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Higher flexibility in input N:P ratios results in more balanced phosphorus budgets in two long-term experimental agroecosystems

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ABSTRACT

Inefficient phosphorus (P) use in intensive agriculture is common in both organic and conventional systems, resulting in P over-application and soil P build-up. Increasing crop P removal and P recycling within farming systems (e.g., via cover crops) and reducing P inputs lower P surpluses, resulting in more balanced P budgets. Lowering P inputs to reduce soil P surpluses is easier with mineral fertilizers for which nitrogen (N) and P inputs can be decoupled, whereas reducing inputs of organic amendments with a constrained N:P stoichiometry (manures, composts) often results in N under-fertilization and lower yields. We computed farm-gate P budgets for several vegetable and grain cropping systems in two long-term California agricultural experiments that vary in terms of inputs (mineral fertilizers, organic fertilizers, manure, yard compost), cash crops (corn, wheat, tomato, broccoli, lettuce), cover crops (type, frequency) and cropping intensity (biennially, annually or biannually). In organic systems, using manure or compost resulted in high P surpluses, whereas using pelleted or liquid organic fertilizers with higher N:P ratios resulted in smaller P surpluses. Systems receiving mineral fertilizers were often very close to P balance when fertilized regularly. Grain rotations generally had small P deficits whereas vegetable rotations had P surpluses due to lower crop P removal and higher output N:P in vegetables. Phosphorus uptake by cover crops was important (12–25 kg P ha^{-1}), but their benefits to soil fertility will depend on the magnitude and timing of P release during residue decomposition. Overall, using organic nutrient sources with a constrained stoichiometry and low N:P ratios resulted in significant P surpluses, confirming the need to use complementary N sources such as N-fixation or N-rich fertilizers to balance P budgets.

1. Introduction

Phosphorus (P) is an important nutrient in agriculture and a major driver of downstream eutrophication (Goulding et al., 2008; Kleinman et al., 2011). Because atmospheric and weathering inputs of P are insufficient to replace soil P removed by harvest, external inputs of P are required to maintain soil fertility and yields, although only a small fraction of P inputs is taken up by crops (Goulding et al., 2008). Consequently, excess P accumulates in soils or is lost via erosion, runoff and leaching, resulting in low P use efficiency (PUE), downstream eutrophication, and the need to better match P inputs and outputs (McLaughlin et al., 2011).

The removal of P by crops varies with crop type and yields – yields typically have a stronger effect than plant P concentration on P export for a given crop (Zhang et al., 2013) – and this affects optimal P input rates and P budgets significantly (Nelson and Janke, 2007; Nesme et al., 2012). Phosphorus uptake efficiency also affects P budgets, as the gap between P application rates that maintain a balanced P budget vs. those that maximize yields can be large, resulting in excessive P fertilization for plants with low P uptake efficiency, e.g., in lettuce (Johnstone et al., 2005). Ultimately, crops with higher yields – e.g., corn (Nelson and Janke, 2007) – or with higher plant P concentration in harvested products – e.g., canola, flax (Nesme et al., 2012) – increase P export and require larger P inputs to maintain soil P availability. Therefore, systems that are under-fertilized may benefit from crops with a low P export – e.g., those that produce more biomass per unit of P uptake (Richardson et al., 2011) –, whereas crops with a high P export can lower P surpluses and soil P levels in over-fertilized

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systems (Li et al., 2011). Thus, the optimal level of crop P removal will depend on management systems and soil P status.

Variations in nitrogen (N) requirements among crops also affect optimal P input rates, as the N:P ratio of crop export affects the N:P ratio of inputs required to balance nutrient inputs and outputs (Nelson and Janke, 2007). Crops with low external N requirements – e.g., N-fixing legumes (Vance, 2001) – allow farmers to use greater quantities of inputs with a low N:P ratio, such as organic amendments (composts and manures) that are often enriched in P relative to N with respect to plant needs (Kleinman and Sharpley, 2003). However, fertilizing exclusively with composts or manures to meet plant N demand often results in P over-fertilization (Sims et al., 2000; Eghball, 2002), saturation of the soil P sorption capacity (Maltais-Landry et al., 2015), and low PUE (Bergstrom et al., 2008) due to low input N:P ratios. Reducing application rates can reduce P over-fertilization, but this may result in insufficient N supply, crop N-deficiency and lower yields (Berry et al., 2002; Kleinman and Sharpley, 2003). Furthermore, P availability is typically lower in organic amendments compared to mineral or processed organic fertilizers (e.g., feather meal) due to a lower P concentration, higher carbon (C) to P ratios, and higher proportion of organic P that must be mineralized prior to plant uptake (Hartz et al., 2000; Frossard et al., 2002; McLaughlin et al., 2011; Takahashi, 2013). Hence, determining input rates of organic amendments that provide adequate N and P crop nutrition while balancing P budgets and minimizing environmental degradation remains a challenge (Kleinman et al., 2011).

Optimizing P input rates is further complicated by variations in soil properties, especially soil P sorption capacity (Simpson et al., 2011) and soil P availability (Kleinman et al., 2011). As a result, P inputs lower than crop removal may be recommended to minimize P losses in soils that have a low sorption capacity and a high soil P availability, whereas soils that are P-depleted or have a high P-fixing capacity may require inputs that exceed outputs to supply sufficient P to crops (Horst et al., 2001; Li et al., 2011).

Increasing P recycling within individual farms may also increase the fraction of P inputs that is recovered in crops and lower the need for external inputs (Simpson et al., 2011). Cover crops – crops grown primarily for soil incorporation rather than harvest – can increase internal P recycling via soil P mobilization (Horst et al.,

Table 1

Selected properties of the three study systems: Russell Ranch Irrigated (RR-Irr), Russell Ranch Rainfed (RR-Rain, where L(O)CC = legume or legume-oat cover crops) and Salinas Organic Cropping Systems (SOCS).

Experiment	Years	Crops[a]	System		Compost	Cover crops		External inputs (average for whole experiment)[j]		
			Name	Code		Frequency	Type	N $\text{kg ha}^{-1}\text{yr}^{-1}$	P	Source
RR-Irr	1994–2011	Grain/ Tomatoes[b, c]	Organic Corn–Tomato	OrgCT	Yes	Every year[e]	Peas–Vetch/Vetch–Fava bean–Oats[f]	135	101	Composted poultry manure
			Mixed Corn–Tomato	MixCT	No	Every other year[e]	Peas–Vetch/Vetch–Fava bean–Oats[f]	75	14[k]	Mineral fertilizers
			Conventional Corn–Tomato	ConvCT	No		None	184	23[k]	Mineral fertilizers
			Conventional Wheat–Tomato	ConvWT	No		None	165	14[k]	Mineral fertilizers
RR-Rain	1994–2011	Wheat/ Fallow[d]	Rainfed Wheat Control	RWCont	No		None	0	3[k]	None
			Rainfed Wheat Fertilized	RWFert	No		None	56	3[k]	Mineral fertilizers
			Rainfed Wheat with L(O)CC	RWLeg	No	Every other year	Peas-Vetch/Vetch-Fava bean-Oats[f]	0	3[k]	None
SOCS	2003–2011	Lettuce/ Broccoli	Control		No	Every 4th year	Peas-Vetch-Fava bean-Rye[g]	204	30	Chicken manure, feather meal, liquid fertilizers[l]
			Compost		Yes	Every 4th year	Peas-Vetch-Fava bean-Rye[g]	435	67	Chicken manure, feather meal, liquid fertilizers, yard compost[l]
			Legume-rye		Yes	Every year	Peas-Vetch-Fava bean-Rye[g]	435	67	Chicken manure, feather meal, liquid fertilizers, yard compost[l]
			Mustard		Yes	Every year	Mustard mix[h]	435	67	Chicken manure, feather meal, liquid fertilizers, yard compost[l]
			Rye		Yes	Every year	Rye[i]	435	67	Chicken manure, feather meal, liquid fertilizers, yard compost[l]

[a] One crop per year in RR, two per year in SOCS.

[b] Grains: corn (1994–2007), sorghum summer cover crop (2008–2009) or wheat (2010–2011).

[c] Varieties: corn (NC4616 (1994–2002, mixed/organic), Pioneer 3162 (1994–2002, conventional), ST7570 (2003–2007, all)); wheat (Yolo (1994–2002), Summit (2003–2005), Cal Rojo (2006–2011));tomato (Hailey 3155 (1994–2004), Heinz 9780 (2005–2011)).

[d] Varieties: Serra (1994–2002), Summit (2003–2005) and Cal Rojo (2006–2011).

[e] Every year until 2009 or only before tomato (2010–2011) for organic; for mixed: only before maize (1994–2004) or tomato (2010–2011), or every year (2004–2009).

[f] Peas (87.0 kg seed ha^{-1}) and vetch (47.4 kg seed ha^{-1}) for 1994–2005 (100% legumes) and vetch (22.4 kg seed ha^{-1}), fava bean (89.6 kg seed ha^{-1}) and oat (28.0 kg seed ha^{-1}) for 2006–2011 (80% legumes and 20% oat).

[g] Seeding rates: Rye (42 kg seed ha^{-1}), fava bean (147 kg seed ha^{-1}), 'Magnus' Pea (105 kg seed ha^{-1}), common vetch (63 kg seed ha^{-1}), and purple vetch (63 kg seed ha^{-1}).

[h] Mixture of *Sinapis alba* (6.7 kg seed ha^{-1}) and *Brassica juncea* (4.3 kg seed ha^{-1}).

