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IMPACT OF REDUCED PHOSPHORUS FERTILIZATION ON GOLF COURSE PUTTING GREENS

MASTER THESIS PRESENTATION

PUTTING GREEN AT DUETE-DE (NOVEMBER 2020)

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OCTOBER 29, 2021

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GOLF COURSE PUTTING GREENS

Golfer´s needs…

- Firm surface (BAKER 2004)
- Fresh and uniform turfgrass color
- Evenness and trueness (DAHL JENSEN 2012)
- Ball roll distance (green speed) (NOLAN 2015)

} **Playing quality**

Course manager´s targets…

- Healthy, homogeneous turfgrass sward
- High tiller density
- Few areas of bare soil

(MC CARTY 2011; MÜLLER-BECK 2019)

} **Turfgrass quality**

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IMPACT OF P FERTILIZATION ON PLAYING QUALITY AND TURFGRASS QUALITY

P undersupply leads to…

- Reddish and purple discoloration (CARROW 2001)

➔ No fresh, green color

- Slim and limp leaves (WISSEMEIER 201…)

➔ Unsatisfactory … behavi…

P supports…

- Turfgrass establishment (WADDINGTO…)
  - New green, se… after wi…
- … and tilling (FRANK and GUERTAL 2013; PRESSARAKLI 2008)
  - …ow cutting height, frequent mowing
- Root development (DACOSTA and HUANG 2006; LYONS et al. 2008)
  - Stress tolerance, firm surface

P over… …o…

- …wering and …ormation (THIEME-HACK 2018)

➔ Weeds

- *Poa annua* encroachment (RALEY et al. 2013)

➔ Softer soil, increased ball hopping (TOLER 2007)

➔ Not too much, but also not too little - It is important to apply the right P rate to ensure good turfgrass quality and playing quality!

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CURRENT DISCUSSION

Reducing P fertilization on golf courses in order to

- save P fertilizer (non-renewable resource) and (COP… …09; JASINSKI 2014)
- limit the risk of P losses (run-off, leachin… …, SOLDAT and PETROVIC 2008)

➔ Many P fertilization recommendations exist. Which one can ensure good turfgrass quality and playing quality even with reduced P rates?

SUSPHOS PROJECT:
SUSTAINABLE P FERTILIZATION ON GOLF COURSES

STERF project from 2017 – 2020; project leader T. S. Aamlid (NIBIO Landvik)

- **5 experimental sites**
- **3 fertilization recommendations (+ Control without P application)**

The data collected in the SUSPHOS project were the basis of my master thesis.

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EXPERIMENTAL SITES IN FIVE COUNTRIES

Fig. 1: Geographical location of the five experimental sites (GOOGLE EARTH 2021).

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P RECOMMENDATIONS (TREATMENTS)

Sufficiency Level of Available Nutrients (SLAN) (CARROW et al. 2004a, b)

- USA
- Mehlich-3 extraction (< pH 2.5)
- SLAN threshold: > 54 mg kg^{-1} soil („no response to P fertilization“)

Minimum Levels for Sustainable Nutrition (MLSN) (WOODS et al. 2014, 2016, 2020)

- USA
- Mehlich-3 extraction (< pH 2.5)
- Statistical model based on soil samples from greens with good quality
- MLSN threshold: > 18 mg kg^{-1} soil

→ **Soil samples and analysis**

Scandinavian Precision Fertilization (SPF) (ERICSSON et al. 2015; KVALBEIN and AAMLID 2016)

- Scandinavia
- Nutrient ratio in plant (N:P:K:Mg:S)
- P rate: 12 % of annual N rate

→ **Nutrient ratio in plant**

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MASTER SUBJECT

Evaluate the impact of the selected P recommendations on…

- Soil PO_4-P concentration
- Soil pH

- Overall impression

- *Poa annua* coverage

- Rooting depth

Turfgrass quality

…at the 5 golf course putting greens over 4 trial years (Duete-DE: 3-year trial).

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HYPOTHESES

A **lower P rate due to MSLN and SPF recommendations** in comparison to a higher P rate due to SLAN recommendation would

- **decrease soil PO_4-P concentrations** without negatively affecting turfgrass quality,
- **suppress *Poa annua*** in the sward, but
- adversely **decrease turfgrass rooting depth**.

SPF recommendation would

- result in **higher P rates and thus unnecessarily higher soil PO_4-P** concentrations compared to MLSN recommendation,
- while turfgrass quality would remain the same.

SOIL SAMPLING AND ASSESSMENTS

Soil samples (0 – 20cm) and analyses

- one pooled sample (10 punctures) per plot
- P extraction Mehlich-3 (PO_4-P, calorimetrically)
- Soil pH (H_2O method)

Dates

Before the trial started and once a year in Nov.

Overall impression

- Visual ratings 1 – 9 (9 = best)
- ≥ 6 considered „acceptable“ (MORRIS 2004)

Coverage (%)

- Sown species
- *Poa annua*, weeds, moss
- Disease
- Bare soil

= 100%

Rooting depth (mm)

- Measured on intact hanging root cylinder

Before the trial started and once a month from Apr. – Nov. each year (number of assessments differ for each year and site)

Fig. 1: Soil sampling at Duete-DE

Fig. 2: Measurement of rooting depth at Landvik-NO

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EXPERIMENTAL DESIGN AND STATISTICS

- Latin square design
- 4 treatments ,4 replicates
- 3 – 4 trial years

Fig. 3: Experimental green with plots at Duete-DE.

Tab. 1: Overview of descriptive and inferential statistics.

