Fertilisation and irrigation have no effects on growth of oak (*Quercus robur, Q. petraea*) stands on abandoned farmland in southwest Sweden

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A B S T R A C T

Low nutrient availability often limits productivity in northern forests. In a nutrient optimisation trial, we investigated the effects of fertilisation and irrigation on soil moisture, leaf area index (LAI) as well as height and radial growth in 25-year-old stands of pedunculate and sessile oak (*Quercus robur* L., *Q. petraea* (Matt.) Liebl.) growing on abandoned farmland in southwestern Sweden. Control (C), fertilisation (F), irrigation (I), and irrigation + fertilisation (IF) treatments were arranged in a randomized complete block design. End of growing season analysis of foliar nutrients guided the quantitative composition of next year's fertiliser mix. Volumetric soil moisture (VWC) was significantly higher in the I and IF treatments compared to the C and F treated stands of both oak species. We did not observe a fertiliser-related reduction in VWC (except for 2015, when VWC in F-treated *Q. robur* stands was significantly lower than the control by about 18 %). This is in line with the unaffected LAI estimates (5.3–5.9) suggesting no stimulation of leaf production that could drive increases in transpiration with subsequent soil moisture depletion. There was no treatment × year interaction for any of the growth-related variables. Treatments had no significant effects on basal area growth, which increased annually by 1.72 and 1.54 $m^2\,ha^{-1}$ on average for *Q. petraea* and *Q. robur*, respectively. Pre-treatment height differences in *Q. petraea* stands (7–12 % taller trees in the C and IF plots) persisted throughout the study resulting in significant effects, while no significant differences in height occurred in *Q. robur*. Periodic annual volume increment varied more strongly following drier periods but there were no significant differences among treatments.

Our findings indicate that fertilisation causes no or only minor increases in oak water use, suggesting that nutrient addition in oak stands within this precipitation regime does not require simultaneous irrigation. Most importantly, our data implies that the soil nutrient legacies of past agricultural use suffice to maximise the productivity of oak stands on abandoned farmland typical of the main oak growing region in southwestern Sweden.

1. Introduction

Water and nutrients are fundamental drivers of forest productivity. Water availability is commonly more strongly limiting in warmer and drier climatic regions, while nutrients, primarily nitrogen, are more strongly limiting tree growth in colder environments (Tamm, 1991). However, forecasted changes in precipitation patterns together with more frequent and severe droughts are already well underway and will erode this long-standing paradigm to some degree as foreshadowed by the extreme 2018 drought that hit large parts of Europe causing large-scale forest damage (Schuldt et al., 2020). Understanding limitations

to growth and physiological processes in trees is therefore key to predicting their responses to environmental change and essential for devising and implementing mitigation and adaptation strategies (Hof et al., 2017; Bolte et al., 2009).

In a warmer and drier future, sessile and pedunculate oak (*Quercus petraea* (Matt.) Liebl., *Q. robur* L.) will play an important role in adapting European forests to climate change due to their high resistance and resilience to drought (Friedrichs et al., 2009, Bolte et al., 2009; Felton et al., 2010; Scharnweber et al., 2011; Merlin et al., 2015; Stimm et al., 2021; Bader et al., 2022), their suitability for various kinds of mixed forest management and potential to store much carbon (Mölder et al.,

2019; Pretzsch et al., 2020; Meyer et al., 2021). Back in the 1700s and 1800s, oak-dominated forests were more common than today in southern Sweden and played an important role both for the royal navy's shipbuilding as well as for the society as rot-resistant, durable wood for building purposes (Eliasson and Nilsson, 1999). Oak forests provide many ecosystem services such as high value timber for industry, firewood, important habitats for biodiversity, landscape aesthetics and valued environments for recreation and other cultural services (Berg et al., 1994; Löf et al., 2016; Mölder et al., 2019). Despite this history and the adaptive potential there are several challenges to an expansion of the area of cultivated oak forests. Due to more expensive seedlings and the need to fence against browsing animals, the establishment of oak plantations are normally more costly compared to conifer plantations (Bergquist et al., 2009). In addition, the rotation time is much longer compared to conifers. In southern Sweden, oak rotation lengths are 150 years or longer and in central Europe those can be up to 250 years (Carbonnier, 1975).

It is therefore important to investigate forest management tools that could improve timber production economy. Fertilisation may be such a tool as elevated nutrient supply may stimulate growth and shorten the rotation for oak and other hardwood species, which could improve profitability and entice forest owners to plant hardwoods.

Previous long-term forest fertilisation trials in stands of forestry-relevant conifer species such as *Pinus sylvestris* and *Picea abies* have highlighted the positive interaction between enhanced water and nutrient supply (Linder, 1987; Bergh et al., 1999; Bergh et al., 2005). The combination of fertilisation and irrigation strongly stimulated tree growth resulting in similar or larger timber volumes than the highest yields obtained with conventional silvicultural measures (Bergh et al., 2014).

However, compared to conifers, the responses of temperate broad-leaved trees to fertilisation and irrigation in young- and mature forests have received far less attention. LeBauer and Treseder (2008) reported that nitrogen (N) fertilisation stimulated the productivity of temperate forests worldwide. A *meta*-analysis by Vadeboncoeur (2010) showed that growth increases in temperate hardwood forests in North America correlated positively with the rate of N fertilisation and further growth stimulation was achieved when multiple nutrients were added. Several North American studies have found positive growth responses of oak stands following fertilisation (e.g. Mitchell and Chandler, 1939; Ward and Bowersox, 1970; Howard et al., 1980; Schreffler and Sharpe, 2003). In Europe, far fewer oak fertilisation studies have been conducted but here growth responses were also positive, at least temporarily (Garbaye et al., 1974; Becker et al., 1996; Ponton et al., 2019). To our knowledge there has been only one oak-related study manipulating both the availability of nutrients and water, showing that the productivity of a young Mediterranean holm oak (*Quercus ilex*) coppiced stand growing at a relatively dry site was solely limited by water shortage (Mayor and Rodà, 1994).

