Poster contribution to
ESPC2- European Sustainable Phosphorus Conference
Berlin, 5-6th March 2015

Future Sustainable Phosphorus Management: Optimum P Supplies of agricultural Soils to meet simultaneously both Sufficiency, Efficiency and Consistency

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Titelblatt Poster ESPC2 2015 Berlin

A) INTRODUCTION

Like generally sustainable development of all life styles sustainable phosphorus (P) management has to meet simultaneously over the long term the basic needs both for biomass use / consumption **(Social component: Sufficiency**), corresponding production **(Economic component: P and monetary efficiency**) and for the natural environmental resources **(Ecological component: Consistency)** referring here mainly to the production and use of food and bio energy. Within these general sustainable aspects especially of P management corresponding sustainable P supplies of the agricultural soils have fundamental importance. This is shown here exemplarily for German agriculture. Future sustainable agriculture and corresponding human nutrition and bio energy systems must be based on more „Closed" systems, because both globally about 85% (arable soils 55%) or nationally i.e. in Germany 97% of mined P passes into the hydrosphere and even more P is stored unused in the agricultural soils **(Tab. 1)**. In this way long-lasting sustainable P supplies of the agricultural soils and corresponding optimum P fertilization are of fundamental importance for future sustainable P management.

B) RESULTS, DISCUSSION, CONCLUSIONS

B1) P surpluses and efficiencies

In spite of very high (apparent) P efficiency of the field balance with 109%, the P efficiency of the total farm balance of German agriculture (2007)is only 55%, because P efficiency of animal production and corresponding stable balance is only 14% with corresponding not tolerable P surpluses of -2.0, 9.5 and 11.5 P $\cdot$ ha^{-1} $\cdot$ yr^{-1} respectively **(Tab. 2). –** Caused mainly by animal mass-consumption and mass-production as well as corresponding (officially) not sustainable manurering recommendations and agricultural and environmental legislation since 1950 not tolerable P- and K-surpluses (-excesses) of 828 and 2327 kg $\cdot$ ha^{-1} are accumulated unused in the soils (soil test classes C, D, E) with a total monetary value of 59,7 Mrd. € (= 3550 € $\cdot$ ha^{-1} **(Tab. 3).** But these soil "P- and K-banks" can and must be exploited (captured) within the next ca.100 years. – In this respect only with soils of soil test P < 5.0 mg CAL-P $\cdot$ 100 g $soil^{-1}$ (and < 10 mg CAL-K $\cdot$ 100 g $soil^{-1}$) there are economical yield increases by fertilizing P (**Fig. 1)** (and K respectively).

B2) Simultaneously needed P efficiency, consistency and sufficiency

Soil concentration target zone of 3-5 mg CAL-P · 100 g soil^{-1} both for optimum yields as well as economical yield increases by fertilized P according to P withdrawal by yields (95-100 % maximum), **(Fig. 1)** and tolerable P losses (~emissions) in respect to limited P eutrophication of surface water (lakes, groundwater ➔ running water ➔ coastal water ➔ sea) **(Fig. 2, Fig. 3)** as well as considering scarcity of mineral phosphorus **(Fig. 4)** must be implemented by corresponding legislation (i.e. Phosphorus Directive) and recommendations for P fertilization and management of soil against individual not tolerable P losses to hydrosphere.

B3) Future sustainable P- (and K-) balances of agriculture by a) sustainable soil P contents, b) corresponding long-term exploited (captured) surplus P of the soils, c) reuse of recycle system P losses and d) P output only by need-oriented animal production (future -55% reduction vs. 2007).

On the basis of the farm balance of German agriculture future exploitation ("capture of the P bank") of formerly not sustainable long-term P accumulation in the soils during the next ca.100 years (8.3 kg P ·ha aa^{-1} · yr^{-1}) together with efficient P recycling in (organic) "waste" (4.2 kg P ·ha aa^{-1} yr^{-1}) and therefore total of (8.3 + 4.2=) 12.5 kg P ·ha aa^{-1} · yr^{-1}) compensates the P output by non sustainable surplus of agricultural market products actually (-11.5 kg P ·ha aa^{-1} · yr^{-1}) and even more in future with only needed agricultural market products (-8.0 kg P ·ha aa^{-1} · yr^{-1}). Therefore in future no mineral fertilizer P, domestic (industrial) and imported feed as well as mineral P feed are needed. Additionally important is the fact that only 27% of the P deficient/ adequate soils (soil test classes A + B) need the reuse of recycle system P losses and correspondingly 73% of the P hypertrophied soils (soil test classes C, D, E) cannot be fertilized in any way within the next 100 years. **(Tab. 9)**. Therefore in the sustainable situation P-farm-, field- and stable-balances are nearly zero with 0.3, 0.2 and 0.1 kg P · ha aa^{-1} · yr^{-1} respectively and P efficiencies of farm- and field balance are 96 and 99% respectively **(Tab. 6)**. Stutter et al. (2012) show similar results for UK only regarding plant production and soil depth of only 7 cm instead here of 30 cm (arable) and 10 cm (grassland) **(Tab. 7).** –

Comparable with the P (non) sustainable situations / balances are the corresponding situations (balances of K (Tab. 8): For the next ca. 145 years there is no need to fertilize K in the sustainable situation and K output by market products will be balanced by capture of surplus K from the corresponding hypertrophied soils.