Parameter	Measurement scale	Descriptive	Inferential	Post-Hoc Tests	
Soil samples					
PO_4-P, pH	Interval	Average	ANOVA, repeated measurements with mixed model	HSD, emmeans, contrasts	n = 4 per year
Assessments					
Overall impression	Ordinal	Median, Minimum, Maximum, Q1, Q3	Kruskal-Wallis rank sum test, Friedman rank sum test	Nemenyi-Test	n = 12 – 32 per year and site
Coverage (*Poa annua*)	Interval	Average, Median, Minimum, Maximum, Q1, Q3	ANOVA, repeated measurements with mixed model	HSD, LSD, emmeans, contrasts	
Rooting depth	Interval	Average, Minimum, Maximum, Q1, Q3	ANOVA, repeated measurements with mixed model	HSD, LSD, emmeans, contrasts	

HSD:Tukey´s Honest Significant Difference; LSD: Fischer´s Least Significant Difference; Q1: Quantile 1; Q3: Quantile 3.

➔ Different measurement scales and data structures necessitated the use of different statistics!

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EVALUATION OF THE CLIMATE CONDITIONS AT THE SITES

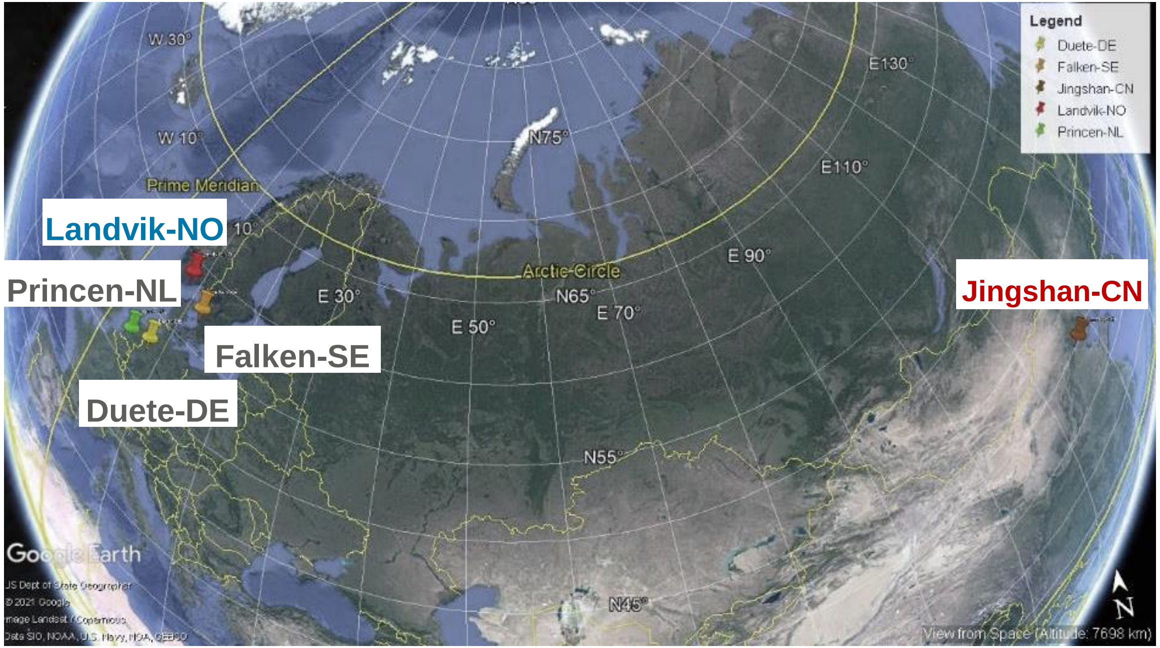
Long-term annual air temperature (° C) and long-term annual precipitation (mm)

Cold, wet

7.8 °C	1.416 mm

Intermediate

10.9 °C	834 mm
9.0 °C	872 mm
9.1 °C	830 mm



Warm, dry

12.0 °C	507 mm

(CLIMATE-DATA 2021; DONKERS 2021; GOOGLE EARTH 2021; VACKERTVÄDER 2021)

Fig. 4: Geographical location and climate of the five experimental sites

➔ The chosen experimental sites differ in climate conditions.

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EVALUATION OF THE SITE CHARACTERISTICS

(Photos: a) PRÄMAßING, b) SINTORN, c) CHEN, d) AAMLID, e) DOKKUMA)

Exper. site / Characteristics	 Duete-DE a)	 Falken-SE b)	 Jingshan-CN c)	 Landvik-NO d)	 Princen-NL e)
Putting green construction	FLL K3	Push-up / USGA	USGA	USGA	USGA
Sown species	*Agrostis stolonifera*	*Agrostis stolonifera*	*Agrostis stolonifera*	*Agrostis stolonifera*	*Festuca rubra* + *Agrostis capillaris*
Poa annua coverage (%)	**55**	**50**	0	10	5
N rates (g m^{-2} y^{-1})	18 – 27	19 – 25	10 – 12	12 – 25	3 – 6
Soil pH	6.7	6.0	**8.3**	5.9	6.3
Soil PO_4-P (mg kg^{-1} soil)	14 – 17	33 – 37	7 – 9	**25 – 29**	6 – 7
PSC (mmol kg^{-1} soil)	4.60	6.72	**8.04**	6.41	4.26
DPS (%)	**36**	**37**	15	**24**	17
Ca (cmol c^{+} kg^{-1} soil)	**2.30**	0.93	**4.60**	0.50	1.00

➔ The sites differed clearly in site characteristics. Did that have any influence?

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PO_4-P CONCENTRATIONS ACROSS ALL YEARS FOR ALL SITES

Tab. 2: Average soil PO_4-P concentration (mg kg^{-1} soil) across all sampling dates for each experimental site in response to different P treatments. Different letters indicate differences between treatments (Tukey contrasts, α = 0.05).

