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Supplement of

Soil properties and not inputs control carbon, nitrogen, phosphorus ratios in cropped soils in the long-term

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Supplementary Material

1. Calculations of the C, N and P inputs, and the N and P outputs and soil system budgets in the Saria field experiment

The amounts of C, N, and P added with the manure were calculated using average values derived from four studies (Arrivets, 1974; Sedogo, 1981; Bonzi, 2002; Kiba, 2012) (Table S1). The manure was considered to have a water content of 20% at the time of application. The amounts of C, N, P added by the seeds were calculated considering the recommended seeding rates for sorghum and cowpea, and using 0.45 g C g^{-1} seed and the mean concentrations of N and P in sorghum and cowpea seeds given in Kiba (2012) for the Saria field experiment. Kiba (2012) estimated the proportion of N derived from the atmosphere in cowpea (Ndfa shoot%) using the variations in natural abundance of ^{15}N in cowpea at flowering and in neighbouring non-fixing plants measured as described in Oberson et al. (2007). The amount of N derived from the atmosphere (Ndfa in shoot kg ha^{-1}) was calculated by multiplying the Ndfa shoot% by the total amount of N taken up in the shoots (kg N ha^{-1}). We considered that the Ndfa in root was 30% of the Ndfa in shoot as suggested by Adjei-Nsiah et al. (2008). The total amount of C fixed in the soil/plant system was calculated using the approach described in Bolinder et al. (2007). The shoot to root ratio of sorghum was considered to be 14.7 (Pieri, 1989; Hien, 2004) which is close to the value of 11.6 published by Bolinder et al. (2007) for North America. We used the average shoot to root ratio of cowpea of 12.6 from Kimiti (2011) which is in agreement with the findings of Saidou et al. (2012) for cowpea cultivars growing in a climatic zone comparable to Saria. We considered the grain and shoot biomass produced by sorghum and cowpea between 1975 and 2010 (Table S2). All biomass data since 1975 were available except for 1980 when sorghum yield was not measured and for 1993 and 2005 when the cowpea yield was not measured. The straw biomass which was not measured in 1979 and 1995 for cowpea and in 2004 for sorghum was estimated using the average harvest indices measured for each crop over the entire study period. The variability of the cowpea and sorghum grain production with time is shown in Figure S1. The N and P concentrations in shoot and grain were measured on sorghum (2008 and 2010) and on cowpea (2009) by Kiba (2012) and considered to be representative for the entire study period (1975 till 2010). The C content of shoot, grain and root was considered to be 0.45 g g^{-1} as in Bolinder et al. (2007). The nutrient concentrations and the biomass data were used to calculate annual the amounts of N and P exported from the field in crop products (grain and straw). The amounts of N and P added through rainfall and dust from the Harmattan wind were calculated using the equations provided by Lesschen et al. (2007) considering an input of 300 kg dust ha^{-1} $year^{-1}$. The following equations were used to calculate the different inputs:

Cinputs = Cnet photosynthesis + Cmanure+ Cseeds (1)

Ninputs =

Nsymbiotic fixation + Nmanure + Nmineral fertilizer + Nrainfall + Ndust + Nseeds (2)

Pinputs = Pmanure + Pmineral fertilizer + Prainfall + Pdust + Pseeds (3)

The N losses by leaching were set to 10 kg N ha^{-1} $year^{-1}$ which is the order of magnitude given by Lesschen et al. (2007) and Bonzi (2002). The N losses by denitrification were calculated using the equation given by Lesschen et al. (2007). The N losses from the added urea were calculated using the results of Bonzi (2002) who used ^{15}N labelled urea to quantify the N losses. His results showed that 31% of the urea N was lost when added in the absence of manure, while 37% of the urea N was lost when added in the presence of manure. Most of these losses were due to volatilization. Since the slope of the field was limited, we assumed that losses through runoff and erosion could be neglected (Hien, 2004; Bonzi, 2002). No information was available on P losses to water. Lesschen et al. (2007) considered P leaching to be negligible but this was probably not correct in the MINFYM2 treatment. The following equations were used to calculate the different outputs:

Noutputs = Ncrop products (grain and straw) + Natmosphere (N_2O+NH_3) + Nleaching (4)

