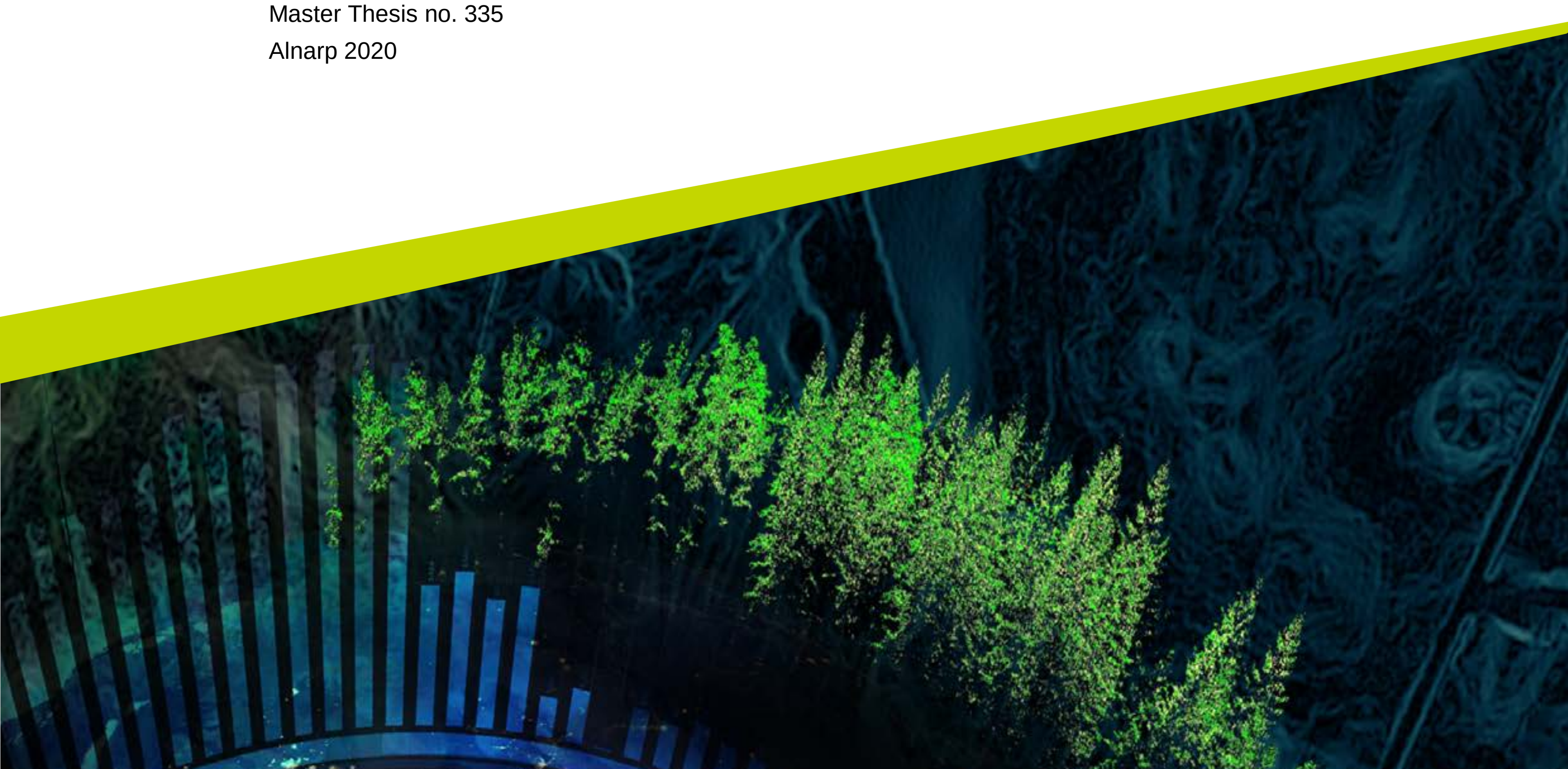
Hybrid walnut: results from a five-year field trial in southwest Sweden 2015-2020