Treatment	**PO_4-P (mg kg^{-1} soil)**				
	Duete-DE	Falken-SE	Jingshan-CN	Landvik-NO	Princen-NL
Control	16 **a**	29 **a**	9 **a**	25 **a**	8 **a**
MLSN	23 **ab**	28 **a**	18 **b**	25 **a**	9 **a**
SPF	27 **b**	29 **a**	16 **ab**	31 **a**	8 **a**
SLAN	41 **c**	45 **b**	40 **c**	46 **b**	23 **b**
p-value	0.001	0.007	0.000	0.003	0.000

- MLSN and SPF: Significantly lower PO_4-P compared to SLAN
- No significant differences between MLSN and SPF
- Control: Rarely significantly lower PO_4-P compared to MLSN or SPF, but always compared to SLAN

➔ Despite the site characteristic differences, soil PO_4-P concentrations for MLSN and SPF were significantly lower compared to SLAN on all sites but …

…why were PO_4-P levels different for MLSN or SLAN between the sites? And what about P rates – were they the same on all sites?

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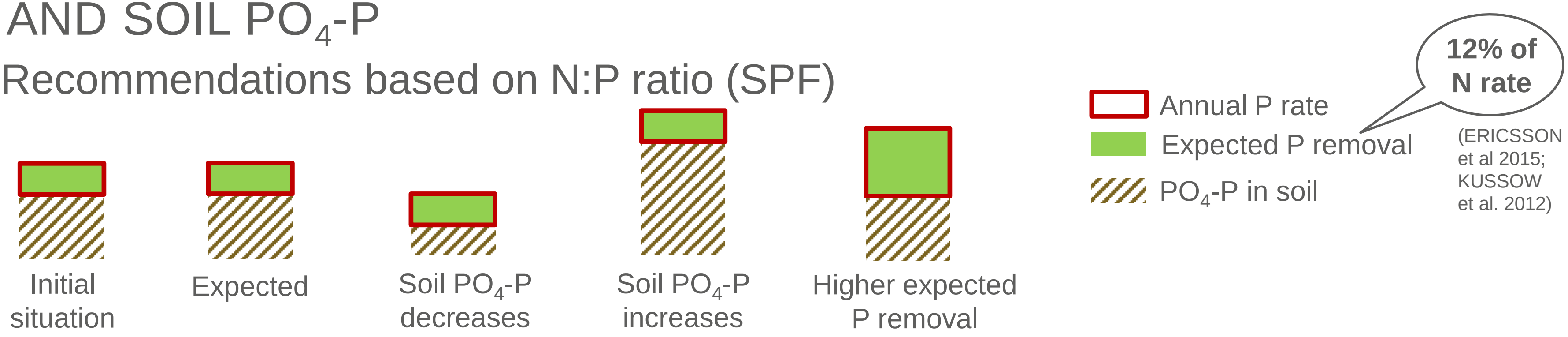
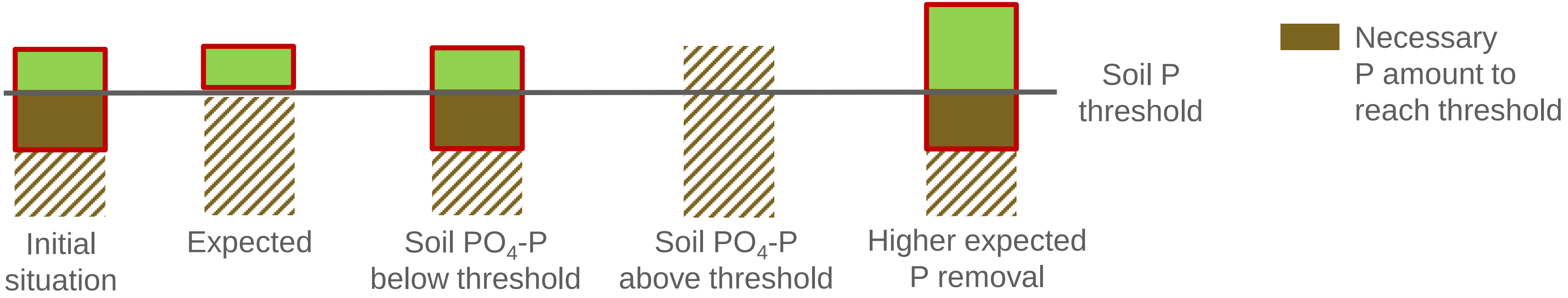
RELATIONSHIP BETWEEN RECOMMENDATION, P RATE, AND SOIL PO_4-P

Recommendations based on N:P ratio (SPF)



Recommendations based on soil sampling and analysis (SLAN, MLSN)



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ANNUAL AND TOTAL P RATES

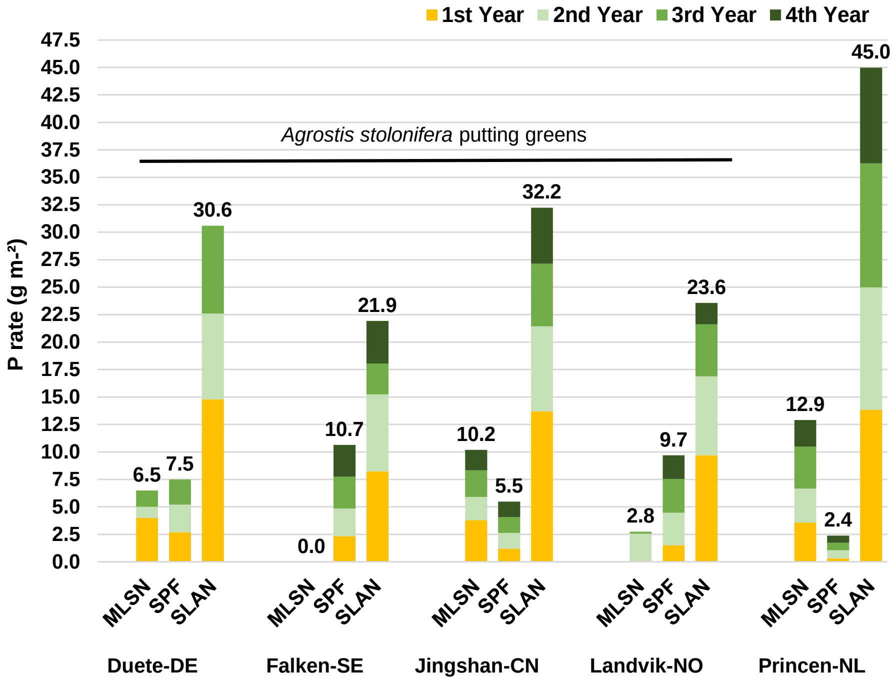

Fig. 5: Annual P rates for each experimental site and trial year.

