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Walnut in Sweden: effects of nurse trees, weed control and fertilization on five-year survival and growth of planted *Juglans* × *intermedia* NG23 and NG38

Jens Peter Skovsgaard[a], Ulf Johansson[b], Jan-Eric Englund[c] and Stefan Juravle[a]

[a]Swedish University of Agricultural Sciences, Southern Swedish Forest Research Centre, Alnarp, Sweden; [b]Swedish University of Agricultural Sciences, Simlångsdalen, Sweden; [c]Swedish University of Agricultural Sciences, Department of Biosystems and Technology, Alnarp, Sweden

ABSTRACT

This study quantified the effects of different establishment practices on survival, dieback and early growth of *Juglans* × *intermedia* NG23 and NG38 planted in a statistically designed field experiment on glacial till in southern Sweden. Establishment practices included the use or absence of nurse trees (*Populus maximowiczii* × *trichocarpa* var. OP42 planted one year before *J.* × *intermedia*), weed control (2 $m^2 \cdot tree^{-1}$) and fertilization (+25 g $N \cdot tree^{-1} \cdot year^{-1}$). NG23 transplants were smaller than NG38 at the time of planting. The overall survival rate was 97%. NG23 suffered marginally more mortality than NG38. Leader shoot dieback occurred in all treatment combinations but was most severe in the presence of nurse trees. NG23 suffered less dieback than NG38. Annual height growth of trees unaffected by dieback increased with increasing levels of precipitation during the growing season (194–407 mm) and with increasing soil quality in terms of nitrogen ($94 \cdot 10^{-3}$–$607 \cdot 10^{-3}$ $g \cdot g^{-1}$), base saturation (14–99%) or available soil water capacity (8.6–30.6 $l \cdot m^{-3}$). It was negatively influenced by poplar nurse trees and positively by fertilization. Weed control had no impact on height growth, possibly due to inefficient implementation. With nurse trees, NG23 had stronger growth than NG38. The opposite was true without nurse trees. It was hypothesized that less growth and more dieback resulted from competition for water.

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Hybrid walnut; silviculture; tree growth; dieback; potential future crop trees

Introduction

Walnut (*Juglans sp.*) is well suited for the production of valuable hardwood timber and can be grown on a relatively short rotation compared to most other broadleaved tree species of commercial interest in Europe (Pretzsch 1995; Becquey 1997; Ehring and Keller 2008; Mohni et al. 2009; Hemery and Simblet 2014; Fernández-Moya et al. 2019; Skovsgaard and Graversgaard 2019; Nicolescu et al. 2020). Furthermore, due to climatic change and predicted increase in temperature the distribution of walnut is likely to expand northwards (Hemery et al. 2010; Gauthier and Jacobs 2011).

The earliest evidence of walnut in Sweden are pollen records dating from 600 to 700 CE (Björkman 2007), shell fragments dating from 1000 to 1100 (Hjelmqvist 1963, 1991) and, depending on the translation from Latin, wooden artefacts mentioned in a medieval charter dating from 1368 (Diplomatarium Suecanum no. SDHK 9346; cf. Peringskiöld 1719). According to unsubstantiated anecdotal evidence walnut was grown by Johan Petersson in the garden he (possibly) founded at Vadstena monastery (Karling 1930, 1931; Larsson 2014), but the earliest source of walnut actually growing in Sweden is a handwritten note in an episcopal household calendar compiled during 1503–1525. The calendar record for 10 July that walnuts should be pickled before they become "woody" (Brask 1525; Stobaeus 2005) indicates that one or more fruit-bearing trees were growing locally.

Persian walnut (*J. regia* L.) was the first walnut species introduced into Sweden. From the 1700s onwards, eastern black walnut (*J. nigra* L.) and other species were also planted (Lundquist 2007). Walnut has been grown mainly in parks and gardens in temperate parts of Sweden, and survival, growth and nut quality have been judged to be satisfactory in many locations (Linnæus 1751; Nitzelius 1946; Lagerstedt 2000; Selin 2000).

In recent decades we have observed spontaneous natural regeneration of walnut along forest margins and into moist forest patches at several locations in southern and central Sweden, wherever seed sources are nearby. Such naturalization has also been reported from Central Europe (Loacker et al. 2007). In Sweden, the expansion sometimes occurs where wych elm (*Ulmus glabra* Huds.) or common ash (*Fraxinus excelsior* L.) decline or die off. This natural spread of walnut further testifies to its potential role in Sweden, particularly in the context of climate change.

The hybrid of Persian (♂) and eastern black (♀) walnut, *J.* × *intermedia* Carr., is known for strong heterosis or hybrid vigour. More specifically, the hybrid has a superior growth capacity, forms a straight stem and is less susceptible to late frost and produces fewer nuts than either of its parent species (Pretzsch 1995). In many other regards, for example morphologically, the *intermedia* hybrid is intermediate between the parents.

CONTACT Jens Peter Skovsgaard jps@slu.se Swedish University of Agricultural Sciences, Southern Swedish Forest Research Centre, S-234 56 Alnarp, Sweden

For these reasons, hybrid walnut is an interesting option for forestry, worthy of consideration on appropriate sites, not least when working with assisted migration at or beyond distributional limits, such as for walnut in Sweden.

If planted on a larger scale than at present, timber from walnut could potentially become a valuable niche product. Walnut is suited to mild or warm climates, is moderately site demanding, performs exceptionally well on deep, rich soils, is sensitive to late frost, and is very winter hardy (Lestrade et al. 2013). However, little is known about the establishment or the wider context and practice of walnut silviculture in Sweden. In particular, the local circumstances that may hamper or favour the survival and growth of walnut are so far unquantified.

Being intolerant of shading, walnut as a forest tree is usually planted at wide spacing (often ranging from 3 to 12 m at planting) and is grown in pure rather than in mixed stands (Becquey 1997; Mohni et al. 2009; Hemery and Simblet 2014; Fernández-Moya et al. 2019; Nicolescu et al. 2020). However, research based on field experiments indicates that walnut can benefit from being grown in mixed stands, particularly with nitrogen-fixing species (Schlesinger and Williams 1984; Campbell and Dawson 1989; Chifflot et al. 2006; Clark et al. 2008). Moreover, nurse or companion species may protect walnut from late spring frost, shelter the stand-interior from wind, reduce competing ground vegetation and, possibly, provide other benefits.

The objective of the analyses reported here was to quantify the effects of different establishment practices on the survival, leader shoot dieback and early height growth of two varieties of the *intermedia* hybrid (hereafter referred to as hybrid walnut). The analyses were based on a field experiment, and the establishment practices included the use or absence of nurse trees, nurse shrubs, weed control and fertilization. Hypotheses are outlined below in connection with each analysis.

Materials and methods

The research was carried out in an ongoing long-term field experiment, experiment no. 1220 in the national series of forestry experiments conducted by the Swedish University of Agricultural Sciences. Experiment 1220 is located at the Bjäre peninsula in Scania, southern Sweden (WGS84: 56.4166°N, 12.7200°E). The distance to the sea (Kattegat) varies from 5 to 7.5 km in all directions going clockwise from south to east-northeast.

We planted the experiment with the purpose to investigate the short- and long-term performance of hybrid walnut on a fertile site in southern Sweden (Skovsgaard et al. 2015). Due to its limited geographical scope, experiment 1220 can be considered only a pioneering case-study.