The strong reliance on conifer monocultures and clear-cutting in Swedish forestry has become a hotly debated issue, especially in view of the new EU Forest Strategy for 2030 (European Commission, 2011). The strategy aims to increase biodiversity and urges initiatives geared towards future-proofing Europe's forests to safeguard their ecosystem services in a changing climate. Diversifying tree species composition is a widely promoted management option and has been shown to have generally favourable effects on many ecosystem services such as increased biodiversity, reduced risk of biotic attack and greater adaptive capacity (Paquette and Messier 2010; Felton et al., 2016; Messier et al., 2022). Incentives to increase the proportion of planted hardwoods aimed at promoting the transition away from conifer monocultures in Sweden go back to the 1980s but are met with reluctance by forest owners due to a presumed unfavourable cost-effectiveness ratio (Madsen et al., 2000; Löf et al., 2019). Therefore, test plantings were established to evaluate the productivity of pedunculate and sessile oak (*Quercus petraea, Q. robur*). The present study was conducted in an oak

nutrient optimisation trial in southwest Sweden with the aim to evaluate the local growth potential and to determine whether this is constrained by soil nutrient supply and/or soil moisture availability. Almost the entire climatically suitable area for growing oaks in Sweden is located in the South and has a long history of agricultural or pastural use (Dröβler et al., 2012; Lindbladh and Bradshaw, 1998). This land use legacy allowed us to determine whether the elevated soil nutrient stocks, resulting from prior agricultural use, suffice to maximise oak growth potential or whether this requires further nutrient additions.

2. Materials and methods

2.1. Site and experimental design

The experiment was carried out in an oak plantation consisting of pedunculate and sessile oak (*Quercus robur, Q. petraea*) located at Restad in SW Sweden (lat. 56° 32′ 08″, long. 12° 58′ 20″, alt. 10 m a.s.l., Fig. 1A). *Quercus robur* reaches its northern distribution limit in Sweden around 60° N, and *Quercus petraea* a little further south and closer to the coastline. The experimental site is situated within an agricultural landscape on flat terrain and the oak plantation was established on a former agricultural field. Prior to planting, the site was used as a nursery for Norway spruce (*Picea abies*) seedlings since the 1960s.

The soil profile had a deep top layer with a sand sediment overlaying clay horizons with redoximorphic features (mottles) and a water table depth of 1–2 m, typical of a planosol (Fig. 1C). The sparse ground vegetation was dominated by thin-leaved grasses accompanied by low-stature herbs and tree seedlings.

At stand establishment in 1991, the west half (Block III and IV) of the field was planted with 3-year-old seedlings of pedunculate oak (*Quercus robur*) of Dutch origin and the east half (Block I and II) with 2-year-old seedlings of sessile oak (*Quercus petraea*) of Polish origin (Fig. 1B). Spacing in the plantation corresponded to 3000 seedlings per hectare. Simultaneously, an admixture of single seedlings of *Tilia cordata*, *Corylus avellana* and *Fraxinus excelsior* was planted with the aim of creating an understorey in the oak plantation. At the beginning of the experiment in 2008, the stand was homogeneous and dominated by the planted oak trees (91 % of the total volume; Table 1). Key stand parameters were similar across plots designated for each treatment (Table 1). A pre-commercial thinning, prior to treatment initiation, reduced the stem number by 48 % leaving on average 1765 (range: 1542–1977) oak stems ha^{-1} with an average standing volume of 49 m^3 ha^{-1} (range: 35–56 m^3 ha^{-1}).

Our study commenced in 2008 and was running until 2015. It was laid out as a fully randomized block design with four replicates and four treatments (C = control, I = irrigation, F = solid fertiliser, IF = irrigation + solid fertiliser; Fig. 1B). Thus, in total 16 treatment plots. The area of each treatment plot was 625 m^2 (25 m × 25 m), which included a 5 m wide buffer zone, leaving a 400 m^2 (20 m × 20 m) inner plot to which the measurements were restricted. All trees in the inner plots were numbered and labelled.

The commercial fertiliser (four different products with NPK, P and PK from Yara AB; Table 2), was supplied in May each year and the composition of the fertiliser mix was based on the elemental analysis of leaf samples taken in August of the previous year. The quantities of macro- and micronutrients were adjusted to initial target ratios of each element with respect to N according to Linder (1995). Target leaf elemental concentrations and proportions of the essential nutrients required to remove any nutrient limitations to growth were determined in earlier laboratory (Ericsson and Kähr 1993) and field experiments (Linder 1990, Stockfors et al., 1997). Over the total 8-year study period, a total of 662 kg ha^{-1} of N was added to the F and IF treatments (Table 2). In addition, a total amount of 509 kg ha^{-1}P, 603 kg ha^{-1} K, 30 kg ha^{-1} Mg, 143 kg ha^{-1} S and 0.29 kg ha^{-1}B were added to the fertilised treatments. River-fed sprinkle irrigation started in the beginning of May coincident with leaf burst and ceased at the end of September
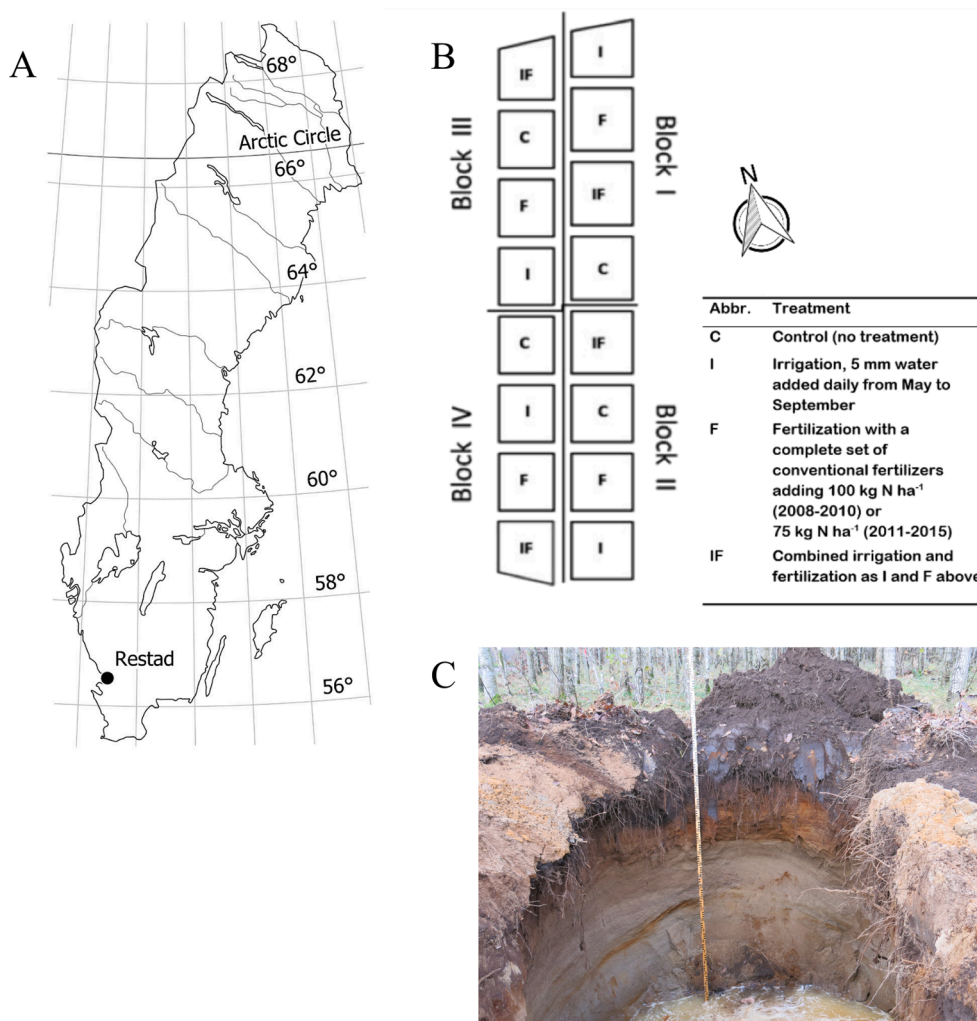
Fig. 1. (A) Study site location in SW Sweden (GSD-Maps of Sweden 1:10 million © Lantmäteriet, 2017), (B) illustration of the experimental design and description of the treatments (Block I and II *Q. petrea,* Block III and IV *Q. robur*), (C) soil profile.