B4) The future (non) sustainable P fertilization recommendations and official regulations (Tab. 9)

…show that SRU (II) and especially governmental [BMELV (I), BMEL (III)] and governmental near institutions [like VDLUFA IV] both influenced by lobby ➔ lobbyism are not willing to accept the facts that:

1. **Any P fertilization irrespective with mineral or organic P fertilizers has no yield effects in soils of P soil test classes C, D and E, but additionally increases the potentials for P emissions into the hydrosphere essentially and plunders the final (± 300 years) P resources last not least mainly with their not sustainable aim to promote and maintain more as twofold too high animal mass consumption and production.**
2. **And vice versa: No P fertilization (in soils of soil test classes C, D and E) within ca. further 100 years reduces P fertilization costs of 250 Mio.€ $\cdot$ yr^{1}within the next ca. 100 years, without any restrictions to yields and (apparent) P efficiency of about 100% as well as with tolerable P emissions to the hydrosphere (consistency) and saving mineral P resources (sufficiency).**

B5) Global deficiency and surplus in the application of phosphate on agricultural areas (Fig. 4)

Area weighted global surplus off phosphate application is higher than its deficiency and therefore the surplus countries (regions) should leave the restricted mineral P reserves to the deficient ones

C) LITERATURE

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Sachverständigenrat für Umweltfragen (SRU 2015): Stickstoff: Lösungsstrategien für ein drängendes Umweltproblem. Hausdruck, Januar 2015, 580 S.

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Tab.1: Phosphorus balance of the global arable soil P system (Stutter et al. 2012)

Input			Output		
	Tg · yr^{-1}	%		Tg · yr^{-1}	%
Total	49	100		49	100
…there from by:					
1. Mineral P fertilizer	14	28	1. Yields	22	45
			…there from by:		
2. Manure P	15	31	1.1 Crop uptake [1)]	10	20
			1.2 Vegetation P uptake into farmed animals	12	25
3. Mineral weathering	20	41			
			2. Surplus	27	55 [100]
			…there from by:		
			2.1 Soil P increase	12	24 [44]
			2.2 Losses to water	15	31 [56]
			[1)] Fertiliser P use efficiency by P fertilized crops: 3 / 14 x 100 = 21 %		

Stutter et al (2012):

"Unlocking the residual P already bound to soils is an essential stage in a sustainable future for agriculture, and one which buys vital decades for development of longer term solutions. Such future plans must necessarily be based on more "closed" systems of nutrient recycling and reuse, instead of the current situation where mined P passes inefficiently through the human food chain into waste waters and to the oceans". [i.e. globally 85% (Cordell et al. 2010) , Germany 97 % (Isermann 2013), but also input as surpluses into the soils ➔ reuse of phosphorus]

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Tab. 2: Farm-, Field- and Stable-P-Balances of agriculture in Germany (2007) [Frede and Bach 2010]

Balance parameters	kg P · ha $^{-1}$ · yr $^{-1}$		
	Farm-Balance	**Field-Balance**	**Stable-Balance**
- Mineral fertilizers	**[61] 6.8**	**6.8 [53]**	-
- Recycled "wastes" (Sewage sludge, bio composts, animal meal, etc.)	3.1	3.1	-
- Manure	-	**12.8 [100]**	-12.8
- Domestic feed	3.7	-	3.7
- Farm feed	**11.2 [100]** { -	-	17.2
- Imported feed	3.4	-	3.4
- P-Mineral feed	4.1	-	4.1
- Output by yields	-	-24.7	-
- Plant market products (net)	-7.4	-	-
- Animal market products	-4.1	-	- 4.1
1. Total Input	**21.1**	**22.7**	**28.4**
2. Total Output	**-11.5**	**-24.7**	**-16.9**
3. Balance	**9.5**	**-2.0**	**11.5**
4. Apparent P efficiency (%)	**55**	**109**	**14**

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Tab.3:

A) Since 1950 accumulated P- and K-surpluses (-excesses) in the agricultural soils (soil test classes C, D, E) of Germany caused mainly by animal-mass-production and animal mass-consumption as well as corresponding (official) wrong manuring recommendations and agricultural legislation

B) Their actual monetary values.

But this soil "P- and K- bank" can be exploited (captured) within the future ca. 100 years

Long-term accumulated P-and K-surpluses (-excesses)

Accumulated P-and K-surpluses (-excesses)	A) Surpluses		B) Monetary values (2015)	
	[Mio. t]	kg · ha aa^{-1}	[Mrd. €]	€ · ha aa^{-1}
1. P (1950 - 2007) (Frede and Bach 2010)	13,9	828	30,3 (2,18 € / kg P)	1 805
2. K (1950 - 2000) (Köster and Nieder 2007)	39,1	2 327	29,4 (0,75 € / kg K)	1 745
3. P and K	53,0	3 155	59,7 (11)	3 550
4. compare actual yearly subsidies by the EU	-	-	5,4 (1)	320

