisation rates from crop residues in soil have

489   been intensively studied and described, with substantially less advanced developments for P

490   mineralisation. Decay constants were adjusted for the mean annual temperature (18 °C) and

491   precipitation (364 mm) at Cunderdin, in the central wheat belt of WA (31.65° S, 117.24° E) using the

492   multiplicative temperature and moisture factors of the SOCRATES model (Grace *et al.*, 2006). The

493   adjusted decay constants were 0.16, 0.01 and 0.01 for k_{Pi}, k_{Po} and k_{Pm}, respectively. Climate averages for

494   Cunderdin, Western Australia, are comparable to Aleppo, Syria (36°10'N, 37°12'E), and other locations

495   with Mediterranean-type climate (eg. South Africa, parts of Chile, California, etc.).

496

497 The model was applied to the amounts of crop residues and their P characteristics under various

498 scenarios typical of the southern Australian grain cropping region (Table 1), and the amount of P

499 released into soil or assimilated in the proliferating microbial biomass are presented in Table 2.

500 Phosphorus transformations in the short and medium term (Table 2) range from rapid net release of Pi

501 into soil (green manure) to microbial biomass immobilisation of Pi from the soil exchangeable fractions

502 that is sustained up to 1 year (wheat stubble). The predictions support the large variation reported in

503 the literature for Pi released from crop residues under different scenarios (*eg.* Fuller 1956). Model

504 predictions estimated half-lives for the labile P component (4 weeks) and the recalcitrant residue P and

505 microbial biomass components (70 weeks) under average climatic conditions at Cunderdin, Western

506 Australia. Most of the P release from crop residues occurred within 1 year of their application to soil;

507 hence, we propose the model is most relevant over this time-span.

508

509 Model predictions were compared under the contrasting climate scenarios of Los Baños, Philippines

510 (14°10′N 121°13′E) and Harpenden, United Kingdom (51°48′N 0°21′W). Harpenden, the site of

511 Rothamsted Research, has a temperate maritime climate, with a mean temperature of 9.5 °C and mean

512 annual precipitation of 697 mm, which is comparable with the central corn belt of North America. Los

513 Baños, the site of the International Rice Research Institute headquarters, has a tropical marine climate

514 with a mean temperature of 27.1 °C and mean annual precipitation of 1942 mm. At Los Baños, the

515 predicted half-lives of soluble (Pi) and stable (Po) components of residue P were 2 weeks and 21 weeks,

516 respectively, compared to half-lives of 7 weeks and 100 weeks at Harpenden.

517

518 Although typical residue characteristics will differ under contrasting climates, we compared the model

519 predictions for the release of P from the medium-productivity green manure and wheat crops (see Table

520 1) under the contrasting climate scenarios. For the green manure crop, there was rapid release of P

521 under the tropical climate scenario in the first 4 weeks (7.1 kg P ha^{-1}) compared to the temperate

522 climate scenario (1.4 kg P ha^{-1}) (Table 1). However, after 1 year, P release was similar for the tropical and

523   temperate climate scenarios. Predicted P release from the wheat crop residue (Table 1) after 1 year was

524   0.7 kg P ha^{-1} and 0.3 kg P ha^{-1} under the tropical and temperate climate scenarios, respectively, but was

525   similar at 4 weeks. The assimilation of P and its release by the microbial biomass was largely unaffected

526   by climate factors.

527

528   A sensitivity analysis was conducted to assess the robustness of model predictions against variation in

529   the model parameters (Table 3). Model predictions of P release from crop residues were highly sensitive

530   to doubling or halving the parameters for the concentration and speciation of P in the residues, and in

531   the uptake of P by the microbial biomass following residue addition (Table 3). By comparison, doubling

532   or halving the coefficients for decay of the water-soluble and stable components of crop residue P and

533   for microbial biomass P had a smaller effect on P release. The initial P concentration of the crop

534   residues, notably cereal straw or green manure, influenced the sensitivity of the model predictions to

535   other parameters. While predicted P release from cereal straw (0.05 % P) was dramatically influenced by

536   P uptake by the microbial biomass, this parameter had a smaller effect on P release from green manure

537   residue (Table 3).

538

539   The amount of P immobilised by the microbial biomass was the most important parameter in predicting

540   the dynamics of P release from residues, and emphasised the importance of the microbial biomass as a

541   pool of soil P as well as the driver of P mineralisation and organic matter decomposition. Doubling or

542   halving the estimate of 1 mg P taken up by the microbial biomass per gram of C added to soil as wheat

543   straw resulted in model predictions ranging from 30 % of initial P content immobilised to 47 % of initial P

544   content released after 1 year, respectively (Table 3). For a green manure crop, the effect was less

545   significant, but the timing of P release was affected, with 6 % or 27 % of P content released, respectively

546   after 4 weeks if microbial biomass P uptake was doubled or halved. Given the range of reported values

547   in the literature, there is cause for uncertainty over the averaged value applied in the model. For

548   example, in a single soil type, Kwabiah *et al.* (2003) found the amount of P taken up by the microbial

549   biomass to range from less than 1.5 to more than 3 mg P g^{-1} C applied for different organic residues.