Table 1
Quadratic mean diameter (QMD), Lorey's mean height (H_L), number of stems (N), basal area (BA) and standing volume (V) of the two studied oak species (*Q. petraea*, *Q. robur*) prior to the start of the fertilisation study in 2008. Means and standard errors were based on four replicates (blocks) for each treatment (tree species pooled). Values in brackets refer to all trees including admixed species.

Treatment	Stand characteristics					Removal	
	QMD, cm	H_L, m	N, st ha^{-1}	BA, m^2 ha^{-1}	V, m^3 ha^{-1}	N, st ha^{-1}	V, m^3 ha^{-1}
C	9.0 ± 0.3	9.7 ± 0.2	1660 ± 111	10.4 ± 0.3	51 ± 2	1533 ± 87	24 ± 2
	(7.4 ± 0.4)	(9.3 ± 0.2)	(2797 ± 267)	(11.6 ± 0.2)	(55 ± 2)	(2066 ± 456)	(30 ± 1)
F	8.7 ± 0.3	9.1 ± 0.4	1716 ± 78.4	10.1 ± 0.4	47 ± 3	1604 ± 25	24 ± 2
	(6.6 ± 0.4)	(8.6 ± 0.4)	(3535 ± 371)	(11.8 ± 0.5)	(52 ± 3)	(1700 ± 50)	(26 ± 1)
I	8.3 ± 0.5	9.0 ± 0.6	1846 ± 118	10.0 ± 0.5	46 ± 4	1643 ± 155	23 ± 4
	(6.6 ± 0.5)	(8.4 ± 0.6)	(3474 ± 422)	(11.4 ± 0.5)	(51 ± 4)	(1742 ± 183)	(27 ± 6)
IF	8.7 ± 0.1	9.4 ± 0.3	1788 ± 24	10.7 ± 0.1	51 ± 2	1418 ± 174	22 ± 4
	(6.9 ± 0.2)	(8.9 ± 0.2)	(3277 ± 162)	(12.1 ± 0.1)	(55 ± 2)	(1560 ± 255)	(28 ± 6)

each year. The irrigation rate equalled 5 mm of rainfall per day during the growing season resulting in about 600 mm of extra water in the I and IF treatments.

2.2. Climate and meteorological data

The study site is located in close proximity to the seashore (2 km) and thus characterised by a maritime climate (Fig. 2). The long-term mean annual precipitation in this area (from 1871 to 2015) is 757 mm (range: 450–1176 mm) and the mean annual temperature is 7.9 °C (Fig. 2;

SMHI, Swedish Institute for Meteorology and Hydrology). Meteorological data for the study period was obtained from the nearby weather station in Mellby, *ca.* 5 km south of our study site (Lantmet, SLU fältforsk), except for 2008 when, due to technical failure, data was fetched from the official weather station in Halmstad, located *ca.* 13 km north of our study site (SMHI, Swedish Institute for Meteorology and Hydrology; Fig. 3). The Standardized Precipitation-Evapotranspiration Index (SPEI) was calculated on a 3-month time scale to characterise dry and wet conditions during the study period (R package *SPEI*, Beguería and Vicente-Serrano, 2017).

Table 2
Commercial fertiliser products used in experiments in specific years, and annual supply (kg ha^{-1}) for N, P, K Mg, S and B in the F and IF treatments.

|	Product 1	Product 2	N	P	K	Mg	S	B
2008	Opticrop 21–3-10	Yara Superfosfat P20	98	87	46	5	22	0.1
2009	Yara Mila 21–3-10	Yara Superfosfat P20	98	87	46	5	22	0.1
2010	Yara Mila 21–3-10	Yara Superfosfat P20	98	87	46	5	22	0.1
2011	Yara Mila 21–4-7		74	13	24	3	11	
2012	Yara Mila 21–4-7		74	13	24	3	11	
2013	Yara Mila 21–4-7	Yara PK 11–21	74	74	139	3	19	
2014	Yara Mila 21–4-7	Yara PK 11–21	74	74	139	3	19	
2015	Yara Mila 21–4-7	Yara PK 11–21	74	74	139	3	19	
Total			**662**	**509**	**603**	**30**	**143**	**0.3**
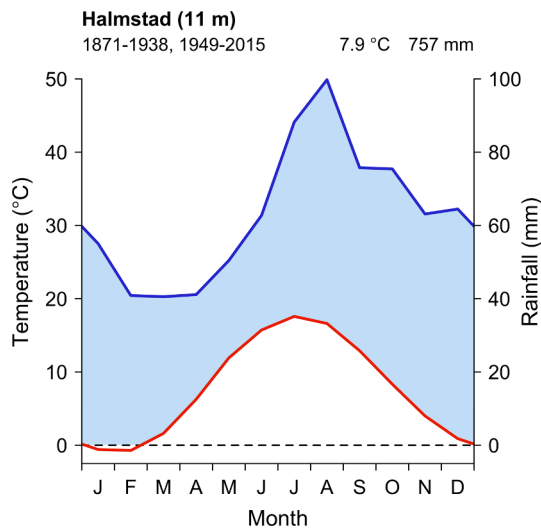
Fig. 2. Walter-Lieth climate diagram for the study area showing the monthly mean temperature (red line, left *y*-axis) and the average sum of monthly precipitation (blue line, right *y*-axis) based on data from the Swedish Meteorological and Hydrological Institute's weather station at Halmstad (56° 40′ 25″ N, 12° 55′ 27″ E) spanning the available time periods 1871–1938 and 1949–2015. Humid conditions are indicated by the blue shading between the red and the blue line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Soil measurements

Volumetric soil water (VWC) content was measured at irregular intervals during the 2008 and 2013–2015 growing seasons in the upper 25 cm of the soil profile using a portable time domain reflectometry (TDR) device (Tektronix SP232 and 1502C, Tektronix Inc. Beaverton, USA). In 2013 and 2015, VWC was measured from mid-May until the end of September. In 2008 and 2014, measurements were taken from the start of July until the end of September.