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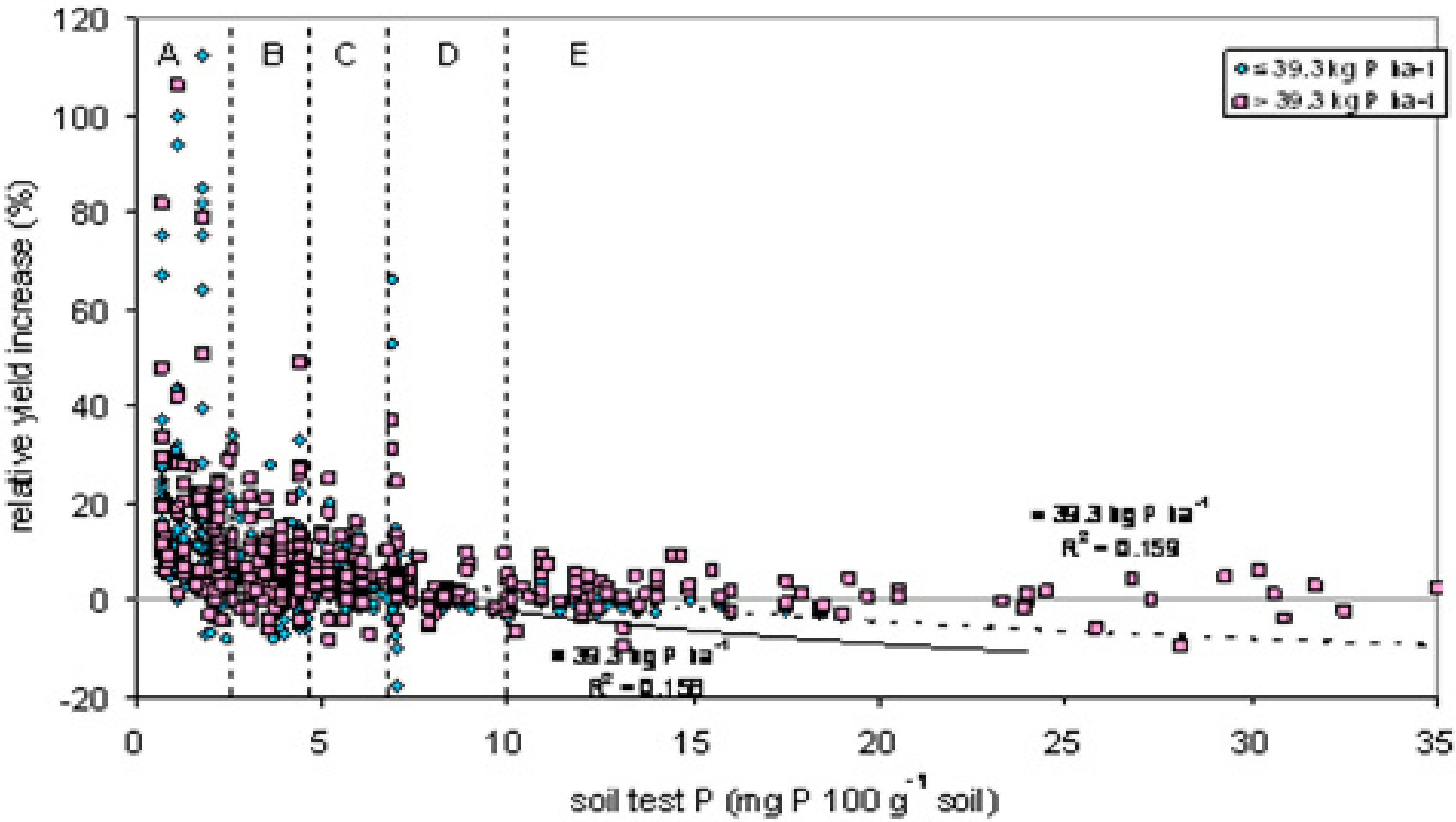

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Fig. 1: Only yield increase by fertilized P with soil test P < 5.0 mg CAL-P · 100g -1 soil (soil test classes C, D, E)
Kuchenbuch and Buczko (2011):

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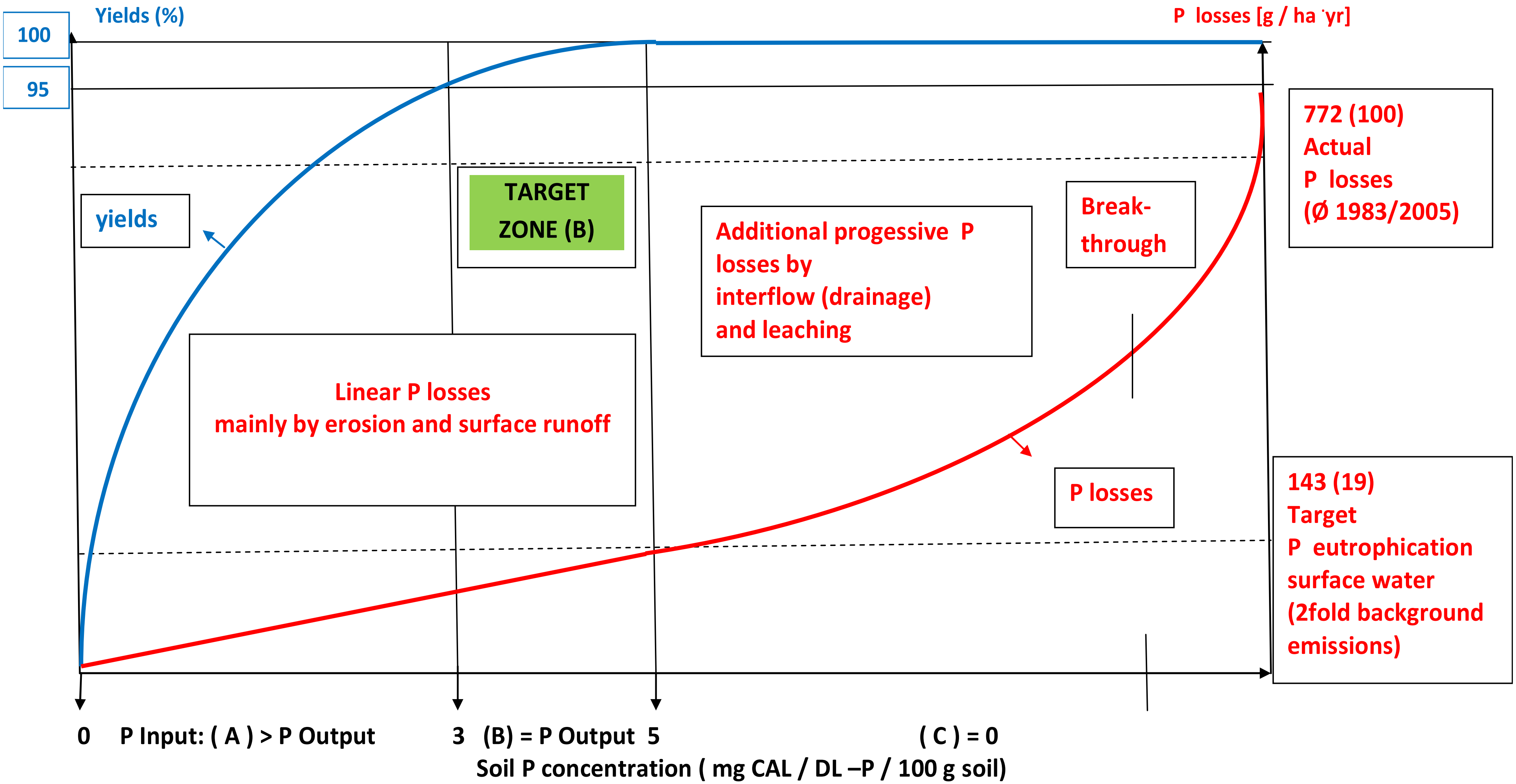