[i] Seeding rate: 90 kg seed ha^{-1}.

[j] Only including fertilizers and composts, i.e. excluding inputs from N-fixation (75 $\text{kg N ha}^{-1}\text{yr}^{-1}$ in RR, 67 $\text{kg N ha}^{-1}\text{yr}^{-1}$ in SOCS when legume cover crops are grown) and seeds/transplants.

[k] Includes a one-time 49 kg P ha^{-1} application in 1999.

[l] $N–P_2O_5–K_2O$: chicken manure/feather meal (4–4–2 before 2007, 8–1–1 afterwards), liquid fertilizers (2.5–2–1.5 in 2005–2006, 6–2–0 in 2007–2008, 5–1–1 afterwards).

2001) and by taking up P in their biomass that will be released during residue decomposition (Cavigelli and Thien, 2003; Damon et al., 2014). In addition, because legume cover crops can add large amounts of N via N-fixation (Vance, 2001), they increase the N:P ratio of inputs, allowing for organic inputs to be used at higher rates without leading to P surpluses. Therefore, cover crops could increase PUE, directly and indirectly via their effects on N, thereby helping to balance P budgets in agroecosystems.

The overall objective of this study was to evaluate the long-term impact of different management systems on P balance, N:P stoichiometry, and PUE in California agroecosystems. We computed farm-gate P budgets in two long-term experiments by quantifying inputs (fertilizers, manures, composts, crop seeds/transplants) and outputs via crop removal (Oehl et al., 2002; Cao et al., 2012) to determine the effects of: 1. Fertility sources, i.e., organic amendments (manure, compost) with low N:P compared to high N:P fertilizers (processed organic, mineral), 2. Cash crops, i.e., grain (wheat, corn) or vegetables (tomato, lettuce, broccoli) with variable crop removal N:P ratios, and 3. Cover crops (frequency and type), including N-fixing legumes.

These two long-term experiments allowed us to evaluate the cumulative effects of factors that may have a small annual effect, such as cover crops, because the small annual signal of these factors (e.g., P mineralization from residues) relative to background values (e.g., soil P pools) is easier to identify when annual values are added to compute cumulative fluxes. In addition, we compared grain and vegetable crops directly, which is unique in long-term experiments in North America. Finally, consistent data acquisition protocols and the availability of archived samples to compute system-specific fluxes in these long-term studies reduce the need to rely on assumptions and literature values, allowing for a more accurate estimation of P fluxes.

2. Materials and methods

2.1. Russell Ranch Sustainable Agricultural Facility (RR)—Davis (California, USA)

RR (established in 1993) compares agricultural systems rather than individual factors, and it does not have a fully factorial design. This approach allows to optimize individual systems to maximize their performance and reach their full potential, reducing the bias when comparing agroecosystems that vary in management—e.g., cultivars, nutrient inputs. However, it is harder to isolate the contribution of a single factor across systems, and these experiments are often more difficult to describe—see Denison et al. (2004) for more information on RR.

In RR, we focused our study on two experiments with multiple systems: 1. Four irrigated two-year grain-tomato systems (RR-Irr) supplied with variable P, and 2. Three two-year rainfed wheat systems (RR-Rain) that were usually not fertilized with P (Table 1). The crops grown in these experiments (tomato, wheat and corn) are major crops in the Central Valley of California. We used data from six 0.4 ha plots per system (total: 42 plots) that were randomly allocated across two similar soil types: Yolo silt loam (fine-silty, mixed nonacid, thermic Typic Xerothents) and Rincon silty clay loam (fine, montmorillonitic, thermic Mollic Haploxeralfs). Legume or legume-oat cover crops (L(O)CC), grown in three systems during the winter (October–March), consisted of hairy vetch (*Vicia dasycarpa*) and 'Magnus' pea (*Pisum sativum*) in 1994–2005, and fava bean (*Vicia faba*), hairy vetch and 'Montezuma' oat (*Avena sativa*) in 2006–2011 (Table 1).

RR-Irr systems were either under conventional (mineral fertilizers only), mixed (mineral fertilizers with L(O)CC) or certified organic (manure with L(O)CC) management (Table 1), and nutrient management was based on crop N requirements (see below for details). Three RR-Irr systems consisted of a tomato (*Solanum lycopersicum*) and corn (*Zea mays*) rotation—organic corn-tomato (OrgCT), conventional corn-tomato (ConvCT), and mixed corn-tomato (MixCT). The fourth system was a winter wheat (*Triticum aestivum*) and tomato rotation—conventional wheat-tomato (ConvWT). For the corn-tomato rotations, the grain grown varied as follows: corn (1994–2007), a summer sorghum cover crop (2008–2009—*Sorghum bicolor*) or winter wheat (2010–2011). A fallow replaced sorghum in 2008 in ConvCT, whereas a fallow replaced both tomato and sorghum (but not cover crops) in MixCT in 2008. In ConvWT, tomato alternated with wheat from 1994 until 2011. Corn, wheat and tomato varieties changed among systems and years during the study period (Table 1).

Each RR-Irr system had six replicate plots (three under grain and three under tomato in any given year), and N input rates and forms varied among systems. Nitrogen inputs were lowest in MixCT (mineral fertilizers applied only before tomato in 1994–2008 and before tomato and grain in 2009–2011) because the goal of this system is to replace a fraction of N fertilizers with N-fixation from L(O)CC. Nitrogen fertilization was intermediate in OrgCT because a fraction of its N inputs was designed to come from N-fixation via L(O)CC, and N in the composted poultry manure applied (1.83% N, 1.37% P) is only partially plant-available. The systems that received mineral fertilizers before every crop (ConvCT and ConvWT) had the highest N fertilization rates. N-fixation inputs of L(O)CC – estimated as 75 kg N ha^{-1} yr^{-1} in years when L(O)CC were grown (J. Six, unpublished data) – are not explicitly included in N fertilization rates, although including N-fixation inputs would make total N inputs in OrgCT larger than in conventional systems. The OrgCT system was cover-cropped every year until 2009 and only before tomatoes afterwards, whereas cover crops were grown only before corn (1994–2004) or tomatoes (2010–2011), or every year (2004–2009) in the MixCT system. ConvCT and ConvWT were never cover-cropped.

RR-Rain systems (six plots per system) varied based on N input rates and forms: a wheat-fallow system fertilized with mineral fertilizers at a rate of 112 kg N ha^{-1} biennially (Rainfed Wheat Fertilized—RWFert), a wheat-fallow system not fertilized with N (Rainfed Wheat Control—RWCont), or a wheat-L(O)CC system receiving an estimated 75 kg N ha^{-1} yr^{-1} via N-fixation biennially (Rainfed Wheat L(O)CC—RWLeg). In each of these systems, three plots were in wheat and three in fallow or L(O)CC in any given year (Table 1). Besides seeds, no P was added except in 1999 when 49 kg P ha^{-1} were added to all plots (Table 1). Wheat varieties changed during the experiment and L(O)CC – same mixtures as RR-Irr – were grown during the fallow years of RWLeg only.

The RR systems allowed us to compare the effects of crop rotations on P budgets – grain-vegetable in RR-Irr vs. pure grain in RR-Rain – whereas the fixed crop rotation in RR-Irr allowed us to determine how input type (manure vs. mineral fertilizer) affected P budgets. Input type was the main difference between organic and conventional nutrient management in these systems, whereas other differences among these systems (e.g., pest control) should have a small impact on P budgets. Finally, the RR-Rain systems were useful to identify the effects of cover crops on P budgets because other management factors (except N fertilization) did not vary among RR-Rain systems.

2.2. Salinas Organic Cropping Systems (SOCS) – Salinas (California, USA)

All SOCS plots (established in 2003) were under certified organic double-cropping production of lettuce (*Lactuca sativa*) and broccoli (*Brassica oleracea*—Table 1), a typical rotation in the Salinas Valley of California (Brennan and Boyd, 2012a). In 2004, spinach (*Spinacia oleracea*) was grown instead of broccoli, and only lettuce was grown in 2011. The SOCS experiment is under tillage-intensive management that is typical for farms in this region. We used five systems for this experiment (Table 1), with four replicate plots per system established on a common soil: Chualar loamy sand (fine-loamy, mixed, superactive, thermic Typic Argixerol). All systems were fertilized equally during the production of vegetables with pre-plant organic pelleted chicken manure, feather meal and liquid organic fertilizers of plant or fish origin. Yard compost (7.6 Mg ha^{-1}, C/N ~ 22, 1.5% N, 0.25% P) was added to four of the five systems before each cash crop to provide organic matter—see Brennan and Boyd (2012a) for details.

Cover-cropping frequency – every winter or every fourth winter from October/November until February/March – and species composition varied among systems: pure ‘Merced’ rye (*Secale cereale*), a mustard mixture of ‘Ida Gold’ white mustard (*Sinapis alba*) and ‘Pacific Gold’ Indian mustard (*Brassica juncea*), or a mixture of rye, fava bean, ‘Magnus’ Pea, common vetch (*Vicia sativa*), and purple vetch (*Vicia benghalensis*) thereafter referred to as the legume-rye mixture (Table 1). Seeds of the legume-rye mixture were mixed together with appropriate *Rhizobium* inoculants (Brennan and Boyd, 2012a) and planted simultaneously. We estimated that cover crops fixed 67 kg N ha^{-1} each time the legume-rye mixture was grown, based on computations detailed in Brennan and Boyd (2012b). The five systems we used are the ‘control’ system with no yard compost and legume-rye cover crops every 4th year, and four systems that received yard compost before each vegetable crop and had variable cover-cropping management: ‘compost’ (legume-rye cover crops every 4th year), rye cover crop annually, mustard cover crop annually, and legume-rye cover crops annually.