In August 2013, 10 soil samples were collected from five horizons (litter, 0–5, 5–10, 10–20, 20–30 cm) at each control plot using an auger. Samples from the same horizon were pooled and stored at 6–8 °C prior to analyses. Carbon (C), nitrogen (N) and sulphur (S) concentrations in the soil samples were determined by combustion using an elemental analyser (CNS-2000, Leco Corp., St. Joseph, MI, USA). Multi-elemental soil analysis was performed using inductively coupled plasma optical emission spectrometry (Optima 7300 DV ICP-OES, PerkinElmer Inc., Waltham, MA, USA; Supplementary Fig. 1).

2.4. Foliar nutrient sampling and analysis

Between 2008 and 2015, 10–15 sun-lit leaves were collected in the upper crown of three codominant individuals per plot in August each year. These samples were pooled across the two oak species and the same treatment, resulting in one composite sample per treatment and year. The composite samples were dried at 85 °C for 48 h and then ground in a cyclone mill (Cyclotec 1093 sample mill, Tecator, Sweden). Sub-samples were vacuum-dried at 70 °C for 24 h. For elemental analysis about 50 mg of each sub-sample were wet-digested in nitric and perchloric acid in an open digestion system, and then analysed by inductively coupled plasma mass spectrometry (Sciex Elan 6100 ICP-MS system, PerkinElmer Inc., Norwalk, CT, USA). For N and C determination, 4–7 mg of each sub-sample were weighed into tin capsules. These samples were analysed in an elemental analyser unit (ANCA-NT solid/liquid preparation module, Europa Scientific ltd., Crewe, UK).

2.5. Leaf area index measurement

The leaf area index (LAI) of all plots was measured on overcast days in August 2011 using a portable plant canopy analyser (LAI-2000, LI-COR, Lincoln, NE, USA). In each treatment plot, eight recordings were taken from the plot borders using a 180-degree view restrictor with the sensor directed towards the plot centre. The control sensor was placed at an open field close to the experimental stand and set to log every 15 s during the measurement campaign.

2.6. Measurements of tree growth

Plots were assessed at establishment in 2008, and re-measured in the autumns of 2009, 2011, 2013 and 2015. All trees within the inner plots were crosswise calipered to determine stem diameter at breast height (DBH1 and DBH2; 130 cm above ground). Simultaneously, tree species, tree class (social position), tree status (remaining, removed, missing, wind-felled) and tree properties (crown performance, technical damage, vitality) were recorded. Plotwise measurements of systematically selected sample trees, identified by a stratified sampling algorithm (Karlsson et al., 2012), included total tree height (H) and height to the first living branch (CL). Un-numbered small trees (DBH < 45 mm) were registered in 1 cm diameter classes for remaining and removed trees, and 10 sample trees were measured for DBH and H. DBH was calculated as $\sqrt{(DBH1 \times DBH2)}$ and basal area (BA) as $\sum DBH^2 \times \pi/4$. The volume of sample trees was calculated from single tree volume functions (Hagberg and Matérn, 1975) using the variables DBH, H and CL. Top height (H$_{dom}$) for each plot was calculated as the height according to the height curve (Näslund, 1936) at the mean diameter of the 100 by diameter largest trees per hectare. Site index (SI; estimated top height at 100 years total age) was determined from tree species-specific site index curves (Elfving pers. comm.).

2.7. Statistical analyses

All statistical computations were performed using the free software environment R (version 4.1.3, R Core Team, 2022). Volumetric soil water content was modelled separately for each year using generalised additive mixed models (GAMM, R package *mgcv*, Wood, 2011) including 'treatment' as a categorical predictor (with the 4 levels C, I, F, IF) and a smoother for 'time', which was allowed to vary with treatment level representing a 'time × treatment' interaction. The random term consisted of 'treatment' nested in 'block' to account for the repeated measures nature of the data. The *post-hoc* analysis involved successively pooling two treatment levels at a time resulting in six combinations. Each of those combinations translated into a GAMM with a common smoothing term for the two pooled treatment levels (representing the null hypothesis of no difference between the two pooled treatment levels). Using a series of likelihood ratio tests, each of these constrained GAMMs was compared with the original model allowing separate smoothers for each treatment level. The resulting *P*-values were multiplicity-adjusted using the false-discovery method (Benjamini and Hochberg, 1995). Linear mixed effects models (LME) were applied to each oak species to analyse LAI and growth variables, including 'treatment', 'time' and their interaction as predictors and 'block' as a random term accounting for the design and the repeated measures (R package *nlme*, Pinheiro et al., 2022). The 'treatment' term represented a categorical variable (with the 4 levels C, I, F, IF), while the regressor 'time' (in years) denoted the time effect over the 8-year study period. We added a quadratic term for 'time' to the LME for periodic annual increment (PAI) to accommodate the curvilinear trend in the data. Species-specific models were applied since oak species were grown in pure stands (blocks I and II: *Q. petraea*, blocks III and IV: *Q. robur*),
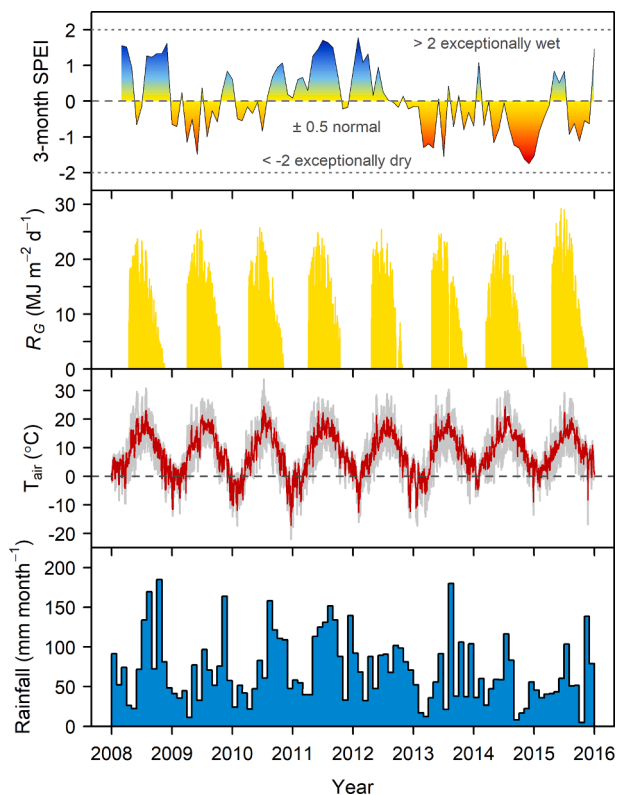
prohibiting testing for a species effect (Fig. 1). Model diagnostic plots (standardised residuals vs fitted values and quantile–quantile plots) were used to evaluate the underlying assumptions of homoscedasticity and normality. No gross deviations from normality were detected but heteroscedasticity occurred at times and was modelled using exponential, constant or constant plus power variance functions (*varExp*, *varIdent* or *varConstPower* in R package *nlme*, Pinheiro et al., 2022). *Post-hoc* testing was performed using Tukey contrasts (R package *emmeans*, Lenth, 2022) and the associated *P*-values were adjusted for multiple testing using the false-discovery rate method (Benjamini and Hochberg, 1995).