Fig.2: Soil P concentration target zone both for optimum yields (95 – 100 % maximum), tolerable P losses in respect to limited P eutrophication of surface water (running water, coastal water, sea) and scarcity of phosphorus of Germany should be reached by corresponding legislation (i.e. Phosphorus Directive), recommendations for P fertilization and management of soils against the individual P losses [supplemented by Isermann (2014) according to AMERY (IPW 7, Uppsala 2013)]

2.2 Konsequenzen für P-Austräge

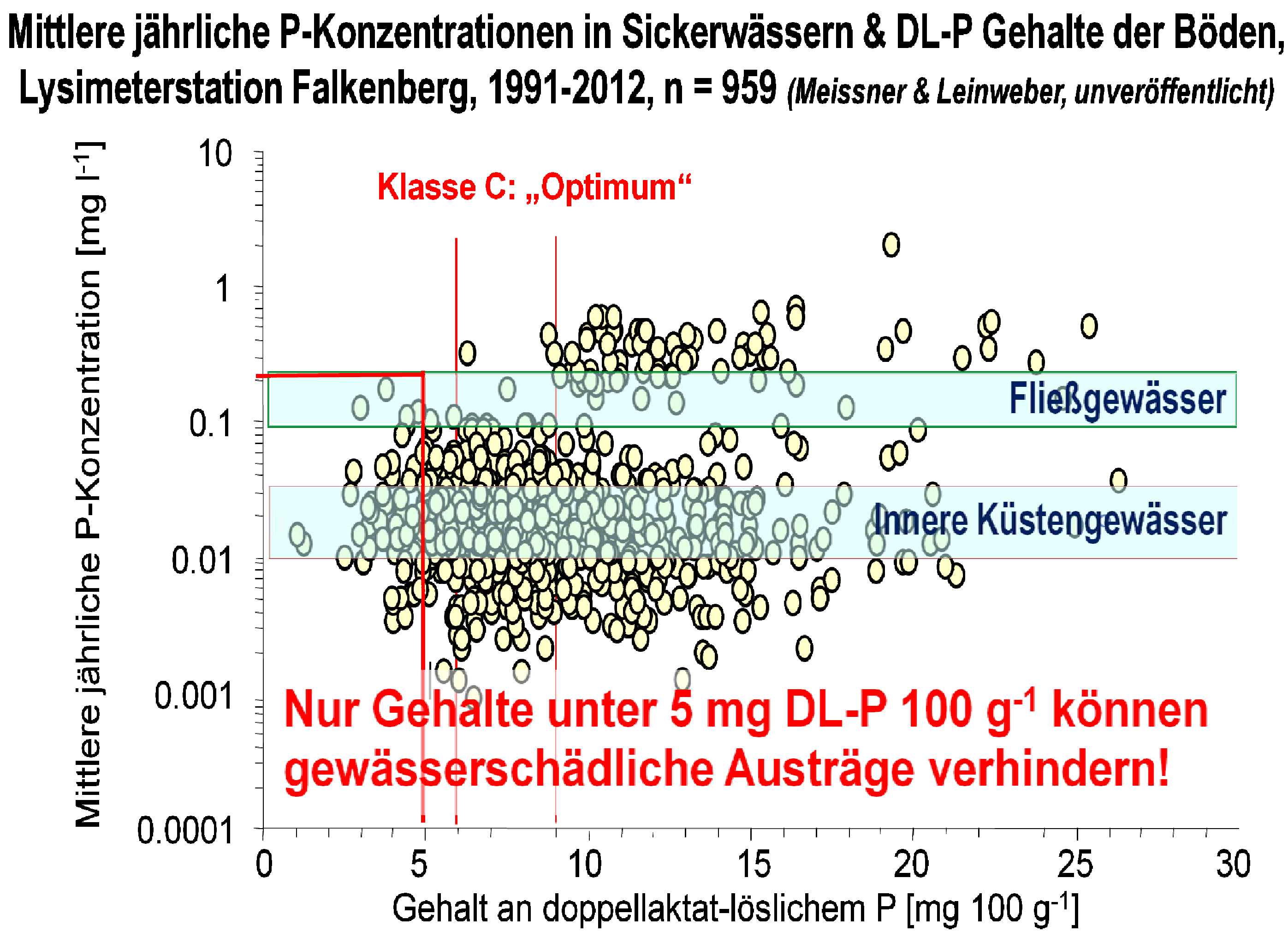

Fig.3: Average yearly P concentration in seepage waters and DL-P-contents of (agricultural) soils: In respect to running waters and coastal waters (P-eutrophication) only contents of < 5,0 mg DL-P ·100 g^{-1} soil can be tolerated. [P. Leinweber, Deutsche P-Plattform Berlin (2014)]