The SOCS systems complement the RR systems via a vegetable-only crop rotation and variable cover-cropping type and frequency among systems. Furthermore, we were able to quantify the effects of yard compost and processed organic fertilizers on P budgets by comparing the control system to other systems receiving compost.

2.3. Quantification of inputs

In each system, we quantified P added via fertilizers, manure, compost, plant seeds, and transplants (plants and soil). We used manufacturer-specified N and P concentrations for fertilizers, and measured P concentration (expressed on a dry weight basis) in manure, composts, plants and soils using digestion with sulfuric acid (H_2SO_4) and peroxide (H_2O_2), followed by P determination using the ascorbic acid method (Thomas et al., 1967). Briefly, 50 mg of material were mixed with 5 mL of H_2SO_4, 1 mL H_2O_2 was added and the mixture was heated at 360 °C. Additions of H_2O_2 were repeated until color in the sample disappeared. Phosphorus concentration was estimated rather than measured when samples were unavailable for analysis: sorghum seed %P (assumed to be identical to corn), spinach seed %P (assumed to be 0.5% P) and %P in tomato transplants (assumed to be equal to the mean of lettuce and broccoli transplants, but applied to a larger seedling and soil weight). Nitrogen concentration was determined for manure and compost by flash combustion followed by quantification using a thermal conductivity detector (CNS analyzer model NA 1500, Carlo Erba, Italy), in which tin capsules filled with dried material are combusted at 1050 °C.

We report inputs as kg P ha^{-1} yr^{-1} by rotation in all systems. Because RR systems are two-year rotations, mean annual inputs from manures, fertilizers, seeds and transplants for a given system are calculated by averaging inputs for the grain and the tomato phase in RR-Irr systems, or by averaging inputs for the wheat and fallow phase in RR-Rain. Because SOCS systems double-crop lettuce and broccoli with variable cover-cropping frequency, mean annual inputs from compost, organic fertilizers and transplants (lettuce, broccoli) are the sum of inputs for the lettuce and broccoli phase. Phosphorus inputs for cover crop seeds are either equal to the annual input rates for systems cover-cropped annually (rye, mustard, legume-rye) or inputs for the legume-rye mixture divided by four for systems cover-cropped every 4th year (compost, control).

In RR-Irr, P inputs varied across systems, rotations, and years. We present the range of inter-annual variability for each rotation and system resulting from differences in application/seeding rates and P content—inputs were identical for replicate plots of a given system-rotation-year combination. Composted poultry manure added 50–114 kg P ha^{-1} yr^{-1} (tomato) or 163–300 kg P ha^{-1} yr^{-1} (corn) to OrgCT in 1994–1998 when manure inputs targeted crop N requirements, 78–115 kg P ha^{-1} yr^{-1} (tomato, corn, sorghum summer cover crop) in 1999–2007 and 2009–2011 when manure inputs were reduced to limit P over-fertilization, or no P (wheat, 2008). In ConvCT and ConvWT, mineral fertilizers ($N–P_2O_5–K_2O$: 15–15–15) provided 22 kg P ha^{-1} yr^{-1} (corn, tomato) or no P (wheat, 2008 fallow) whereas in MixCT, 22 kg P ha^{-1} yr^{-1} (tomato) or no P (corn, wheat, 2008) was applied. ConvCT, ConvWT and MixCT received an additional 49 kg P ha^{-1} from fertilizers in 1999. Phosphorus was also added to RR-Irr systems via seeds (0.13–0.18 kg P ha^{-1} yr^{-1} for corn, 0.42 kg P ha^{-1} yr^{-1} for wheat, 0.21–0.23 kg P ha^{-1} yr^{-1} for sorghum, 0.59–0.65 kg P ha^{-1} yr^{-1} for cover crops) and tomato transplants (0.63–0.77 kg P ha^{-1} yr^{-1}).

Wheat seeds added 0.35–0.42 kg P ha^{-1} yr^{-1} in all RR-Rain systems, and cover crop seeds added P in RWLeg at a similar rate as in RR-Irr. All RR-Rain systems received 49 kg P ha^{-1} from mineral fertilizers in 1999.

In SOCS, P fertilization of cash crops was identical among systems but decreased from 28 to 4 kg P ha^{-1} yr^{-1} for lettuce production and from 26 to 10 kg P ha^{-1} yr^{-1} for broccoli production during the experiment. This was the result of using fertilizers with a higher N concentration at the end of the experiment compared to 2003 (all $N–P_2O_5–K_2O$), from 4–4–2 to 8–1–1 (pelleted chicken manure and feather meal) and from 2.5–2–1.5 to 5–1–1 (liquid organic fertilizers). In contrast, N supply was kept relatively constant among years and identical among systems in any given year: 22 kg N ha^{-1} yr^{-1} for spinach, 56–74 kg N ha^{-1} yr^{-1} for lettuce or 134–170 kg N ha^{-1} yr^{-1} for broccoli. Yard compost was added at identical rates among the four systems that received it, providing 37.8 kg P ha^{-1} yr^{-1}. Seeds supplied 0.4 kg P ha^{-1} yr^{-1} (spinach), 0.42 kg P ha^{-1} yr^{-1} (rye), 0.09 kg P ha^{-1} yr^{-1} (mustard) or 1.93 kg P ha^{-1} yr^{-1} (legume-rye) whereas transplants added 0.32 kg P ha^{-1} yr^{-1} (lettuce) and 0.65 kg P ha^{-1} yr^{-1} (broccoli).

2.4. Quantification of outputs

In RR, we determined total P concentration (expressed on a plant dry weight basis) in harvested grain, fruit or leaves using $H_2SO_4–H_2O_2$ digestion, and combined total P concentration with dry yields determined by mechanical harvest to quantify P removal. We did not measure root P concentration or biomass as roots were not exported and were not a P output. For corn and tomato in 1994–2008, P concentration was estimated with a 2% acetic acid extraction (UC-Davis analytical lab, QuikChem method 12-115-01-1-C). We converted these values into total P with conversion factors: 1.107 times acetic acid P in corn ($R^2 = 0.85$, $p < 0.001$, $n = 15$) and 1.047 acetic acid P in tomato ($R^2 = 0.92$, $p < 0.001$, $n = 20$). Conversion factors were computed with a subset of samples that spanned the range of P reported across systems. In 2009–2011, we measured total P concentration directly for tomato. For wheat, we measured total P concentration in eight years (1994, 1999, 2002, 2003, 2004, 2008, 2010, 2011) for each system, spanning the range in varieties grown and yields. We used the average total P concentration during these eight years to estimate P concentration for years not measured in this subset.

In SOCS, we converted the total cash crop dry biomass into yields with harvest indices of 0.26 computed for lettuce in this system (E. Brennan, unpublished data) and 0.24 reported for broccoli grown in the region (R. Smith, unpublished data). The harvest index of lettuce was lower than expected – 0.49 to 0.70 (R. Smith and E. Brennan, unpublished data) – as the density in SOCS targeted romaine heads whereas romaine hearts (inner part of the head) were harvested for most of the field, resulting in lower biomass export. Spinach and broccoli biomass was incorporated into the soil rather than harvested in 2004 and 2005 because pests made crops unmarketable. Phosphorus concentration was measured in total biomass for all years and in broccoli crowns for 2005 (when crowns were incorporated into the soil) using nitric acid/hydrogen peroxide microwave digestion followed by quantification via Inductively Coupled Plasma Atomic Emission Spectrometry (UC-Davis analytical lab, Method 590). We used P concentration measured in total biomass (expressed on a plant dry weight basis) directly for all years because the crown data were only available for one year (2005) that was not representative of growing conditions experienced during the majority of the experiment.

2.5. Phosphorus balance and other metrics of phosphorus use

We computed P budgets for individual plots with inputs and outputs specific to each year and each cropping cycle, and we averaged input, output and P balance values among the plots under the same conditions in a given year for presentation. Cumulative P balances – 1994–2011 (RR) or 2003–2011 (SOCS) – were also computed. We computed a separate budget for SOCS to estimate the upper boundary of P removal, using a harvest index of 0.7 for lettuce (if heads had been harvested rather than hearts) and broccoli P concentration 1.57 times larger (using the 2005 broccoli crown data to compute a conversion factor).

We computed PUE using inputs from fertilizers, manures and composts via the “partial factor productivity” method (McLaughlin et al., 2011):

$$\text{PUE} = \text{Yield}/\text{P inputs}$$

where PUE is in kg yield kg^{-1} P, and dry yields and inputs are in kg ha^{-1} yr^{-1}. We computed fertilizer recovery in crops ($P_{recovery}$), or PUE via the “balance” method (McLaughlin et al., 2011):

$$P_{recovery} = \text{P uptake}/\text{P inputs}$$

where $P_{recovery}$ is a percentage, and P uptake and inputs are in kg P ha^{-1} yr^{-1}. For individual crops, we computed annual PUE and $P_{recovery}$ only for years when P inputs were added or yields removed. Because many systems were fertilized during only one crop or had inputs with no crop removed, we computed cumulative PUE and $P_{recovery}$ using cumulative yields, P removal and inputs during the whole study period, which aggregates yields, P uptake and P inputs from multiple crops. Combining data from crops with different yields and P uptake dynamics has its limitations, but this allowed us to quantify the overall PUE and $P_{recovery}$ for each system independently of differences in P applications among different crops in rotation. We also computed N:P ratios for inputs (fertilizers, manures, composts) and outputs in each plot, both on an annual basis and using cumulative N and P additions.