3. Results

3.1. Meteorological conditions

The SPEI values did not indicate any exceptionally wet or dry periods but highlighted 2008, 2011 and 2012 as relatively moist years and the 2013 spring and the second half of 2014 as comparatively dry (Fig. 3).

Mean monthly air temperature during May to September ranged between 9.9 and 20.1 °C and precipitation varied between 18 mm and 179 mm for the time period 2008 to 2015 (Fig. 3). July was rather warm in 2010 (19.4 °C) and 2014 (20.1 °C) but did not coincide with low precipitation. Precipitation was low in May 2008 (23 mm), July (38 mm) and September (49 mm) 2013. May and June were warm (14.1 °C/ 17.0 °C) with low precipitation (18 mm/39 mm) in 2016.

3.2. Volumetric soil water content

Volumetric soil water content (VWC) varied with meteorological conditions and vegetation water use during the growing season and between years (e.g., 2014 was a relatively dry year) but the growing season means per treatment showed relatively consistent patterns across years with only slight differences among the two oak species (Fig. 4). Generally, control (C) and fertilised (F) stands had similar growing season averages of VWC values, which were significantly lower than in the irrigated (I) or irrigated and fertilised (IF) plots. Exceptions to this pattern occurred in *Q. robur* stands in 2013, when VWC control values were not significantly different from the I and IF treatments and also in 2015, when VWC in C stands was significantly higher by 22 % than in the F stands. In all years, apart from 2008, maximum VWC values in *Q. petraea* stands were seen in the IF treatment (around 30 vol%), which were significantly higher than those of the remaining treatments (Fig. 4).

3.3. Foliar nutrient ratios

Foliar N concentration was quite high in all treatments (Supplementary Table 1). Following the start of fertilisation in 2008, there was a minor increase in leaf N in the fertilised treatments. Except for the P/N and K/N ratios, all N-related leaf nutrient ratios remained above or very close to target values irrespective of treatment (Fig. 5). Especially the Ca/N and Mn/N ratios always greatly exceeded the target thresholds. At the end of the 2008 growing season, P/N ratios in the fertilised treatments (F, IF) were somewhat below the target ratio of 10. Starting from 2009, potassium also dropped slightly below the target ratio of 35, in the fertilised treatments (especially IF). These deviations prompted upward adjustments of P and K doses in the following supply regimes. However, despite the attempts to raise P- and K-availability in relation to N, in most years the P/N-ratio remained below its target in the fertilised treatments.

3.4. Leaf area index

In 2011, three years after treatment initiation, stand LAI for both oak species was similar across treatments ranging between 5.3 and 5.9

Fig. 3. 3-month Standardized Precipitation-Evaporation Index (SPEI), daily global radiation (R_G) during the growing season, air temperature (T_{air}), and monthly rainfall near the study site. The red line in the T_{air} plot indicates daily means and the surrounding grey area gives the daily minima and maxima. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
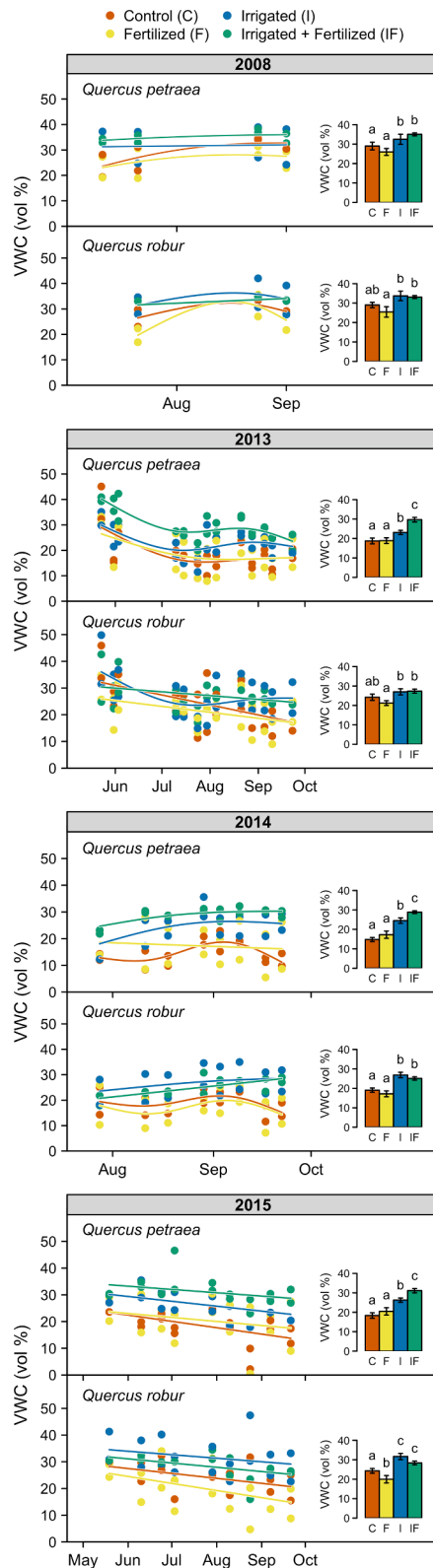
Fig. 4. Volumetric soil moisture based on time-domain reflectometry (VWC) in the top 25 cm of the soil profile in sessile and pedunculate oak stands subjected to control (C), fertilisation (F), irrigation (I), or irrigation + fertilisation (IF) treatments. Manual recordings were taken during the 2008 and the 2013–2015 growing seasons. Lines represent generalized additive model smoothers. Bar chart inserts indicate the mean growing season VWC. Different lower-case letters indicate statistically significant differences (alpha level of 0.05 *post-hoc* analysis based on Tukey contrasts).