Tab. 4:

A) As consequences of different future demands and mine productions (Isermann 2014, according to Blanco 2011)

B) Depletion times of world phosphate rock (PR) reserves of 65 000 Mt with 32% P_2O_5 = 21 000 Mt P_2O_5 = 9 100 Mt P with 14% P(US Geological Survey 2011, according to International Fertilizer Development Center 2010)

Definitions: 1. Reserves: Phosphate rock that can be economically produced at the time of the determination to make suitable products, reported as tons of concentrate

2. Resources: Phosphate rock of any grade that may be produced at some time in the future, including reserves.

A) Future world phosphate rock demands and mine productions as 2050 scenarios		B) Depletion times of phosphate rock reserves [years]
[Mt PR · yr^{-1}]	[Mt P · yr^{-1}]	
164	23	396
176 (2010)	25	369
202	28	322 [1)]
216	30	301
236	33	275
		(average about 300 / BGR 2014)

[1)] Compare: Phosphate rock reserves of 16 000 Mt P_2O_5 (USGS 2010): Depletion time: 79 years

Conclusion (Blanco 2011):

" Nevertheless, from the perspective of long-term food security, even a perspective of 300-400 years into the future is very short. Sooner or later the supply will become scarce, calling for P resource management policy initiatives. Policies encouraging a more efficient fertilizer use should be investigated. Recycling and reuse of P resources are other relevant options which should be taken into consideration (Dawson and Hilton 2011)" re1921a

Tab.5: On the basis of the farm balance of German agriculture future exploitation ("capture of the P bank") of formerly not sustainable long-term P accumulation in the soils during the next ca.100 years (8.3 kg P ·ha aa^{-1} · yr^{-1}) together with efficient P recycling in (organic) "waste" (4.2 kg P ·ha aa^{-1} yr^{-1}) and in the total of (8.3 + 4.2=) 12.5 kg P ·ha aa^{-1} · yr^{-1}) compensates the P output by non sustainable surplus of agricultural market products actually (-11.5 kg P ·ha aa^{-1} · yr^{-1}) and even more in future with only needed agricultural market products (-8.0 kg P ·ha aa^{-1} · yr^{-1}). Therefore in future no mineral fertilizer P, domestic (industrial) and imported feed as well as mineral P feed are needed.

Arable Land (AL): 11.8 Mio. ha; soil depth: 30 cm Grass Land (GL): 5.0 Mio. ha; soil depth:10 cm Agricultural Area: 16.8 Mio. ha aa	P-Balance-Parameters [kg bzw. t P] (P x 2.291 = P_2O_5)) Reference: Farm balance
1. Long term accumulated P-Surplus/ -Excess (1950 / 2007) (Frede u. Bach 2010)	900 kg P ·ha aa^{-1} · 57 yrs = 15.8 kg P· ha aa^{-1}· yr^{-1}
2. Natural background: P by mineral weathering (Total P delivery from (in-)organic reserves in Germany: 5-20 kg P·ha aa^{-1}· yr^{-1} (Fink 2007)	ca. 2.0 mg CAL-P · 100 g soil^{-1} = 72 kg CAL-P · ha aa^{-1} (AL: 63 bzw. GL: 9 kg CAL-P ·ha aa^{-1})
3. Sustainable optimum soil P contents	4 (3 bis 5) mg CAL-P · 100 g soil^{-1} = 144 kg CAL-P · ha aa^{-1}
4. Needed sustainable P enrichment in the soils (3. minus 2.)	2.0 mg CAL-P · 100 g soil^{-1} = 72 kg CAL-P ha aa^{-1} (AL: 63 bzw. GL: 9 kg CAL-P· ha aa^{-1})
5. Long term exploited (captured) P without P fertilization in the soils corresponding the soil- test-classes C, D and E (1. minus 4.)	(900 – 72=) 828 kg CAL-P · ha aa^{-1} x 16.8 Mio. ha aa = 13.9 Mio. t CAL-P = 8.3 kg P· ha aa^{-1} · yr^{-1} during 100 yrs
...corresponding actual yearly mineral P fertilization by captured P surplus cited above	1.3fold of aktual (2010-2013) Mineral-P-consumption of 0.115 Mio. t P ·yr^{-1} = 6.8 kg P · ha aa^{-1} · yr^{-1}
6. Completing P capture (5.) by P-recycling of (organic) „waste" like sewage sludge, bio compost, animal meal, etc.	70 000 t P· yr^{-1} (sewage sludge: 35 000 t P, Bio compost, etc.: 35 000 t P) = 4.2 kg P· ha aa^{-1}· yr^{-1} (Römer 2011)
7. Capture of formaly accumulated P surpluses of the soils (5.) and efficient P-recycling (6.) there are no future needed mineral P-fertilizers, domestic and imported feed as well a mineral P feed	8.3 + 4.2 = 12.5 kg P ·ha aa^{-1} · yr^{-1} [100]
8. Compare:8.1 P output by non sustainable surplus market products (Frede u. Bach 2010)	-11.5 kg P ·ha aa^{-1} · yr^{-1} [91]
8.2 P output by future sustainable needed market products **(Sufficiency)** (Isermann 1994 / 2015, UBA 2014)	- 8.0 kg P ·ha aa^{-1} · yr^{-1} [71]

