

Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a Confirmed

- ☒ ☐ The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
- ☒ ☐ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
- ☒ ☐ The statistical test(s) used AND whether they are one- or two-sided
Only common tests should be described solely by name; describe more complex techniques in the Methods section.
- ☒ ☐ A description of all covariates tested
- ☒ ☐ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
- ☒ ☐ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
- ☒ ☐ For null hypothesis testing, the test statistic (e.g. F , t , r) with confidence intervals, effect sizes, degrees of freedom and P value noted
Give P values as exact values whenever suitable.
- ☒ ☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
- ☒ ☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
- ☒ ☐ Estimates of effect sizes (e.g. Cohen's d , Pearson's r), indicating how they were calculated

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection	No code was used for data collection.
Data analysis	All data analyses were conducted using R (version 4.1.1, R Core Team, 2021). We used the R package SoilR (Sierra et al. 2014) to implement a radiocarbon version of the models, and used the R package FME (Soetaert and Pedzoldt 2010) to obtain parameter values using inverse data-assimilation (see reference in the paper). All code for reproducing the results is available at this repository. https://doi.org/10.5281/zenodo.8070747

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

All data are available at this repository. <https://doi.org/10.5281/zenodo.8070747>

Human research participants

Policy information about [studies involving human research participants and Sex and Gender in Research.](#)

Reporting on sex and gender

Use the terms sex (biological attribute) and gender (shaped by social and cultural circumstances) carefully in order to avoid confusing both terms. Indicate if findings apply to only one sex or gender; describe whether sex and gender were considered in study design whether sex and/or gender was determined based on self-reporting or assigned and methods used. Provide in the source data disaggregated sex and gender data where this information has been collected, and consent has been obtained for sharing of individual-level data; provide overall numbers in this Reporting Summary. Please state if this information has not been collected. Report sex- and gender-based analyses where performed, justify reasons for lack of sex- and gender-based analysis.

Population characteristics

Describe the covariate-relevant population characteristics of the human research participants (e.g. age, genotypic information, past and current diagnosis and treatment categories). If you filled out the behavioural & social sciences study design questions and have nothing to add here, write "See above."

Recruitment

Describe how participants were recruited. Outline any potential self-selection bias or other biases that may be present and how these are likely to impact results.

Ethics oversight

Identify the organization(s) that approved the study protocol.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description

The long-term field experiment is located in South-West Sweden (58°20'49.9"N 13°07'36.1"E) at the field station Lanna, which is maintained by the Swedish University of Agricultural Sciences (SLU). Mean annual temperature and mean annual precipitation were 6.1°C and 558 mm in the period 1961-1990, and 7.3°C and 584 mm in the period 1991-2020. The experiment is located at 75 m a.s.l. on a plain of Quaternary glacial clay deposits. The glacial clay is overlain by an approximately 30 cm thick postglacial silty clay loam (Johansson, 1944). The area was drained in the late 19th century to enable crop production (Mattson et al., 1950). The soil is classified as an Udertic Haploboroll with a silty clay topsoil and a clay subsoil both with strong coarse subangular blocky structure (Bergström et al., 1994). The soil in the uppermost 20 cm is very fine-textured, and contains 42% clay and 15% fine silt (Table S1). The soil pH was on average 6.3 over the 53 years of observation, and there was no significant effect of P application (see Supplement Fig. S2).

The experiment consists of two identical halves, one started in 1936 and the other in 1941. In each of the two halves of the experiment, each treatment is replicated twice (total n = 4). (Each treatment used to be replicated four times in each half of the experiment until the 1970s when two replicates per experimental half were used for a new, additional lime treatment.). For the present study, only three treatments were considered. A control treatment that does not receive P, a P addition treatment (called P treatment in the following) in which 1.75 g P m⁻² yr⁻¹ is applied, and a second P addition treatment (called P6 in the following), in which the same amount of P per year is added but concentrated every six years, i.e., 10.5 g P m⁻² every 6th year. P is added as superphosphate. In addition, all three treatments (Control, P, and P6) receive 0.5 kg Ca(NO₃)₂ m⁻² annually. The plot size is 7.0 m × 7.0 m. The experiment (which has the reference number R3-1001) comprises also lime treatments that are not considered here, but were recently analyzed regarding the effects of liming on soil P dynamics by Simonson et al. (2018) and effects of liming on crop yields by Börjesson and Kirchmann (2022). During the first 20 years of the experiment, a fixed seven-year crop rotation was maintained, consisting of winter wheat, peas, spring cereals, ley, ley (2nd year), spring cereals, and fallow. During each rotation, all plots were fertilized twice with farmyard manure at a rate of 2.0 kg m⁻². Since the late 1950s, the rotation has changed, now consisting mainly of cereals and occasionally oilseed rape and fallow. Manure is no longer used since the 1950s and no P fertilizer other than the experimental treatment is applied. The soil is ploughed once per year, down to 20 cm, and crop residues are left on the field.