Poutputs = P crop products (grain and straw) (5)

The N and P soil system budgets were calculated as follow:

Nsoil system budget = Ninputs - Noutputs (6)

Psoil system budget = Pinputs - Poutputs (7)

2. Soil, plant and manure analyses in the Saria field experiment

Representative plant (grain and stover) and manure samples were taken in 2008, 2009 and 2010 and analysed for N with a CN analyser (Vario Pyro Cube, Elementar GmbH, Hanau Germany). They were analysed for P after ashing at 550°C, solubilisation of ashes in concentrated HCl and P analysis in colorimetry using malachite green (Ohno and Zibilske 1991). ^{15}N in plant samples was measured using an isotope ratio mass spectrometer (Isoprime 100, Isoprime Ltd., Manchester UK) connected to the CN analyser.

Representative soil samples were taken during the dry season in 2009 and 2013 from the top 10 cm. Soil pH was measured in a 1:10 soil:water ratio. Total C and total N were measured using a CN analyser. Total P was digested with H_2SO_4 and H_2O_2 (Anderson and Ingram, 1993) and analysed colorimetrically. The method of Saunders and Williams (1955) delivered extremely low results and therefore total organic P (Po) was measured after a NaOH-EDTA extraction as proposed by Bowman and Moir (1993). Microbial nutrients were quantified after having incubated the soils in the absence of fresh residue addition at 60% of the water holding capacity and 25°C for 2 weeks. Microbial C and N (Cchl, Nchl) were derived from the difference in C and N measured in 0.5 M K_2SO_4 extracts of soil samples fumigated with $CHCl_3$ or not as described by Vance et al. (1987). The C and N concentrations in the extracts were measured with a Total Organic Carbon analyser TOC-L and with a Total Nitrogen measuring unit TNM-L (Shimadzu, Kyoto, Japan). The total dissolved nitrogen (DN) of the non-fumigated sample was taken as a proxy for soil mineral N. Microbial P (Phex) was derived from the difference in resin extractable P of soil samples fumigated or not with hexanol after Kouno et al. (1995). Resin extractable P was then measured colorimetrically. Based on the recovery of an inorganic P spike, Phex was corrected for sorption of P released from microbial cells during extraction. We corrected for incomplete microbial C, N and P extractions by using the k_C, k_N, and k_P factors mentioned in Table 1 (0.45 for C and N and 0.4 for P) in order to compare our results to those presented in this Table. The average values of total P, C and N, organic P, resin extractable P and microbial C, N and P concentrations of the replicates 2, 3, and 4 of the treatments CON, MIN1, MINFYM1 have been reported in Traoré et al. (2015). The data on grain and straw biomass, nutrient concentration, nutrient export and N_2 fixation by cowpea shoots have been reported in Kiba (2012).

3. Calculations of the C, N and P input, N and P outputs, and C, N and P soil system budgets in the Wagga Wagga field experiment

Average wheat and lupin yields (grain and total dry matter) were calculated for the period 1979-2002. Concentrations of N and P in wheat and lupin grain and in wheat straw have not been determined each year. Therefore, they were averaged across treatments and years to calculate N and P outputs with grains, and the return of N and P to the soil with crop residues. Since N concentrations in lupin straw were not available, we used a typical value of 9 g N kg^{-1} in lupin straw at maturity (Ann McNeill, personal communication). Annual dry matter of subterranean clover was not determined in the trial but we assumed an average of 7 t ha^{-1} $year^{-1}$ (Murray Unkovich, personal communication). Total N_2 fixed in the shoots and roots was taken from Unkovich et al. (2010) for a total shoot dry matter of 7 t ha^{-1} for subterranean clover and of 8 t ha^{-1} for lupin. We considered recommended sowing densities for lupin, wheat and subterranean clover for the region and the N and P concentrations of grain to calculate the inputs of N and P with seed. The inputs of N and P by rainfall were taken from McKee and Eyre (2000). The total C, N and P inputs were calculated with equations (1), (2), and (3).

Given the difficulties of estimating the losses of C from the soil to the atmosphere we relied on the results of Heenan et al. (2004) who measured and modelled the changes in soil organic C and total N in the 0 to 10 cm horizon between 1979 and 2000 in the different treatments of the trial. We used the slope of the linear change of C and N stocks (kg ha^{-1}) with time as an estimate of the yearly C and N soil system budget in the 0-10 cm horizon. We compared the N budget derived from Heenan et al. (2004) with the budget calculated in this study to check the validity of our calculations.

The losses of N and P due to the export of wheat and lupin grains were calculated knowing the biomass produced and the nutrient concentration. The losses of N due to stubble burning were estimated to be 100% in burnt wheat straw and 30% in burnt lupin straw, which drops leaves early and does not burn completely (Heenan et al., 2004). Bünemann et al. (2006) estimated the losses of P due to burning to be 50% in wheat straw and 15% in lupin straw, as a fraction of the P was returned to the soil as ashes, while the rest was transported away as dust. In accordance with Heenan et al. (2004), losses of N and P by erosion and runoff were considered to be negligible due to the limited slope (less than 2%) and the good drainage of the site. N losses by leaching and to the atmosphere were also probably very low in this grazed system as no N fertilizer was added (Murray Unkovich and Guangdi Li, personal communications). We considered a total annual N loss of 15 kg ha^{-1} year which is on the lower side of the N losses by leaching reported by Ridley et al. (2004) for legume based grazed systems in Southern Australia, and no P loss (Warwick Dougherty, personal communication). The total N and P outputs and budgets were calculated with equations (4), (5), (6) and (7) including the outputs related to burning.

The soil data shown here originates from Bünemann et al. (2006) and Bünemann et al. (2008). Samples were taken in 2005 from 0-5 cm in blocks 1, 3 and 5. We considered in this work the total organic P measured by the method of Saunders and Williams (1955).

4. Calculations of the C, N and P input, N and P outputs, and C, N and P soil system budgets in the DOK field experiment

The amounts of N and P added as mineral fertilizers and manure and exported in plant products were recorded for the entire duration of the experiment by Agroscope, based on elemental analyses of manures and plant products. The average annual inputs with fertilizer and manure between 1978 and 2006 were reported in Oberson et al. (2013), except for MIN. However, we include in the present work the period 1978 to 1991 when MIN was not fertilized, a period which was excluded in Oberson et al. (2013). The amounts of N and P added by seeds were calculated from the average sowing/planting density and the N and P concentration of seeds or planting material (Flisch et al., 2009). The annual N inputs by N_2 fixation in the shoots of white and red clover in the grass-clover leys, and the proportion of grass N derived from the clover during the second year of ley phase have been reported by Oberson et al. (2013) based on a two-year study. The amount of N fixed from the atmosphere contained in the clover roots was calculated considering that shoots and roots had the same %Ndfa and a shoot to root N ratio of 2.46 as proposed by Unkovich et al. (2010) for annual pasture legume species. Since the ley phases lasted either 2 or 3 years, we proceeded as follows: the annual N fixation in clover shoots reported in Oberson et al. (2013) for 2007 was multiplied with the number of years of ley phase. The yields obtained in 2007 were in the range of grass-clover yields reported for the entire duration of the DOK field experiment

(Gunst et al., 2007), and the grass-clover yields of treatments MIN, ORG and MINORG remained fairly stable between 1978 and 2005 (Gunst et al., 2007). Likewise, the clover proportions reported by Oberson et al. (2013) agreed with proportions reported earlier for the DOK field experiment (Besson et al., 1992). Further, we assumed that the N transfer to the grass would still be negligible during the first year of ley (<5% to around 20% of grass N derived from legume N, Oberson et al., 2013) and included it only in the 2nd on 3rd year of ley phase, when on average 53% of grass N was derived from clover. Finally, we calculated the root N in relation to the fixed N amount accumulated in clover during one year, irrespective whether the ley phase lasted two or three years. Doing so, we account for the uncertainties in those estimates (Unkovich et al., 2010) and for the fact that legume N was transferred to grass. The annual N inputs by N_2 fixation in the shoots of soybean have been reported by Oberson et al. (2007). We revised them, using the treatment specific average soybean yields reported by Jossi et al. (2009), since the yields determined in microplots installed in plots of the DOK experiment (Oberson et al., 2007) significantly exceeded the yields obtained on the entire field plot. We added to the amounts of fixed N in the shoots the amount of fixed N_2 contained in the roots using the shoot to root N ratio of 1.63 proposed for soybean by Unkovich et al. (2010) and the same Ndfa in % as in the shoots. The average annual input by symbiotic fixation was calculated for each rotation period (*i. e.*, considering the type and duration of legume crop included) and averaged for the entire duration from 1978 till 2006. The annual inputs by wet and dry depositions were taken from Bosshard (2007) for N and from Spiess (2011) for P. The total N and P inputs were calculated with equations (2) and (3).