The varieties of hybrid walnut in the experiment include NG23 and NG38. The OP42 hybrid poplar clone (*Populus maximowiczii* Henry × *trichocarpa* Torr. & A. Gray ex Hook var. OP42) was used as a nurse tree, and autumn olive (*Elaeagnus umbellata* Thunb.) as a nurse shrub.

Experimental design

The experiment was installed in blocks subjecting the two types of hybrid walnut to contrasting levels (absent or present) of nurse trees, nurse shrubs, weed control and fertilization. Due to the shelter effect of nurses (trees and/or shrubs) and its possible long-term implication, each combination of nurse trees and nurse shrubs was planted in geographically separate blocks in a 2^2 factorial design with the factors “with or without nurse trees” and “with or without nurse shrubs” (Table 1). Each combination was replicated twice, once in a large block with 64 walnut trees and, due to budget restrictions and limitations in land availability, once in a small block with 24 walnut trees. Each block was surrounded by a buffer zone with or without nurse trees (the same as in the block).

The large blocks with 64 walnut trees were installed in a 2^3 factorial design with the treatment levels (Table 2) replicated eight times in an 8 × 8 Latin square. The randomization of the Latin squares was done using PROC PLAN in SAS. The small blocks with 24 walnut trees were installed in a completely randomized design with three replicates of each treatment level. A total of 352 walnut trees were planted across the eight blocks.

Hybrid walnut was planted in a square pattern at a spacing of approximately 4.24 m × 4.24 m within a matrix of poplar trees planted at an approximate initial spacing of 3 m × 3 m (Figure 1). Each walnut tree was located at the crossing of diagonals between four poplar trees. Autumn olive was planted at “unused” crossings of diagonals between four poplar trees, i.e. at approximately 2.12 m × 2.12 m.

Treatment specifications

Nurse trees: The intended role of the nurse tree treatment was to shelter walnut primarily from late frost. To initiate frost protection as quickly as possible we decided to plant the walnut experiment within an existing stand of OP42 poplar. OP42 poplar, a very fast-growing tree in youth, was planted in spring 2014, i.e. one year before the walnut. The plantation was fenced. Shortly before planting of the poplar trees, the whole area was treated with glyphosate for weed control. At installation of the experiment in spring 2015 all poplar trees in blocks designated for treatment without nurse trees were removed by pulling them out of the ground. Remaining nurse trees were removed by felling at ground level in spring 2018. By then, walnut (mean height = 167 cm, maximum height = 428 cm) had generally grown out of the late frost zone and was, or was about to become, overtopped by nurse trees (mean height ≈ 335–685 cm, depending on block location). Coppice regrowth shoots on nurse tree stumps were removed in June 2019.

Table 1. Overview of whole-block treatments.

Block	Nurse trees	Nurse shrubs
α	No	No
β	No	Yes
γ	Yes	No
δ	Yes	Yes

Table 2. Overview of within-block treatments.

Treatment	Walnut variety	Weed control	Fertilization
A	NG23	No	No
B	NG23	No	+25 g N
C	NG23	Yes	No
D	NG23	Yes	+25 g N
E	NG38	No	No
F	NG38	No	+25 g N
G	NG38	Yes	No
H	NG38	Yes	+25 g N

Nurse shrubs: Autumn olive was planted on 21 April 2015. The bareroot transplants (size 50–80 cm) were raised in a nursery at Pinneberg north of Hamburg, Germany. Their origin could not be traced. The intended role of the actinorhizal nurse shrub was to enrich the soil thereby enabling the establishment and long-term growth of walnut. However, from 2015 to 2018 the mean height of autumn olive increased only from 65 to 108 cm. Moreover, widespread mortality occurred in autumn olive, by spring 2018 amounting to 23% and following the summer drought that year dramatically increasing to 75%. A t-test of the height growth of individual walnut trees without dieback or damage to the leader shoot indicated no significant effect of nurse shrubs ($P = 0.453$) at this stage of stand development. So, due to the short time since planting and the distant location of nurse shrubs relative to walnut trees combined with modest growth and substantial mortality, autumn olive did not take effect within the observation period and was excluded from the analyses.

Hybrid walnut: Walnut was planted on 31 March and 1 April 2015. The one-year-old bareroot transplants were raised and delivered by Pépinières Guillot Bourne SA, France, from their commercial nursery stock. A total of 180 trees of each of two different walnut hybrids (NG23, 0 + 1, size class 60–80 cm, and NG38, 0 + 1, size class 80–100 cm) were available for the experiment. Both types were of selected half-sib seed origin. The transplants were undercut in the nursery. Both walnut types are of unspecified French origin.

Fertilization: Each walnut tree designated for this treatment received a granulated 21-4-7 NPK fertilizer (manufactured by Yara) once annually in May or June for a period of six years (2015–2020). According to the manufacturer's specification the fertilizer included 20.6% N (7.9% as nitrate, 12.7% as ammonium), 3.6% P, 6.6% K, 0.9% Mg and 3.0% S. Each tree was given 121 g of fertilizer within a radius of 20 cm from the tree. This quantity equates to 25 g N. Based on general knowledge of walnut, N was the element of key interest, while the combination of nutrient elements ensured a balanced fertilizer. The dose was set at 25 g N inspired by Goodman et al. (2013, 2014) and other literature on walnut nutrition. The first application took place on 22 June 2015, i.e. shortly after planting.

Weed control: Control of competing ground vegetation (hereafter referred to as weed control) was carried out with glyphosate across the whole area in 2014 prior to the planting of poplar. By spring 2015 no significant competing ground vegetation had emerged, but quickly did so already during that year. Weed control as part of the experimental treatments was carried out by shielded spot spraying with glyphosate (dose: 4 l·ha^{-1} Roundup) during dry weather on a circular area of approximately 2 m^2 (radius = 0.80 m)

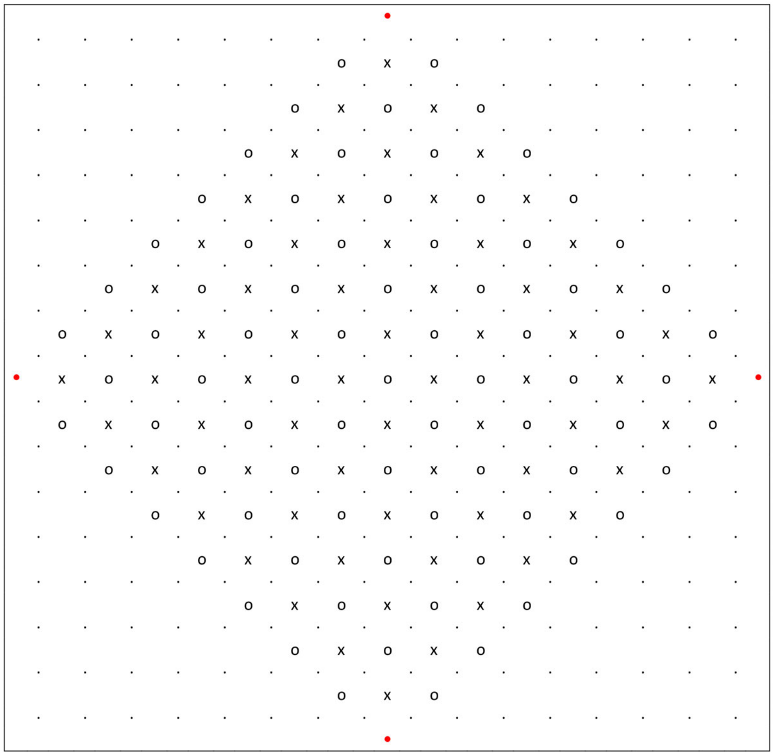

Figure 1. Location of walnut trees (x) among nurse trees (·) and nurse shrubs (o). One full block with 64 walnut trees (● = plot corner (and nurse shrub)). The distance between nurse trees is 3 m × 3 m, with rows running parallel to the black frame. The distance between walnut trees is 4.24 m, with rows at an angle of 45° to nurse tree rows. Nurse shrubs are located at a distance of 2.12 m from walnuts, in a similar spatial arrangement.