- Depending on the site and year: P rates were different
- Depending on the treatment: P rates were different
- MLSN and SPF: Lower annual and total P rates compared to SLAN
- MLSN total P rates < SPF total P rates: Duete-DE, Falken-SE, Landvik-NO
- MLSN total P rates > SPF total P rates: Jingshan-CN and Princen-NL

Sites with low initial soil P

➔ P rates differed depending on recommendation, trial year, and/or site.

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CHANGES IN PO_4-P CONCENTRATIONS ON ALL SITES

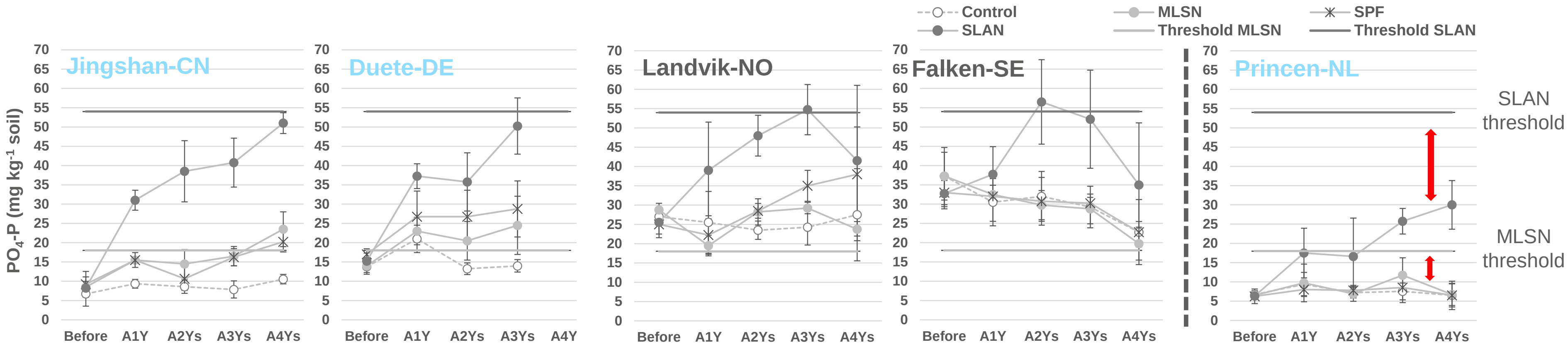

Fig. 6: Soil PO_4-P concentration (mg kg^{-1} soil) in response to different P treatments. Five sampling dates, one in each trial year (four for Duete-DE). Error bars represent the spatial variation at plot scale (n = 4).

- **SLAN**: Increased soil PO_4-P but just 2 of 5 sites reached the threshold
- **MLSN**: At all *Agrostis* sites: Soil PO_4-P was above threshold but at Jingshan-CN not before 3rd trial year

  At the *Fr + Ac* site: Soil PO_4-P was below threshold

➔ **What might be the reasons for these gaps?**

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THE REASONS MIGHT BE…

Higher plant uptake than predicted

- *Poa pratensis*: + P supply, + P concentration in clippings (NUS et al. 1993)
- P uptake calculation: biomass and P concentration in clippings } **Not measured!**

➔ Weak indicator: constant soil PO_4-P in SPF treatment

Soil extraction method

- Different extracting methods lead to different results due to different extracted P pools (WUENSCHER et al. 2016)
- Calcareous soils OLSEN recommended (ZORN and KRAUSE 1999) but Mehlich-3 suitable for most soils (FRANK et al. 1998; SIMS 2000)

➔ Methods might be more important for P availability, but cannot explain the gap ➔ P rate calculation

P losses due to leaching

- Green construction (large pores, high infiltration rate) (USGA 2018)
- Low P retention due to low Al + Fe (PSC), low Ca (AMELUNG 2018; MAGUIRE et al. 2001)

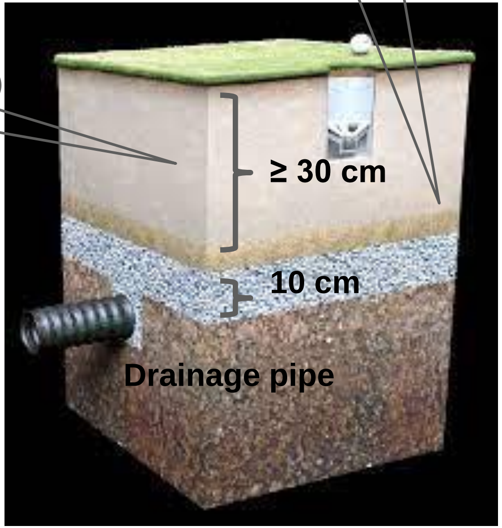

Fig. 7: USGA putting green construction (USGA 2018)

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PO_4-P CONCENTRATIONS AT JINGSHAN-CN

Calcareous; pH high; PSC high, DPS low, Ca high, P rates MLSN > SPF

Tab. 3: Influence of different P treatments on soil PO_4-P (mg kg^{-1} soil). Different letters indicate differences between treatments (HSD, α = 0.05 (bold) and 0.10 (italic), ns = not significant).