Nucul hibrid: rezultatele unui experiment din sud-vestul Suediei 2015-2020

Ștefan Juravle

Master Thesis • 30 credits
EUROFORESTER
Master Thesis no. 335
Alnarp 2020



Hybrid walnut: results from a five-year field trial in Southern Sweden 2020

Nucul hibrid: rezultate ale unui experiment din sudul Suediei

Ștefan Juravle

Supervisor: Jens Peter Skovsgaard, SLU, Southern Swedish Forest Research Centre

Assistant supervisor: Jan-Eric Englund, SLU, Department of Biosystems and Technology

Examiner: Magnus Löf, SLU, Southern Swedish Forest Research Centre

Credits: 30 ECTS

Level: Advance level A2E

Course title: Master thesis in Forest Science

Course code: EX0984

Programme: Euroforester Master Programme SM001

Course coordinating dept: Southern Swedish Forest Research Centre

Place of publication: Alnarp

Year of publication: 2020

Keywords: **Hybrid walnut, NG23, NG38, fertilization, fork, future crop tree, nurse trees**

Swedish University of Agricultural Sciences

Southern Swedish Forest Research Centre

Publishing and archiving

Approved students' theses at SLU are published electronically. As a student, you have the copyright to your own work and need to approve the electronic publishing. If you check the box for **YES**, the full text (pdf file) and metadata will be visible and searchable online. If you check the box for **NO**, only the metadata and the abstract will be visiable and searchable online. Nevertheless, when the document is uploaded it will still be archived as a digital file.

If you are more than one author you all need to agree on a decision. You can find more information about publishing and archiving here: https://www.slu.se/en/subweb/library/publish-and-analyse/register-and-publish/agreement-for-publishing/

☒ YES, I/we hereby give permission to publish the present thesis in accordance with the SLU agreement regarding the transfer of the right to publish a work.

☐ NO, I/we do not give permission to publish the present work. The work will still be archived and its metadata and abstract will be visible and searchable.

Abstract

A crossbreeding between american black walnut and Persian walnut lead to the development of a hybrid walnut (*Juglans x intermedia*). In a field trial from southwest Sweden have been tested the impact of different levels of nurse trees, fertilization and weed control on the early growth of two hybrid walnut varieties: NG23 and NG38. In order to quantify those effects, a series of qualitative and quantitative traits have been analysed.

The results indicated that the hybrid NG38 has a more active change in height, compared to the other hybrid. Also, the mean total height reached by undamaged trees was higher for NG38 saplings.

When it comes to qualitative assessments, NG38 had a lower number of branches and the thickest branches had a larger diameter. The NG23 walnuts have had significantly more branches and significantly lower diameters of the thickest branch. Damages occurred on the leading shoot were significantly less frequent on NG23 walnuts. The frequency of future crop trees also differed significantly between the two varieties, NG23 walnuts accounting for two thirds of the total number.

Fertilization increased significantly the change in height, but also the frequency or the size of other less desirable characteristics. Trees that have been damaged at the top of the leading shoot during first growing season, turned into forked trees if fertilized. The number of branches and the diameter of branches were significantly larger on fertilised trees.

Companion nurse trees influenced significantly and negatively the development of the walnuts.

Considering these findings, can be concluded that both hybrids can establish and grow well in southwestern Sweden during juvenile stages, but in order to make unquestionable recommendations regarding long term management, more observations are needed.

Keywords: Hybrid walnut, NG23, NG38, fertilization, fork, future crop tree, nurse trees

Popular science summary

Nucul comun (*Juglans regia L.)* și nucul negru american (*Juglans nigra L.)* sunt specii apreciate în industriile producătoare de mobilă și furnir. În ciuda lemnului foarte valoros, nucul comun datorită selecției in vederea producției de fructe și a temperamentului pronunțat de lumină, nu produce un volum foarte mare de lemn utilizabil. Nucul negru american, pe de altă parte datorită dominanței apicale, dă dovadă de o capacitate crescută de a produce lemn prelucrabil. Într-o încercare de a combina caracteristicile celor doua specii, în 1977 într-o pepinieră din Franța a luat naștere *Juglans x intermedia,* sau nucul hibrid. Acesta demonstrează o creștere care o depășește pe a ambilor părinți, fiind în același timp mai rezistent la boli, dăunători și înghețuri târzii.