around each walnut tree designated for this treatment. Weed control was repeated once annually in September for a period of three years (2015–2017). In 2015, weed control was performed in two steps, on 16 July (mowing of grass) and on 8 September (spraying with glyphosate). In consecutive years, weed control was performed only by spraying with glyphosate, on 9 September 2016 and 17 September 2017, respectively. A planned spraying in 2018 was cancelled as all field vegetation was dry after an extreme summer drought.

Site conditions and location of blocks

The experiment was established on former agricultural land in moderately undulating terrain. Patches of ancient beech, oak and mixed beech-oak forest are scattered over the surrounding landscape (Figure 2). All blocks are surrounded by the stand of OP42 poplar that was planted one year before the experiment was installed.

The large blocks are located at higher elevation (approximately 90 m above sea level) with mesic soil conditions (site I). The small blocks are located at lower elevation (approximately 85 m above sea level) with moist soil conditions (site II). Being located at the south-eastern base of a gentle hill slope stocked with tall, scattered oak trees the small blocks are better sheltered from the predominantly westerly winds.

Soils were sampled on 2 July 2015 by taking one sample from the centre of each block with an equal representation to a depth of 60 cm. In most profiles the plough layer extended to a depth of 30 cm and did not include any plough pan. In block γ_{Small} groundwater was visible at 50 cm and in δ_{Small} at 60 cm.

The soil analyses included pH, the chemical elements P, Ca, K, Mg, C and N_{Dumas}, cation exchange capacity (CEC), base saturation (BS), humus content and soil texture (Table 3). For the subsequent analysis of height growth, a proxy for the maximum content of soil water available for plants (available soil water capacity, ASWC) was derived from soil texture and humus content based on general pedotransfer functions. Pedotransfer functions for Sweden (Kätterer et al. 2006) were not directly applicable, so a combination of two functions for similar soil types in Himmerland, a region in northern Denmark, was used.

ASWC is the estimated soil water content between field capacity (pF_2) and the permanent wilting point ($pF_{4.2}$) and was calculated based on Madsen and Platou (1983) as

$$\text{ASWC} = 2.130 \times \text{humus} - 0.020 \times \text{clay}_{0-2} + 0.380 \times \text{silt}_{2-20} + 0.164 \times \text{sand}_{20-200} + 1.956 \quad (1)$$

where the resulting ASWC is expressed in volume percentage, humus and texture variables are expressed in standardized percentages (i.e. humus and texture classes add up to 100%), $\text{clay}_{0\text{-}2}$ refers to the same clay fraction as in our soil analysis, $\text{silt}_{2\text{-}20}$ refers to the fraction 2–20 µm, and $\text{sand}_{20\text{-}200}$ refers to the fraction 20–200 µm. The fractions needed to calculate ASWC were derived based on simple linear interpolation.

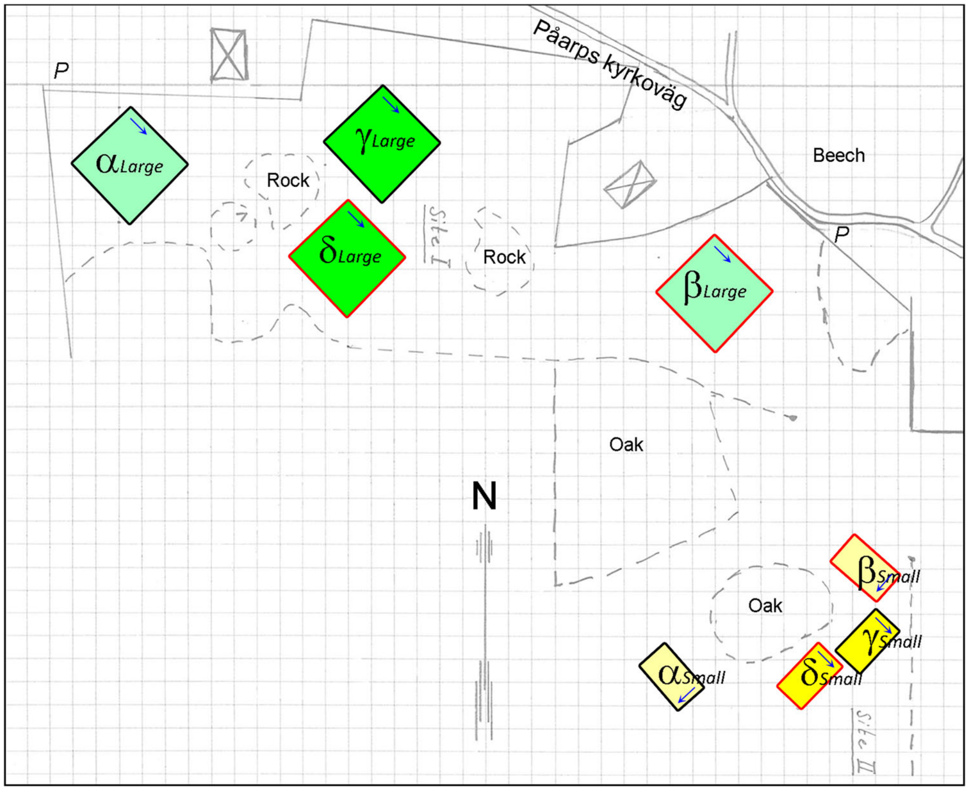

Figure 2. Location of experimental blocks (α, β, γ and δ). Legend: green interior = large blocks (site I), yellow interior = small blocks (site II), light shading = no nurse trees, dark shading = with nurse trees, black border = no nurse shrubs, red border = with nurse shrubs; blue arrows indicate the origin and direction of measurements; *P* = parking; Påarps kyrkoväg = nearby dirt road.

Table 3. Summary of soil characteristics at the time of planting.

Site	Site I				Site II			
Block	α_{Large}	β_{Large}	γ_{Large}	δ_{Large}	α_{Small}	β_{Small}	γ_{Small}	δ_{Small}
Humus (%)	2.4	1.8	1.8	1.8	5.3	2.7	6.8	12.9
Clay (< 2 µm, %)	9.0	8.0	8.0	8.0	10.0	8.0	8.5	5.5
Silt (2-63 µm, %)	29.0	21.0	23.0	24.0	29.0	27.0	28.5	41.0
Sand (63-2000 µm, %)	62.0	71.0	69.0	68.0	61.0	65.0	63.0	53.5
pH ($CaCl_2$)	4.5	4.6	5.1	4.7	5.0	4.4	6.0	6.3
N (10^{-3} g/g)	122.0	113.0	94.0	106.0	253.0	138.0	347.0	606.5
C/N	11.6	9.4	11.3	10.0	12.3	11.5	8.3	11.9
CEC (meq/(10^2 g))	9.9	8.6	7.9	8.4	14.8	10.0	16.6	28.3
BS (%)	14.1	29.1	43.0	25.0	48.6	20.0	91.4	98.8

Notes: The concentration of individual elements is shown only for N. Legend: C = carbon, N = nitrogen, CEC = cation exchange capacity, BS = base saturation.