Exper. site	**Treatment**	**PO_4-P (mg kg^{-1} soil)**				
		Before	After1Y	After2Ys	After3Ys	After4Ys
Jingshan-CN	Control	7	9 **a**	9 **a**	8 **a**	11 **a**
	MLSN	9	16 **b**	15 **a**	17 **a**	24 **b**
	SPF	9	16 **b**	11 **a**	16 **a**	20 **b**
	SLAN	8	31 **c**	39 **b**	41 **b**	51 **c**
	ANOVA p-value	0.537	0.000	0.001	0.000	0.000
	HSD (α=0.05)	**ns**	**5.4**	**12.5**	**9.0**	**7.6**
	HSD (α=0.10)					

Y =Year/Years

pH decreased, thus P sorption to Al and Fe might have increased

Warm and dry climate: probably high irrigation rates, rain seldom with high rates

- PO_4-P concentrations were lower than expected for MLSN and SLAN ➔ most likely leaching
- PSC and DPS not useful ➔ P bounded to Ca in high pH soils (AMELUNG 2018; KREUSER 2012)
- P rates for SPF were twice as low as for MLSN ➔ N:P ratio better to reduce P rates

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PO_4-P CONCENTRATIONS AT DUETE-DE

pH slightly higher; PSC low, DPS high, Ca high, P rates MLSN < SPF

Tab. 4: Influence of different P treatments on soil PO_4-P (mg kg^{-1} soil). Different letters indicate differences between treatments (HSD, α = 0.05 (bold) and 0.10 (italic), ns = not significant).

Exper. site	**Treatment**	**PO_4-P (mg kg^{-1} soil)**				
		Before	After1Y	After2Ys	After3Ys	After4Ys
Duete-DE	Control	14 **a**	21 **a**	13 **a**	14 **a**	-
	MLSN	14 **a**	23 **a**	21 **ab**	25 **a**	-
	SPF	17 **b**	27 **ab**	27 **bc**	29 **a**	-
	SLAN	15 **ab**	37 **b**	36 **c**	50 **b**	-
	ANOVA p-value	0.013	0.015	0.001	0.003	-
	HSD (α=0.05)	**2.4**	**12.3**	**9.5**	**18.2**	-
	HSD (α=0.10)					

Y =Year/Years

pH increased, P sorption to Ca increased?

Thatch and organic material ➔ less leaching?

Fig. 8: Spade sample from Duete-DE

- PO_4-P significantly lower for MLSN and SPF compared to SLAN
- PO_4-P concentrations were lower than expected for SLAN, not for MLSN
  ➔ P retention in soil enough for MLSN threshold thus low PSC
- Recommendations based on soil analysis (and low threshold) better than N:P ratio

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PO_4-P CONCENTRATIONS AT FALKEN-SE

pH slightly lower; PSC medium, DPS high, Ca low, P rates MLSN < SPF

Tab. 5: Influence of different P treatments on soil PO_4-P (mg kg^{-1} soil). Different letters indicate differences between treatments (HSD, α = 0.05 (bold) and 0.10 (italic), ns = not significant).

Exper. site	**Treatment**	**PO_4-P (mg kg^{-1} soil)**				
		Before	After1Y	After2Ys	After3Ys	After4Ys
	Control	37	31	32 **a**	29 **a**	23 *ab*
	MLSN	37	33	30 **a**	29 **a**	20 *a*
	SPF	33	32	31 **a**	30 **a**	23 *ab*
Falken-SE	SLAN	33	38	57 **b**	52 **b**	35 *b*
	ANOVA p-value	0.613	0.431	0.004	0.002	0.057
	HSD (α=0.05)	**ns**	**ns**	**16.4**	**12.6**	**ns**
	HSD (α=0.10)					*13.0*

Y =Year/Years

Breakdown of irrigation system

- PO_4-P significantly lower for MLSN and SPF compared to SLAN from 2nd year
- PO_4-P decreased slowly for MLSN due to no P application (still above threshold)
- P retention on this green, probably less leaching but is it necessary to increase soil PO_4-P?

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INTERIM CONCLUSION

- Using MLSN and SPF fertilization recommendations, P rates could be reduced compared to SLAN recommendation at all sites.
- Average soil PO_4-P concentrations were significantly lower for MLSN or SPF recommendations compared to SLAN at all sites.

Nevertheless there were considerable differences between the putting greens!

- On the greens with initial medium soil P levels (> 18 mg kg^{-1} soil; Falken-SE and Landvik-NO) and at Duete-DE (low initial soil P level), the MLSN recommendation led to lower P rates than SPF. The reverse was the case on golf greens with low initial levels and low P retention (Jingshan-CN and Princen-NL) probably due to P losses.

- P rates according to MLSN and SPF recommendations were sufficient to meet the MLSN threshold on most sites, except at Princen-NL and in some years at Jingshan-CN. Soil PO_4-P concentrations were almost always below SLAN threshold.

How did that affect turfgrass quality?

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OVERALL IMPRESSION

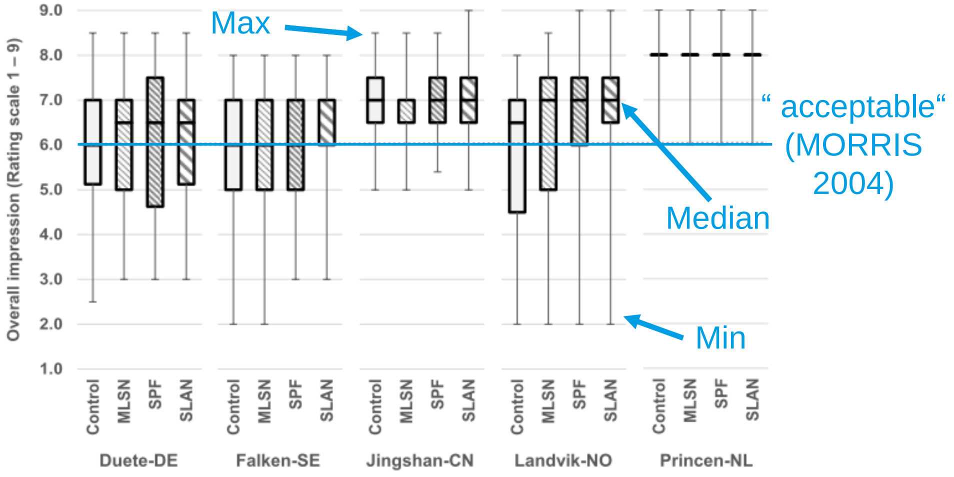

Fig. 9: Impact of P treatments on overall impression (scale 1 – 9) across all dates for each site.