The annual C inputs and the changes in soil organic C stocks were quantified for each treatment by Leifeld et al. (2009) for the 0 to 20 cm horizon between 1979 and 2004. As it was difficult to obtain reliable information on the losses of soil C, we did not estimate the total C outputs from the different treatments. Instead, an estimate of the yearly C budget in the 0-20 cm soil layer could be derived from the slope of the linear change of soil C stocks with time (kg ha^{-1} year^{-1}) reported by Leifeld et al. (2009).

The total N and P outputs from the soil/plant system were calculated as the sum of N and P exported by agricultural products and of N and P losses to the environment (water, atmosphere and deep soil horizons). We used the average annual exports by products from 1978 and 2006 from Oberson et al. (2013), including for MIN the period from 1978 to 1991 when MIN was not fertilized. The losses of N from the added fertilizers were calculated from the study of Bosshard et al. (2009) who studied the fate of ^{15}N labelled manure and mineral fertilizer added to the MIN and ORG treatment over a period of 3 years. The amount of N fertilizer lost to the environment was calculated from the amount of ^{15}N that could not be recovered in the soil/plant system (considering a soil depth of 50 cm) over a period of 3 years. Since MINORG received as much manure as ORG we considered that both treatments lost the same amount of N from the fertilizer to the environment. Nitrogen can also be lost from soil N reserves and not only from added N fertilizers. Since no information was available on the amount of N lost from native soil stocks to the environment (atmosphere, deep soil horizons, water), we estimated it as follows. We considered the concentrations of soil total N given in Bosshard (2007) for the layers 0-20 and 30-50 cm sampled in 1977, and the concentration of soil N measured by Oberson et al. (2013) in the 0-20 cm layer of the NON treatment. From these data we estimated the stocks of N present in the first 50 cm in 1977 and in 2006. The amount of N lost from the native stock of organic matter present in the first 50 cm of the NON treatment was calculated as the stock evaluated for 1977 minus the stock evaluated for 2006 plus the sum of N inputs (by atmospheric depositions, symbiotic fixation and the seeds) minus the exportations by crops. This yielded a loss of 10 kg N ha^{-1} $year^{-1}$ which was considered to be additive to N lost from the added fertilizers. The calculated N budget (sum of inputs – sum of outputs) was compared to the change in total soil N calculated independently by Bosshard (2007) for the 0-50 cm soil layer in the treatments MIN and ORG over the first 26 years of the DOK field experiment for a plausibility check. The P losses to the environment were not measured in this experiment. We used the P losses calculated by Prasuhn et al. (2004) for another cultivated area of northern Switzerland including similar soils and cropping systems. The total N and P outputs and budgets were calculated with equations (4), (5), (6) and (7).

The following soil analyses were conducted on soil sampled between 2004 and 2009 taken from the 0 to 20 cm soil layer in plots of rotation unit c or b, or both. The pH, total C and total N (soil sampled in 2006) have been published in Oberson et al. (2013). Other soil data have not yet been published. Anion exchange resin extractable P (as an indicator for available P) and microbial P were measured on soil samples taken in 2009, and microbial C, N on soil samples taken in 2004, using the methods described in section 2 of the supplementary materials. Organic P and total P were determined as described by Saunders and Williams (1955), on soil sampled in 2005. Total soil P content was measured on soil ashed at 550°C and extracted with 0.5 M H_2SO_4. Mineral N was the sum of N-NO_3 and N-NH_4 extracted with 1 M KCl and measured colorimetrically (soil sampled in 2004).