The local climate was believed to be very similar to that of the LantMet climate station Glimminge-2 located at 40 m above sea level 5.0 km south-southwest of the experiment. During 2015–2019, the monthly average air temperature (170 cm above ground level) ranged from −1.4 to 20.0 °C, with daily absolute minimums down to −17.8 °C and maximums up to 32.9 °C. The annual precipitation ranged from 451 to 837 mm and the penta-precipitation during May-September from 194 to 407 mm (249, 261, 407, 194 and 306 mm for 2015, 2016, 2017, 2018 and 2019, respectively).

Data collection

All walnut trees were measured for total tree height (H) at planting and were re-measured annually during the observation period (2015–2020). Re-measurements were to the tallest live bud and were carried out prior to initiation of growth. Annual change in the total height of each individual tree, hereafter referred to as annual height growth (I_H), was derived from these measurements.

During the early summer of 2017, a detailed retrospective inventory of recurring leader shoot dieback was conducted. The dieback symptoms included a desiccated tip as well as soft necrotic tissue at the tip of or along the leader shoot. No biotic or abiotic agent, or combination of agents, was identified.

All nurse trees were measured for total tree height and stem diameter at 1.30 m above ground level (DBH) in spring 2016 and 2018.

Statistical analyses

The observation period reported here included the first five growing seasons after planting (2015–2019). The analyses included the survival, dieback of the leader shoot, and height growth of individual walnut trees. In addition to these analyses, we present an inventory status for the nurse trees at the time of their removal (spring 2018).

Throughout the analyses any variable with calendar year as a subscript refers to either spring status or that year's growing season. All statistical analyses were carried out using *SAS* software, version 9.4.

Nurse tree analysis

The inventory of poplar nurse trees included a test for the statistical correlation of nurse tree height (arithmetic mean height H_{PM} and maximum height H_{Pmax}, respectively) with each of the basic soil variables.

Survival analysis

The survival of walnut was analysed by comparing across blocks, walnut types and other experimental factors. Due to high survival rates and little variability, no further formal analysis or hypothesis testing was possible.

Dieback analysis

Unexpected dieback mainly of the leader shoot occurred on many walnut trees shortly after planting and in most cases occurred repeatedly on the originally damaged trees for several years. No late frost damages were observed anywhere in the experiment.

Based on the detailed retrospective inventory of leader shoot dieback in spring 2017 we analysed to what extent the dieback was related to block type (small vs. large, fertile vs. less fertile), the use of nurse trees (with vs. without nurse trees) or walnut type (NG23 vs. NG38). The analyses were conducted as chi-square tests based on observed frequencies of dieback damage originating between the time of planting and spring 2017.

Height growth analysis

The most common recovery response to dieback was that one or more sub-apical shoots took over, which in most cases led to forking (branching out) immediately below the top or further down the stem. Even when the leader shoot would still be alive, apical dominance / epinastic control often seemed weakened and one or more branches (lateral shoots) tended to take over. As a result, when recording total tree height based on the highest living point on the tree at any re-measurement occasion, "growth" derived from these measurements does not reflect true growth but is confounded by factors influencing the dieback.

The growth response to experimental treatments can be gauged only in terms of true growth (rather than in terms of change in total tree height), i.e. annual height growth derived from measurements of trees without dieback or damage to the leader shoot. By autumn 2019 / spring 2020 this had reduced the potential data set from 352 to 58 trees and had created an imbalance across nurse tree treatments and walnut types in the distribution of trees valid for the analysis of height growth (cf. results section). Nevertheless, we considered the resulting data representative of other treatment combinations and of the variation in site conditions within the experiment. To further corroborate this claim, row and column in the Latin square blocks were checked for systematic effects in a preliminary analysis including all trees, and no such effects were found.

Thus, the original statistical design could not be taken full advantage of in the growth analysis. We consequently analysed the remaining undamaged walnut trees as originating from a randomized block experiment.

The annual height growth of walnut (I_H) was modelled using a first-order autoregressive (AR(1)) model. Potential independent variables included all experimental factors (with walnut type, weed control and fertilization nested within nurse tree treatment in the blocks) and, as covariates, seedling size at the time of planting (reflecting the inherent growth potential of each individual tree), all soil variables (reflecting block-specific site conditions) and precipitation during the growing season (reflecting year-to-year fluctuations in water availability for tree growth).

Due to the confounding of seedling size at the time of planting (H_{2015}) and walnut type it could be argued that only one of these variables should be included in the regression. However, it was decided to include both H_{2015} and walnut type among potential independent variables as H_{2015} might then account for any dependence of I_H on original tree size apart from that expressed through walnut type. To possibly circumvent the problem, relative growth rate was tested as an alternative dependent variable, but invariably provided no better fit than I_H did.

Due to a strong correlation between most soil chemical elements and, to some extent, soil texture variables, humus and soil water capacity, it was decided to focus the attention on BS (an integrative indicator of soil fertility), ASWC (an indicator of the maximum quantity of soil water available for plant growth) and N (often regarded as the most important individual soil chemical element for walnut growth). To avoid collinearity in the model, it was decided to fit three separate models, one for each soil variable.

The full AR(1) model may be specified as follows:

$$I_{Hni} = \mu + a_n + \beta_1 I_{Hnj} + \beta_2 S_{ns} + \beta_3 T_{nt} + \beta_4 P_i + \varepsilon_{ij} \quad (2)$$

where I_H denotes annual height growth in any year during the observation period, μ is the overall mean, α is the level associated with one or the other nurse tree treatment within which the randomized treatments and all other covariates are nested, S is a soil variable (N, BS or ASWC), T are indicator variables of treatment (walnut type, weed control or fertilization), P is the precipitation during May to September (the penta-precipitation), β are coefficients, subscript n identifies nurse tree treatment, subscript s identifies soil variables, subscript t identifies treatments, and the variance-covariance structure of ε_{ij} is $\sigma^2\rho^{|i-j|}$, where σ^2 is the variance with normally distributed errors, ρ accounts for the within-subject correlation between measurements, $|\rho| < 1$, and i and j specify year and previous year, respectively.

All measurements were equally spaced in time (one year apart). Given the limited number and the slight imbalance of data available for the analyses of undamaged trees, no interactions were included in the fitting of the models, except those related to the presence or absence of nurse trees. The removal of nurse trees in spring 2018 was not considered in the analyses. In other words, the effect of the nurse treatment was included for the whole duration of the observation period. This was justified by the possible carry-over or after-effect of shelter (whether positive or negative), a phenomenon known for example from forest regeneration under the uniform shelterwood system (Rowe 1964; Burschel and Schmaltz 1965; Skovsgaard and Henriksen 1996; Löf and Welander 2000).