Tab.6: Sustainable phosphorus balances i.e. of German agriculture by sustainable de-intensification: A) Actually non sustainable, B) via future sustainable (capture surplus soil P and recycling P system losses and C)Sustainable (minus 55% animal production and capture surplus soil P) to meet simultaneously P efficiency, sufficiency and consistency

Balance parameters	kg P ·ha aa^{-1} · yr^{-1}								
	A) Non sustainable			B) via sustainability			C) Sustainable		
	Actual Situation (2007)			Aimed (2020)			Aimed > 2020		
	Frede and Bach (2010)			Isermann (2013/15)			Isermann (2015)		
Balance types	Farm	Field	Stable	Farm	Field	Stable	Farm	Field	Stable
Mineral fertilizer	6.8	6.8	-	0	0	-	0	0	-
Recycled system losses (Sewage sludge→ struvite, bio compost animal meal, etc.)	3.1	3.1	-	4.2	4.2	-	0	0	-
Manure (farmyard manure, slurry)	-	12.8	-12.8	-	12.8	-12.8	-	5.8 (-55%)	-5.8
Domestic feed (industrial feed)	3.7	-	3.7	0	-	0	0	-	0
Farm feed	-	-	17.2	-	-	17.2	-	-	7.7 (-55%)
Imported feed	3.4	-	3.4	0	-	0	0	-	0
Mineral P feed	4.1	-	4.1	0	-	0	0	-	0
Capture surplus soil P (soil test classes C, D, E)	0	0	-	8.3	8.3	-	8.3	8.3	-
Output by yields	-	-24.2	-	-	-24.2	-	-	-13.9	-
Plant market products	-7.4	-	-	-7.4	-	-	-6.2 (-16%)	-	-
Animal market products	-4.1	-	-4.1	-4.1	-	-4.1	-1.8 (-55%)	-	-1.8
1. Total Input	21.1	22.7	28.4	12.5	25.3	17.2	8.3	14.1	7.7
2. Total Output	-11.5	-24.7	-16.9	-11.5	-24.7	-16.9	-8.0	-13.9	-7.6
3. Balance	9.5	-2.0	11.5	1.0	0.6	0.3	0.3	0.2	0.1
4. P efficiency (%)	55	109	14	92	97	24	96	99	23

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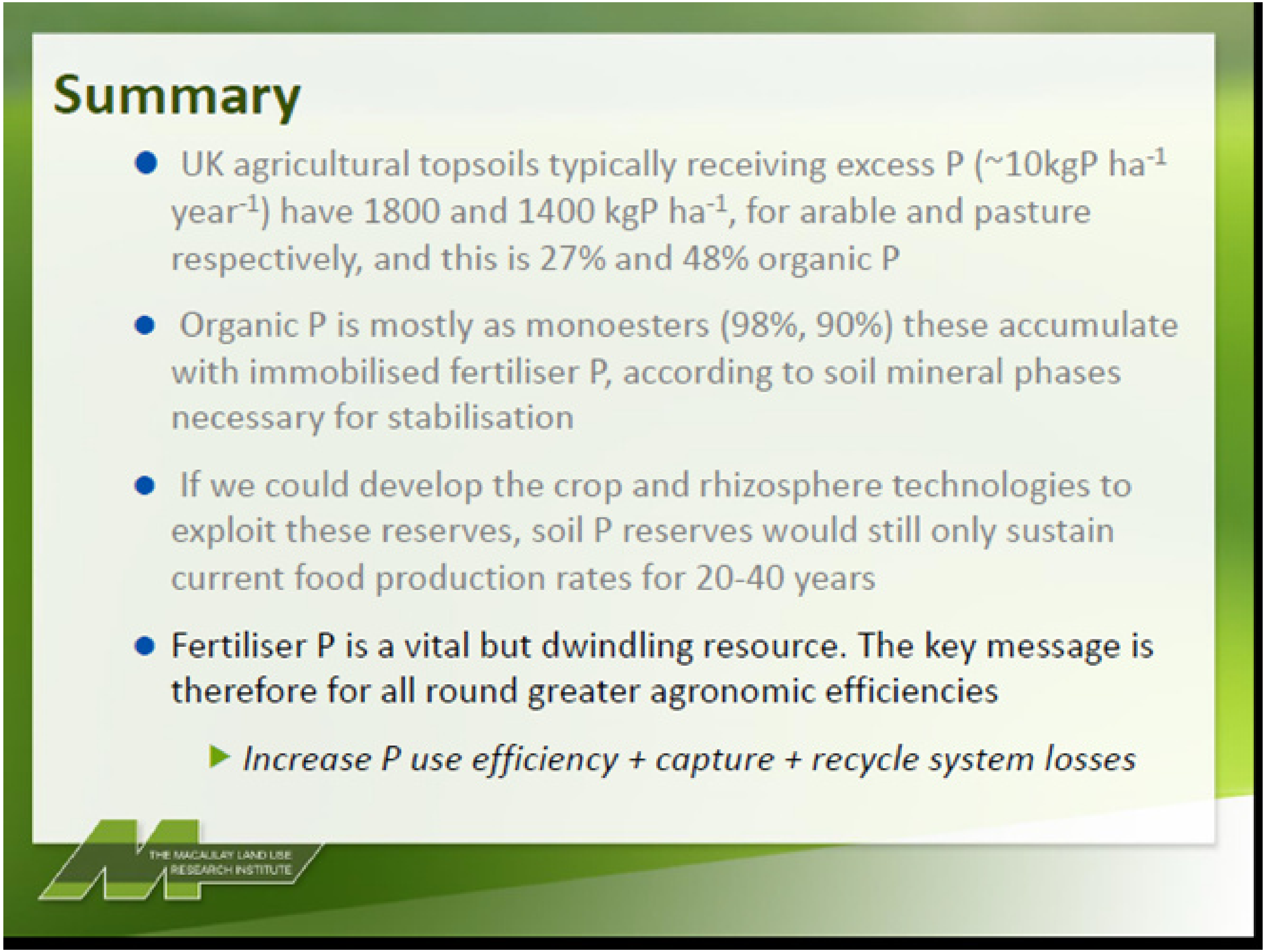