Research sample

Soil samples from the uppermost 20 cm have been collected every six years before P fertilization. These samples were air-dried, and sieved (<2 mm) whereby roots were removed from the soil. Until 2019, soil samples of the replicates of each treatment were combined prior to the chemical analyses (pH and P-AL) and archiving of the samples. Archived soil samples from all three treatments (Control, P, and P6) exist from the years 1968, 1977, 1980, 1989, 2001, 2003, 2013, 2015, and 2019, with the exception that from 1968 only two samples (Control and P) have been conserved. In addition, the total P content of the yields (grains) was determined every year for the period 1995-2009.

For the present study, soil samples from all four replicates of the three treatments (Control, P, and P6) were collected. Specifically, one composite sample consisting of five cores of the uppermost 20 cm of each plot was taken in the autumn of 2021. These samples

were air-dried, and sieved (<2 mm) whereby roots were removed from the soil. In contrast to the samples of the previous years, samples of all replicates were analyzed separately. Together with the archived soil samples, the soil samples examined in the present study cover a period of 53 years (1968-2021) and form a 10-point time series.

Sampling strategy	The experiment consists of two identical halves, one started in 1936 and the other in 1941. In each of the two halves of the experiment, each treatment is replicated twice (total $n = 4$). For the present study, only three treatments were considered. A control treatment that does not receive P, a P addition treatment (called P treatment in the following) in which 1.75 g P m ⁻² yr ⁻¹ is applied, and a second P addition treatment (called P6 in the following), in which the same amount of P per year is added but concentrated every six years, i.e., 10.5 g P m ⁻² every 6th year. Soil samples from the uppermost 20 cm have been collected every six years before P fertilization. These samples were air-dried, and sieved (<2 mm) whereby roots were removed from the soil.
Data collection	Crop yields have been measured (almost) every year since the beginning of the experiment. Soil samples from the uppermost 20 cm have been collected every six years before P fertilization. These samples were air-dried, and sieved (<2 mm) whereby roots were removed from the soil. Until 2019, soil samples of the replicates of each treatment were combined prior to the chemical analyses (pH and P-AL) and archiving of the samples. Archived soil samples from all three treatments (Control, P, and P6) exist from the years 1968, 1977, 1980, 1989, 2001, 2003, 2013, 2015, and 2019, with the exception that from 1968 only two samples (Control and P) have been conserved. In addition, the total P content of the yields (grains) was determined every year for the period 1995-2009. For the present study, soil samples from all four replicates of the three treatments (Control, P, and P6) were collected. Specifically, one composite sample consisting of five cores of the uppermost 20 cm of each plot was taken in the autumn of 2021. These samples were air-dried, and sieved (<2 mm) whereby roots were removed from the soil. In contrast to the samples of the previous years, samples of all replicates were analyzed separately. Together with the archived soil samples, the soil samples examined in the present study cover a period of 53 years (1968-2021) and form a 10-point time series.
Timing and spatial scale	The experiment consists of two identical halves, one started in 1936 and the other in 1941. Archived soil samples from all three treatments (Control, P, and P6) exist from the years 1968, 1977, 1980, 1989, 2001, 2003, 2013, 2015, and 2019, with the exception that from 1968 only two samples (Control and P) have been conserved.
Data exclusions	no data was excluded
Reproducibility	This is a field experiment (and the description of the experiment allows to repeat the experiment in a different location).
Randomization	The plots of the field experiments are randomized
Blinding	Sample identity was not disclosed to lab personal (blinding of sample identity)
Did the study involve field work?	☒ Yes ☐ No

Field work, collection and transport

Field conditions	Mean annual temperature and mean annual precipitation were 6.1°C and 558 mm in the period 1961-1990, and 7.3°C and 584 mm in the period 1991-2020. The experiment is located at 75 m a.s.l. on a plain of Quaternary glacial clay deposits.
Location	The long-term field experiment is located in South-West Sweden (58°20'49.9"N 13°07'36.1"E) at the field station Lanna, which is maintained by the Swedish University of Agricultural Sciences (SLU).
Access & import/export	We did not import or export samples.
Disturbance	We did not cause disturbance.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involvement in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involvement in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging