Redistribution of soil phosphorus from grassland to cropland in an organic dairy farm

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Abstract

Limited knowledge is available on inner farm nutrient transfer from organic grassland to arable land in organic farms. This study quantifies the phosphorus (P) mobilization of permanent grassland and different arable crops for inner farm P transfer and discusses in how far P reserves in grassland soils can be a component of sufficiency P management in organic farming. A North German organic dairy farm with sufficient soil P supply is analyzed. Over three years its P balance showed an average deficit of 7.9 kg ha^{-1} yr^{-1} in permanent grassland and 10.9 kg ha^{-1} yr^{-1} in arable land. Maize (30.5 kg P ha^{-1} yr^{-1}), grass-clover (23.9 kg P ha^{-1} yr^{-1}) and mixed faba bean and oats (19.8 kg P ha^{-1} yr^{-1}) had the highest P uptake in cropland. At grassland, grazing intake of P by livestock was 15.9 kg P ha^{-1} yr^{-1} and via storage feed and manure it directly fed arable land with 64 kg P yr^{-1} (average 1 kg P ha^{-1} yr^{-1}). Especially on grassland, soil P mining does not endanger soil fertility yet, according to sufficient available P-contents in the soils (CAL-extract averages [mg 100 g^{-1} P]: grassland 14.7, arable land 6.7). Generally, the inclusion of unexploited grassland sites with high soil P contents in farm nutrient flows (via feed conserves for livestock or biogas) would address unused soil P reserves for redistribution.

Keywords: *pasture, phosphorus-cycle, P-scarcity, P-balances, grazing, organic farming*

Zusammenfassung

Umverteilung von Bodenphosphor aus Dauergrünland zu Ackerland in einem ökologischen Milchviehbetrieb

Zum Nährstofftransfer von Grünland zu Ackerland in ökologischen Betrieben gibt es nur wenige Untersuchungen. Diese Fallstudie eines norddeutschen ökologischen Milchviehbetriebs mit ausreichenden Phosphor (P)-Reserven in Böden quantifiziert die P-Mobilisierung aus Böden von Dauergrünland und von Ackerland für die innerbetriebliche P-Umverteilung detailliert. Möglichkeiten der Steigerung dieses Flusses werden vor dem Hintergrund schwindender weltweiter P-Reserven diskutiert. Die mittleren P-Bilanzen in Dauergrünland und Ackerland im untersuchten Betrieb über drei Jahre waren negativ (-7,9 bzw. -10,9 kg ha^{-1} Jahr^{-1}). Bei den Ackerkulturen hatten Mais (30,5 kg P ha^{-1} Jahr^{-1}), Rotkleegras (23,9 kg P ha^{-1} Jahr^{-1}) und Ackerbohnen/Hafer-Gemenge (19,8 kg P ha^{-1} Jahr^{-1}) die höchste P-Aufnahme. Auf Grünland, wurden 15,9 kg P ha^{-1} Jahr^{-1} durch Beweidung aufgenommen. 64 kg P Jahr^{-1} (ca. 1 kg P ha^{-1}) wurden durch Futterkonserven von Grünland über die Wirtschaftsdünger auf das Ackerland umverteilt. Vor allem in Grünland sind die negativen P-Bilanzen im untersuchten Betrieb derzeit noch unproblematisch für die Bodenfruchtbarkeit, da ausreichend pflanzenverfügbares P vorhanden ist (mittlere P Gehalte in CAL-Extrakt [mg 100 g^{-1} P]: Grünland 14.7, Ackerland 6.7). Generell könnten z. B. bisher ungenutzte und möglicherweise hohe P-Vorräte bisher wenig genutzter Grünlandflächen durch Intensivierung der Biomasseabfuhr für die Tierfütterung oder Biogasgewinnung adressiert und umverteilt werden.

Stichworte: *Grünland, Phosphor-Kreislauf, P-Knappheit, P-Bilanz, Beweidung, Ökologischer Landbau*

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1 Introduction

Phosphorus (P) is a non-renewable resource and an essential plant nutrient. Accumulations of fertilizer P in soils have to be avoided to increase fertilizer efficiency and soil reserves should be addressed to save limited worldwide P resources (Cordell et al., 2009). In Western Europe, conventional crop production historically relied on high P fertilizer application rates and considerable soil reserves accumulated (Barberis et al., 1996; Schröder et al., 2011; Tóth et al., 2014). For this reason, organic farmers today often neglect the import of P fertilizers in arable crops and in grassland. Supported by the principles of organic production (Council Regulation (EC) 834/2007), they rely on the soil ecosystem to nourish their plants and also on the backflow of nutrients with wastes from animal or plant production mostly from their own farms. Without fertilizer imports soil reserves must cover balance deficits. In this situation biological processes are of high importance for a successful P acquisition (Richardson et al., 2009; Simpson et al., 2011).

As phosphate diffusion is limited in soils (Schachtman et al., 1998), root density and distribution are very important factors for physical access to the soil volume and for phosphate acquisition (Ho et al., 2005; Vance, 2001). Microbial activity in the root zone and mycorrhiza further enhance biological P turnover (Oberson and Joner, 2005; Whitehead, 2000; Smith and Read, 2010). In grassland, different plant species, high rooting density and the permanent vegetation cover, as well as droppings of grazing livestock, might favor a continuous P uptake from soil reserves. The importance of biological activation of P in grassland is described in various studies. For example, biological uptake and translocation of P to the soil surface with plant material from deeper soil layers is reported from an analysis of grassland soils along a precipitation gradient in the Great Plains (USA) (Ippolito et al., 2010). Also, sufficient P supply in the topsoil of extensive Australian grassland farms with limited available P reserves and without fertilizer input is explained by P cycling upwards from the subsoil by deep rooting perennial-grassland plants (Cornish, 2009).

Nutrient mining in grassland and the transfer of its nutrients to arable land made grassland historically the 'mother of arable land', but at the same time adequate fertilization measures are demanded to cover deficits (Klapp, 1971). Worldwide 40.5 % of the terrestrial areas are grassland (excluding Greenland and Antarctica, Suttie et al., 2005). In Germany grassland constitutes 28 % of agricultural land and represents 56 % of the organic farmland (Federal Statistical Office, 2014). As 67 % of German organic farms have both arable land and permanent grassland (Rahmann and Nieberg, 2005) plant nutrient redistribution from grassland to arable land is of special interest here.

The assessment of nutrient flows in farms is an important prerequisite for an improved nutrient management (Oenema et al., 2003). But there are only a small number of detailed studies available on P flows in organic farms under inclusion of grassland and with grazing animals. For instance, Steinshamn et al. (2004) calculated nitrogen (N) and P flows in a Norwegian mixed dairy farm. They found negative overall soil surface balances of 6.3 kg P ha^{-1} yr^{-1}. Fystro (2014) analyzed N, P, potassium (K) and magnesium (Mg) cycling in Norwegian organic grassland dairy farms. Here additional P input to the intensively used inner farm area is generated from feed imports from remote grassland in the hills that was defined to be outside the system boundary. But most of the P is imported via concentrates and outweighs the exports via milk. Möller (2009) analyzed the P, N, K and Mg flows in an organic dairy system. Due to low N-efficiency when applying livestock manures in legume rich grassland, he suggests the redistribution of nutrients originating there via manures to N-demanding arable crops under consideration of adequate P and K loads. By inference P, K and Mg should be preferably applied in mineral form in grassland, which traditionally has high legume proportions and biological N fixation in organic farms. Due to higher K/P-relations in grassland based feedstocks compared to those from arable crops, on farm level this would indicate a relatively higher transfer of K when P is used as reference for the manure application in cropland. On 26 German organic farms, farm gate deficits of -3 kg P ha^{-1} yr^{-1} (range -14 to 4 kg P ha^{-1} yr^{-1}) including grassland were found (Haas et al., 2007). For Austria farm gate P-balances from -1.9 to 7.8 kg P ha^{-1} yr^{-1} were observed (Lindenthal, 2000). In the Swedish research farm Öjebyn, barn balances of 0.5 kg P yr^{-1} cow^{-1} in organic as well as in conventional farming (Gustafson et al., 2007), and field balances of 1 and 5 kg P ha^{-1} yr^{-1} respectively, were found (Bengtsson et al., 2003). The farm includes a small amount of pasture, which is excluded from specific calculations. The two latter types of analysis do not offer possibilities to analyze and improve inner farm nutrient flows like nutrient transfer between arable land and grassland. Thus, limited knowledge is available on P flows in organic farms with inclusion of grassland and livestock. Therefore, the objective of the current study is

(1) to quantify P mobilization and the inner farm P transfer at a mixed organic dairy farm in a case study under detailed inclusion of grassland, grazing animals and arable feedstock in North Germany and
(2) to discuss whether grassland can be a component of sufficiency P management in organic farming in the short run.

2 Material and Methods

2.1 Experimental site/ System under study

The dairy farm of the experimental station of the Thünen Institute of Organic Farming, Trenthorst (116 ha), was used as geographical system boundary to determine P flows in the time period between 2010 and 2012. The farm is located in Northern Germany (53°46' N, 10°30' E; 10 to 43 m asl) and was converted from conventional to organic farming in 2001. Mean annual precipitation is 706 mm and mean annual temperature is 8.8 °C (1978 to 2007). For the last decades the grassland can be seen as mostly intact. Solely two plots were subjected to sward cultivating but have not been ploughed during the last five years, meaning the grassland can be defined as 'permanent grassland'. The soils of grassland and arable land are characterized as Cambisols and Luvisols with sandy loamy texture. The mean humus content in the topsoil was 2.2 % (n = 76) for arable land (0 to 30 cm) and 5.3 % in grassland (n = 24, 0 to 10 cm) between 2010 and 2012. Soil properties are listed in Table 1. The plant available P fraction was determined as P (CAL) (100 ml CAL solution (0.1 m Calcium acetate, 0.1 m Calcium lactate, and 0.3 m acetic acid; pH 4.1) and 5 g soil are shaking for 2 h, photometrical P determination) (Schüller, 1969). According to official fertilizing recommendations, the P content of the arable land was categorized as sufficient and of permanent grassland as high (Landwirtschaftskammer Niedersachsen, 2011). The farm did not import organic or mineral P fertilizer since 2001.

The livestock units (1 LU = 650 kg live weight) of the dairy cows and their followers changed during the first year, 2010, from 164.4 LU to 155.7 LU. The year 2011 ended with 136.5 LU and increased to 145.5 LU in 2012. To provide forage and concentrates for the cattle, 62 ha arable land were cultivated with a 6-year crop rotation which consisted of grass-clover (1) – grass-clover (*Lolium perenne, Phleum pratense Trifolium pratense*) (2) – maize (*Zea mays*) (3) – wheat (*Triticum aestivum*) (4) – faba beans (*Vicia faba*) / oats (*Avena sativa*) (5) – triticale (*Triticosecale*) (6).

The permanent grassland (54 ha) with a mixture of grasses, legumes (mostly *Trifolium repens*) and herbaceous plants was used for grazing and storage feed production (silage, hay). A total of 33 ha of grassland, located next to the stable, are divided into 13 plots. In the reference period 2012 they were managed by rotational grazing with duration of 2 to 10 days (7 hours a day from 24 Apr. to 7 Oct.). Three of these plots were also used for a first cut for silage production on May 13th. Another 21 ha remote grassland were used more extensively with full time grazing of young stock, heifers and dry cows (6.8 ha for 205 days) and for harvesting of storage feed (14.2 ha). Additional feed was imported from farm areas outside the dairy crop rotation. No changes in feed stock were assessed in the mass balances for the examined period. Cattle had free access to licking blocks and water. Straw was used as bedding material. Calves were fed with whole milk in the first thirteen weeks. Actual weight of feed supply for the cattle in the stables was used for the calculations.

Due to joint storage facilities and farm management decisions, livestock manure was partly exported from the dairy section to other farm parts.

2.2 Mass flow calculation

Equations to calculate mass flows for the P farm balance are shown in Table 2. Phosphorus contents of materials were based on site specific analyses or reference values (Table 3).

Grazing intake and storage feed yields were analyzed in a detailed field study in 2012 (Ohm et al., 2014). Plot-specific pasture intake was quantified and results were also used as representative for 2010 and 2011. For the few full-time grazing cows in dry period (avg. 14 cows per year), at the

Table 1

Soil properties of arable land (0 to 30 cm) and permanent grassland (0 to 10 cm) (Trenthorst, 2010 to 2012)

utilization	n	pH			P_{CAL} [mg 100 g^{-1}]			K_{CAL} [mg 100 g^{-1}]			Mg ($CaCl_2$) [mg 100 g^{-1}]		
		mean	SD	TV	mean	SD	TV	mean	SD	TV	mean	SD	TV
arable	80	6.4	0.3	> 6.3	6.7	1.6	> 5	12.3	3.1	> 11	10.7	1.9	> 6
grassland	24	5.3	0.2	> 5.6	14.7	1.5	> 5	11.2	4.0	> 11	20.7	3.1	> 14

SD, Standard deviation; TV, threshold value for sufficient soil reserves (Landwirtschaftskammer Niedersachsen, 2011)

Table 2

Equations to calculate mass flows in the P farm balance

P flow = mass flow * specific P content	[1]
Pasture intake = (DM biomass before grazing – DM biomass after grazing) + daily growth rate * days of grazing	[2]
Manure export = Total fodder + litter – milk – net production of live weight – manure output inside the boundaries	[3]
Net production of live weight = weight of sold animals + change in herd size	[4]
Soil P balance grassland = excretion on pasture + slurry + atmospheric deposition – grazing – storage food – losses	[5]
Soil P balance arable land = stable manure + slurry + seeds + atmospheric deposition – crop yield – losses	[6]
P Farm balance = Input – Output = mineral fodder + imported storage fodder + seeds + atmospheric deposition – milk – net production of live weight – manure export – losses	[7]

Table 3

P content of different farm materials, atmospheric P deposition and soil losses.