Tab.7: Sustainable P management within the system nutrition (agriculture, human nutrition, waste and waste water management): Increase P use efficiency + capture of accumulated surplus soil P + recycle system losses (Stutter et al. (2012)

Tab.8: On the basis of the farm balance of German agriculture future exploitation ("capture of the K bank") of formerly not sustainable long-term K accumulation in the soils during the next ca.145 years (16.0 kg K ·ha aa^{-1}·yr^{-1}) compensates the K output by non sustainable surplus of agricultural market products actually (-16.0 kg K ·ha aa^{-1} · yr^{-1}) and even more in future with only needed agricultural especially animal market products (-11.0 kg K ·ha aa^{-1} · yr^{-1}). Therefore no mineral fertilizer K is needed in future 145 years.

Arable Land (AL): 11.8 Mio. ha; soil depth: 30 cm **Grass Land (GL): 5.0 Mio. ha; soil depth:10 cm** **Agricultural Area: 16.8 Mio. ha aa**	**K-Balance Parameters [kg bzw. t K]** **(K x 1.205 = K_2O)** **Reference: Farm balance**
1. Long term accumulated K surplus /-excess (1950 / 2000) (Köster und Nieder 2007)	**2 470 kg K · ha aa^{-1} · 50 yrs = 49 kg K ·ha aa^{-1} · yr^{-1}**
2. Natural background: K by mineral weathering [(i.e. illitic soils: 5.0 mg CAL-K · 100 g soil^{-1}; Scheffer u. Schachtschabel 2010)]	**ca. 4.0 mg CAL-K 100 g soil^{-1}** **= 144 kg CAL-K /ha aa^{-1}** (AL: 126 bzw. GL: 18 kg CAL-K · ha^{-1})
3. Sustainable Optimum soil K-contents (soils with: 13 – 25 % clay)	**8 (6 to 10) mg CAL-K ·100 g soil^{-1}** **= 288 kg CAL-K · ha aa^{-1}**
4. Needed sustainable K enrichment of soils **(3. minus 2.)**	**4.0 mg CAL-K ·100 g soil^{-1}** **= 144 kg CAL-K · ha aa^{-1}** (AL: 126 bzw. GL: 18 kg CAL-K ·ha^{-1})
5. Long term exploited (captured) K without K fertilization in the soils corresponding to the soil test classes C, D and E (1. – 4.) without considering K leaching [only in sandy soils (< 5% clay) 20-50 kg K · ha aa $^{-1}$ · yr $^{-1}$ Scheffer u. Schachtschabel 2010]	**(2 470 – 144 =) 2 327 kg CAL-K · ha aa^{-1} x 16.8 Mio. ha aa** **= 39.1 Mio. t CAL-K** **= 16.0 kg K ·ha aa^{-1} · yr^{-1} during 145 years**
…corresponding actual yearly mineral K fertilization by capture K surplus cited above	**Corresponding the actual mineral K fertilization (2010-2013) of 0.281 Mio.t K · yr^{-1} = 16.7kg K ·aa^{-1} · yr^{-1}**
6. K recycling by (organic) „waste" as sewage sludge, bio compost, animal meal, etc.	**Not determined**
7. Utilisation of long-term accumulated soil K and therefore without needed mineral K fertilizers in future 145 years	**Actual K fertilization (2010 to 2013) 16.7 kg K ·ha aa^{-1} ·yr^{-1} [104]**
8. Compare: 8.1 K output by non sustainable surplus market products (z.B. Gamer und Bahrs 2011)	**-16.0 kg K ·aa $^{-1}$ · a $^{-1}$ [100]** (z.B in Baden-Württemberg**)**
8.2 K output by future sustainable needed market products (Sufficiency) (Isermann 1994 / 2015, UBA 2014)	**- 11.0 kg K ·ha aa^{-1} · yr [70]**