The final models were derived based on stepwise backwards elimination (testing one term at a time, resulting in a final model that cannot be reduced or falsified based on data available). This is in line with the general principle of Ockham's razor ("the simplest model tends to be the best"; Skovsgaard and Vanclay 1997) and, to some extent, that of Karl Popper's principle of falsification for scientific reasoning (any claim to the existence of an effect cannot be made unless it is first shown that a situation of no effect is untenable; Wilkinson 2013). Covariates, treatment effects and interaction terms were considered statistically significant at $P \leq 0.10$.

Results

Nurse trees

The mean height of poplar nurse trees after four growing seasons varied from 3.35 to 6.09 m depending on block location (Table 4). In one of the small blocks the tallest poplar tree had reached an astonishing 8.40 m. There was a large block effect with nurse trees in small blocks being taller than those planted in the larger more exposed blocks.

The strongest statistical correlation (r) of nurse tree height and a soil variable was with BS, where $r = 0.880$ ($P = 0.120$) for H_{PM}, and $r = 0.839$ ($P = 0.161$) for H_{Pmax}. The lack of significance may be attributed, at least partially, to the low number of observations ($n = 4$).

Survival

The overall rate of survival for walnut after five growing seasons was 96.9%. By spring 2020, seven NG23 trees and four NG38 were dead. Out of these, three NG23 trees were located on large blocks and four on small, and two NG38 on each block type. No relationship to any other experimental factor was noted.

Table 4. Poplar nurse tree inventory: arithmetic mean height (H_{PM}), maximum height (H_{Pmax}), stem diameter at breast height (DBH) and stem count per block (N) in spring 2018.

Block	H_{PM} (cm)	H_{Pmax} (cm)	DBH (mm)	N (ha^{-1})
γ_{Large}	335	460	22	1515
δ_{Large}	416	600	31	1577
γ_{Small}	685	840	74	1700
δ_{Small}	609	790	62	1819

Dieback

The frequency of trees undamaged by dieback of the leader shoot was found to be two to three times greater without nurse trees and three to four times greater for NG23 as compared to NG38 (Tables 5–7). The frequency of undamaged trees did not depend on block type, fertilization or weed control.

Height growth

Total tree height at planting (H_{2015}) varied from 51 to 90 cm (mean = 70.1 cm, s = 7.6 cm) for the NG23 variety and from 68 to 147 cm (mean = 110.3 cm, s = 13.1 cm) for the NG38 variety.

The number of walnut trees surviving until spring 2020 and undamaged by leader shoot dieback totalled 58 out of 341 surviving trees for the whole experiment (352 trees were originally planted). These undamaged trees were reasonably balanced across treatments for weed control (26 trees in untreated control vs. 32 with weed control) and fertilization (33 trees in untreated control vs. 25 with fertilization), but less so for walnut type (47 NG23 vs. 11 NG38) and nurse tree treatment (41 without nurse trees vs. 17 with nurse trees).

The confounding of H_{2015} with walnut type was evident for all as well as for undamaged trees (Figure 3). Interestingly, many damaged trees had a substantial, positive net change in total height over the five-year observation period, and some even surpassed the most vigorous undamaged trees. The largest average net change per year was about 90 cm. Only a few trees reduced in height.

The three final AR(1) models were all similar in terms of numeric values of the coefficients (except soil variable coefficients), degree of autocorrelation, residual variance and prediction error as expressed through Akaike's information criterion (Table 8). The studentized residuals indicated some deviation from normality, and a transformation with the logarithm ($\log(I_H + 1)$; not included in this article) had a better fit. However, the results for the two alternatives were similar. Consequently, and due to the ease of interpretation, we preferred the model with no transformation. The overall marginally best model was the one using BS as soil variable.

All three models indicated a positive correlation of annual height growth with last year's growth. Moreover, growth increased with increasing precipitation during the growing season, with penta-precipitation being the statistically most significant predictor of all those included. Likewise, increasing levels of N, BS or ASCW (as derived from soil texture) all led to increasing height growth, with BS being the statistically most significant soil variable.

All three models indicated better growth in the absence of nurse trees. For the main effect, however, the *P*-values were not significant. This indicates that the effect of nurse trees

Table 5. Frequency of undamaged trees (DAMCAT = 0) and trees damaged by dieback (DAMCAT = 1) by block type (large, small; $\chi^2 = 1.21$, $P = 0.271$), nurse trees (no, yes; $\chi^2 = 12.91$, $P = 0.0003$) and walnut type (NG23, NG38; $\chi^2 = 22.08$, $P < 0.0001$).

	DAMCAT		
	0	1	Total
Block Type			
Large	43	213	256
	12.22	60.51	72.73
Small	21	75	96
	5.97	21.31	27.27
Total	64	288	352
	18.18	81.82	100.00
Nurse trees			
No	45	131	176
	12.78	37.22	50.00
Yes	19	157	176
	5.40	44.60	50.00
Total	64	288	352
	18.18	81.82	100.00
Walnut type			
NG23	49	127	176
	13.92	36.08	50.00
NG38	15	161	176
	4.26	45.74	50.00
Total	64	288	352
	18.18	81.82	100.00

Legend: count in top line, frequency percent in bottom line.

Table 6. Frequency of undamaged trees (DAMCAT = 0) and trees damaged by dieback (DAMCAT = 1) by walnut type (NG23, NG38) conditional on nurse trees (no: $\chi^2 = 15.79$, $P < 0.0001$; yes: $\chi^2 = 7.14$, $P = 0.008$).

	DAMCAT		
	0	1	Total
Nurse trees = No			
Walnut type			
NG23	34	54	88
	19.32	30.68	50.00
NG38	11	77	88
	6.25	43.75	50.00
Total	45	131	176
	25.57	74.43	100.00
Nurse trees = Yes			
Walnut type			
NG23	15	73	88
	8.52	41.48	50.00
NG38	4	84	88
	2.27	47.73	50.00
Total	19	157	176
	10.80	89.20	100.00

Legend: count in top line, frequency percent in bottom line.

Table 7. Frequency of undamaged trees (DAMCAT = 0) and trees damaged by dieback (DAMCAT = 1) by nurse trees (no, yes) conditional on walnut type (NG23: $\chi^2 = 10.21$, $P = 0.0014$; NG38: $\chi^2 = 3.57$, $P = 0.059$).

	DAMCAT		
	0	1	Total
Walnut type = NG23			
Nurse trees			
No	34	54	88
	19.32	30.68	50.00
Yes	15	73	88
	8.52	41.48	50.00
Total	49	127	176
	27.84	72.16	100.00
Walnut type = NG38			
Nurse trees			
No	11	77	88
	6.25	43.75	50.00
Yes	4	84	88
	2.27	47.73	50.00
Total	15	161	176
	8.52	91.48	100.00

Legend: count in top line, frequency percent in bottom line.