5. Statistics

Treatment effects on soil parameters were tested using ANOVA of the statistical analysis package SYSTAT 12 (Systat Software Inc., Chicago, USA) Molar ratios were log transformed prior to analysis, to meet the requirements of ANOVA. Likewise, nutrient concentrations were log transformed if Shapiro-Wilk (normal distribution) and/or Levene (equality of variances) tests suggested that assumptions of ANOVA were not met. Data of all field experiments underwent these same procedures, except that the block factor was always considered in the analysis of the Wagga Wagga trial (in agreement with Bünemann et al., 2006).

6. References cited in the supplementary materials

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Table S1. C, N, P concentrations in the manure used in the Saria field experiment, Burkina Faso.

Reference	C	N	P
		g kg^{-1} dry matter	
Arrivets (1974)	355	24.8	5.1
Sedogo (1981)	217	14.7	2.4
Bonzi (2002)	226.2	14.9	2.1
Kiba (2012)	191.2	16.4	3.93
Average	247.4	17.7	3.4
SEM	36.6	2.4	0.7

Table S2. Average sorghum and cowpea productivity in the Saria field experiment (Burkina Faso) for the years 1975 to 2010 expressed in tons of dry matter per ha.

Treatments		**CON**	**MINFYM1**	**MIN1**	**MINFYM2**	**MIN2**	SEM	Statistics Treatment Effect
Sorghum	grain	0.67	2.91	1.59	3.99	2.03	0.128	**
	straw	1.98	5.86	3.42	8.12	4.16	0.625	***
Cowpea	grain	0.42	0.87	0.84	0.76	0.81	0.212	***
	straw	0.83	2.49	1.83	3.61	2.29	0.383	***

Table S3. Element inputs and outputs in the Saria field experiment expressed in kg ha^{-1} $year^{-1}$.

Treatments		**CON**	**MINFYM1**	**MIN1**	**MINFYM2**	**MIN2**
Inputs with seeds[1]	C	6.1	6.1	6.1	6.1	6.1
	N	0.5	0.5	0.5	0.5	0.5
	P	0.1	0.1	0.1	0.1	0.1
Inputs with mineral fertilizers[1, 2]	N	0.0	37.0	37.0	60.0	60.0
	P	0.0	10.0	10.0	10.0	10.0
Inputs with manure[1, 2]	C	0.0	549	0.0	4768	0.0
	N	0.0	35.4	0.0	308	0.0
	P	0.0	6.8	0.0	59.1	0.0
Inputs with N_2 fixation[1]	N	11.1	18.1	18.0	20.1	16.6
Inputs of C with biomass[1, 2]	C	981	3052	1933	4140	2336
Inputs with dust rainfall[3]	N	5.1	5.1	5.1	5.1	5.1
	P	0.7	0.7	0.7	0.7	0.7
Total inputs	**C**	**987**	**3607**	**1939**	**8914**	**2342**
	N	**11.5**	**90.9**	**55.4**	**388**	**77.0**
	P	**0.8**	**17.6**	**10.8**	**69.9**	**10.8**
Output with crop products[1]	N	29.5	79.0	58.5	121.1	71.5
	P	2.9	11.9	7.0	20.4	8.4
Other losses[3, 4]	N	12.6	30.0	24.4	78.3	35.5
	P	0.00	0.00	0.00	0.00	0.00
Total outputs	**N**	**42.1**	**109**	**82.9**	**199**	**107**
	P	**2.9**	**11.9**	**7.0**	**20.4**	**8.4**

[1] derived from data from Kiba (2012), [2] François Lompo (personal communication), [3] derived from Lesschen et al., 2007, [4] derived from data from Bonzi (2002)

Table S4. Statistical correlations analysed for the Saria field experiment (n = 5 representing the 5 treatments)