The methods used to determine PUE and $P_{recovery}$ in this study are less accurate than direct methods (e.g., using P isotopes) for within-year PUE because they do not control for the contribution of soil P and often overestimate annual PUE (McLaughlin et al., 2011). However, direct methods do not account for nutrients added in one year and utilized in subsequent years, although P inputs are not fully taken up by crops in the year following application, especially manures and composts that must be mineralized prior to plant uptake. Therefore, the PUE and $P_{recovery}$ definitions used in this study are relevant for long-term comparisons established on the same soil, especially when comparing fertility sources with a variable nutrient release rate.

2.6. Cover crop phosphorus cycling

Cover crop P uptake in RR was estimated with dry biomass measured by mechanical harvest and P concentration (expressed on a plant dry weight basis) measured in composited samples via H_2SO_4-H_2O_2 digestion on a subset of years (1994, 1997, 1998, 1999, 2004, 2005, 2008, 2010) representative of the different mixtures and growing conditions experienced. We used the average P concentration during these eight years to estimate P concentration in years not measured, using P concentration specific to each system, mixture and cropping cycle (before corn or tomato).

Dry cover crop biomass in SOCS was measured annually using the method outlined in Brennan and Boyd (2012a) and P concentration (expressed on a plant dry weight basis) was measured via H_2SO_4–H_2O_2 digestion for rye and composited samples of legumes or mustards for the two years with available archived samples (2008, 2009). Plot-level P concentration was computed in the legume-rye system using a biomass-weighted average based on the percent of total biomass found in legumes or rye. We used the average P concentration to determine P concentration in years not measured (2004 to 2007, 2010, 2011), using P concentration specific to each system and mixture. However, because no archived samples were available for control and compost systems, we used values from plots cover-cropped every year with the same cover crops (legume-rye) to estimate P concentration for legumes and rye in these systems.

Because we did not measure root biomass and P concentration, P uptake by cover crops and its contribution to P cycling are limited to aboveground biomass in this study.

2.7. Statistical analyses

Plot-level data were analyzed using Repeated Measures ANOVAs (RM-ANOVAs), followed by Tukey HSD tests, where a significant time effect indicates that at least two years were significantly different during the study period. However, RM-ANOVAs do not identify which years are different and it does not test the significance of temporal trends (e.g., an increase in yields during the study period). Therefore, we tested the significance of temporal trends by correlating data with years, using Pearson correlations.

For RR-Irr, we first computed nested RM-ANOVAs with all the available data for a given variable, using systems as the main factor and rotation as the nested factor. We also computed one-way RM-ANOVAs for each rotation (grains, tomato) or crop (corn, wheat) separately. A similar approach was used in SOCS, where nested RM-ANOVAs were first computed (crop nested within system) followed by one-way RM-ANOVAs for individual crops (lettuce, broccoli). For RR-Rain and cover crop data, we computed one-way RM-ANOVAs to differentiate systems and one-way RM-ANOVAs to determine the effect of preceding crop on cover crops in mixed and organic systems. We verified that data met normality and homoscedasticity conditions and applied a log transformation when necessary. All analyses were computed with SPSS (version 22.0, 2013).

Table 2

Mean (±standard deviation) for P inputs, outputs and balance, P use efficiency (PUE) and P input recovery in crops ($P_{recovery}$) for different systems, rotations and crops in Russell Ranch Irrigated (1994–2011–OrgCT = organic corn-tomato, MixCT = mixed corn-tomato, ConvCT = conventional corn-tomato, ConvWT = conventional wheat-tomato). Different letters represent significant differences computed with a Tukey HSD test performed after repeated-measures nested ANOVA, where crop (grain or tomato) was nested within system. Temporal variation and statistical results for inputs, outputs, PUE and $P_{recovery}$ in individual crops are available in Figs. S1, S2, S3. n.s. = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

System	Rotation	Crop	Inputs						Outputs				P balance		PUE[c]		$P_{recovery}$[c]		
			Fertilizers	Crops	CC seeds	Total	Yields		P concentration		P exported								
			kg P ha^{-1}				Mg ha^{-1}	Sig.[b]	%	Sig.[b]	kg P ha^{-1}	Sig.[b]	kg P ha^{-1}	Sig.[b]	kg yield kg^{-1}P	Sig.[b]	%	Sig.[b]	
OrgCT	Grain	Corn	138 ± 66	0.2 ± 0.0	0.6 ± 0.0	139 ± 66	6.8 ± 2.1	B	0.34 ± 0.03	A	22 ± 7	B	117 ± 61	A	54 ± 20	D	18 ± 6	B	
		Sorghum	57 ± 81	0.2 ± 0.0	0.6 ± 0.0	58 ± 81							58 ± 81						
		Wheat	0 ± 0	0.4 ± 0.0	0.0 ± 0.0	0 ± 0	5.0 ± 0.8		0.36 ± 0.00		18 ± 3		−18 ± 3						
	Tomato	Tomato	88 ± 28	0.7 ± 0.1	0.6 ± 0.0	89 ± 28	4.1 ± 0.6		0.45 ± 0.04		19 ± 4		70 ± 28		46 ± 12		21 ± 6		
	Average		101 ± 44	0.5 ± 0.0	0.6 ± 0.1	102 ± 44					19 ± 4		82 ± 42		50 ± 16		19 ± 6		
	Sum[a]		1815	8	11	1834					345		1484		49		19		
MixCT	Grain	Corn	3 ± 13	0.1 ± 0.0	0.6 ± 0.0	4 ± 13	6.2 ± 1.6	B	0.32 ± 0.02	B	20 ± 5	BC	−16 ± 13	C	128 ± N/A	C	46 ± N/A	AB	
		Sorghum	11 ± 16	0.1 ± 0.2	0.6 ± 0.0	12 ± 15							12 ± 15						
		Wheat	0 ± 0	0.4 ± 0.0	0.0 ± 0.0	0 ± 0	6.6 ± 1.2		0.32 ± 0.02		21 ± 3		−21 ±3						
	Tomato	Tomato	24 ± 13	0.7 ± 0.1	0.3 ± 0.3	24 ± 13	4.3 ± 1.4		0.38 ± 0.03		16 ± 5		9 ± 14		181 ± 69		69 ± 26		
	Average		14 ± 12	0.4 ± 0.1	0.4 ± 0.1	15 ± 12					17 ± 6		−2 ± 13		178 ± 68		68 ± 26		
	Sum[a]		247	8	7	262					300		−37		350		121		
ConvCT	Grain	Corn	26 ± 13	0.2 ± 0.0		26 ± 13	11.5 ± 1.5	A	0.30 ± 0.03	B	34 ± 4	A	−8 ± 14	B	496 ± 123	A	146 ± 33	A	
		Sorghum	11 ± 16	0.1 ± 0.2		11 ± 16							11 ± 16						
		Wheat	0 ± 0	0.4 ± 0.0		0 ± 0	6.7 ± 1.8		0.32 ± 0.00		21 ± 6		−21 ± 6						
	Tomato	Tomato	25 ± 12	0.7 ± 0.1		25 ± 12	4.1 ± 1.2		0.38 ± 0.03		16 ± 5		10 ± 15		180 ± 58		69 ± 23		
	Average		23 ± 13	0.5 ± 0.1		23 ± 13					22 ± 5		1 ± 14		318 ± 183		102 ± 48		
	Sum[a]		412	8		420					402		19		301		97		
ConvWT	Wheat	Wheat	3 ± 12	0.4 ± 0.0		3 ± 12	5.4 ± 1.6	B	0.32 ± 0.03	B	17 ± 4	C	−14 ± 12	BC	140 ± N/A	B	39 ± N/A	AB	
	Tomato	Tomato	25 ± 12	0.7 ± 0.1		25 ± 12	4.4 ± 0.9		0.36 ± 0.03		15 ± 3		10 ± 11		183 ± 45		65 ± 16		
	Average		14 ± 12	0.6 ± 0.0		14 ± 12					16 ± 3		−2 ± 11		181 ± 44		63 ± 17		
	Sum[a]		247	10		257					293		−36		357		119		
							Time	28.3	***	2.0	n.s.	9.9	***	691.5	***	126.8	***	50.1	***
						ANOVA[d]	System	51.2	***	23.2	***	27.4	***	3725.8	***	1022.7	***	489.0	***
							Rotation	126.5	***	9.0	**	42.5	***	264.9	***	1029.0	***	310.0	***

[a] Sum refers to the cumulative sum over the whole study period.

[b] Statistical significance refers to the whole system not individual rotations.

[c] For PUE and $P_{recovery}$, the average only includes years when P was added whereas the sum is computed by dividing the cumulative sum of yields or P uptake during the study period by the cumulative sum of P inputs.

[d] F-statistics and statistical significance for each factor used in nested Repeated Measures ANOVAs (System = main factor, Rotation = nested factor).