(Fig. 6).

3.5. Tree growth

BA increased linearly in the oak stands in all treatments during the observation period 2009–2015 resulting in a significant year effect (*Q. petraea*: 1.72 m^2 ha^{-1} yr^{-1}, *Q. robur* 1.54 m^2 ha^{-1} yr^{-1}) but we detected no significant treatment × year interaction or treatment main effect (Fig. 7). Both oak species also showed linear height growth over time at a mean rate of 1.25 m yr^{-1} in *Q. petraea* and 1.13 m yr^{-1} in *Q. robur*. Pre-treatment differences in the height of *Q. petraea* trees persisted throughout the study producing a significant treatment effect with similar heights in the C and IF trees, which were always about 1 m taller than the F and I treated trees (Fig. 7). However, the slopes were similar across treatments and therefore no significant treatment × year interaction occurred. Both, intercepts and slopes were similar across treatments in *Q. robur* and thus no significant treatment effect or an interaction with year were seen.

The *a priori* differences in the height of *Q. petraea* trees caused similar pre-treatment differences in site index (estimated top height at 100 years total age; Fig. 7). These pre-treatment differences persisted throughout the study and translated into small but significant differences between treatments. C and IF stands shared similar site indices of around 31 compared to the slightly but significantly lower values of the F and I stands, whose values did not differ significantly from each other.

Periodical annual volume increment (PAI) of both oak species showed a humped shape in all but the I and IF treated *Q. petraea* trees (Fig. 7). Irrespective of the degree of curvature, the curvilinear trend over time was statistically significant as indicated by a significant effect of year and its quadratic term. The downward trend followed a period of drier meteorological conditions indicated by negative SPEI values < −0.5 in much of 2013 and 2014 (Fig. 3). The drier conditions have not only caused a decline in PAI but also a dramatic increase in variance, so that no significant treatment effect alone or in interaction with time was detected.

4. Discussion

4.1. Volumetric soil water content

Increased soil nutrient supply can lower the root area to leaf area ratio (Kozlowski and Pallardy, 2002) and increase stomatal conductance (Fangmeier et al., 1994), both resulting in higher water consumption. Therefore, we expected significant soil moisture reductions in response to fertilisation but this assumption was not confirmed, except for *Q. robur* in 2015, when growing season means of VWC in F plots were 18 % lower than in the control plots. The largely unaffected soil moisture is in line with the observed lack of an LAI response to nutrient addition (see below), suggesting no leaf area-related changes in transpiration. Although this does not preclude stomata-mediated increases in transpiration, such a response seems unlikely given the lack of a fertiliser effect on foliar gas-exchange (using tree-ring δ^{13}C as a proxy) of sessile oaks in a long-term nutrient addition trial in France (Ponton et al., 2019) and their reportedly conservative water use (Bader et al., 2022). However, since our measurements were restricted to the upper 25 cm of the soil profile, we cannot entirely rule out fertiliser-induced increases in tree water consumption, because of the well-known deep-rooting habit of these oak species allowing them to tap into deep-lying soil moisture reserves (Köstler et al., 1968).

4.2. Leaf nutrient ratios

The fairly high leaf N concentrations and the N-related nutrient ratios suggest favourable soil nutrient conditions across all treatments. With regard to the control, this is indicative of large soil nutrient stocks that have accumulated over many years of agricultural use (Falkengren-
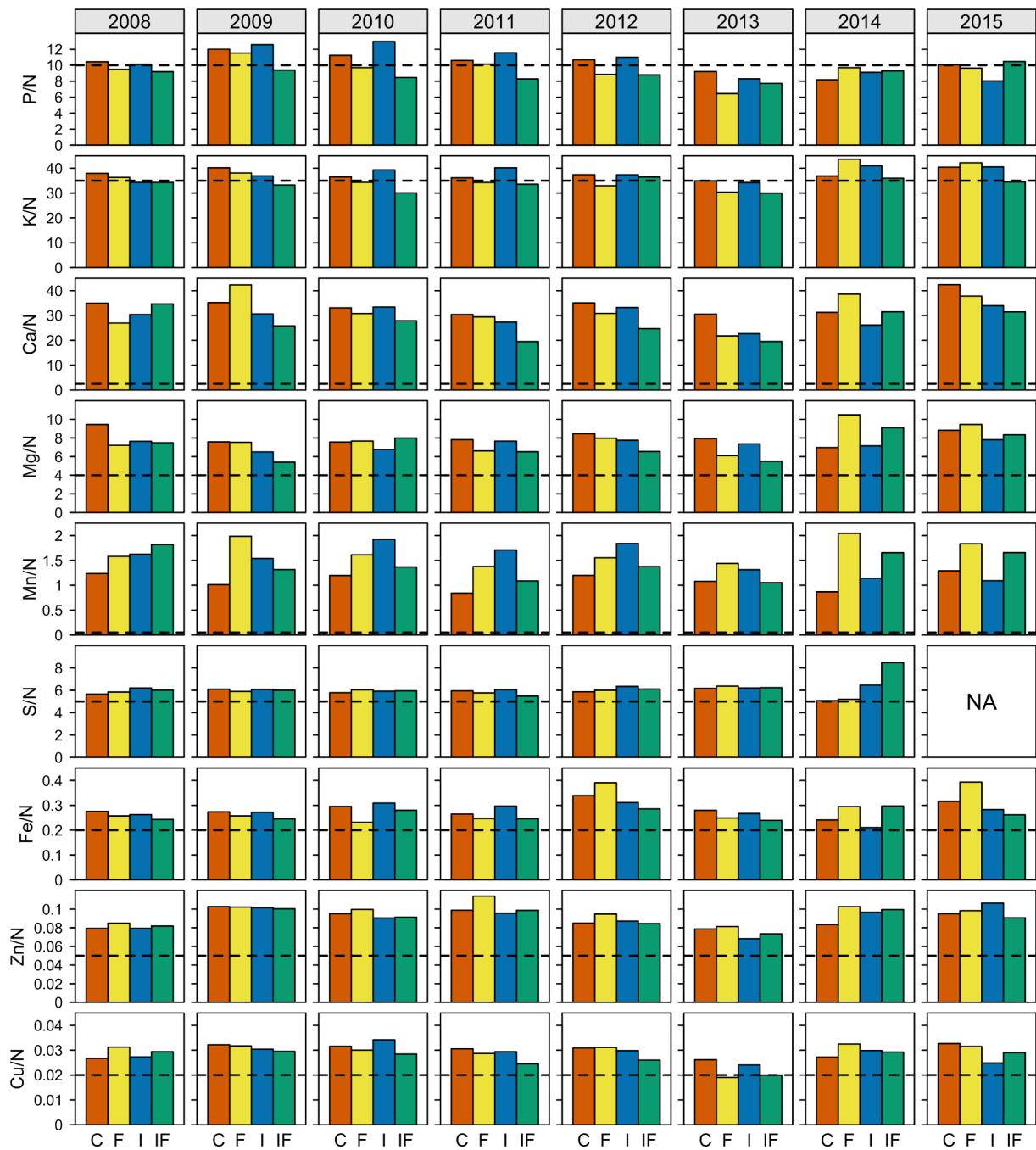
Fig. 5. Nutrient ratios in oak foliage (species pooled) as a function of treatment (C = control, I = irrigation, F = fertilisation, IF = irrigation + fertilisation) from 2008 to 2015. Bars represent composite samples across blocks, thus there are no standard errors available. Dashed lines indicate optimal nutrient ratios according to Linder (1995). NA = data not available due to technical failure.