Tab. 6: Mean overall impression (Rating scale 1 – 9) in response to different P at Duete-DE and Jingshan-CN. Different letters indicate differences between the trial years for each P treatment (p-value < 0.05).

Exper. site	Treatment	Overall impression (Rating scale 1 - 9)					Friedman rank test
		Before[a]	1st Year	2nd Year	3rd Year	4th Year	p-value
Duete-DE	Control	2.5	5.5 **a**	6.0 **ab**	7.0 **b**	-	0.018
	MLSN	2.5	5.5 **a**	6.5 **ab**	7.0 **b**	-	0.022
	SPF	2.5	5.0 **a**	6.5 **ab**	7.5 **b**	-	0.018
	SLAN	2.5	5.5 **a**	6.5 **ab**	7.3 **b**	-	0.018
Jingshan-CN	Control	5.8	6.3	7.0	7.0	7.0	0.100
	MLSN	5.3	6.3 **a**	7.0 **ab**	7.0 **ab**	7.0 **b**	0.044
	SPF	5.0	6.5 **a**	7.0 **ab**	7.0 **ab**	7.8 **b**	0.010
	SLAN	5.3	6.3 **a**	7.0 **ab**	7.0 **ab**	8.0 **b**	0.010

[a] *Results reported at the first assessment date (Jingshan-CN: July 2017, Duete-DE: April 2018) before the trial started. Values not used for statistical analysis (Friedman test).*

- Median visual turfgrass quality was acceptable or even better (≥ 6.0 – 8.0) (MORRIS 2004)

  ➔ Good quality thus lower P rates and P levels

- Overall impression increased over time for all treatments at Duete-DE (less *Poa annua*) and for all P treatments at Jingshan-CN (higher P availability)

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POA ANNUA COVERAGE

- High P supply promotes *Poa annua*, (GUERTAL and MC ELROY 2018) low P supply reduces *Poa annua* (THIEME-HACK 2018)

  ➔ Could not be confirmed in this study (no significant differences 5% level between treatments across all years)
- 2-year study: no P application reduced *Poa annua* by 2 % (RILEY et al. 2013)

  ➔Could be confirmed in this study at Falken-SE (significant differences in 2nd year; 2 – 3 % decline by lower P rates)
- P rates better indicator for *Poa annua* encroachment than soil PO_4-P (RILEY et al. 2013)
- ➔ No correlation found in this study either

Tab 7: Influence of different P treatments on *Poa annua* coverage (%) Different letters indicate differences between treatments (Tukey contrasts, α = 0.05; ns = not significant).

Exper. site	Treatment	*Poa annua* (%)					
		Before[a]	1st Year	2nd Year	3rd Year	4th Year	All years[c]
Duete-DE	Control	49.1	44.4	35.5	32.6	-	37.2
	MLSN	51.5	46.7	36.8	33.3	-	38.6
	SPF	48.8	45.4	38.2	32.2	-	38.3
	SLAN	50.5	45.7	36.3	33.8	-	38.3
	p-value	0.816[b]	0.764	0.213	0.183	-	0.274
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**	-	**ns**
Falken-SE	Control	47.3	48.2	48.4 **a**	47.1 **a**	47.5	47.8
	MLSN	50.0	50.3	47.9 **a**	47.9 **ab**	46.7	47.9
	SPF	49.0	49.7	49.0 **a**	50.1 **ab**	47.3	48.9
	SLAN	53.3	53.6	50.8 **b**	50.6 **b**	49.1	50.7
	p-value	0.195[b]	0.316	0.005	0.023	0.407	0.077
	Tukey (α=0.05)	**ns**	**ns**			**ns**	**ns**
Landvik-NO	Control	6.3	5.5	7.6	8.1	3.3 **a**	5.9
	MLSN	8.8	7.7	14.6	14.5	6.0 **ab**	10.4
	SPF	6.5	7.4	12.6	18.1	9.4 **b**	12.1
	SLAN	4.3	4.7	10.1	8.8	6.0 **ab**	7.3
	p-value	0.408[b]	0.620	0.154	0.179	0.054	0.066
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**		**ns**
Princen-NL	Control	5.0	2.7	2.5	8.9	8.2	6.1
	MLSN	5.0	2.6	2.8	11.1	6.5	6.3
	SPF	5.0	2.6	3.0	13.7	6.5	7.1
	SLAN	5.0	2.4	3.3	12.9	6.5	6.9
	p-value	-	0.972	0.445	0.462	0.950	0.803
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**

[a] Poa annua registered at the first assessment date (Duete-DE = April, Falken-SE = July, Landvik-NO = June, Princen-NL = July). [b] Statistics: ANOVA and HSD (α=0.05). [c] Duete-DE 3-year trial, all others 4-year trials.

ROOTING DEPTH

From
30 to 55 mm
after 3 years

- Across all years: No significant differences in rooting depth between recommendations on 4 of 5 sites

  ➔ Probably due to high distribution of the subsamples

- Jingshan-CN: Significantly increased rooting depth due to higher P rates (SLAN), which most likely increased plant available P (MARSCHNER and RENGEL 2012)

- Landvik-NO: Increased rooting depth due to no P application

  ➔ Indicating: Lower rates stimulate root growth (LYONS et al. 2008)

Tab 8: Influence of P treatments on rooting depth (mm).