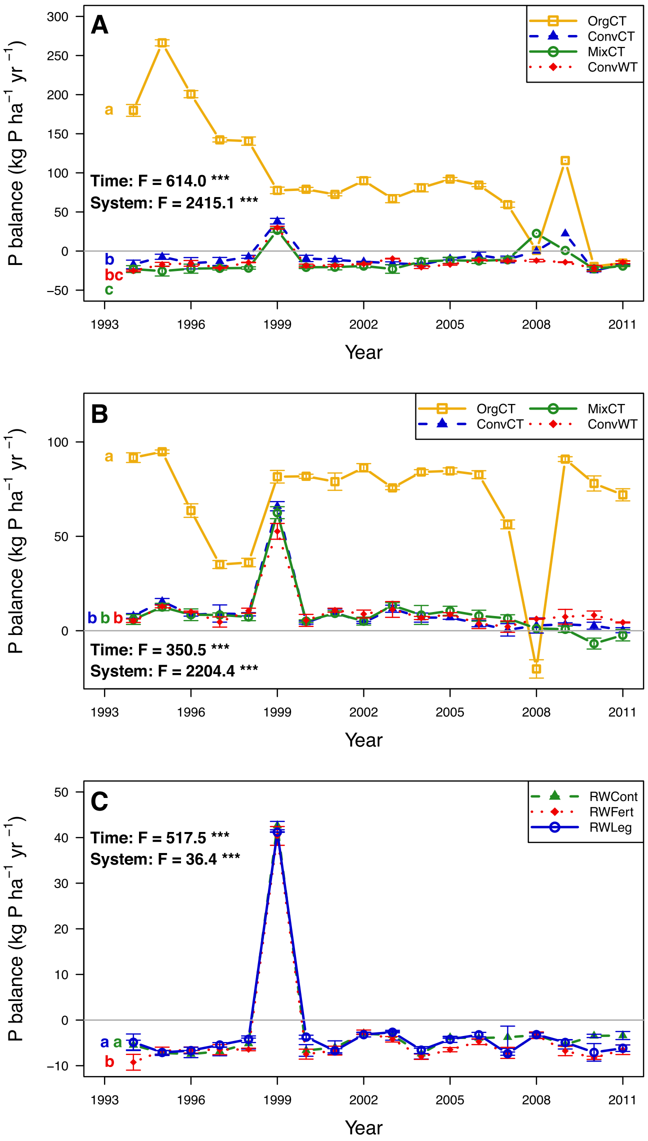

Fig. 1. Mean (±standard deviation) for P balance of A) Russell Ranch Irrigated—grains (corn, sorghum cover crop or wheat) B) Russell Ranch Irrigated—tomato and C) Russell Ranch Rainfed wheat. OrgCT = organic corn-tomato, ConvCT = conventional corn-tomato, MixCT = mixed corn-tomato, ConvWT = conventional wheat-tomato, RWCont = rainfed wheat control, RWFert = rainfed wheat fertilized, RWLeg = rainfed wheat with cover crops. Systems with open symbols and solid lines have cover crops. Different letters represent significant differences computed with a Tukey HSD test performed after repeated-measures ANOVA for different cropping cycles separately (in RR-Irr) and system as the main factor. No grains were harvested in RR-Irr for 2008 and 2009 (sorghum summer cover crop or fallow), mineral fertilizers were added to all RR systems except the organic system in 1999 (explaining the large surplus observed for that year), and no manure was added to the grain phase in the organic system in 2010 and 2011. n.s. = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

3. Results

3.1. Phosphorus budgets in RR-Irr systems

Phosphorus inputs were highest and most variable in the organic corn-tomato system (OrgCT), intermediate in the conventional corn-tomato system (ConvCT), and lowest in conventional wheat-tomato (ConvWT) and mixed corn-tomato (MixCT) systems (Table 2, Fig. S1).

Tomato P concentration and export were highest in OrgCT, whereas ConvCT had the lowest P concentration and the highest yields and P export for corn (Table 2, Fig. S2). OrgCT had the highest wheat P concentration and lowest yields, and ConvCT and MixCT systems had the highest wheat P export (Table 2, Fig. S2). Overall, ConvCT and ConvWT had the highest and lowest total P outputs, respectively, as P export was lower with wheat than corn (Table 2). We found many significant temporal trends for yields, P concentration and P export (see Table S1 for details).

OrgCT had a large P surplus whereas other systems were close to P balance: OrgCT had P surpluses that were seven times larger than other systems during tomato production, and OrgCT had large P surpluses as compared to P deficits in ConvCT and MixCT during corn production (Table 2, Fig. 1A, B). In all systems, wheat had a negative P balance whereas the sorghum cover crop and fallow had a P surplus, as these were fertilized despite the lack of harvest (Table 2, Fig. 1A). OrgCT had lower PUE and $P_{recovery}$ than other systems, and corn had higher PUE and $P_{recovery}$ than tomato in ConvCT (Table 2, Fig. S3). Overall, P surpluses decreased with time whereas PUE and $P_{recovery}$ increased (Table S1).

Table 3
Mean (±standard deviation) for P inputs, outputs and balance, P use efficiency (PUE) and P input recovery in crops ($P_{recovery}$) for different systems in Russell Ranch Rainfed (1994–2011—RWCont = rainfed wheat control, RWFert = rainfed wheat fertilized, RWLeg = rainfed wheat with cover crops). Temporal variation and statistical results for outputs are available in Fig. S4.

System	Rotation	Inputs				Outputs			P balance	PUE[b]	$P_{recovery}$[b]
		Fertilizers kg P ha^{-1}	Crops	CC seeds	Total	Yields Mg ha^{-1}	P concentration %	P exported kg P ha^{-1}	kg P ha^{-1}	kg yield kg^{-1} P	%
RWCont	Average	3 ± 12	0.2 ± 0.0		3 ± 12	3.4 ± 1.1	0.31 ± 0.02	5.3 ± 1.6	−2.4 ± 11	93 ± N/A	26 ± N/A
	Sum[a]	49	3		52			95	−43	1248	386
RWFert	Average	3 ± 12	0.2 ± 0.0		3 ± 12	4.9 ± 1.3	0.28 ± 0.02	6.6 ± 1.8	−3.8 ± 11	123 ± N/A	35 ± N/A
	Sum[a]	49	3		52			120	−68	1772	485
RWLeg	Average	3 ± 12	0.2 ± 0.0	0.3 ± 0.0	3 ± 12	3.9 ± 1.1	0.30 ± 0.02	5.8 ± 1.7	−2.6 ± 11	116 ± N/A	34 ± N/A
	Sum[a]	49	3	6	58			104	−46	1411	417

[a] Sum refers to the cumulative sum over the whole study period.
[b] For PUE and $P_{recovery}$, the average only refers to 1999 whereas the sum is computed by dividing the cumulative sum of yields by the cumulative sum of P inputs.

3.2. Phosphorus budgets in RR-Rain systems

With the exception of the 1999 fertilizer addition, seeds provided the only P inputs in RR-Rain systems, with higher inputs in the wheat-L(O)CC system (Table 3). All systems had a negative P balance for the study period, and higher P export and yields in the wheat fertilized system resulted in the largest P deficit among RR-Rain systems, despite lower P concentration and higher PUE and $P_{recovery}$ (Table 3, Figs. 1, S4). Yields, P export and P deficits decreased with time in the unfertilized wheat control system (Table S1).

3.3. Phosphorus budgets in SOCS rotations

Cumulative phosphorus inputs were nearly 300 kg ha^{-1} larger with compost addition in SOCS, but decreased substantially during the experiment because the N:P of organic fertilizers used during broccoli and lettuce production increased (Table 4, Fig. S1C, D).

Overall, yields and P export were lower in lettuce than in broccoli (Table 4). Phosphorus export, broccoli P concentration and lettuce yields were highest in legume-rye and lowest in control, whereas broccoli yields and lettuce P concentration were similar among systems (Table 4, Fig. S5). There was a general increase in broccoli P concentration, and in lettuce yields and P export, with time (Table S1).

All systems had a positive P balance, and compost inputs increased cumulative P surpluses by 2.5 fold and decreased cumulative PUE and $P_{recovery}$ by half compared to the control system without compost inputs (Table 4, Figs. 2, S6). The compost system (i.e., yard compost before each vegetable crop and infrequent cover-cropping) had the highest P surplus and lowest PUE and $P_{recovery}$, although differences with other systems receiving compost were small (Table 4). The substantial reduction in P inputs during the experiment lowered P surpluses in all systems, especially for lettuce, and consequently PUE and $P_{recovery}$ increased (Table S1, Figs. 2, S6).

Phosphorus budgets computed using a higher harvest index for lettuce (i.e. harvesting lettuce heads rather than hearts) and a higher P concentration for broccoli (i.e. using crown P concentration measured in 2005) increased P exported (by 1.6–2.7 fold), PUE (by 2.7 fold for lettuce only) and $P_{recovery}$ (by 1.6–2.7 fold), resulting in an overall 13–35% reduction in P surpluses (Table S2).

3.4. N:P ratios among systems

In RR-Irr, output N:P was lower than input N:P for systems with mineral fertilizers but the reverse was true for the organic (OrgCT) system (Table 5). Output N:P was lowest in OrgCT, higher in tomato than in grains, and including N-fixation inputs from cover crops increased input N:P to values more similar to output N:P (Table 5). In RR-Rain, output N:P was highest with mineral N fertilizer, and including N-fixation inputs in these estimates increased the input N:P in the cover-cropped system (Table 5).

In SOCS, output N:P was higher with frequent cover-cropping and in broccoli compared to lettuce, but was generally lower than input N:P, especially when N-fixation inputs were included (Table 5). Cover-cropping with a legume-rye mixture increased the N:P of outputs and inputs when including N-fixation relative to cover-cropping with rye or mustard alone (Table 5).