Independent variable X (unit)	**Dependent variable Y (unit)**	**Equation**	**r^2**	**SE**	***p***
C inputs (kg ha^{-1} year^{-1})	N inputs (kg ha^{-1} year^{-1})	Y = 0.047 * X – 44.3	0.982	23.7	0.001
C inputs (kg ha^{-1} year^{-1})	P inputs (kg ha^{-1} year^{-1})	Y = 0.009 * X – 8.95	0.988	3.42	<0.001
C inputs (kg ha^{-1} year^{-1})	N budget (kg ha^{-1} year^{-1})	Y = 0.030 * X – 89.2	0.935	28.5	0.007
C inputs (kg ha^{-1} year^{-1})	P budget (kg ha^{-1} year^{-1})	Y = 0.007 * X – 11.7	0.964	4.65	0.003
N budget (kg ha^{-1} year^{-1})	P budget (kg ha^{-1} year^{-1})	Y = 0.219 * X + 8.21	0.990	2.40	<0.001
C inputs (kg ha^{-1} year^{-1})	Soil total C (g kg^{-1})	Y = 0.0004 * X + 1.26	0.996	0.08	<0.001
C inputs (kg ha^{-1} year^{-1})	Soil total N (mg kg^{-1})	Y = 0.039 * X + 154	0.998	6.16	<0.001
C inputs (kg ha^{-1} year^{-1})	Soil dissolved N (mg kg^{-1})	Y = 0.003 * X + 7.44	0.876	4.23	0.019
C inputs (kg ha^{-1} year^{-1})	Soil total P (mg kg^{-1})	Y = 0.014 * X + 81.1	0.927	14.3	0.008
C inputs (kg ha^{-1} year^{-1})	Soil organic P (mg kg^{-1})	Y = 0.004 * X + 9.30	0.836	7.22	0.029
C inputs (kg ha^{-1} year^{-1})	Soil inorganic P (mg kg^{-1})	Y = 0.009 * X + 71.8	0.891	12.2	0.016
C inputs (kg ha^{-1} year^{-1})	Soil resin P (mg kg^{-1})	Y = 0.003 * X + 1.35	0.957	2.45	0.004
C inputs (kg ha^{-1} year^{-1})	Soil microbial N (mg kg^{-1})	Y = 0.003 * X + 1.13	0.948	2.41	0.005

C inputs (kg ha^{-1} year^{-1})	Soil microbial P (mg kg^{-1})	Y = 0.002 * X – 0.449	0.943	1.44	0.006
Molar N :P ratio in inputs	Molar Nmic :Pmic	Y = 0.436 * X – 0.972	0.993	0.37	<0.001
Soil total C (g kg $^{-1}$)	Soil total N (g kg^{-1})	Y = 102 * X + 26.0	0.998	6.50	<0.001
Soil total C (g kg $^{-1}$)	Soil total P (mg kg^{-1})	Y = 36.6 * X + 35.5	0.916	15.4	0.010
Soil total C (g kg $^{-1}$)	Soil organic P (mg kg^{-1})	Y = 11.4 * X – 4.57	0.791	8.18	0.044
Soil total N (mg kg $^{-1}$)	Soil organic P (mg kg^{-1})	Y = 0.112 * X – 7.82	0.810	7.81	0.038
Soil microbial N (mg kg $^{-1}$)	Soil microbial P (mg kg $^{-1}$)	Y = 0.561 * X – 1.01	0.968	1.08	0.002

Table S5. Element inputs and outputs in the Wagga Wagga field experiment.

Treatments			**WL-M-C**	**WL-B-C**	**WW-B-C**	**WS-M-D**	**WS-M-C**
Inputs with seeds	C	t ha^{-1} year^{-1}	0.04	0.04	0.04	0.02	0.02
	N	kg ha^{-1} year^{-1}	2.82	2.82	1.64	1.12	1.12
	P	kg ha^{-1} year^{-1}	0.25	0.25	0.25	0.20	0.20
Inputs with mineral fertilizers[1]	P	kg ha^{-1} year^{-1}	20.0	20.0	20.0	20.0	20.0
Inputs with N_2 fixation	N	kg ha^{-1} year^{-1}	77.5	77.5	0.00	122	122
Inputs in biomass	C	t ha^{-1} year^{-1}	6.10	5.70	5.38	7.11	7.10
Inputs with dust rainfall[2]	N	kg ha^{-1} year^{-1}	5.20	5.20	5.20	5.20	5.20
	P	kg ha^{-1} year^{-1}	0.40	0.40	0.40	0.40	0.40
Total inputs	**C**	**t ha^{-1} year^{-1}**	**6.10**	**5.70**	**5.38**	**7.11**	**7.10**
	N	**kg ha^{-1} year^{-1}**	**85.5**	**85.5**	**6.84**	**129**	**129**
	P	**kg ha^{-1} year^{-1}**	**20.6**	**20.6**	**20.6**	**20.6**	**20.6**
Output with crop products[1]	N	kg ha^{-1} year^{-1}	76.1	74.6	46.9	39.8	38.3
	P	kg ha^{-1} year^{-1}	8.21	8.25	7.10	6.01	5.80
Losses related to fire[1]	N	kg ha^{-1} year^{-1}	0.00	24.2	28.2	0.00	0.00
	P	kg ha^{-1} year^{-1}	0.00	1.76	2.23	0.00	0.00
Other losses[3]	N	kg ha^{-1} year^{-1}	15.0	15.0	15.0	15.0	15.0
	P	kg ha^{-1} year^{-1}	0.00	0.00	0.00	0.00	0.00
Total outputs	**N**	**kg ha^{-1} year^{-1}**	**91.1**	**114**	**90.1**	**54.8**	**53.3**
	P	**kg ha^{-1} year^{-1}**	**8.21**	**10.0**	**9.33**	**6.01**	**5.80**

[1] data from Bünemann et al. (2006); [2] data derived from McKee and Eyre (2000); [3] data derived from Ridley et al. (2004).

Table S6. Statistical correlations analysed for the Wagga Wagga field experiment (n = 5 representing the 5 treatments)

Independent variable X (unit)	**Dependent variable Y (unit)**	**Equation**	**r^2**	**SE**	***p***
C Heenan budget (kg ha^{-1} $year^{-1}$)[1]	N Heenan budget (kg ha^{-1} $year^{-1}$)[2]	Y = 0.107 * X – 9.21	0.994	2.27	<0.001
C Heenan budget (kg ha^{-1} $year^{-1}$)	N budget (kg ha^{-1} $year^{-1}$)[3]	Y = 0.281 * X + 44.7	0.907	24.1	0.012
C Heenan budget (kg ha^{-1} $year^{-1}$)	P budget (kg ha^{-1} $year^{-1}$)	Y = 0.007 * X +13.8	0.823	0.91	0.033
C Heenan budget (kg ha^{-1} $year^{-1}$)	Soil total C (g kg^{-1})	Y = 0.029 * X + 20.6	0.857	3.12	0.024
C Heenan budget (kg ha^{-1} $year^{-1}$)	Soil microbial C (mg kg^{-1})	Y = 0.003 * X + 1.66	0.898	0.27	0.014
C Heenan budget (kg ha^{-1} $year^{-1}$)	Soil total N (g kg^{-1})	Y = 0.046 * X + 40.9	0.864	4.87	0.022
C Heenan budget (kg ha^{-1} $year^{-1}$)	Soil dissolved N (mg kg^{-1})	Y = 0.044 * X + 36.1	0.926	3.31	0.009
C Heenan budget (kg ha^{-1} $year^{-1}$)	Soil microbial N (mg kg^{-1})	Y = 0.046 * X + 40.9	0.864	4.87	0.022
C Heenan budget (kg ha^{-1} $year^{-1}$)	Soil organic P (mg kg^{-1})	Y = 0.116 * X + 160	0.873	11.8	0.020
C Heenan budget (kg ha^{-1} $year^{-1}$)	Molar C:P ratio inputs	Y = 0.420 * X + 843	0.928	31.3	0.008
Molar C:P ratio inputs	Molar soil C:N ratio	Y = - 0.024 * X + 35.0	0.981	0.38	0.001
Molar C:P ratio inputs	Molar soil C:P ratio	Y = 0.254 * X – 109	0.780	15.7	0.047
Molar C:P ratio inputs	Molar soil N:P	Y = 0.024 * X – 13.3	0.820	1.32	0.034

Soil total C (g kg $^{-1}$)	Soil total N (g kg^{-1})	Y = 0.101 * X -0.434	0.996	0.05	<0.001
Soil total C (g kg $^{-1}$)	Soil organic P (mg kg^{-1})	Y = 3.96 * X + 77.8	0.971	5.63	0.002
Soil total N (g kg $^{-1}$)	Soil organic P (mg kg^{-1})	Y = 39.2 * X + 94.7	0.980	4.69	0.001
Soil microbial C (g kg $^{-1}$)	Soil microbial N (mg kg^{-1})	Y = 0.121 * X – 8.97	0.987	1.57	<0.001
Soil microbial N (g kg $^{-1}$)	Soil microbial P (mg kg^{-1})	Y = 0.217 * X – 0.676	0.872	1.10	0.020