Parameter	Year	P content	Comment	Source
Permanent grassland	2012	3.92 g kg^{-1} DM	± 0.6, n = 17	Farm specific, different cuts
Grass-clover	2010	3.10 g kg^{-1} DM	± 0.2, n = 2	Farm specific, different silos
	2011	3.20 g kg^{-1} DM	± 0.4, n = 3	
	2012	3.00 g kg^{-1} DM	± 0.3, n = 5	
Maize silage	2010	2.80 g kg^{-1} DM	± 0.4, n = 4: 2011 and 2012	Farm specific
	2011	3.10 g kg^{-1} DM	MV of 2.9 and 3.3	
	2012	2.45 g kg^{-1} DM	MV of 2.4 and 2.5	
Triticale	2010-2012	2.78 g kg^{-1} DM	± 0.096, n = 4, 2005	Resident experimental data† of rye
Spring wheat grain	2011	3.34 g kg^{-1} DM	± 0.17, n = 8: 2004 and 2005	Resident experiment†
Winter wheat grain	2010, 2011	3.31 g kg^{-1} DM	± 0.14, n = 8: 2004 and 2005	Resident experiment†
Faba bean grain	2010-2012	6.75 g kg^{-1} DM	2002-2005	Resident experiment‡
Oats grain	2010-2012	3.6 g kg^{-1} DM	2002-2005	Resident experiment‡
Triticale straw	2010-2012	0.9 g kg^{-1} DM	± 0.11, n = 4, 2005	Resident experimental data† of rye
Winter wheat straw	2010, 2011	0.65 g kg^{-1} DM	± 0.28, n = 4, 2005	Resident experiment†
Spring wheat straw	2011	0.5 g kg^{-1} DM	± 0.09, n=8: 2004 and 2005	Resident experiment†
Faba bean straw	2010-2012	1.3 g kg^{-1} DM		Characteristic values§
Oat straw	2010-2012	1.1 g kg^{-1} DM		Characteristic values§
Milk	2010-2012	0.97 g kg^{-1} FM	± 0.09, n = 24	Swedish study¶
Animal fresh mass	2010-2012	7.5 g kg^{-1} FM		France Study#
Solid manure	2010- 2011	1.01 g kg^{-1} OS	2009: 1.004 and 2010: 1.017	Farm specific
Slurry	2010	0.154 g kg^{-1} OS	± 0.02; n = 3	Farm specific
	2011	0.151 g kg^{-1} OS	± 0.03, n = 6: 2010 and 2012	
	2012	0.148 g kg^{-1} OS	± 0.045, n = 3	
Wheat, oat and triticale seeds	2010-2012	3.5 g kg^{-1} FM		Characteristic values used for imported seeds§
Faba bean seeds		4.7 g kg^{-1} FM		
Maize seeds		3.3 g kg^{-1} FM		
Grass seeds		3.0 g kg^{-1} FM		
Clover seeds		6.4 g kg^{-1} FM		
Atmospheric deposition	2010-2012	0.2 kg ha^{-1}		LLUR††
Soil losses	2010-2012	0.3 kg ha^{-1} a^{-1}		Swedish study‡‡
Mineral feed	2010-2012	20 g kg^{-1} OS	Mineral feed	Supplier specification
Lick minerals	2010-2012	40 g kg^{-1} OS	Rindereimer, eco certified	Supplier specification

† Paulsen and Schochow, 2007

‡ Böhm, 2007

§ Kape et al., 2008 (Organic characteristic values of Ministry of Agriculture in Mecklenburg-Vorpommern)

¶ Gustafson et al., 2007

Nesme et al., 2012

†† LLUR (Landesamt für Landwirtschaft, Umwelt und Ländliche Räume Schleswig Holstein), 2014

‡‡ Modin-Edman et al., 2007

DM= Dry matter, FM= fresh matter, OS= Original substance, MV= mean value

remote plots dry matter (DM) intake was estimated at 10 kg d^{-1} cow^{-1} (Jeroch et al., 1999). According to Knowlton and Herbein (2002) livestock excretes 50 to 80 % of P intake. In a study with Holstein dairy cows, a low P diet with 0.31 % P was tested, leading to 45 % P digestibility (Wu et al., 2001). Due to comparable feedstuff concentrations in Trenthorst (mean of 0.33 % P in the ration) this value was used for calculating the net P export from the grazed plots. Total sold animals, sold farming products, actual forage, grain and straw harvests and manure application were taken from the farm database. Harvest yields were measured with a drive-on scale and corrected to the actual dry matter contents in storage (grains 85 to 88 %, straw 84 to 85 %, grass-clover silage 35 %, haylage 70 %, hay 86 %, maize 28.5 to 32.1 % DM each).

Phosphorus input from seeds was calculated according to the concentrations in Table 3 and the following seed densities (fresh matter = FM, 86 % DM): 220 kg wheat, 180 kg triticale, faba bean 70 kg in combination with 170 to 180 kg of oats, 20 kg maize and for the grass-clover plots 15 kg in proportion of 70 % grass seeds and 30 % clover seeds per ha.

The feed flow into the stable, also for mineral feed and lick mineral, was taken from the actual feeding lists. Manure, litter, feeding rests and storage residues were transferred to the manure storage. No P losses were assumed between stable and manure storage.

Herd management data of the farm based on regularly scheduled weighing of each animal, as well as departure dates and weights, provided data of net live weight production. Milk exports were taken from yearly delivery accounts. Also milk supply to the calves was specified by the actual feeding lists for inclusion in the internal farm circle of P. Phosphorus flows entering the manure cycle were determined based on P input in the stable and P output in animal products (milk, weight gains).

The atmospheric deposition of P given by official values for the farm region is 0.2 kg ha^{-1} yr^{-1} (LLUR, 2014). Only minor losses of P from the soil by leaching had to be considered for farm land (Cooke and Williams, 1973; White, 2006) and low P losses through surface runoff and erosion were anticipated on the site under study due to the plain nature of the area. Therefore P losses from the soil by leaching and run-off were estimated to be 0.3 kg P ha^{-1} yr^{-1}. This is in line with a Swedish study (Modin-Edman et al., 2007) and with mean estimated losses from German soils (Scheffer and Schachtschabel, 2010).

Soil P balances of grassland and arable land (Table 2, Eq. [5, 6]) indicated the net change of P soil reserves. The farm balance is calculated by inputs minus outputs (Table 2, Eq. [7]). Drinking water for the cows was not considered because P contents were below the detection limit. If concentrations had been set to a threshold of 1 mg L^{-1}, 3,000 m^3 drinking water per year for the cows would have accounted for only for 3 kg P yr^{-1}. In the farm balance outputs crossing the system boundary were: sold milk, net production of live weight, manure export and run off. The software e!sankey 3.2 (IFU Hamburg, Germany) was used to visualize results.

3 Results

In grassland, grazing management regimes on the plots differed in intensity and frequency, resulting in high ranges in dry matter (DM) yields (Figure 1) and in high differences in P in plant material that is harvested or grazed between the plots (mean intake by grazing 15.9 kg P ha^{-1} yr^{-1} ± 2.7; range 9.5 - 20.7 kg P ha^{-1} yr^{-1}; mean export per cut by harvesting 6.9 kg P ha^{-1} yr^{-1} ± 2.9, range 3.5 to 12.5 kg P yr^{-1}; ± values are characterizing the standard deviations). Phosphorus mobilization potential from the grassland soils (including applied P from organic fertilizers and animal droppings) is characterized by plant uptake of up to 23.4 kg P ha^{-1} yr^{-1}. In the study this maximum value was reached on plot 1105 with herbage taken up by grazing livestock and exported by additional harvests (Figure 1). The total estimated grazing intake of cows and young stock on the farm was 160,062 kg DM yr^{-1} (Table 4). From the total amount of grazed P (627 kg yr^{-1}), 282 kg P yr^{-1} (8.62 kg P ha^{-1} yr^{-1}) were removed from the fields with milk and meat, and 345 kg were excreted at pasture. Considering also manure imports and harvest exports the mean soil P balance for grassland was -429 kg yr^{-1} or -7.9 kg ha^{-1} yr^{-1} (Table 4) which means a P stock reduction in soil.