3.5. Phosphorus uptake by cover crops

In RR, cover crop biomass did not vary among systems although P concentration and P uptake were highest in the organic system (Table 6, Figs. 3, S7). In the mixed system, biomass, P concentration and P uptake were higher when cover crops preceded grains compared to tomato (Table 6). In SOCS, the legume-rye mixture had higher P concentration and biomass than mustard and higher P uptake than rye and mustard, whereas compost addition or frequency of cover-cropping did not affect P uptake by cover crops (Table 6, Figs. 3, S7).

4. Discussion

4.1. The effects of fertility source on P budgets

Input type was the main driver of differences in P balance in the systems we studied. Using low N:P poultry manure as the only external input to meet crop N demand resulted in substantial P surpluses and low PUE compared to other systems, consistent with previous studies (Kleinman and Sharpley, 2003; Bergstrom et al., 2008). This illustrates the consequences of considering P inputs as a secondary concern when applying manure in N-limited systems (Nesme et al., 2011). We have shown previously that excessive P applications compared to crop demand resulted in soil P accumulation and saturation of the P sorption capacity in these systems (Maltais-Landry et al., 2015). As a result, soil P concentrations (39 mg P_{Olsen} kg^{-1} soil) are approaching the "very high" category (>40 mg P_{Olsen} kg^{-1} soil) where no further P application is recommended (Li et al., 2011), increasing the risks of P losses to surrounding ecosystems via leaching and runoff (Sims et al., 2000; Eghball, 2002). In addition, the average annual N input in the RR long-term experiment was lower in the organic (150 kg N ha^{-1} yr^{-1}) compared to the conventional (200 kg N ha^{-1} yr^{-1}) corn-tomato system when corn was grown (1994–2007), consistent with Berry et al. (2002), resulting in lower grain yields in organic

Table 4

Mean (±standard deviation) for P inputs, outputs and balance, P use efficiency (PUE) and P input recovery in crops ($P_{recovery}$) for different systems, rotations and crops in Salinas Organic Cropping Systems (2003–2011). Different letters represent significant differences computed with a Tukey HSD test performed after repeated-measures nested ANOVA, where crop (lettuce vs. broccoli) was nested within system. Temporal variation and statistical results for inputs, outputs, PUE and $P_{recovery}$ in individual crops are available in Figs. S1, S5, S6. n.s. = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

System	Rotation	Inputs							Outputs				P balance		PUE[c]		$P_{recovery}$[c]		
		Fertilizers	Compost	Transplants	CC seeds	Total	Yields		P concentration		P exported								
		kg P ha^{-1}					Mg ha^{-1}	Sig.[b]	%	Sig.[b]	kg P ha^{-1}	Sig.[b]	kg P ha^{-1}	Sig.[b]	kg yield kg^{-1} P	Sig.[b]	%	Sig.[b]	
Control	Lettuce	15 ± 12	0 ± 0	0.3 ± 0.0		16 ± 12	0.7 ± 0.2	C	0.41 ± 0.06	A	2.7 ± 0.8	C	13 ± 12	B	97 ± 81	A	38 ± 32	A	
	Broccoli	14 ± 6	0 ± 0	0.6 ± 0.1		15 ± 6	1.7 ± 0.3		0.44 ± 0.08		7.9 ± 1.9		9 ± 9		144 ± 51		68 ± 27		
	Average	15 ± 9	0 ± 0	0.5 ± 0.2	1.9 ± 0.0	16 ± 9					4.7 ± 2.9		11 ± 11		115 ± 72		50 ± 33		
	Sum[a]	222	0	7	4	233					61		172		62		27		
Compost	Lettuce	15 ± 12	19 ± 0	0.3 ± 0.0		35 ± 12	0.8 ± 0.2	B	0.43 ± 0.05	A	3.3 ± 0.9	B	32 ± 12	A	26 ± 13	C	11 ± 5	C	
	Broccoli	14 ± 6	19 ± 0	0.6 ± 0.1		34 ± 6	1.7 ± 0.3		0.45 ± 0.07		8.3 ± 1.6		28 ± 9		56 ± 14		27 ± 7		
	Average	15 ± 9	19 ± 0	0.5 ± 0.2	1.9 ± 0.0	34 ± 9					5.2 ± 2.8		30 ± 11		37 ± 20		17 ± 10		
	Sum[a]	222	284	7	4	517					67		449		29		13		
Rye	Lettuce	15 ± 12	19 ± 0	0.3 ± 0.0		35 ± 12	0.9 ± 0.1	A	0.44 ± 0.06	A	3.7 ± 0.6	A	31 ± 12	A	29 ± 14	B	12 ± 5	BC	
	Broccoli	14 ± 6	19 ± 0	0.6 ± 0.1		34 ± 6	1.8 ± 0.2		0.47 ± 0.07		9.1 ± 1.3		27 ± 9		58 ± 11		29 ± 7		
	Average	15 ± 9	19 ± 0	0.5 ± 0.2	0.4 ± 0.0	34 ± 9					5.8 ± 2.8		29 ± 11		40 ± 19		19 ± 10		
	Sum[a]	222	284	7	3	516					75		441		31		15		
Mustard	Lettuce	15 ± 12	19 ± 0	0.3 ± 0.0		35 ± 12	0.8 ± 0.1	A	0.42 ± 0.05	A	3.5 ± 0.5	A	31 ± 12	A	29 ± 13	B	12 ± 5	BC	
	Broccoli	14 ± 6	19 ± 0	0.6 ± 0.1		34 ± 6	1.8 ± 0.2		0.47 ± 0.07		9.2 ± 1.4		27 ± 9		59 ± 12		30 ± 7		
	Average	15 ± 9	19 ± 0	0.5 ± 0.2	0.1 ± 0.0	34 ± 9					5.7 ± 3.0		29 ± 11		40 ± 20		19 ± 11		
	Sum[a]	222	284	7	1	514					74		440		31		15		
Legume-rye	Lettuce	15 ± 12	19 ± 0	0.3 ± 0.0		36 ± 12	0.9 ± 0.2	A	0.43 ± 0.06	A	3.9 ± 0.6	A	33 ± 12	A	31 ± 14	B	13 ± 5	B	
	Broccoli	14 ± 6	19 ± 0	0.6 ± 0.1		34 ± 6	1.9 ± 0.1		0.49 ± 0.09		9.8 ± 1.1		27 ± 10		60 ± 8		31 ± 7		
	Average	15 ± 9	19 ± 0	0.5 ± 0.2	1.9 ± 0.0	35 ± 9					6.2 ± 3.1		30 ± 11		42 ± 19		20 ± 11		
	Sum[a]	222	284	7	15	528					80		448		33		16		
							Time	145.5	***	24.7	***	176.3	***	5878.5	***	840.5	***	403.6	***
						ANOVA[d]	System	22.5	***	2.1	n.s.	24.1	***	1434.7	***	298.8	***	348.2	***
							Rotation	336.3	***	24.9	***	262.7	***	232.0	***	257.0	***	162.1	***

[a] Sum refers to the cumulative sum over the whole study period.

[b] Statistical significance refers to the whole system not individual rotations.

[c] For PUE and $P_{recovery}$, the average only includes years when P was added whereas the sum is computed by dividing the cumulative sum of yields during the study period by the cumulative sum of P inputs.

[d] F-statistics and statistical significance for each factor used in nested Repeated Measures ANOVAs (System = main factor, Rotation = nested factor).

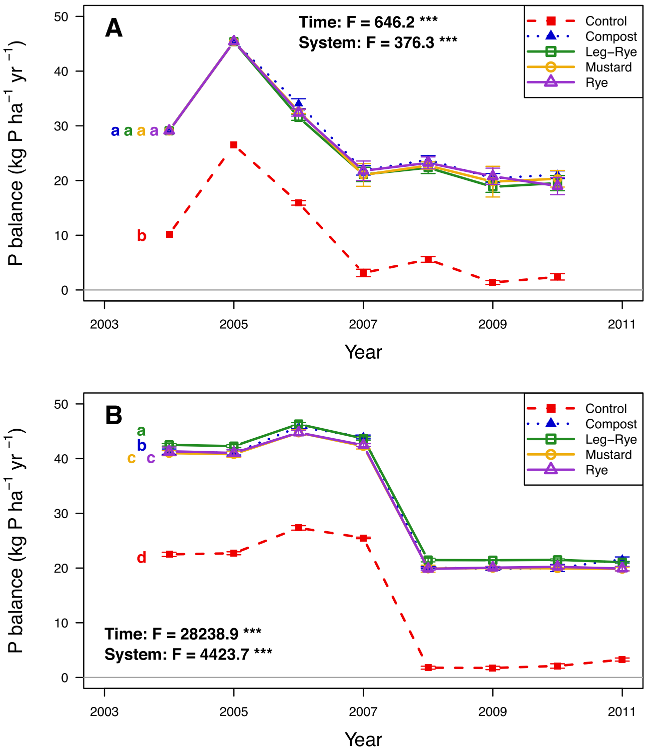

Fig. 2. Mean (±standard deviation) for P balance of A) broccoli and B) lettuce production in Salinas Organic Cropping Systems. Systems with open symbols and solid lines have cover crops. In A), spinach was grown instead of broccoli for 2004. Different letters represent significant differences computed with a Tukey HSD test performed after repeated-measures ANOVA for different cropping cycles separately and system as the main factor. n.s. = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

plots. This highlights how using only low N:P poultry manure to meet crop N demand (e.g., in RR) results in a direct trade-off between adequate crop N nutrition and P over-fertilization. Using manures with higher N:P ratios (e.g., cattle or swine) increases N inputs while reducing P inputs in excess of crop removal, but these manures have other limitations, such as higher application costs due to low N content for cattle or high water content for swine (Kleinman and Sharpley, 2003; Nelson and Janke, 2007), and unavailability in some regions (e.g., swine manure in California). Thus, combining organic amendments with N inputs that do not contain P (e.g., urea) in hybrid systems would increase input N:P and could help improve P balances, consistent with integrated soil fertility management (ISFM), a framework that aims to increase yields, nutrient-use efficiency and soil organic matter using complementary fertilization approaches (Vanlauwe et al., 2010).