550   Microbial biomass P uptake was not correlated with any of the residue characteristics measured. Other

551   studies reported that the microbial biomass took up 0.3 mg P/g C added as cellulose + N, 0.8 mg P/g C

552   added for grass + N (Chauhan *et al.*, 1979), 1.0 mg P/g C added as mature wheat straw or 1.5 mg P/g C

553   added as young wheat residues (Iqbal, 2009). The factors determining variation in the amount of P taken

554   up by the microbial biomass after addition of C substrate is unclear (eg Kwabiah *et al.*, 2003a), but may

555   be related to the fractions and lability of C in residues. Alternatively, Oberson and Joner (2005) make a

556   detailed assessment of the significant methodological problems related to the determination of

557   microbial P in soil, which may account for some of the differences among and even within studies.

558   Notably, they highlight inaccuracies associated with predicting total microbial biomass P from the

559   proportional amount that is extracted and measured (by application of K_p factors). The significant

560   influence of soil type and microbial community composition on the proportion of microbial biomass P

561   that is released by cell lysis and extracted from soil can lead to significant differences in the estimation

562   of microbial P in soil. Given the range of reported values, and the impact on model predictions, there is

563   certainly cause for further elucidation of P uptake by the microbial biomass following the addition of

564   crop residues to soil.

565

566

567   ## 7. Concluding remarks

568   The body of literature as well as our modelling confirm that the contribution of crop residues to P

569   availability is likely to be significant only under conditions where large amounts of crop residues with

570   relatively high P concentration are applied to soil. Crop residues with low P concentration, such as cereal

571   stubble (eg. due to re-translocation of a large proportion of stubble P into grain), will not make an

572   agronomically significant contribution to soil P availability either in the short or long term. However, a

573   productive green manure crop may release sufficient P to meet the requirements of a subsequent cash

574   crop.

575

576   Much research and discussion has been devoted towards developing productive low-input farming

577   systems. However, the consensus of the works discussed in this review is that the organic cycling of P is

578   intricately linked with the inherent productivity of the site, including climate. The release of P from crop

579   residues is significantly reduced in systems where the P-status of crops and soils is low, compared to

580   where it is high (*eg*. Blair and Boland, 1987). In fact, addition of crop residues to soil in low-P systems

581   can stimulate the uptake and immobilisation of significant amounts of soil P by the microbial biomass

582   (*eg*. Bünemann *et al.*, 2012), reinforcing the reliance on P inputs for sustained crop productivity. Whilst

583   the most significant management option impacting the biological cycling of P is a green manure

584   rotation, one must consider whether there is any net benefit to the P nutrition of a subsequent crop if P

585   is mined from the exchangeable fractions and subsequently returned to those fractions after cycling

586   through the microbial biomass in the following cropping rotation. Any P benefit may relate to the

587   capacity of the manure crop to scavenge or solubilise pools of P that are otherwise unavailable to the

588   cash crop.

589

590   The literature review and modelling have identified key areas of knowledge gaps that should be

591   prioritised for further elucidation. Notably, P release from crop residues is strongly influenced by the

592   concentration and speciation of P in the residues, as well as by the uptake of P by the microbial biomass

593   following residue addition. However, a wide range in values has been reported for these key

594   parameters, and the factors that determine them remain poorly elucidated. Soil pH and tillage practices

595   are both known to influence organic matter mineralisation rates in soil, but empirical data relating to

596   their impact on P release from crop residues are lacking. Although burning crop residues is a common

597   practice in many farming systems, there is currently little information on the effect of burning on soil P

598   availability. We envisage that future elucidation of the identified knowledge gaps will increase our

599   capacity to estimate P release from crop residues and will consolidate the model presented here,

600   enhancing its capacity to accurately predict the contribution of crop residue P to soil P availability.

601

602   This review has not addressed the capacity for P supply from organic sources other than crop residues.

603   Indeed, there is a requirement for crop models to take into account the P supply to crops from a variety

604   of sources, including composts, animal manures (*eg*. APSIM Manure; Probert *et al*., 2004), green

605   manures and mineral fertilisers as we move towards more sustainable sources for managing the P

606   nutrition of cropping systems (Palm *et al.*, 1997).

607

608   Of the identified opportunities to enhance the efficient cycling of P in cropping systems, the potentially

609   most readily manipulated is reducing P loading into grain with greater retention of P in crop residues;

610   its feasibility, at least, warrants investigation. The long-term, cumulative effect of repeated cropping

611   cycles where high-P residues are returned to soil may lead to a significant accumulation of organically-

612   cycled P and reduced requirement for fertiliser P inputs.