The soil P balance of arable land resulted in -676 kg P yr^{-1} or -10.9 kg P ha^{-1} yr^{-1} (Table 5). Slurry was brought out every

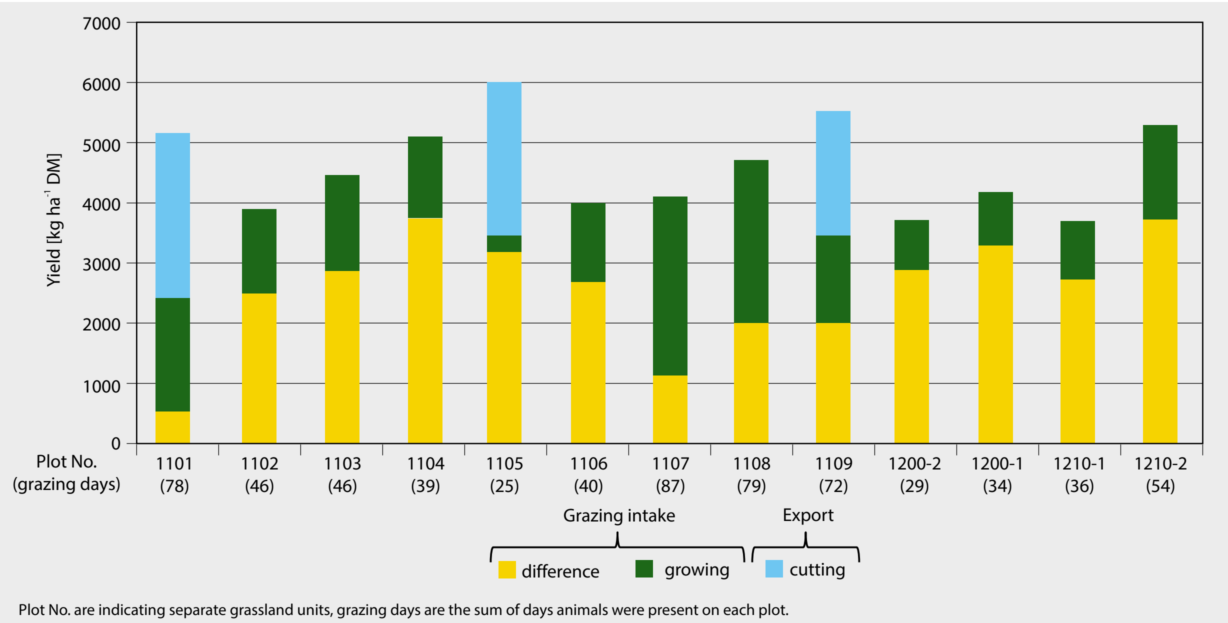

Figure 1
Herbage yields by grazing (Table 2, Eq. [2]) and cutting in pasture plots neighbouring the stable, Trenthorst 2012.

Table 4
Data basis and calculation of the average soil P balance of grassland (Trenthorst, 54 ha, 2010 to 2012).

Soil P balance grassland		Mass flow				P flow	
		Total [kg yr^{-1}]	SD [kg yr^{-1}]	[kg ha^{-1} yr^{-1}]	SD [kg ha^{-1}]	Total [kg yr^{-1}]	[kg ha-1 yr^{1}]
=	Excretion	-	-	-	-	345	6.4
+	manure application	501,427 FM	± 597,123	9,286 FM	-	75	1.4
+	Atmospheric deposition	-	-	-	-	11	0.2
	Grazing intake neighbouring plots (33ha)	*131,362 DM*	-	*3,980 FM*	*± 751*	*514.9*	*†15.6*
	Grazing intake remote plots (6.8 ha)	*28,700 DM*	-	*4,221 FM*	-	*112.5*	*16.5*
-	Grazing‡ (total) (39.8 ha)	160,062 DM	-	4,046 DM	± 724	627	11.6
-	Storage food (23.3 ha)	55,408 DM	-	2,422 DM	± 577	217	4
-	Losses (runoff, leaching)	-	-	-	-	16	0.3
Balance (Table 2, Eq. [5])						**-429**	**-7.9**

† Italic numbers: based on actual grazed area
‡ grazing and storage food data: year 2012 as representative

year (mean 2,166,341 kg FM), solid manure was applied at some of the plots only in 2010 (281,798 kg FM) and 2011 (254,936 kg FM). P exports varied between crops and years. The mean P export of the different crops was in descending order [kg P ha^{-1} yr^{-1}]: Maize (silage) 30.4 ± 11.1, range 17.7 - 38.2, grass-clover 23.7 ± 6.3, range 17.3 - 32.4, faba bean and oats in mixed cropping (grains) 19.4 ± 8.5, range 10.3 - 27.1, wheat and triticale (grains) 9.1 ± 3, range 5.5 - 14.3, and cereal straw 1.25 ± 0.6, range 0.8 - 2.4. Straw of oats and faba beans as well as cereal straw in the headlands remained on the plots. For calculation of the P redistribution from soil-to-plant-back-to-soil with mulched clover grass no yields were determined. They were estimated to 4 kg P ha^{-1} according to the three lowest grass clover yields per cut found in the study. Due to their uncertainty the values of on-site recycling of P via mulching were not visualized. In total grassland and arable land had a mean P balance of -1,105 kg yr^{-1}.

The farm P flow is visualized in Figure 2 according to the values from Table 3 to 6 and gives an impression of the demand and transfer of P in and between the different farm segments. The boundary around the cycle indicates the farm gate for bought inputs (imported fodder, seeds) and outputs (milk, net production of live weight, exported manure). Fodder (imported and from farm own origin, from arable land and grassland), grazed grass and milk for calves were the sources for P input into the stable. In the stable the

Table 5
Data basis and calculation of the average soil P balance of arable land (Trenthorst, 62 ha, 2010 to 2012).

Soil P balance arable land		Mass flow			P flow	
		Total [kg yr^{-1}]	SD [kg yr^{-1}]	[kg ha^{-1} yr^{-1}]	Total [kg yr^{-1}]	[kg ha^{-1} yr^{-1}]
=	Stable manure	178,911 FM	± 155,522	2,886 FM	181	2.9
+	Slurry	2,166,341 FM	± 1,092,222	34,941 FM	329	5.3
+	Seeds	710 FM	± 30	11.4 FM	28	0.45
+	Atmospheric deposition	-		-	12	0.2
	Grass-clover silage (21 ha)	*163,639 DM*	*± 46,852*	*7,705 DM*	*504.2*	*23.7*
	Maize silage (10 ha)	*113,324 DM*	*± 54,550*	*10,998 DM*	*313.2*	*30.4*
	Grain (total, seeds) (30.5 ha):	*96,423 DM*	*± 27,955*	*3,279 DM*	*365.7*	*12.5*
	Oats and beans (9.9 ha)	*34,859 DM*	*± 15,779*	*3,798 DM*	*173.1 (193.4) †*	*19.4*
	Triticale (10.4 ha)	*28,392 DM*	*± 8,170*	*2,731 DM*	*80.5 (78.8) †*	*7.6*
	Wheat (10.2 ha)	*33,172 DM*	*± 6,047*	*3,309 DM*	*112.1 (106.8) †*	*10.7*
	Straw (triticale, wheat) (19 ha) ‡	*28,413 DM*	*± 570*	*1,505 DM*	*24*	*1.25*
-	Crop yield (total)	401,800 DM		-	1,207	19.5
-	Losses (run of, leaching)	-		-	19	0.3
Balance (Table 2, Eq.[6])					**-676**	**-10.9**

† Based on total DM yields (based on avg. DM yields),
‡ without headlands,
FM, DM: Fresh matter, dry matter, SD: Standard deviation.