Exper. site	Treatment	Rooting depth (mm)					
		Before[a]	1st Year	2nd Year	3rd Year	4th Year	All years[c]
Duete-DE	Control	30	41	61	50	-	51
	MLSN	30	39	61	54	-	52
	SPF	28	39	64	55	-	53
	SLAN	27	37	67	55	-	54
	p-value	0.714[b]	0.110	0.168	0.349	-	0.518
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**	-	**ns**
Falken-SE	Control	130	131	148	160 **ab**	130	143
	MLSN	125	127	150	156 **a**	135	144
	SPF	125	129	153	160 **ab**	135	146
	SLAN	130	138	159	169 **b**	134	151
	p-value	0.834[b]	0.414	0.341	0.029	0.619	0.100
	Tukey (α=0.05)	**ns**	**ns**	**ns**		**ns**	**ns**
Jingshan-CN	Control	159	122	118	105 **a**	110 **a**	111 **a**
	MLSN	149	128	119	108 **a**	112 **ab**	115 **ab**
	SPF	142	130	118	118 **b**	113 **ab**	118 **ab**
	SLAN	157	130	121	120 **b**	117 **b**	121 **b**
	p-value	0.366[b]	0.273	0.715	0.012	0.034	0.037
	Tukey (α=0.05)	**ns**	**ns**	**ns**			
Landvik-NO	Control	50	53	86	89	117	91
	MLSN	78	65	67	78	93	78
	SPF	56	69	60	75	95	78
	SLAN	66	58	63	84	91	78
	p-value	0.536[b]	0.691	0.163	0.224	0.088	0.159
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**
Princen-NL	Control	81	78	98	93	90	90
	MLSN	84	82	100	89	95	92
	SPF	86	85	103	85	95	93
	SLAN	88	82	102	99	104	98
	p-value	0.726[b]	0.195	0.724	0.079	0.159	0.095
	Tukey (α=0.05)	**ns**	**ns**	**ns**	**ns**	**ns**	**ns**

[a] Values measured at the first assessment date (Duete-DE = April, Falken-SE = July, Landvik-NO = June, Princen-NL = July). [b] Statistics: ANOVA and HSD (α=0.05). [c] Duete-DE 3-year trial, all others 4-year trials.

Different letters indicate differences between treatments (Tukey contrasts, α = 0.05, ns = not significant).

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WERE THE HYPOTHESES RIGHT?

✓ Yes
O Not clear
X No

A **lower P rate due to MSLN and SPF recommendations** in comparison to a higher P rate due to SLAN recommendation would

- **decrease soil PO_4-P concentrations** without negatively affecting turfgrass quality, ✓
- **suppress *Poa annua*** in the sward, but O
- adversely **decrease turfgrass rooting depth**. O

SPF recommendation would

- result in **higher P rates and thus unnecessarily higher soil PO_4-P** concentrations compared to MLSN recommendation, O
- while turfgrass quality would remain the same. ✓

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FOR PRACTICAL FERTILIZATION

- Each putting green is different, thus there is no " the one and only" recommendation that reduces P fertilization and at the same time maintains good turfgrass quality.
- To switch from SLAN recommendation to MLSN recommendation reduces fertilizer input without negatively influencing turfgrass quality regardless of putting green but…
  - The P savings will differ between putting greens.
  - Some greens might be more sensitive to lower soil PO_4-P concentrations or reduced P rates than others.
  - Soil PO_4-P concentrations might be even lower than MLSN threshold without degrading turfgrass quality and playing quality.

NEVERTHELESS: P fertilization recommendations based on soil samples might not be the best choice for sustainable P fertilization on putting greens as long as their thresholds are above soil P retention.

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FOR PRACTICAL FERTILIZATION

- To switch from SLAN recommendation to SPF recommendation reduces fertilizer input without negatively influencing turfgrass quality regardless of putting green but…
  - When using SPF, it must be kept in mind that special situations increasing N rate (i.g. winter damage) will increase the P rate.
  - On putting greens with low soil P retention recommendations based on N:P will probably lead to lower P fertilization than recommendation based on soil analysis.
- For sustainable P fertilization it seems to be more important to applicate P in low rates frequently and to keep an eye on the conditions at the application dates (rainfall, irrigation).
- Low single P rates might also support to suppress *Poa annua*.

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FOR FUTURE RESEARCH

I would chose…

- Less or more uniform experimental sites
- Same number of assessment dates for each site

I would record…

- Weather and irrigation
- Biomass
- Objective assessments of turfgrass quality

I would analyse…

- Total P concentration in soil
- P in drainage water
- P and N in clippings

And if I still had time and money left, I would…

- Test different soil extraction methods to find out, which one describes rootzone P availability best
- Develop new soil characteristics or other parameters that (better) describe or predict:
  - Rootzone P sorption capacity
  - P leaching risk
  - Turfgrass sufficient P supply

P FERTILIZATION ON GOLF GREENS

“~~GOLF~~ IS DECEPTIVELY SIMPLY AND ENDLESSLY COMPLICATED.”

- ARNOLD PALMER -

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PO_4-P CONCENTRATIONS AT PRINCEN-NL

PSC low, DPS low, Ca low, P rates MLSN > SPF

Tab. 9: Influence of different P treatments on soil PO_4-P (mg kg^{-1} soil). Different letters indicate differences between treatments (HSD, α = 0.05 (bold) and 0.10 (italic), ns = not significant).

Exper. site	**Treatment**	**PO_4-P (mg kg^{-1} soil)**				
		Before	After1Y	After2Ys	After3Ys	After4Ys
Princen-NL	Control	7	9	7	8 **a**	7 **a**
	MLSN	7	10	7	12 **a**	7 **a**
	SPF	6	8	8	9 **a**	7 **a**
	SLAN	6	18	17	26 **b**	30 **b**
	ANOVA p-value	0.403	0.097	0.099	0.000	0.000
	HSD (α=0.05)	**ns**	**ns**	**ns**	**5.5**	**6.6**
	HSD (α=0.10)					

Y =Year/Years

PSC and DPS seem to be useful parameters

- PO_4-P significantly lower for MLSN and SPF compared to SLAN only in last two years
- PO_4-P concentrations were lower than expected for MLSN and SLAN ➔ most likely leaching
- PSC, DPS, and Ca useful parameters
- P rates for SPF were four times lower than for MLSN ➔ N:P ratio better to reduce P rates

Lower N rates due to *Fr* + *Ac*

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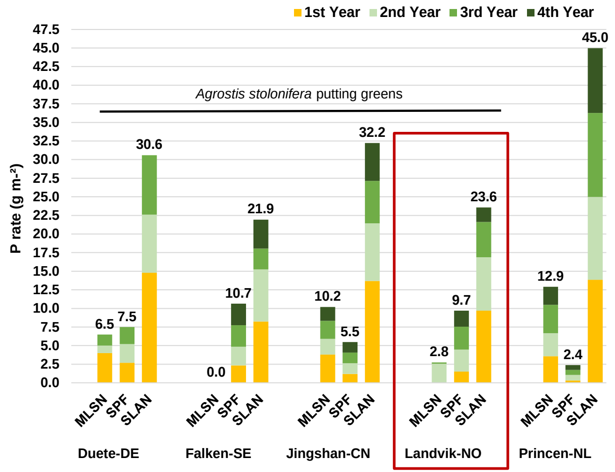
PO_4-P CONCENTRATIONS AT LANDVIK-NO

pH optimum; PSC medium, DPS low, Ca low, P rates MLSN < SPF

Tab. 10: Influence of different P treatments on soil PO_4-P (mg kg^{-1} soil). Different letters indicate differences between treatments (HSD, α = 0.05 (bold) and 0.10 (italic), ns = not significant).

Exper. site	**Treatment**	**PO_4-P (mg kg^{-1} soil)**				
		Before	After1Y	After2Ys	After3Ys	After4Ys
Landvik-NO	Control	27	26 *ab*	24 **a**	24 **a**	28
	MLSN	29	20 *a*	28 **a**	29 **a**	24
	SPF	25	22 *ab*	29 **a**	35 **a**	38
	SLAN	26	39 *b*	48 **b**	55 **b**	42
	ANOVA p-value	0.101	0.065	0.000	0.000	0.499
	HSD (α=0.05)	**ns**	**ns**	**8.8**	**11.0**	**ns**
	HSD (α=0.10)		*17.3*			

Y =Year/Years



- No P application or low P rates for MLSN affected PO_4-P directly ➔ MLSN good choice
- Certain retention in soil as PO_4-P for SPF and SLAN increases
- Studies have proven considerable losses by P run-off ➔ Risk due to high precipitation

(RICE and HORGAN 2010)

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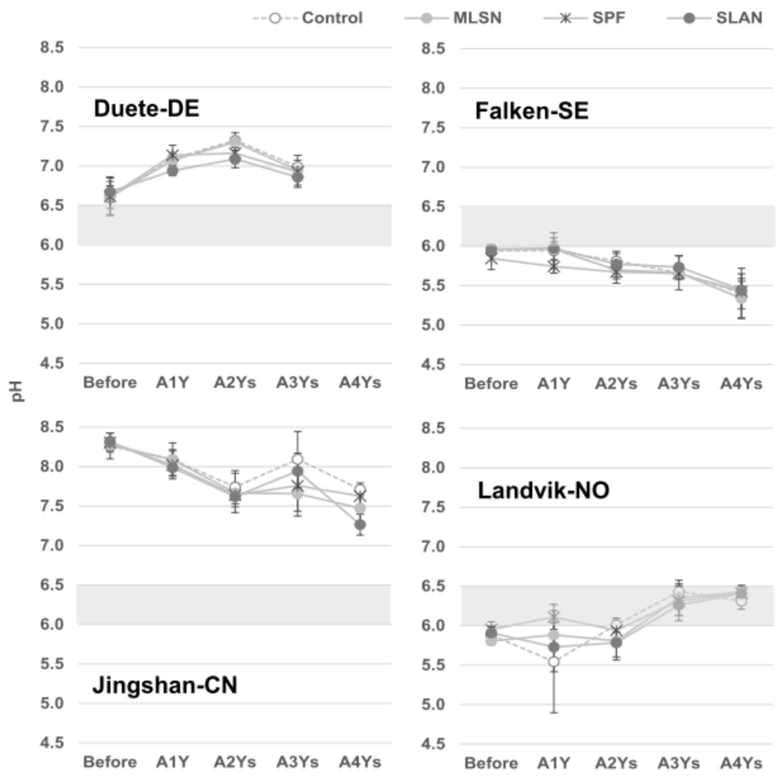
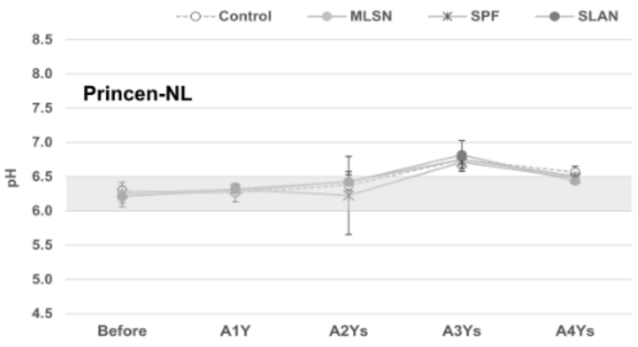
SOIL PH





Exper. site	Treatment	pH				
		Before	After1Y	After2Ys	After3Ys	After4Ys
Jingshan-CN	Control	8.3	8.1	7.7	8.1	7.7 **b**
	MLSN	8.3	8.1	7.7	7.7	7.5 **ab**
	SPF	8.3	8.0	7.6	7.8	7.6 **b**
	SLAN	8.3	8.0	7.6	7.9	7.3 **a**
	ANOVA p-value	0.862	0.761	0.802	0.446	0.020
	HSD (α=0.05)	**ns**	**ns**	**ns**	**ns**	**0.4**
	HSD (α=0.10)					

Y =Year/Years

➔ Little soil pH response to different recommendations.