613

614   We propose that the work described here i) presents a basis for estimating the contribution of crop

615   residues to soil P availability to a subsequent crop, and ii) acts as a template for further research to

616   identify priority aspects of organic P cycling for elucidation.

617

623

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891

892 Table 1: Typical biomass and P content of post harvest residue of common crops under low, medium

893 (med) and high productivity scenarios in the southern Australian grain cropping region. The values

894 presented are referenced from survey data for multiple sites and seasons where available, and values

895 representing consensus in the literature where survey data was unavailable.

896 Extreme values were omitted hence the range of possible scenarios will extend beyond the "high" and

897 "low" productivity scenarios depicted.

	Green manure			wheat stubble			legume stubble			canola stubble		
	low	med	high	low	med	high	low	med	high	low	med	high
Residue biomass (t ha^{-1}) *,[a]												
	2.4	4.8	7.2	1.8	3.6	5.4	2.1	5.4	7.2	1.8	4.2	5.4
Residue P concentration (kg t^{-1})												
	1[b]	3[b]	4[b]	0.2[c]	0.5[c]	1[c]	0.2[d]	0.5[d]	1.2[d]	0.5[e]	0.7[e]	1.1[d]
Residue P amount (kg ha^{-1})												
	2.4	14	30	0.4	1.8	5.4	1.1	2.7	7.2	0.9	2.9	5.4
Soluble Pi (% of total P)**												
	70	70	80	50	50	50	50	50	50	50	50	50

898 *Based on average yield expectation and average harvest index, includes roots at a root:shoot ratio = 0.2

899 after grain export (Jackson et al., 1996)

900 **Estimates of soluble Pi in crop residues are averaged values were derived from various sources and

901 described in detail in 'Amount and fractions of P in crop residues', above. (Chang, 1939; Kaila, 1949;

902 Birch, 1961; Jones and Bromfield, 1969; Bromfield and Jones, 1972; White and Ayoub, 1983; Friesen and

903 Blair, 1988; Ha et al., 2008; Noack et al., 2012).

904 a. Jackson et al. (1996); b. Reuter and Robinson (1997); c. Schultz and French (1976); d. Schultz and

905 French (1978); e. Rose et al. (2008) and Bill Bowden, unpublished data.

906

907

Table 2: Model predictions of the fate of crop residue P from common crops under low, medium (med) and high productivity scenarios in the southern Australian grain cropping region. Model predictions are based on the typical crop biomass and P content scenarios described in Table 1 and adjusted for mean temperature and precipitation at Cunderdin, in the central wheatbelt of Western Australia (31.65° S, 117.24° E). Transformations after 4 weeks and 1 year depict the half-life of the soluble component of crop residue P and the term of an annual crop rotation, respectively.

	Green manure			wheat stubble			legume stubble			canola stubble		
	low	med	high	low	med	high	low	med	high	low	med	high
P release after 4 weeks (kg ha^{-1})												
	-0.2	2.9	6.8	-0.7	-1.1	-0.9	-0.7	-1.6	-1.3	-0.5	-1.1	-0.9
Δ microbial biomass P after 4 weeks (kg ha^{-1})												
	1.0	2.1	3.1	0.8	1.6	2.3	0.8	2.3	3.1	0.8	1.8	2.3
P release 1 year (kg ha^{-1})												
	1.3	11	22	-0.2	0.3	2.3	-0.2	0.4	3.1	0.2	0.9	2.4
Δ microbial biomass P after 1 year (kg ha^{-1})												
	0.6	1.3	1.9	0.5	1.0	1.4	0.5	1.4	1.9	0.5	1.1	1.4

Negative values of P release = microbial biomass immobilisation of Pi from the exchangeable soil Pi pool.

Table 3: The effect of halving (x0.5) or doubling (x2) model parameters on the predicted release/immobilisation of P from crop residues after 4 weeks and 1 year of decomposition. Two contrasting crop residues: a mediu- productivity wheat stubble and a medium-productivity green manure crop (described in Table 1) are presented. The sensitivity to soluble Pi content was assessed at 20 % or 80 % of the total P content. Values represent the percentage of the initial P content of the crop residue, with negative values representing immobilisation of soil Pi.

	P concentration (mg g dry weight^{-1})		Soluble Pi (% of total P)		P uptake by microbial biomass (M_{Pm})		decay constant soluble Pi (k_{Pi})		decay constant stable Po (k_{Po})		decay constant microbial biomass (k_{Pm})	
	x0.5	x2	20	80	x0.5	x2	x0.5	x2	x0.5	x2	x0.5	x2
Green manure (3 kg P t^{-1})												
4 weeks	4	27	-1.0	24	27	5.6	6.1	38	19	21	20	21
1 year	43	79	46	80	79	66	74	75	69	82	72	78
Wheat straw (0.5 kg P t^{-1})												
4 weeks	-147	-18	-74	-48	-18	-147	-70	-48	-62	-58	-62	-57
1 year	-30	47	3	38	47	-30	20	22	12	33	3	43