In contrast to manure, the yard compost used in this study had a N:P similar to crop removal (mean = 6.1), resulting in a smaller imbalance between N and P supply relative to crop demand. However, as compost applications were made primarily to increase organic matter, not to fertilize for N or P (all SOCS systems were fertilized with processed organic fertilizers), yard compost had no effect on yields or P export and P surpluses increased substantially via P inputs 2–6 times higher than crop removal. Furthermore, because of their low nutrient content, yard composts have a slow nutrient release and a low short-term PUE, and they cannot supply a significant fraction of nutrient demand in the following crop (Hartz et al., 2000; Sinaj et al., 2002). Thus, other approaches may be more effective to increase organic matter inputs and avoid P surpluses, such as increasing *in situ* organic matter inputs (cover-cropping, cash crops with high post-harvest residues) and reducing organic matter loss (e.g., reduced tillage) to lower compost inputs required to maintain soil organic matter and minimize associated P surpluses.

Systems receiving mineral fertilizers where N and P inputs can be decoupled had more balanced P budgets than those fertilized with manure, consistent with findings of Oehl et al. (2002). However, P surpluses also occur with mineral fertilizers (Cao et al., 2012), especially in vegetable production (Oelofse et al., 2010; Nesme et al., 2011; Yan et al., 2013). The systems receiving only mineral fertilizers in our study were close to P balance, and given their N:P ratios, they did not accumulate soil P substantially (Maltais-Landry et al., 2015). Systems that received fertilizer on a biennial basis had higher PUE than systems receiving fertilizers annually, but this came at the expense of lower grain yields, most likely because of lower N inputs. Therefore, coupling annual N inputs with biennial P inputs may increase both yields and PUE in these systems, highlighting how trade-offs between yields and nutrient-use-efficiency are more easily addressed when fertilizers are included in fertility management.

Pelleted or liquid organic fertilizers are formulated from a variety of materials with various levels of N and P, resulting in a more flexible stoichiometry than manures or composts. Consequently, P surpluses can be lowered while maintaining N supply and yields (e.g., in SOCS after switching to high N:P fertilizers), although P surpluses also occur with processed organic fertilizers (Oelofse et al., 2010; Nesme et al., 2012). Furthermore, processed organic fertilizers with a high N:P ratio (e.g., blood or feather meal) are more expensive per unit of nitrogen, which may limit their use even in high-value vegetable crops where they are typically used. Despite these limitations, they provide an alternative to improve P budgets in many organic systems, although comparing how different processed organic fertilizers (e.g., blood vs. feather meal) affect P budgets relative to mineral fertilizers remains to be done.

Table 5

Mean (±standard deviation) for input and output N:P ratios for different systems and rotations in Russell Ranch Irrigated (RR-Irr, where OrgCT = organic corn-tomato, MixCT = mixed corn-tomato, ConvCT = conventional corn-tomato, ConvWT = conventional wheat-tomato), Russell Ranch Rainfed (RR-Rain, where RWCont = rainfed wheat control, RWFert = rainfed wheat fertilized, RWLeg = fertilized with cover crops) or Salinas Organic Cropping Systems (SOCS). Different letters represent significant differences computed with a Tukey HSD test performed after repeated-measures nested ANOVA, where crop was nested within system, or with repeated-measures ANOVA for individual crops. Archived samples for wheat were analyzed by system, hence wheat was compared with a one-way ANOVA (time as a fixed effect), where wheat for RR-Irr in conventional wheat is compared to RR-Rain systems. All statistical tests were made with means, and must be interpreted within a given site and crop (e.g., total within RR-Irr) where letters denoting significance are aligned to facilitate comparisons within a given site and crop. n.s. = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

Experiment	System	Rotation	Inputs				Outputs				ANOVA			
			No N-fixation		With N-fixation[a]									
				Sum[b]		Sum[b]		Sig.			Crop	Term	F	Sig.
RR-Irr[c]	OrgCT	Corn	1.4 ± 0.3	1.3	2.0 ± 0.4	1.9	3.2 ± 0.3	B			Corn	Time	2.8	n.s.
		Tomato	1.4 ± 0.3	1.4	2.2 ± 0.4	2.2	3.8 ± 0.5		C			System	80.7	***
		Total	1.4 ± 0.3	1.3	2.1 ± 0.4	2.0	3.5 ± 0.5			C				
	MixCT	Corn[d]	0.0 ± N/A	0.0	1.5 ± N/A	21.5	3.3 ± 0.2	B			Tomato	Time	27.7	***
		Tomato	5.6 ± 2.5	5.1	6.5 ± 1.4	6.0	5.2 ± 1.3		B			System	62.9	***
		Total	5.5 ± 2.7	4.5	6.5 ± 1.5	7.8	4.2 ± 1.3			B				
	ConvCT	Corn	10.2 ± 2.0	9.2			3.9 ± 0.3	A			All	Time	10.6	***
		Tomato	7.0 ± 1.4	6.4			5.7 ± 0.8		B			System	104.1	***
		Total	8.6 ± 1.7	7.8			4.8 ± 1.1			A		Rotation	109.1	***
	ConvWT	Wheat	3.4 ± N/A	48.1			5.8 ± 1.0	b						
		Tomato	7.0 ± 1.4	6.4			6.5 ± 0.6		A					
		Total	7.1 ± 1.2	11.4			6.1 ± 0.9							
RR-Rain[c]	RWCont		0.0 ± N/A	0.0			4.9 ± 0.7	b			Wheat	System	8.8	***
	RWFert		1.1 ± N/A	16.0			7.0 ± 1.4	a						
	RWLeg		0.0 ± N/A	0.0	0.8 ± N/A	10.7	5.8 ± 1.2	b						
SOCS	Control	Lettuce	9.3 ± 7.4	4.4	11.5 ± 10.4	5.5	4.8 ± 0.6	C			Lettuce	Time	123.0	***
		Broccoli	10.9 ± 5.7	9.9	10.9 ± 5.7	9.9	6.4 ± 0.3		C			System	26.5	***
		Total[e]	10.1 ± 6.5	6.9	11.2 ± 8.3	7.5	5.6 ± 1.0			C				
	Compost	Lettuce	6.0 ± 2.2	5.3	6.5 ± 2.6	5.8	4.9 ± 0.7	C			Broccoli	Time	82.1	***
		Broccoli	7.9 ± 2.0	7.7	7.9 ± 2.0	7.7	6.5 ± 0.3		C			System	12.7	***
		Total[e]	6.9 ± 2.3	6.4	7.2 ± 2.4	6.7	5.7 ± 1.0			C				
	Rye	Lettuce	6.0 ± 2.2	5.3			5.7 ± 1.2	B			All	Time	137.3	***
		Broccoli	7.9 ± 2.0	7.7			6.6 ± 0.7		BC			System	45.0	***
		Total[e]	6.9 ± 2.3	6.4			6.2 ± 1.1			B		Rotation	15.0	***
	Mustard	Lettuce	6.0 ± 2.2	5.3			6.1 ± 1.3	AB						
		Broccoli	7.9 ± 2.0	7.7			7.2 ± 1.0		AB					
		Total[e]	6.9 ± 2.3	6.4			6.6 ± 1.2			A				
	Legume-rye	Lettuce	6.0 ± 2.2	5.3	8.2 ± 2.9	7.3	6.5 ± 1.3	A						
		Broccoli	7.9 ± 2.0	7.7	7.9 ± 2.0	7.7	7.3 ± 1.1		A					
		Total[e]	6.9 ± 2.3	6.4	8.0 ± 2.5	7.5	6.9 ± 1.2			A				

[a] Fixation estimated at 75 kg N haper year with legume cover crops in RR (J. Six, unpublished data) or 67 kg N ha (Brennan and Boyd, 2012b).

[b] Sum refers to the cumulative sum over the whole study period.

[c] Only 1994–2007 in RR (when data available for all systems and crops).

[d] Corn in the mixed system did not receive any N.

[e] Broccoli only includes data for 2006–2010, when yields were harvested, except for “sum” column where data from 2004 and 2005 are included.

4.2. The effects of crop rotation on P budgets

The type of crop being grown affects P balances via differences in P removal rates and the N:P ratio of harvest (Nelson and Janke, 2007). In this study, grains generally had smaller P surpluses than vegetables via lower output N:P and higher P removal and PUE, consistent with Nesme et al. (2011), as illustrated by a 2–3 fold increase in P removal and PUE, a 30% reduction in harvested N:P ratio, and a P deficit with corn compared to tomato in the conventional corn-tomato system, where nutrient additions were equal for both crops. Variations in crop P removal between grains depended on systems, as corn and wheat had similar P export in organic and mixed systems, whereas corn had much higher P export than wheat in the conventional system. This was likely due to the N limitation of corn yields in the organic and mixed systems that resulted in lower P uptake, as corn and wheat often have similar P balances (Nesme et al., 2011).