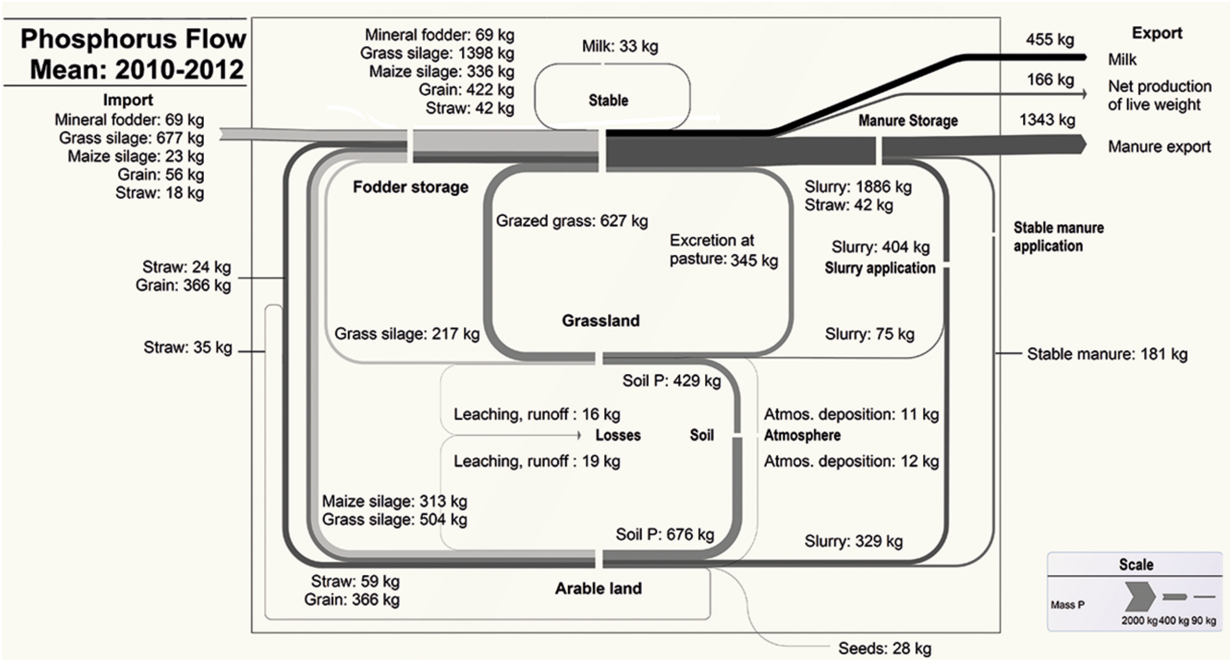

Figure 2

Mean yearly phosphorus imports and exports at the farm gate and internal flows between and within different farm parts of the dairy farm Trenthorst between 2010 and 2012 based on practice data.

fodder was transferred into animal products and manure. One part of the manure was redistributed to the arable land and grassland. Another part was exported to farmland outside the dairy system. Biomass products from arable land and grassland were fodder for cows. P flows via the soil are shown in the middle of Figure 2: P from the soil buffered the gap between P in biomass export and natural losses and P in manure and atmospheric input at arable land and grassland. The quantities of P that are flowing in the different farm parts are described in the following.

Table 6

Data basis and calculation of the P farm balance (Trenthorst, 2010 to 2012).

	P balance farm	Mass flow		P flow
		Mean [kg yr^{-1}]	SD [kg yr^{-1}]	kg yr^{-1}
=	Mineral fodder	2,617 FM	± 233	69
+	Imported storage fodder and straw	265,868 DM	± 76,224	774
+	Seeds (62 ha)	710 FM	± 30	28
+	Atmospheric deposition (116 ha)	-	-	23
-	Milk	469,086 FM	± 19,655	455
-	Net production of live weight	22,091 FM	± 1,015	166
-	Manure export	-	-	1,343
-	Losses (run of, leaching) (116 ha)	-	-	35
Balance (Table 2, Eq. [7])				**-1,105**

FM, fresh matter; DM, dry matter; SD, standard deviation

Altogether, the farm balance (Table 6, Figure 2) showed total P outputs of 1,964 kg yr^{-1}. The sum of total inputs from imports and depletion of P soil reserves was 1,976 kg P yr^{-1}. Net losses from atmospheric deposition and leaching were 12 kg P yr^{-1}. The export of meat was 75,722 kg live weight during the three-year period. The change in herd size from 164.4 LU to 145.5 LU accounted for 9,450 kg. Therefore, the net production of live weight was 66,272 kg in three years, which corresponds to 166 kg P yr^{-1}. Another 455 kg P a^{-1} were exported in form of sold milk (Table 6). The P flows from the fed biomass to manure in storage accumulated to 1,887 kg P yr^{-1}. Another 42 kg P yr^{-1} in the manure originated from straw that was used as bedding material. Only 585 kg P (30.3 %, Figure 2) from this amount were recycled within the dairy crop rotation under the management regime of the farm under study (87.2 % at arable land, 12.8 % at grassland). Assuming no unaccounted losses the mean P output at the stable gate was in sum 2,894 kg P per year with milk, meat and manure for storage and excretion at pasture (Figure 2). This P originated from stable inputs of 41.7 % with forage and concentrates from farm own production in the arable crop rotation (Table 5), of 21.7 % from grazing intake and bound in animal products, of 7.5 % with roughage conserves from permanent grassland (Table 4), and of 2.4 % with purchased mineral feed additions. Another 26.7 % of the P was imported with feedstuff and litter (Table 6) from plots outside of the defined system boundary. These were mainly clover-grass silage and small amounts of maize silage, grains and straw (Figure 2). In the years 2010, 2011, and 2012 an internal flow of 32.9 kg, 21.4 kg and 43.8 kg P with whole milk was calculated to fed the calves, respectively. Imported seeds, mineral feed additions and imported feed and litter totaled 871 kg P yr^{-1} as inputs at the system boundary. Focused only on feedstuff (without calves' milk), grassland directly accounted for 29.2 % of the P supplied to the cattle, on average (Figure 2). In quantifying the redistribution of P from grassland to arable land by the material flows 217 kg P yr^{-1} were transferred from grassland to the stable as conserved feed. From this amount, 78 kg P yr^{-1} were converted into animal products. A total of 139 kg P yr^{-1} ended up in manure, from which 75 kg P yr^{-1} were reapplied on grassland. The difference of 64 kg P yr^{-1} (which is 29.4 % of the P from storage fodder from grassland) must have been covered by soil reserves of grassland. It is transferred to arable land via feed conserves and manure. On average this means that on the farm under study grassland (54 ha) serves arable land (62 ha) with ~1 kg P ha^{-1} yr^{-1}.

4 Discussion

4.1 Uncertainties in balance calculation

Any material balance of farm flows under practical conditions must deal with uncertainties and assumptions. For this study all sub-processes have a consistent P-balance leading to a reliable balance on farm level. The P concentrations in plant materials highly influence the calculated P flows, especially in high yielding crops. Uncertainties might be caused by the settings for P concentrations, digestibly of feed, mass determinations and temporal system boundaries for storage of feed or manure. Due to the important effects of sampling and nutrient concentration in plants and manure, P flows should preferably be based on farm specific results. Also the three years studied showed high variability in P flows along with varying annual yields and differences in manure management and exports (Table 5). Representative periods should be used for calculations of long term trends in inner farm P transfer. Even with uncertainties and variability, e. g., in P contents of materials, the analysis of nutrient farm flows is an important step in order to address and balance out spatial differences in P soil reserves on farms by cropping management and manure redistribution

4.2 Grassland in farm P cycle

Grazing animals indirectly reduced the pressure of the forage production on arable land by 627 kg P yr^{-1} (10.1 kg P ha yr^{-1}) due to feed stuff from grassland compared to hypothetic scenarios solely producing forage crops in arable rotations. Compared to Swedish organic dairy farms (Gustafson et al., 2007) P concentration in grassland plants in this study is high, likely caused by high P level in the soil. A depletion of P in soil through continuous mining would probably lead to lower P concentrations in plants in the near future. How long grassland yields will be unaffected is completely unclear due to missing knowledge on biochemical and activation forces that might improve P availability with declining P reserves (Antunes et al., 2012; Schick et al., 2012). Regular soil analyses and/or plant tissue analyses on available P contents and also yield checks, should be used as a practical measure to avoid critical situations and to track the dynamics.

To follow the idea of grassland providing nutrients to arable land, nutrient transfer from areas with high soil P reserves and high activation potential to areas with lower soil P reserves should be improved. In the current study, high differences in the DM intake of grazing cows were obvious (Figure 1). This indicates a potential for a future improvement of swards, grazing management and storage feed yields on grassland in targeting enhanced P flows and transfers. A forced and controlled mining of soil P in grassland of the examined site, seems to be acceptable at the current soil P levels. In experimental loamy soils with P contents well over the agricultural optimum, phytomining over 7 to 16 yr only decreased the P content between 11 and 37 %, showing additional buffer capacities of soils for longer time periods (Svanback et al., 2015).

4.3 Arable land in P farm cycle

According to the methodology used in this study, variations in P mobilization for different crops were generally related to biomass DM yields (Table 5) and its P content. Different P acquisition strategies of plants were not considered in detail to explain differences in uptake. Generally, high P uptake of crops serves the biological P cycle on the farm. It can be expected that long-term immobilization of P in soil can be partly prevented by P remaining in biomass and thus be made available more rapidly after decomposition for plant and microbial uptake in general (Richardson et al., 2009; Schnug et al. 2003). Therefore, mulching of clover grass and even the direct backflow of straw after harvest and root biomass might support the rapid P cycling in soils on the farm. Inclusion of the high P yielding faba beans (in mixed cropping) improved P uptake compared to the lower P yielding cereals in monocultures (Simpson et al., 2011). Generally, the varying P uptake of species can be caused by, e. g., root growth patterns, root hairs, proton and organic acid release of roots, acid and alkaline phosphatases excreted by roots and microorganisms as well as mycorrhiza (Eichler-Löbermann et al., 2008; Jungk and Claassen, 1986; Scheffer and Schachtschabel, 2010; White, 2006). Yet, the high P levels found in the analyzed soils will interfere with mycorrhization (Gosling et al., 2006). Any factors that alter the level of primary production and inputs, as well as the transformation of organic carbon, will additionally affect the dynamics of organic P in soil (Condron and Tiessen, 2005).

While P concentrations in plant tissue in arable crops and soils on the site under study are still sufficient (Table 1, Kuchenbuch and Buczko, 2011) P exports were found to be higher than from grassland. As with grassland, it is not predictable how long soil reserves will be sufficient, especially under low yield conditions of organic farming and crop rotations with high biological P transfer by feed crops. Further analyses of buffering effects of soil P reserves for P supply to plants in systems with restricted P input are of high interest for an efficient use of P soil reserves in organic farming and should be further addressed in research.

4.4 Entire P farm cycle

In the study, P exports of livestock products and manure were not balanced referred to the farming system. The farm gate deficit of 1,105 kg P yr^{-1} needed to be mobilized from soil under actual farm conditions (Figure 2). The manure P export was 473 kg higher than P import with feed and seeds. If this amount were to be spread within the system P, exported products and losses would be reduced to 632 kg P yr^{-1}. This deficit would be innate to the system. Kuchenbuch and Busczko (2011) recommend external P fertilizers when P (CAL) is lower than 4.4 mg 100 g^{-1} P in the topsoil. Therefore the level of P concentrations in soils under study can still be decreased without endangering soil fertility. Stutter et al. (2012) evaluated the soil P reserves for Germany and estimated more than 3,000 kg P per ha^{-1} in the upper 15 cm layer for agricultural land irrespective of its plant accessibility. However, the plot-specific P mining potential that can be tolerated without endangering soil fertility is unknown. Finding a system specific optimal P level for the yield levels and crop rotations of organic farming and defining suitable fertilization strategies needs further scientific work. Especially biological mechanisms should be addressed as they have an important role for P cycling and activation (Dotaniya and Meena, 2015; Talgre et al., 2014; Péret et al., 2014; Gerke and Meyer, 1995). On the actual farm reducing the P export through manure would prolong the period of acceptable soil P mining.

4.5 Potential role of grassland for an improved P supply

Beside the mentioned possibility to intensify the grassland use on farm, grassland might act as transformer for sparingly soluble phosphate rock to plant available forms. Due to the higher intensity of biological processes and lower pH values of grassland soils than arable soils, mineral P fertilizers might be correctly placed here and their P might be transferred from here in the arable farm cycle via feeding and resulting manures (Mengel et al., 2001; Möller, 2009). As the import of mineral fertilizers in organic farming according to European standards is restricted to low solubility products mainly sparingly soluble rock phosphates are available for mineral P supply (Council Regulation (EC) No 834/2007), this aspect could be of special importance for this farming system (MacNaeidhe and O'Sullivan, 1999; Sinclair et al., 1990).

Meanwhile, the nutrient supply of 34 % of the German grassland is categorized as high or very high (Scheffer and Schachtschabel, 2010) caused by former P balance surpluses. Nowadays in Germany, 209,600 ha of permanent grassland is unprofitable or abandoned (Federal Statistical Office, 2014). Also biomass from nature conservation areas, e. g., from neglected grassland where biomass needs to be removed to achieve nature protection targets, could be valuable (Diacon-Bolli et al., 2012; Isselstein et al., 2005; Sutherland 2002). Its potential to substitute other fodder sources for ruminants could be exploited and thus it could act as a new P source for P redistribution. Due to the fact that the feed and energy demand of dairy cows changes throughout lactation, grassland of very different quality could be integrated more actively in farm nutrient and P flows. For example, extensively managed grassland can be a fitting fodder source in the first phase of the dry period (Barth et al., 2012), thus avoiding malnutrition-caused diseases. Its use relieves the pressure for forage production on arable land or on high quality pastures. This biomass is also discussed as substrate for bio-energy generation in biogas plants (Ebeling et al., 2013; McKenzie, 2013) but the potential for nutrient transfer is not yet in focus. With 56 % of grassland in German organic farms, these aspects are worth looking into to address and use P accumulations in soils by vegetative mining and redistribution as part of a sustainable use of worldwide P resources.

5 Conclusions

The P balance of the 116 ha North German organic dairy farm Trenthorst showed a net P export of 1,105 kg P yr^{-1} over three reference years. The deficit is supplied from soil P reserves. Visualizing farm specific P flows is helpful to develop P management on farm. Due to high variations in yields and P contents of the different materials, the use of farm specific values and representative farm periods are suggested. In the presented situation, grassland directly fed arable land with 64 kg P yr^{-1} (this was ca. 1 kg P ha^{-1} yr^{-1}) from soil reserves of grassland via manure. Yield increase by sward improvement and optimizing grazing and cutting management might improve this positive loop. Despite several years without external P supply the mining of soil P on grassland does not yet endanger soil fertility on the site under study, since available P (CAL) contents in the soil are still sufficient. But especially for the extensive conditions and for the wide range of crops used in organic farming it is unclear how long soil P reserves can be addressed. If critical situations are avoided based on evaluation of soil and plant analyses, forced and controlled P mining on grassland sites with P contents over the agricultural optimum and redistribution to arable land could be a component of sufficiency P management to preserve worldwide mineral P resources. The inclusion and use of remote or marginal grassland sites with sufficient soil P supply in nutrient cycling by ruminant and biogas systems should be evaluated as source for redistribution of nutrients in landscapes and farms.