Grerup et al., 2006; Compton and Boone, 2000). The sometimes slightly suboptimal leaf P/N ratio in the fertilised treatments (especially in the IF treatment) may reflect N-driven modulations of root P uptake and/or N-induced changes in P solubility in the soil resulting in relatively higher N uptake rates (Grunes, 1959). Also, in highly nitrifying soil environments, as is likely to be the case here, a sizeable portion of the NH_4^+ in the applied ammonium nitrate fertiliser may be converted to NO_3^-, resulting in a large NO_3^- pool, which in turn would increase competitive displacement of PO_4^{3-} at anion exchange sites and thus stimulate P leaching. The occasionally suboptimal K/N ratio in the IF treatments probably mirrors increased K^+ leaching linked to increases in

percolating water due to irrigation, and, given its low binding strength, competitive displacement may further contribute to such losses (Blum et al., 2018). The nutrient uptake capacity of *Q. robur* roots for K^+ and NH_4^+ has been shown to decrease with increasing soil depth but remained steady for P (Göransson et al., 2007) indicating that P translocated to deeper horizons with percolating water can still be accessed by this deep-rooting tree species. A related isotope tracer study also revealed considerable N uptake from deeper soil depths in *Q. robur*, strongly suggesting that the uptake of other nutrients from deeper down in the profile is also possible (Göransson et al., 2006).
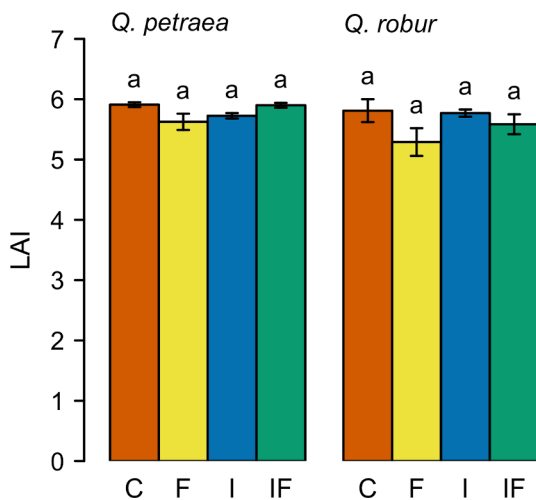
Fig. 6. Leaf area index (LAI) of *Q. petraea* and *Q. robur* stands subjected to control (C), fertilisation (F), irrigation (I), or irrigation + fertilisation (IF) treatments. LAI recordings were taken in 2011. Same lower-case letters indicate no statistically significant differences among treatment levels at α = 0.05 (linear mixed effects model results).

4.3. LAI

In broadleaf forests that have not yet reached canopy closure, fertilisation and irrigation may increase LAI under nutrient- or water-limited conditions (Smethurst et al., 2003; Le Dantec et al., 2000; Iio et al., 2014). However, our LAI estimates > 5 indicate closed canopy conditions (Asner et al., 2003; Iio et al., 2014) implying little scope for fertiliser-driven increases in LAI. Consequently, we found no significant treatment effect on LAI for either oak species.

4.4. Tree growth

We sought to evaluate oak productivity on abandoned farmland typical of this region close to the northern oak distribution limit in southern Sweden (the northern border for oak in Sweden is at approx. 60 °N). In addition, we aimed to ascertain whether the agricultural soil nutrient legacies suffice to exploit the maximum growth potential or whether larger nutrient quantities are needed to achieve this.

Height growth, PAI and site index of our experimental oak stands were similar to the figures reported for stands of the same age of these oak species in unfertilised, unmanaged long-term observation plots in Germany and Poland (Pretzsch et al., 2014).

Leaving aside some pre-treatment differences that persisted throughout the study (height of *Q. petraea,* site index for both species), our findings indicate no water or nutrient limitation of stem growth variables in these two oak species under the current nutrient and water regimes. Similar results were found in newly established oak plantations on former agricultural sites in the same region (Löf, 2000).