[1] C Heenan budget: C soil budget system derived from Heenan et al. (2004); [2] N Heenan budget: N soil budget system derived from Heenan et al. (2004); [3] N budget: N soil budget system calculated in this study

Table S7. Element inputs and outputs expressed in kg ha^{-1} $year^{-1}$ in the DOK field experiment

Treatments		**NON**	**MIN**	**ORG**	**MINORG**
Inputs with seeds	N	2.67	2.67	2.67	2.67
	P	0.38	0.38	0.38	0.38
Inputs with manure and mineral fertilizers[1]	N	0.0	93.0	107	155
	P	0.0	30.0	27.0	41.0
Inputs with N_2 fixation[1, 2]	N	47.0	56.7	77.9	60.9
Inputs with dust rainfall	N[3]	32.0	32.0	32.0	32.0
	P[4]	0.40	0.40	0.40	0.40
Total inputs	**C[5]**	**0.96**	**1.41**	**2.40**	**2.81**
	N	**81.7**	**184**	**219**	**250**
	P	**0.78**	**30.8**	**27.8**	**41.8**
Output with crop products[1]	N	144	218	207	248
	P	19	33	32	38
Other losses	N[3, 6]	10.0	48.0	62.0	62.0
	P[7]	0.80	0.80	0.80	0.80
Total outputs	**N**	**154**	**266**	**269**	**310**
	P	**19.8**	**33.8**	**32.8**	**38.8**

[1] data derived from Oberson et al. (2013); [2] data derived from Oberson et al. (2007); [3] data from Bosshard (2007); [4] data from Spiess (2011); [5] data from Leifeld et al. (2009); [6] data from Bosshard et al. (2009); [7] data from Prasuhn et al. (2004).

Table S8. Statistical correlations analysed for the DOK field experiment (n = 4 representing the 4 treatments)

Independent variable X (unit)	**Dependent variable Y (unit)**	**Equation**	**r^2**	**SE**	***p***
C Leifeld budget (t ha^{-1} $year^{-1}$)	Soil total C (g kg^{-1})	Y = 10.6 * X + 14.4	0.979	0.22	0.011
C Leifeld budget (t ha^{-1} $year^{-1}$)	Soil total N (g kg^{-1})	Y = 1.02 * X + 1.78	0.921	0.04	0.040
C Leifeld budget (t ha^{-1} $year^{-1}$)	Soil organic P (mg kg^{-1})	Y = 253 * X + 458	0.960	7.13	0.020
C Leifeld budget (t ha^{-1} $year^{-1}$)	Soil microbial P (mg kg^{-1})	Y = 62.9 * X + 47.2	0.853	3.61	0.076
C Leifeld budget (t ha^{-1} $year^{-1}$)	Molar soil C :Po ratio	Y = 27.2 * X + 87.9	0.916	1.14	0.043
P budget (kg ha^{-1} $year^{-1}$)	Soil total P (mg kg^{-1})	Y = 8.08 * X + 729	0.991	8.59	0.004
P budget (kg ha^{-1} $year^{-1}$)	Soil inorganic P (mg kg^{-1})	Y = 5.61 * X + 325	0.952	14.3	0.024
Soil total C (g kg^{-1})	Soil total N (g kg^{-1})	Y = 0.095 * X + 0.406	0.924	0.04	0.038
Soil total C (g kg^{-1})	Soil organic P (mg kg^{-1})	Y = 24.0 * X + 113	0.993	2.91	0.003
Soil total N (g kg^{-1})	Soil organic P (mg kg^{-1})	Y = 236 * X + 33.3	0.950	8.00	0.025

[1] C Leifeld budget: C soil budget system derived from Leifeld et al. (2009)

Figure S1. Cowpea and sorghum grain yields in the cowpea sorghum rotation in the Saria field experiment between 1975 and 2010. Note the different y scales.