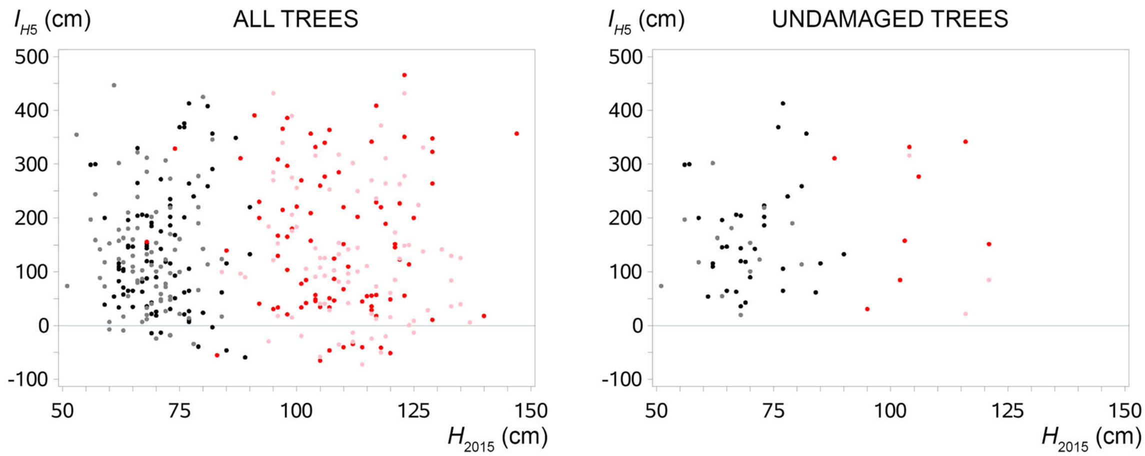

Figure 3. Five-year change (I_{H5}, 2015–2020) in individual tree height vs. tree height at planting (H_{2015}) for all walnut trees (left) and undamaged walnut trees (right). Legend: black = NG23 without nurse trees, grey = NG23 with nurse trees, red = NG38 without nurse trees, pink = NG38 with nurse trees.

Table 8. Parameter estimates and fit statistics for three alternative AR(1) models of annual walnut height growth (I_H) during 2015-2020 using either N, BS or ASCW as predictor variable for soil characteristics.

Variable/Treatment	NT	Type	Fert	Model N Estimate	*P*-value	Model BS Estimate	*P*-value	Model ASCW Estimate	*P*-value
Intercept				−16.09	0.237	−23.41	0.086	−21.28	0.134
Penta-precip				0.17	<.0001	0.17	<.0001	0.17	<.0001
N/BS/ASWC				0.060	0.018	0.48	0.001	1.24	0.030
Nurse trees	No			13.51	0.346	16.28	0.233	13.77	0.341
	Yes			0	.	0	.	0	.
Type (NT)	No	NG23		−12.84	0.098	−12.68	0.089	−12.86	0.100
	No	NG38		0	.	0	.	0	.
	Yes	NG23		0.15	0.991	2.44	0.845	0.76	0.954
	Yes	NG38		0	.	0	.	0	.
Fert (NT)	No		No	−14.49	0.021	−14.55	0.016	−14.35	0.023
	No		Yes	0	.	0	.	0	.
	Yes		No	−24.49	0.028	−29.81	0.007	−23.77	0.033
	Yes		Yes	0	.	0	.	0	.
ρ				0.2771		0.2442		0.2830	
σ^2				1211.83		1173.49		1219.21	
AIC				2837.0		2828.9		2831.6	

Abbreviations and symbols: NT = nurse trees, Type = walnut type, Fert = fertilization, ρ = within-subject correlation between measurements, σ^2 = residual variance, AIC = Akaike's information criterion. Units of measurement for I_H: cm, for penta-precipitation: mm (i.e. the numeric value equals litre per square metre of land area), for N: 10^{-3} g·g^{-1}, for BS: %, for ASWC: volume percentage (i.e. 10 times the numeric value equals litre of water per cubic metre of soil volume).

was more clearly expressed through its interaction with the two significant treatment factors walnut type and fertilization. The nesting effect of walnut type within the nurse tree treatment was significant only at the 10% level. In the absence of nurse trees, NG38 grew faster, whereas in the presence of nurse trees, NG23 grow faster, but not significantly so. Fertilization had a positive impact on height growth and more so in the presence of nurse trees.

Discussion

The analyses indicated very high five-year survival rates, surprisingly high frequencies of leader shoot dieback and promising height growth rates for hybrid walnut.

Nurse trees

Wind, soil fertility, or the combination of both clearly had an impact on the growth of poplar, with larger growth in the small blocks located in the more sheltered and fertile parts of the area. Due to the strong growth of the poplar, the nurse trees rapidly overgrew walnut and gradually transformed into a low shelterwood.

The strong influence of poplar nurse trees on the growth of walnut, naturally lead to the hypothesis of an inverse relationship for height growth. Due to the widespread occurrence of leader shoot dieback, we did not attempt to test this hypothesis.

Survival

The overall survival rate of 96.9% for walnut was very high and exceeded all expectations. NG23 had 75% more dead trees than NG38. However, considering the low number of dead trees, the practical significance of the large percentage difference can be questioned.

Similarly high survival rates of both hybrid types were observed after five years in a field experiment planted on former agricultural land in England (Clark and Hemery

2010) and after approximately ten years in a large-scale operational test on forest land in the southwest of Germany (Arnold et al. 2011; Ehring et al. 2014). In England survival was 100% for both hybrids, in Germany it was 89% for NG23 and 88% for NG38.

Dieback

Leader shoot dieback occurred in all treatment combinations but most severely in the presence of poplar nurse trees. The hybrid variety NG23 suffered less than NG38. So far, no biotic or abiotic damaging agent, or combination of agents, were identified. We have seen leader shoot dieback in other plantings of hybrid walnut but generally far from the extent observed in experiment 1220.

Based on these observations, we hypothesize that leader shoot dieback may depend on hybrid variety, carry-over effects of nursery conditions, (rough) handling in the nursery or during storage or transportation, competition for water (such as with nurse trees), autumn frost hardiness (cold acclimation) or a combination of any of these.

One factor that could play a role in the dieback is the undercutting of the seedlings in the nursery. Walnut, and particularly hybrid walnut, develops a strong taproot that is undercut prior to lifting as it would otherwise become impractical to handle the nursery stock. Lateral roots develop only weakly in the first year of growth. As a result, the root system of a one-year-old hybrid walnut transplant looks like a short thick stick with few thin lateral fine roots, somewhat like the upper part of a broken root of the cultivated western carrot (*Daucus carota* (L.) subsp. *sativus* (Hoffm.)).

It is well-known that undercut walnut is sensitive to transplanting (Rebmann 1907). Planting success is mainly determined by root system morphology and the seedling's nutrient status. Undercutting substantially enlarges the shoot/root ratio. This, in turn, may lead to reduced water supply or altered tree-internal competition for water as compared to a tree with undisturbed root development, resulting in less water being available for growth in the terminal leader shoot (Kozlowski et al. 1991; Kozlowski and Pallardy 1997). This could help explain our result that the smaller NG23 suffered less from dieback than the larger NG38.

If the dieback were strongly related to the shoot/root ratio, it might be expected that root system recovery over time would gradually compensate for any imbalance in this ratio, and the dieback would eventually disappear. No such indications were observed in experiment 1220 during 2015–2020 but rather a recurring dieback. No root system investigations were carried out to quantify root recovery.

In addition to undercutting, the quality of undercutting and any desiccation during storage or transportation could also play a role (Aldhous and Mason 1994). Most of the transplants received for the experiment had fringed edges at the base of the taproot and cracks in the wood extending upwards. This could indicate a rather rough undercutting and a subsequent larger risk of desiccation due to more debarked or damaged tissue. We did not sort by or take records of root system quality for individual transplants and consequently could not analyse the possible impact of this factor on leader shoot dieback.