The high background level of soil nutrients at our study site (Supplementary Fig. 1), resulting from legacy effects of the former century-long agricultural and subsequent nursery use (Lindbladh and Bradshaw, 1998), are clearly reflected in the high leaf N concentrations and favourable leaf nutrient ratios (Fig. 5). Such legacy effects can last for many decades or even centuries, as has been shown for other Swedish and Danish oak plantations and North American deciduous forests growing on abandoned farmland (Falkengren-Grerup et al., 2006; Ritter et al., 2003; Compton and Boone, 2000). By contrast, in a strongly nutrient-limited forest in France, *Q. petraea* showed a rapid and vigorous growth stimulation of 42–45 % in response to fertilisation (N + Ca, NPK + Ca + Mg; Ponton et al., 2019), which corroborates the assumption of nutrient saturation at our site. Similarly, Becker et al. (1996) reported
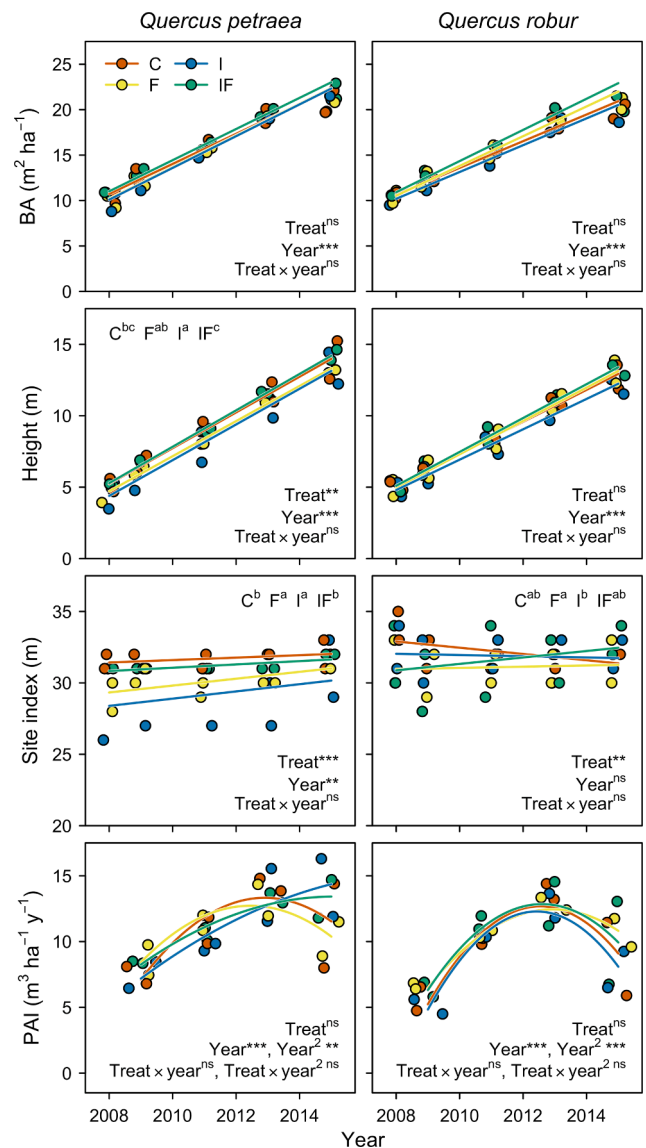

Fig. 7. Basal area (BA) (A), height (B), site index (C) and periodic annual volume increment (PAI) (D) for *Quercus petraea* and *Q. robur* stands exposed to irrigation and/or fertilisation treatments from 2008 to 2015 (C = control, I = irrigation, F = fertilisation, IF = irrigation + fertilisation). Symbols indicate block means (n = 2 per oak species). Please note that a small amount of jitter was added to the x-values (years) to separate overlapping symbols. Lines indicate linear mixed effects model fits (incl. a quadratic term for year in the PAI model). Different lower-case letters indicate statistically significant differences at α = 0.05 (*post-hoc* analysis based on Tukey contrasts). ns = not significant, ** P < 0.01, *** P < 0.001.

fertiliser-driven increases in BA growth of 15 % in 'young' *Q. robur* trees (≤110 years old) and 25 % in older individuals (>110 years old) growing on nutrient-impoverished alluvial terraces in north-eastern France. Interestingly, in both studies the nutrient-driven growth stimulation was only temporary with the greatest impact during the first three years followed by a gradual decrease in magnitude until the effect had completely disappeared after 9 years (Ponton et al., 2019; Becker et al., 1996). The waning growth stimulation was attributed to new limitations arising from micronutrient shortage, nutrient imbalances or resource competition. Remarkably, this phenomenon of a rapidly diminishing fertiliser effect also occurred in oak-dominated forests on nutrient-poor soils in the southern USA, where significant radial growth increases only lasted 2–4 years after N-fertilisation (maximum stimulation of *ca.* 60 % in 30–40-year-old *Q. alba,* 104 % in 30–70-year-old

Q. velutina and 37 % in 30–70-year-old *Q. coccinea;* McQuilkin, 1982). In the same study, P-addition stimulated growth in only one of the local oak species (*Q. alba)* at one particular site and to a lesser extent than N-addition (+23 %, McQuilkin, 1982). Strong fertiliser-induced growth responses have also been reported for 40-year-old common aspen (*Populus tremula*) in Sweden and other hardwood species in North America but as these studies only assessed the short-term response (up to 3 years), no conclusions can be drawn about the duration of the growth stimulation (Shoulders and Wittwer, 1979; Nilsson and Wasielewski, 1987; Daugaviete et al., 2003).

The growth of coniferous stands on forest soils commonly increases drastically in response to nutrient addition, but at the same time wood density often decreases (Linder, 1987; Bergh et al., 1999; Lundgren, 2004). In ring-porous hardwoods, such as oak, wood density increases with increased growth rate (Zobel and van Buijtenen, 1989) and usually results in harder and stronger wood, *i.e.,* the mechanical properties are affected. Density increases in the wood of red oak (*Q. rubra*) and white ash (*Fraxinus americana*, also ring-porous) in response to fertilisation (Szopa et al., 1977; Mitchell, 1972) suggest that such density changes might also occur in the two oak species studied here if they are growing on nutrient-poor soils, where a fertiliser-induced growth stimulation can be expected (Ponton et al., 2019; Becker et al., 1996**)**.

5. Conclusions

Our findings suggest that the local precipitation regime and the legacy nutrient pools, which have built up in the soil in the course of a long history of agricultural and subsequent nursery use, suffice to support oak growth without water or nutrient limitation. Further nutrient additions on this type of abandoned farmland soil are redundant and will likely increase N (NO_3^-) leaching and thus groundwater pollution (depending on subsoil clay content), especially in conjunction with irrigation. Excess ammonium (NH_4^+) from fertiliser inputs is likely to reduce base saturation by competitively displacing base cations from cation exchange sites, which could develop into nutrient imbalances. Continual fertiliser additions may also affect trace gas emissions through reductions in soil microbial activity and diversity resulting in decreased soil respiration rates as has been shown for an oak-dominated hardwood stand in the US (*Q. rubra, Q. velutina;* Bowden et al., 2004). High N availability also promotes denitrification (Harrison and Webb, 2001) implying that excess N from fertiliser inputs may cause higher N_2O emissions and thus contribute to climate forcing. However, fertilisation could certainly be a viable management option for stands on less fertile sites or may be considered for single-tree fertilisation to produce high quality trees with shortened rotation, as these commonly yield very high revenue. Although irrigation remained ineffective under current conditions, it may become more relevant in the future, and at other site types, given the climate projections for the Scandinavian region (Yiou et al., 2020). Irrigation may also promote growth in oak stands on drier sites in south-eastern Sweden, where moisture is likely to be a limiting factor at least sometimes during the growing season.

CRediT authorship contribution statement

Carl Svensson: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Martin Karl-Friedrich Bader:** Methodology, Formal analysis, Data curation, Visualization, Writing – original draft, Supervision. **Magnus Löf:** Conceptualization, Methodology, Data curation, Funding acquisition. **Ulf Johansson:** Data curation. **Johan Bergh:** Conceptualization, Methodology, Data curation, Funding acquisition, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120700.

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