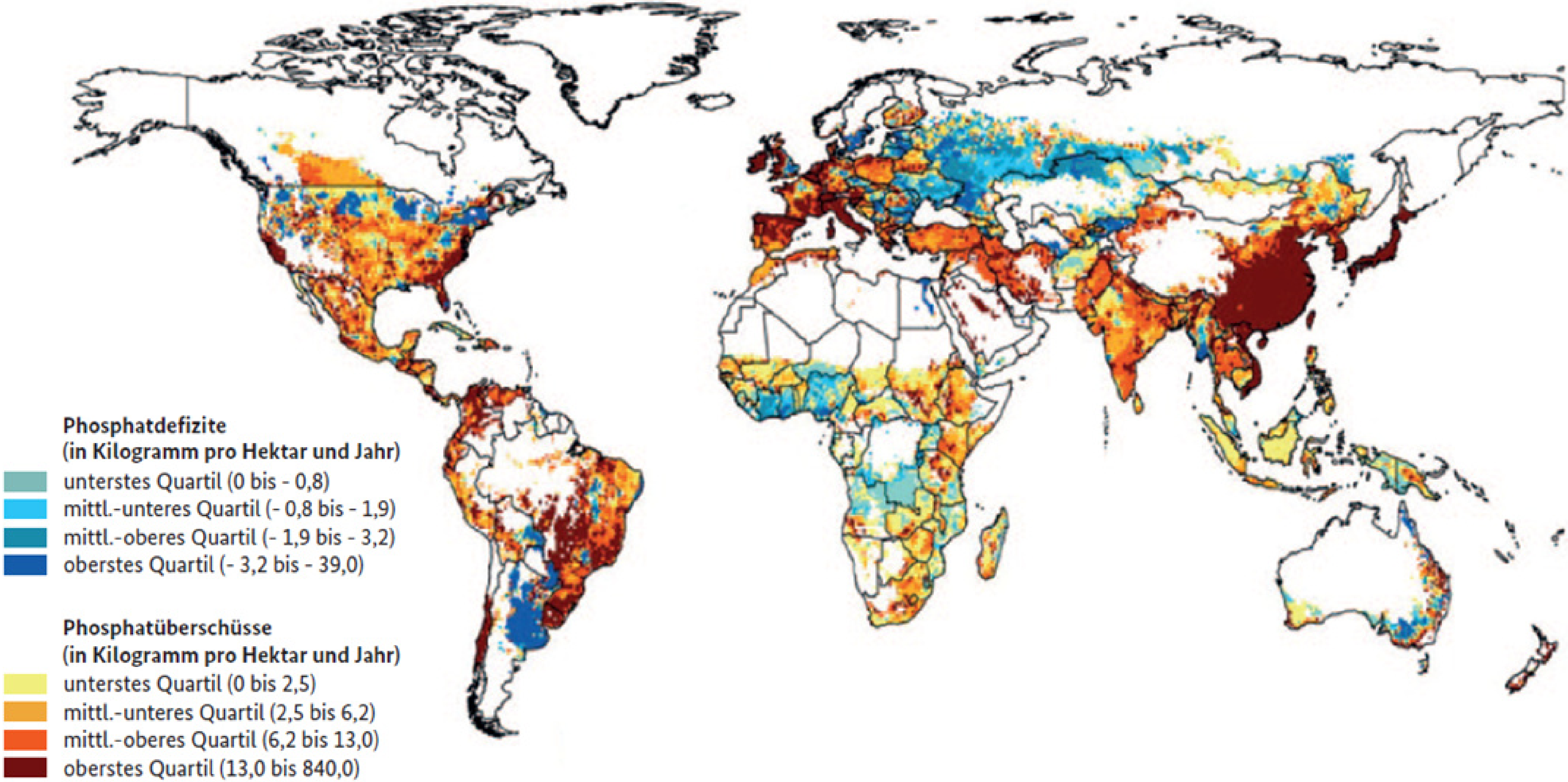
Tab.9: P regulations (DÜV / BMEL) and recommendations (SRU, VDLUFA, Isermann) in Germany considering simultaneously economical (efficiency, yield response), ecological (consistency: Minimizing the P emissions to hydrosphere: -80% till 2020!) and social (sufficiency: Need oriented production and saving animal P resources) needs

1. **Further on not sustainable corresponding official regulations (I + II DÜV / BMEL) and recommendations (II SRU and IV VDLUFA)**
2. **Future sustainable according to Isermann (1985 / 2013), Köster u. Nieder (2007), Gutser (2012 /2013), Römer (2014), Leinweber (2014), Müller (2014), etc.**

P soil test classes			Characteristics of P-fertilization			P-recommendations and regualtions (BMEL) (O= P-Output, -removal; 8.7 kg P = 20 kg $P_2O_5 \cdot ha^{-1} \cdot yr^{-1}$				
						1. Not sustainable				2. sustainable
A-E (mg CAL-P $\cdot$ 100 g soil^{-1})	Shares (%) (DLG/439/2008)		Yield effect [dt / kg P]	Effiziency [%]	Emissions to hydrosphere [g $P \cdot ha^{-1} \cdot yr^{-1}$]	I DÜV (BMELV 2007)	II SRU (14.01.15) Novell. DÜV 2007	III Draft Novell. DÜV BMEL (18.12.14)	IV VDLUFA (1997) und (2012/13)	V Isermann (1985 /2013) and others (s. title point 2)
A (< 2.1)	6	27	High	high	very low (BG)	> O	> O	O+ >8,7	> O	> O
B (2.1 – 4.4)	21		Middle	middle	low	> O	> O	O + > 8.7	> O	O
C (4.5-9.0)	37	73	0 (seldom)	≥ 0	middle	O + 8.7	O	O + 8.7	O	0
D (9.1-15.0)	25		0	0	High	O + 8.7	< O	O	0.5 x O	0
E (> 15.0)	11		0	0	very high	O+ 8.7	< O	till 2017:O 2018:0,75O 2020:0.5 O	0	0

1. **Any P fertilization irrespective with mineral or organic P fertilizers has no yield effects in the P soil test classes C, D and E, but additionally increases the potentials for P emissions into the hydrosphere essentially and plunders the final (± 300 years) P resources last not least mainly with the aim to promote and maintain animal mass consumption and production.**
2. **And vice versa: No P fertilization (in C, D and E) within about further 100 years reduces P fertilization costs of 250 Mio.€ $\cdot$ yr^{1}within the next ca. 100 years, without any restrictions to yields and (apparent) P efficiency of about 100% as well as with tolerable P emissions to the hydrosphere (consistency) and saving mineral P resources (sufficiency)** re2031

Quelle: MacDonald et al. (2011)



Phosphatbilanz für landwirtschaftliche Flächen für das Jahr 2000

Fig.4: Global deficiency and surplus in the application of phosphate on agricultural areas in the year 2000