The larger frequency of dieback in blocks with nurse trees could relate to competition between poplar and walnut for water. Alternatively, poplar could have damaged walnut leader shoots by mechanical interference, for example due to whipping during strong winds. However, we did not observe any indication of such mechanical damage.

In addition to the factors mentioned above, the observed dieback could relate to autumn frost hardiness or cold acclimation. There are no investigations specifically comparing NG23 and NG38 in this regard, but research indicates that NG23 ranks between Persian and eastern black walnut with Persian walnut apparently being the least hardy (Guàrdia et al. 2013a; see also Ebrahimi et al. 2020) and that cold acclimation in Persian walnut has a high degree of heritability and correlates inversely with the growth rate of DBH (Guàrdia et al. 2013b, 2016).

Finally, storage conditions (Jacobs et al. 2008), the quantity and quality of arbuscular mycorrhiza on the hybrid walnut, mediating nutrient uptake (Mortier et al. 2020) and asynchrony in shoot and root phenological relationships (Mohamed et al. 2020) and any disturbance in these could possibly also contribute to the explanation of dieback.

Although leader shoot dieback is well-known among foresters working with hybrid walnut, the phenomenon has received little attention in scientific literature. However, dieback similar to the one observed for hybrid walnut in experiment 1220 has been observed also in a large Persian walnut progeny and provenance trial in England and was unrelated to genetic origin (Clark 2017). Whether or not this holds for a larger range of sites or provenances of Persian walnut or even for hybrid walnut, remains to be tested.

Height growth

In the AR(1) model specified, treatment is a between-subjects factor because treatment levels can change only between subjects. In other words, measurements on each subject are for the same treatment level. Time is a within-subject factor because measurements on the same subject are taken at different points in time within the same treatment level. Interest lies in how treatment means change (treatment effect), how treatment means change over time (time effect), and how differences in treatment means change over time (treatment by time interaction).

Annual height growth of trees unaffected by dieback increased with increasing levels of precipitation during the growing season and increasing soil quality (in terms of nutrient status as well as available soil water capacity), was negatively influenced by poplar nurse trees and positively by fertilization. Weed control had no impact on height growth. With nurse trees, the hybrid variety NG23 (which was smaller at planting) had a stronger growth than NG38, whereas the opposite was true without nurse trees. The correlation with the previous year's growth ranged from 0.24 to 0.28.

The three alternative model specifications, differing only by soil variable, resulted in final models including the same explanatory variables and with very similar coefficients, fit and prediction statistics. This reflects the strong correlation among soil variables and gives no clear indication as to whether N (as an individual chemical element), the general soil nutrient status (BS), or the soil water available for tree growth (ASCW), was the most important for the growth of hybrid walnut. However, all these strongly influenced growth and in all cases with increasing levels leading to more growth.

The magnitude of the effects of environmental as well as experimental factors can be illustrated based on LS-means estimates derived from the final model. Based on the model using BS as an indicator of soil characteristics, we focused on the overall LS-means estimates and those of four contrasting examples (Table 9). The four examples were specified by penta-precipitation (200 or 400 mm) and BS (20 or 90%), reflecting dry and wet summers for poor and rich soils derived from glacial till.

The LS-means estimates indicated an overall reduction in annual height growth by 38% due to the presence of poplar nurse trees. With poplar nurse trees, the estimates indicated an increase by astonishingly 364% due to fertilization, but still resulting in "only" 82% of the growth expected with fertilization without nurse trees. Clearly, fertilization compensated partially for competition for water. This is in line with other research indicating increasing water use efficiency with increasing fertilization (Goodman et al. 2014).

The overall reduction in annual height growth due to nurse trees generally lingered around 16 cm for any given combination of BS and penta-precipitation. On a relative scale, the model predicted hybrid walnut to respond substantially more to nurse trees on poor soils than on rich soils in years with low precipitation during the growing season. With ample penta-precipitation the overall responses with or without nurse trees differed less.

Generally, nurse species are used in silviculture to aid the establishment of other, more sensitive tree species. For walnut, positive effects have been documented particularly with nitrogen-fixing nurse or companion species (Clark et al. 2008; Niccoli et al. 2021). Although western balsam poplar (*P. trichocarpa*), the male genitor of OP42, can fix nitrogen, the fixation occurs not through symbiosis with nodule-inhabiting, N_2-fixing microorganisms (Doty et al. 2016) and possibly benefits mainly itself. Clearly, in experiment 1220, any added nitrogen due to the presence of poplar could not compensate walnut for the water uptake associated with its extremely strong growth. Based on justified arguments (cf. section on treatment specifications), autumn olive was believed to not contribute significantly to nitrogen availability for walnut and was omitted from the analyses.

LS-means estimates indicated that NG38 established without nurse trees in dry summers is expected to grow 7.5 times more on rich soils than on poor soils, but only 2.2 times more together with nurse trees. NG23 ranges in-between these extremes. In wet summers the expected impact of soil fertility on height growth was only by a factor 1.5–1.9. So, on rich soils or with more penta-precipitation the growth expectations for NG23 and NG38 differed less.

In absolute measure and within the frame conditions of these examples, the annual height growth of NG38 was predicted to range between 5 cm (with nurse trees, dry summer, poor soil) and 97 cm (without nurse trees, wet summer, rich soil). For NG23, the estimates ranged between 8 and 84 cm.

Similar growth rates and similar variation were observed in other comparable experiments. On former agricultural land in England (Clark and Hemery 2010) and in a forest setting in Palatinate, Germany (Mettendorf 2008), NG38 grew faster than NG23. However, in a large-scale operational test in Baden-Württemberg, Germany, including 55 plots across a wider range of site types and all on forest land (Arnold et al. 2011; Ehring et al. 2014), NG23 grew faster than NG38. In Germany, the two hybrids differed marginally. In England, NG38 was smaller than NG23 at planting (i.e. the opposite of experiment 1220) but outgrew NG23 within five years. It was speculated that slow establishment in general and the difference in growth pattern could relate to the shoot/root ratio at planting and that it takes a while for the trees to re-balance (Clark and Hemery 2010).

In experiment 1220 it was very clear that smaller transplants (NG23) grow better when subjected to competition for water (with poplar nurse trees), and larger transplants (NG38) grow better when not (without nurse trees). This result adds to the interpretation of the results from England.

The general experience that the growth of walnut declines with increasing content of clay and silt above a certain soil

Table 9. Overall LS-means estimates and LS-means estimates for different combinations of penta-precipitation (200 or 400 mm) and BS (20 or 90%) for the AR(1) model using BS as indicator of soil characteristics.