Phosphorus removal also varied among vegetables: tomato and lettuce had the highest and lowest rates of P removal in this study, respectively. Higher P surpluses in vegetables may result from P over-application to increase soil P availability for crops that have a low P uptake efficiency, e.g., in lettuce (Johnstone et al., 2005). However, other drivers of P over-fertilization in vegetable production systems – e.g., fertilizers being a small fraction of expenses, thereby providing little incentive to reduce over-fertilization – also play a role (Johnstone et al., 2005; Oelofse et al., 2010). Furthermore, the N:P ratio of crop removal in vegetables is typically high (Nelson and Janke, 2007), which increases the likelihood of P surpluses compared to other crops. Therefore, differences in management as well as crop physiology affect how P balances vary among crops, and both could be targeted to increase PUE of agroecosystems.

High yields can increase P removal for a given crop and lead to more balanced P budgets in systems with P surpluses (Simpson et al., 2011), as we found for corn in the conventional vs. organic system and for lettuce when using a higher harvest index. We also found that changes in P concentration within a crop affected P balances, but to a lesser extent than did yields (Zhang et al., 2013). For example, P removal in wheat was greater in systems with higher yields – conventional corn and mixed systems in RR-Irr, and the N-fertilized system in RR-Rain – despite lower plant P concentration and higher N:P ratios in crop removal. This resulted in higher PUE that can be beneficial in low-input systems and systems established on P-depleted soils (Richardson et al., 2011)

Table 6
Mean (±standard deviation) for cover crop biomass, P concentration and P uptake for different systems and rotations in Russell Ranch Irrigated (RR-Irr, where OrgCT = organic corn-tomato, MixCT = mixed corn-tomato), Russell Ranch Rainfed (RR-Rain, where RWLeg = rainfed wheat with cover crops) or Salinas Organic Cropping Systems (SOCS). Temporal variations in yields and P concentration can be found in Fig. S7.

Experiment	System	Rotation	Cover crops			
			Biomass Mg ha^{-1}	P content %	P uptake kg P ha^{-1}	Sum[a]
RR–Irr	OrgCT	Grain	4.2 ± 0.9	0.44 ± 0.09	19 ± 7	
		Tomato	4.0 ± 1.0	0.45 ± 0.10	18 ± 7	
		Average	4.1 ± 0.9	0.45 ± 0.06	19 ± 6	339
	MixCT	Grain	3.9 ± 0.9	0.39 ± 0.09	15 ± 5	
		Tomato	3.2 ± 1.4	0.35 ± 0.09	12 ± 6	
		Average	3.8 ± 1.0	0.38 ± 0.05	15 ± 5	264
RR–Rain[b]	RWLeg		3.7 ± 1.7	0.34 ± 0.11	12 ± 4	108
SOCS[c]	Control		7.1 ± 0.3	0.33 ± 0.00	23 ± 1	47
	Compost		7.5 ± 0.6	0.33 ± 0.00	25 ± 2	49
	Rye		7.1 ± 0.8	0.31 ± 0.00	22 ± 2	174
	Mustard		5.5 ± 1.4	0.29 ± 0.02	16 ± 4	125
	Legume-rye		7.5 ± 0.9	0.33 ± 0.02	24 ± 3	195

[a] Sum refers to the cumulative P uptake (kg P ha^{-1}) over the whole study period.
[b] The mean takes into account only years when cover crops are grown whereas the cumulative sum includes wheat years when no cover crops were grown.
[c] The mean in Control and Compost systems only takes into account years with cover crops whereas the cumulative sum includes fallow years with no cover crops.

where reducing crop P removal can ultimately allow for a reduction of external P inputs. Grain quality may be affected by nutrient dilution at high PUE however (Zhu et al., 2012), with potential impacts on farm profitability, highlighting how the net outcome (positive or negative) of differences in crop P removal is context-dependent.

4.3. The effects of cover crops on P budgets

Cover crops took up an average of 12–25 kg P ha^{-1} yr^{-1} in their aboveground biomass and could reduce P losses by a similar magnitude in these systems. However, P transfer from cover crop residues to cash crops is variable, with 5–27% of cover crop residue P being recovered in subsequent crops (Noack et al., 2014), accounting for 5–40% of P uptake in these subsequent crops (Damon et al., 2014). In our study, cover crops were incorporated into the soil only a few weeks before planting of subsequent crops to better synchronize residue nutrient release and nutrient uptake from subsequent crops (Cavigelli and Thien, 2003; Simpson et al., 2011). Residue P recovery in subsequent crops was estimated using ^{33}P labeling as 8–14% for SOCS and 13–22% for RR, resulting in a mean transfer of 2.3 to 2.8 kg P ha^{-1} (range: 0.5–9 kg P ha^{-1} yr^{-1}) to subsequent crops (Maltais-Landry et al., 2015 Maltais-Landry and Frossard, 2015). This is similar to the amount of P removed by lettuce but lower than rates of removal by grains, tomato or broccoli. However, we likely underestimated the contribution of residue P to P uptake in subsequent cash crops, because we did not include P uptake and subsequent transfer to cash crop from cover crop roots. Furthermore, using cover crops that increase soil P fertility substantially (e.g., *Phacelia tanacetifolia*) (Eichler-Loebermann et al., 2008) could also increase P transfer to subsequent cash crops. Therefore, our results highlight the potential of cover crops to increase soil P fertility, which would allow for lower P input rates while reducing soil P losses (Sharpley and Smith, 1991). If using different species and including P transfer from cover crop roots is confirmed to increase P transfer to subsequent crops more than is suggested by our estimates, then the contribution of cover crops to

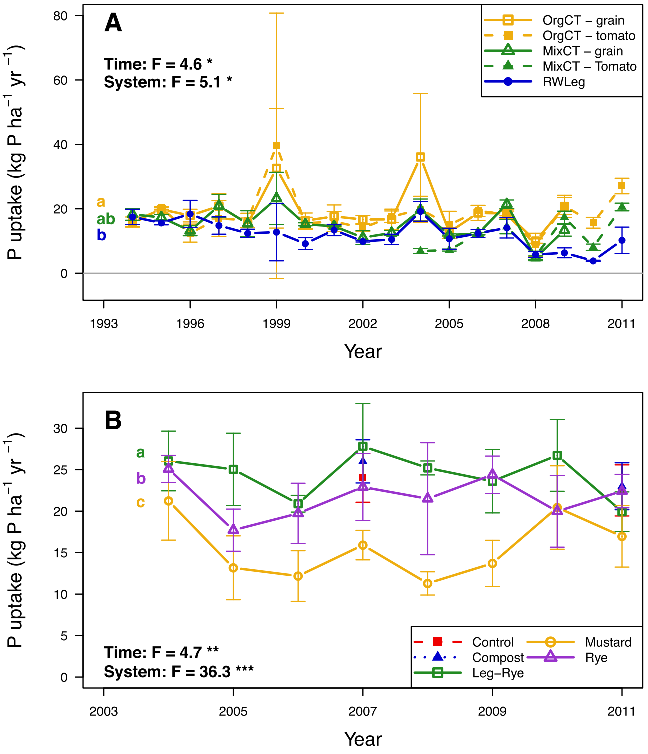

Fig. 3. Mean (±standard deviation) for cover crop P uptake in A) Russell Ranch (OrgCT = organic corn-tomato, MixCT = mixed corn-tomato, RWLeg = rainfed wheat with cover crops) and B) Salinas Organic Cropping Systems. Different letters represent significant differences computed with a Tukey HSD test performed after repeated-measures ANOVA with system as the main factor. In Russell Ranch, P uptake was higher before grain in mixed ($F = 22.8$, $p < 0.01$) but not organic ($F = 0.2$, n.s.) systems. In Salinas Organic Cropping Systems, mustard < other systems when only 2007 and 2011 were analyzed, i.e. years when control and compost systems were cover-cropped ($F = 9.5$, $p < 0.001$). n.s. = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

soil P fertility could be comparable to other cover crop benefits, such as increasing organic matter inputs (Vanlauwe et al., 2010) and in the case of legumes, providing higher N inputs and input N:P ratios via N-fixation (Vance, 2001).

5. Conclusions

Types of P input affected P budgets substantially in these systems, as inputs with a low N:P and constrained stoichiometry (manures, composts) often generated high P surpluses due to a lower flexibility in matching input and output N and P. Inputs with flexible N:P could reduce P over-fertilization by providing additional N to manure- or compost-based systems. For example, applying manure to meet crop P demand and using N-fixation or mineral fertilizers to supply the remaining N required could ensure optimal crop growth while reducing the use of mineral fertilizers. However, systems that cannot use mineral fertilizers due to the constraints of organic certification (e.g., OrgCT) may require high-cost processed organic fertilizers to reduce P over-fertilization.

Crop choice also affected P balances through differences in rates of crop removal, the N:P ratio of harvested products, and management, as grains typically had low or non-existent P surpluses due to high P export and low N:P ratios in crop removal. Cover crops could reduce P inputs, increase PUE and reduce P losses via plant uptake and residue mineralization, whereas higher input N:P via N-fixation in legumes can further improve PUE. Overall, results from these long-term experiments confirm that combining nutrient sources – manures, composts, cover crops, and mineral fertilizers – in hybrid systems is more likely to balance N:P stoichiometry in inputs and crop removal, and improve the PUE of agroecosystems than using only one type of input to meet crop demand, consistent with frameworks such as integrated soil fertility management.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.03.007.

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