Acknowledgement

We thank the ifu Hamburg for the opportunity to use e!Sankey! We thank Jacqueline Felix and Karina Schuldt for the assistance with field work and Johannes von Bremen for the improvement of the English text.

References

Antunes PM, Lehmann A, Hart MM, Baumecker M, Rillig M (2012) Long-term effects of soil nutrient deficiency on arbuscular mycorrhizal communities. Funct Ecol 26(2):532-540

Barberis E, Marsan FA, Scalenghe R, Lammers A, Schwertmann U, Edwards AC, Maguire R, Wilson MJ, Delgado A, Torrent J (1996) European soils overfertilized with phosphorus : 1. Basic properties. Fert Res 45(3):199-207

Barth K, Brinkmann J, Harms J, Isselstein J, Krömker V, March S, Müller J, Schumacher U, Spiekers H, Winckler C (2012) Euter- und Stoffwechselgesundheit bei Biomilchkühen [online]. To be found at <http://literatur.ti.bund.de/digbib_extern/dn050112.pdf> [quoted 02.12.2015]

Bengtsson H, Öborn I, Jonsson S, Nilsson I, Andersson A (2003) Field balances of some mineral nutrients and trace elements in organic and conventional dairy farming : a case study at Öjebyn, Sweden. Eur J Agron 20(1–2):101-116

Böhm H (2007) Mineralstoffgehalte in Körnerleguminosen und Sommergetreide. In: Zikeli S (ed) Zwischen Tradition und Globalisierung : Beiträge zur 9. Wissenschaftstagung Ökologischer Landbau, Universität Hohenheim, 20.-23.03.2007. Berlin : Köster, pp 20-23

Condron LM, Tiessen H (2005) Interactions of organic phosphorus in terrestrial ecosystems. In: Turner BL, Frossard E, Baldwin DS (eds) Organic phosphorus in the environment : [papers presented at the Organic Phosphorus Workshop, held July 2003, Ascona, Switzerland]. Wallingford : CABI, pp 295-307

Cooke GW, Williams RJB (1973) Significance of man-made sources of phosphorus : fertilizers and farming. Water Res 7(1–2):19-33

Cordell D, Drangert JO, White S (2009) The story of phosphorus : global food security and food for thought. Global Environ Change 19(2):292-305

Cornish P (2009) Phosphorus management on extensive organic and low-input farms. Crop Pasture Sci 60(2):105-115

Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91, (2007) [online]. To be found at <www.wipo.int/wipolex/en/details.jsp?id=7876> [quoted at 14.01.2016]

Diacon-Bolli J, Dalang T, Holderegger R, Bürgi M (2012) Heterogeneity fosters biodiversity : linking history and ecology of dry calcareous grasslands. Basic Appl Ecol 13(8):641-653

Dotaniya ML, Meena VD (2015) Rhizosphere effect on nutrient availability in soil and its uptake by plants : a review. Proc Natl Acad Sci, India, Sect B 85(1):1-12

Ebeling D, Breitsameter L, Bugdahl B, Janssen E, Isselstein J (2013) Herbage from extensively managed grasslands for biogas production : methane yield of stands and individual species. Grassl Sci Europe 18:560-562

Eichler-Löbermann B, Köhne S, Kowalski B, Schnug E (2008) Effect of catch cropping on phosphorus bioavailability in comparison to organic and in organic fertilization. J Plant Nutr 31(4):659-676

Federal Statistical Office - Deutschland / Statistisches Bundesamt (2014) Ackerland und Dauergrünland des ökologischen Landbaus in Deutschland und Dauergrünland nach Art der Nutzung im Zeitvergleich [online]. To be found at <https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/LandForstwirtschaftFischerei/FeldfruechteGruenland/FeldfruechteGruenland.html> [quoted at 30.7.2015]

Fystro G (2014) Nitrogen, phosphorous and potassium : balances and efficiency ; slide presentation of original data ; Miljømelkseminar , Bioforsk Norway, 31 Oct. 2014, Molde, Norway

Gerke J, Meyer U (1995) Phosphate acquisition by red clover and black mustard on a humic podzol. J Plant Nutr 18(11):2409-2429

Gosling P, Hodge A, Goodlass G, Bending GD (2006) Arbuscular mycorrhizal fungi and organic farming. Agric Ecosyst Environ 113(1–4):17-35

Gustafson GM, Salomon E, Jonsson S (2007) Barn balance calculations of Ca, Cu, K, Mg, Mn, N, P, S and Zn in a conventional and organic dairy farm in Sweden. Agric Ecosyst Environ 119(1–2):160-170

Haas G, Deittert C, Köpke U (2007) Farm-gate nutrient balance assessment of organic dairy farms at different intensity levels in Germany. Renew Agr Food Syst 22(3):223-232

Ho MD, Rosas JC, Brown KM, Lynch JP (2005) Root architectural tradeoffs for water and phosphorus acquisition. Funct Plant Biol 32(8):737-748

Ippolito J, Blecker S, Freeman C, McCulley R, Blair J, Kelly E (2010) Phosphorus biogeochemistry across a precipitation gradient in grasslands of central North America. J Arid Environ 74(8):954-961

Isselstein J, Jeangros B, Pavlu V (2005) Agronomic aspects of biodiversity targeted management of temperate grasslands in Europe : a review. Agron Res 3(2):139-151

Jeroch H, Drochner W, Simon O (1999) Ernährung landwirtschaftlicher Nutztiere : Ernährungsphysiologie, Futtermittelkunde, Fütterung. Stuttgart : Ulmer, 544 p

Jungk A, Claassen N (1986) Availability of phosphate and potassium as the result of interactions between root and soil in the rhizosphere. Z Pflanzenernähr Bodenkd 149(4):411-427

Kape H-E, Wulffen von U, Roschke M (2008) Richtwerte für die Untersuchung und Beratung zur Umsetzung der Düngeverordnung in Mecklenburg-Vorpommern [online]. To be found at <http://www.lms-beratung.de/upload/59/1294212632_30690_19228.pdf> [quoted 10.12.2015]

Klapp E (1971) Wiesen und Weiden : eine Grünlandlehre. Berlin : Parey, 620 p

Knowlton KF, Herbein JH (2002) Phosphorus partitioning during early lactation in dairy cows fed diets varying in phosphorus content. J Dairy Sci 85(5):1227-1236

Kuchenbuch RO, Buczko U (2011) Re-visiting potassium and phosphate-fertiliser responses in field experiments and soil-test interpretations by means of data mining. J Plant Nutr Soil Sci 174:171-185

Landwirtschaftskammer Niedersachsen (2011) Richtwerte für die Düngung in Niedersachsen [online]. To be found at <http://www.lwk-niedersachsen.de/index.cfm/portal/pflanze/nav/341/article/11622.html> [quoted 10.01.2015]

Lindenthal T (2000) Phosphorvorräte im Boden, betriebliche Phosphorbilanzen und Phosphorversorgung im Biologischen Landbau : Ausgangspunkte für die Bewertung einer großflächigen Umstellung ausgewählter Bundesländer Österreichs auf Biologischen Landbau hinsichtlich des P-Haushalts. Wien : Univ Bodenkultur, 273,107 p

LLUR - Landesamt für Landwirtschaft Umwelt und ländliche Räume Schleswig-Holstein (2014) Nährstoffe in Gewässern Schleswig-Holsteins : Entwicklung und Bewirtschaftungsziele. Flintbek : LLUR, 91 p, SchrR LLUR D 24

MacNaeidhe FS, O'Sullivan AN (1999) The evaluation of phosphorus sources for nutrient budgeting on organic farms : end of project report ARMIS 4510 [online]. To be found at <http://www.teagasc.ie/research/reports/environment/4510/eopr-4510.pdf> [quoted 08.12.2015]

MacKenzie G (2013) Marginal grassland has potential for anaerobic digestion [online]. To be found at <http://www.fwi.co.uk/business/marginal-grassland-has-potential-for-ad.htm> [quoted 09.12.2015]

Mengel K, Kosegarten H, Kirkby EA, Appel T (2001) Principles of plant nutrition. Dordrecht : Springer, 849 p

Modin-Edman A-K, Öborn I, Sverdrup H (2007) FARMFLOW : a dynamic model for phosphorus mass flow, simulating conventional and organic management of a Swedish dairy farm. Agr Syst 94(2):431-444

Möller K (2009) Inner farm nutrient flows between arable land and permanent grassland via the stable in organic cropping systems. Eur J Agron 31(4):204-212

Nesme T, Toublant M, Mollier A, Morel C, Pellerin S (2012) Assessing phosphorus management among organic farming systems : a farm input, output and budget analysis in southwestern France. Nutr Cycl Agroecosyst 92(2):225-236

Oberson A, Joner EJ (2005) Microbial turnover of phosphorus in soil. In: Turner BL, Frossard E, Baldwin DS (eds) Organic phosphorus in the environment : [papers presented at the Organic Phosphorus Workshop, held July 2003, Ascona, Switzerland]. Wallingford : CABI, pp 133-164

Oenema O, Kros H, de Vries W (2003) Approaches and uncertainties in nutrient budgets : implications for nutrient management and environmental policies. Eur J Agron 20(1-2):3-16

Ohm M, Schüler M, Warnecke S, Paulsen HM, Rahmann G (2014) Measurement methods on pastures and their use in environmental life-cycle assessment. Organic Agric 4(4):325-329, doi:10.1007/s12165-014-0072-4

Paulsen HM, Schochow M (eds) (2007) Anbau von Mischkulturen mit Ölpflanzen zur Verbesserung der Flächenproduktivität im ökologischen Landbau : Nährstoffaufnahme, Unkrautunterdrückung, Schaderregerbefall und Produktqualitäten ; Abschlussbericht zum Forschungsprojekt gefördert mit Mitteln des Bundesprogramms Ökologischer Landbau (Projekt Nr. 03OE113), Laufzeit und Berichtszeitraum: 01.03.2003-31.10.2006. Braunschweig : FAL, 114 p, Landbauforsch Völkenrode SH 309

Péret B, Desnos T, Jost R, Kanno S, Berkowitz O, Nussaume L (2014) Root architecture responses : in search of phosphate. Plant Physiol 166(4):1713-1723

Rahmann, G, Nieberg H (2005) New insights into organic farming in Germany : empirical results of a survey in 218 farms. Landbauforsch Völkenrode 55(3):193-202

Richardson AE, Barea JM, McNeill AM, Prigent-Combaret C (2009) Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. Plant Soil 321(1-2):305-339

Schachtman DP, Reid RJ, Ayling SM (1998) Phosphorus uptake by plants : from soil to cell. Plant Physiol 116(2):447-453

Scheffer F, Schachtschabel P (2010) Lehrbuch der Bodenkunde. Heidelberg : Spektrum Akad Verl, pp 412-420

Schick J, Haneklaus S, Schnug E (2012) Baltic manure WP 4 standardisation of manure types with focus on phosphorus prototype model for the phosphorus turnover in soils (P-Engine) in relation to varying environmental conditions in the Baltic Sea Region [online]. To be found at <http://balticmanure.eu/download/Reports/pengine_report_final.pdf> [quoted 09.12.2015]

Schnug E, Rogasik J, Haneklaus S (2003) The utilisation of fertiliser P with special view to organic farming. Landbauforsch Völkenrode 53(1):1-11

Schröder JJ, Smit AL, Cordell D, Rosemarin A (2011) Improved phosphorus use efficiency in agriculture : a key requirement for its sustainable use. Chemosphere 84(6):822-831

Schüller H (1969) Die CAL-Methode, eine neue Methode zur Bestimmung des pflanzenverfügbaren Phosphates in Böden. Z Pflanzenernähr Bodenkd 123 (1):48-63

Simpson RJ, Oberson A, Culvenor RA, Ryan MH, Veneklaas EJ, Lambers H, Lynch JP, Ryan PR, Delhaize E, Smith FA, Smith SE, Harvey PR, Richardson AE (2011) Strategies and agronomic interventions to improve the phosphorus-use efficiency of farming systems. Plant Soil 349(1-2):89-120

Sinclair AG, Dyson CB, Shannon PW (1990) The long-term effectiveness of reactive phosphate rock as a phosphate fertilizer for New Zealand pastures [online]. To be found at <http://www.grassland.org.nz/publications/nzgrassland_publication_977.pdf> [quoted 09.12.2015]

Smith SE, Read DJ (2010) Mycorrhizal symbiosis. Amsterdam : Elsevier, 787 p

Steinshamn H, Thuen E, Bleken MA, Brenøe UT, Ekerholt G, Yri C (2004) Utilization of nitrogen (N) and phosphorus (P) in an organic dairy farming system in Norway. Agric Ecosyst Environ 104(3):509-522

Stutter MI, Shand CA, George TS, Blackwell MS, Bol R, MacKay RL, Richardson AE, Condron LM, Turner BL, Haygarth PM (2012) Recovering phosphorus from soil : a root solution? Environ Sci Technol 46(4):1977-1978

Sutherland WJ (2002) Conservation biology : openness in management. Nature 418(6900):834-835

Suttie JM, Reynolds SG, Batello C (2005) Grasslands of the world [online]. To be found at <http://www.fao.org/docrep/008/y8344e/y8344e00.htm> [quoted 09.12.2015]

Svanback A, Ulen B, Bergstrom L, Kleinman PJA (2015) Long-term trends in phosphorus leaching and changes in soil phosphorus with phytomining. J Soil Water Conserv India 70(2):121-132

Talgre L, Lauringson E, Roostalu H, Makke A (2014) Phosphorus and potassium release during decomposition of roots and shoots of green manure crops. Biol Agric Horticult 30(4):264-271

Tóth G, Guicharnaud R-A, Tóth B, Hermann T (2014) Phosphorus levels in croplands of the European Union with implications for P fertilizer use. Eur J Agron 55:42-52

Vance CP (2001) Symbiotic nitrogen fixation and phosphorus acquisition : plant nutrition in a world of declining renewable resources. Plant Physiol 127(2):390-397

White RE (2006) Principles and practice of soil science : the soil as a natural resource. Malden Mass : Blackwell, pp 201-228

Whitehead DC (2000) Nutrient elements in grassland : soil-plant-animal relationships. Wallingford : CABI, 369 p

Wu Z, Satter LD, Blohowiak, AJ, Stauffacher RH, Wilson JH (2001) Milk production, estimated phosphorus excretion, and bone characteristics of dairy cows fed different amounts of phosphorus for two or three years. J Dairy Sci 84(7):1738-1748