Variable/Treatment	NT	Type	Fert	Overall estimate	Combi-estimate	Combi-estimate	Combi-estimate	Combi-estimate
Penta-precip				283.40	200	200	400	400
BS				31.66	20	90	20	90
Nurse trees	No			42.6	22.8	56.3	56.7	90.5
	Yes			26.2	6.5	40.3	40.4	74.2
Type (NT)	No	NG23		36.2	16.5	50.3	50.4	84.2
	No	NG38		48.9	29.1	63.0	63.0	96.9
	Yes	NG23		27.4	7.7	41.5	41.6	75.4
	Yes	NG38		25.0	5.2	39.1	39.1	73.0
Fert (NT)	No		No	35.3	15.5	49.4	49.4	83.2
	No		Yes	49.9	30.1	63.9	64.0	97.8
	Yes		No	11.3	−8.4	25.4	25.4	59.3
	Yes		Yes	41.1	21.4	55.2	55.3	89.1

Abbreviations and symbols: NT = nurse trees, Type = walnut type, Fert = fertilization. Units of measurement for LS-means estimates of I_H: cm, for penta-precipitation: mm (i.e. the numeric value equals litre per square metre of land area), for BS: %.

texture optimum or with waterlogging (Becquey 1997; Fernández-Moya et al. 2019) could not be demonstrated within our experiment. In the large-scale experiment in Germany, waterlogging as well as low pH impeded growth and mortality was higher (Arnold et al. 2011; Ehring et al. 2014). In contrast, height growth in our experiment correlated strongly with penta-precipitation (ranging from 194 to 407 mm). This is consistent with the notion that summer precipitation should not fall below 150 mm for Persian walnut (Giannini and Mercurio 1997; Mohni et al. 2009). Other than these general statements we found no specific quantification in the literature for either of the two types of hybrid walnut regarding the influence of soil quality or summer precipitation.

Consistent with the LS-means estimates for walnut type, the estimates for fertilization ranged between −8 and 98 cm. The negative value was for no fertilization with nurse trees and points to a caveat in the model specification or in the data available for model derivation. The gain in annual height growth due to fertilization was predicted to range from approximately 15 to 30 cm, depending on the specification of environmental conditions.

We did not investigate the impact of different fertilization doses and consequently cannot advise regarding any dose–response optimum whether in terms of growth, allocation of growth (stem vs. roots), cost effectiveness or ecological sustainability. However, the dose applied in our experiment (25 g N per tree) had the largest photosynthetic efficiency in an experiment with eastern black walnut in Spain (Goodman et al. 2014). Moreover, any fertilization shifted biomass allocation away from stem to root biomass (Goodman et al. 2013).

Interestingly, weed control had no influence on the growth of hybrid walnut in this experiment. We attribute this to three characteristics of the weed control carried out: 1. it spanned only a radius of 0.8 m around each walnut tree, 2. it was initiated (too) late in the first year, and 3. the dose applied was too small to kill or significantly reduce competing ground vegetation.

In the large-scale experiment in Germany, grass impeded height growth and led to more losses of the main stem axis (Arnold et al. 2011; Ehring et al. 2014). This is consistent with our observed response to competition for water in terms of growth as well as dieback frequency. This lends support to our conjectures regarding the absent effect of weed control in experiment 1220. Possibly, the hybrid walnut in our experiment were all subjected to relatively high levels of competition for water from uncontrolled ground vegetation, resulting in less growth and more dieback.

The positive and significant correlation of annual height growth with the previous year's growth quantified parts of the carry-over effect of environmental conditions from year to year and of the genetically inherent growth potential which could not otherwise be accounted for, for example through initial tree height. For the growth of (young) trees, the temporal correlation among within-subject measurements generally tends to decrease with increasing time lag, as specified in our AR(1) models.

The strong influence of soil quality and summer precipitation observed within this experiment is typical of many walnut species. Consistent with its strong heterosis or hybrid vigour, hybrid walnut responds strongly to less optimal conditions such as when growing on poor soil (low BS, low ASWC) or when exposed to summer drought (low penta-precipitation).

Stem quality

In addition to a growth reduction or, rather, a reduction in the net change of tree height, dieback of the leader shoot may severely disturb monopodial growth, leading to unintended early branching out and loss of continuity in the formation of a single straight stem. From a timber production perspective, loss of the main vertical axis is a key problem.

In 2020, we conducted a complete inventory of stem quality in experiment 1220 and identified potential future crop trees (Juravle 2020). Based mainly on absence of forking (branching out) and on stem straightness we identified a total of 54 potential future crop trees. No spatial requirements regarding the minimum distance between potential future crop trees were considered, i.e. all trees were considered on equal terms. NG23 accounted for approximately two-thirds of the selected cohort. There was an almost complete overlap between undamaged and potential future crop trees. In a wider perspective, this cohort of trees (the 54 individuals without dieback symptoms) could potentially be a promising material for breeding purposes, selected under local environmental conditions.

The main problem was forking or, in other words, the lack of a single main stem. NG38 had fewer branches than NG23, and the diameter of the thickest branch on each tree was larger for NG38. Similar observations were made in an experiment in the southwest of Germany, but only 5% of the trees had lost their main stem axis (Arnold et al. 2011; Ehring et al. 2014).

In hybrid walnut, leader shoot dieback and the associated loss of apical dominance in the main stem quickly leads to one or more lateral branches competing for and taking over apical dominance. This relates to the growth behaviour of walnut. The undisturbed stem of a juvenile walnut tree has a monopodial development (quoted from Sabatier and Barthélémy 2001 and Solar and Štampar 2003) while lateral shoots are weaker and in a subordinate position. In some cases, the main stem develops lateral branches in the same growing season of its extension (Sabatier and Barthélémy 2001).

Combined with the strong and rapid growth of hybrid walnut, this means that the time frame for identifying and "correcting" for the gradual weakening or loss of leader shoot through formative pruning or tying-up of a lateral shoot to substitute the leader, is quite limited. No such formative shaping was attempted in experiment 1220 during 2015–2020. Nevertheless, considering the expected final spacing of potential future crop trees in walnut for timber production, typically 50–60 trees per ha, the impression by May 2022 was that there were enough high-quality trees within the experiment and that, due to the dynamics of a lateral shoot taking over as leader shoot, the number of potential future crop trees is not diminishing at this stage of stand development.

Conclusions

The combination of high survival rates, promising growth rates (depending on soil and climate) and the occurrence of severe and widespread leader shoot dieback makes it difficult to form a firm conclusion. Survival and growth indicate that hybrid walnut could perform well on glacial till soils in southern Sweden. With less dieback, the potential of NG23 clearly exceeds that of NG38. With more dieback, OP42 poplar should not be used as a nurse for hybrid walnut. The dieback indicates that there is a problem to solve or circumvent before hybrid walnut can be recommended on a larger scale.

It is not clear at this stage, to which extent the dieback problem should be solved in the forest, in transit procedures, in the nursery, or whether it will vanish with increasing age. Regardless of the solution or outcome, it is essential to carefully choose the cultivar and a matching site and to provide intensive care during the first years after planting of hybrid walnut.

Due to its limited geographical scope, experiment 1220 can be considered only a pioneering case-study. We suggest to further investigate a wider range of walnut species and varieties (including other types of hybrid walnut), the possible role of water availability (irrigation), the possible role of weed control (complete control) and, as a mean to possibly circumvent or alleviate the dieback problem, stumping-back of transplants already at planting (to improve the shoot/root ratio).

To investigate these factors, we initiated a new field experiment in Sweden replicated on a wider range of site types and including detailed recordings of nursery stock quality (Skovsgaard et al. 2023). However, more fundamental research is also needed, and we encourage continued and reinforced efforts on the potential role of walnut in northern temperate parts of Europe in the context of climate change and forest adaptation.

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