Într-un experiment înființat în sud-vestul Suediei au fost testate două varietăți, NG23 și NG38. NG38 a înregistrat o înălțime totală medie de 3,4 m la sfârșitul a cinci sezoane de vegetație. Numărul semnificativ mai mare de crengi, precum și diametrul mai mare al celei mai groase crengi fac din acest hibrid o opțiune mai puțin dorită când vine vorba de plantații înființate cu scopul de a produce lemn de înaltă calitate. Numărul de puieți care au înregistrat vătămări ale lujerului terminal a fost mai mare în cazul acestei varietăți. De cealaltă parte, NG23 a dovedt o rezistență sporită la factorii care au produs pagube în rândul puieților de NG38, numărul acestora fiind semnificativ mai mic. De asemenea, cel mai mare număr de puieți selecționați ca potențiali arbori de viitor au fost NG23.

Fertilizarea a dovedit a avea și avantaje și dezavantaje. Înalțimea medie afost semnficativ și pozitiv influențată de acest tratament. Puieții fertilizați au avut o rată a înfurcirilor semnificativ mai mare, comparativ cu puieții nefertilizați, iar numărul de crengi și diametrul mediu al celei mai groase crengi a fost mai mare la puieții care au primit îngrășământ.

Prezența speciei însoțitoare de plop s-a dovedit a fi detrimenntală în creșterea și dezvoltarea puieților de nuc hibrid. Creșterea mai rapidă a plopilor, precum și concurența pentru resursele de apă din sol, au condus la o înălțime totală medie semnificativ mai mică a nucilor acompaniați de puieții de plop.

Acest experiment a demonstrat că rezulate promițătoare pot fi obținute de către ambii hibrizi. În timp ce NG38 înregistrează o creștere activă în stadiul juvenil, expusă înghețurilor timpurii (și târzii), NG23 etalează o sensibilitate mai redusă și un trunchi de o calitate superioară. Pentru a concluziona care dintre hibrizi și care tratament este optim pentru a produce lemn de înaltă calitate, cercetări ale modului de dezvoltare în stadiile următoare de creștere sunt necesare.

Table of contents

List of tables

List of figures

1. Introduction

Persian walnut

Juglans regia L. is a tree species known under many different names, such as Persian walnut, English walnut, common walnut, or just walnut *(Aradhya et al. 2007).* The appellative ’’Persian’’ refers to its natural range or main origin in Asia (*Fig. 1*). However, walnut was also present in glacial refugia in the Balkans and central Europe. The main expansion of walnut throughout north and central Europe was most likely the result of walnut's use and dispersion from ancient Greece (*Pollegeoni et al. 2017*). Nowadays, the chief purpose of walnut plantations is still fruit production while timber comes as a by-product (*Bernard et al. 2017*).

Besides alimentary value, the good technical and aesthetic properties of the wood make this species a valuable timber producer appreciated by veneer and furniture industry (*Coelho et al. 2008*). Among European broadleaved tree species it is one of the most valued and consistently demanded, mostly by furniture and veneer industry where is sold for high prices (up to 2000 €/m^3). Walnut for gun stocks is also in high demand, mainly the special burl wood (or “radica di noce” in Italian) that fetches very high prices.

The general interest in walnut timber started to decrease with increasing availability of tropical hardwoods. Consequently, walnut has been little and infrequently planted, especially as a forest species. Some consumers are aware that usage of tropical timber may contribute to deforestation and as a result, they could become reluctant when comes to tropical timber purchases. Even if not, with a decrease of tropical hardwood supply (e.g., Madagascar ebony, rosewoods, https://cites.org/eng/app/appendices.php), walnut might be in the future in greater demand. What still makes the walnut to be overlooked by foresters, is the slow growth rate and relatively long rotation periods and also its reputation of being “site demanding”, “frost sensitive” and “of poor stem form” (*Hemmery, 2000*).

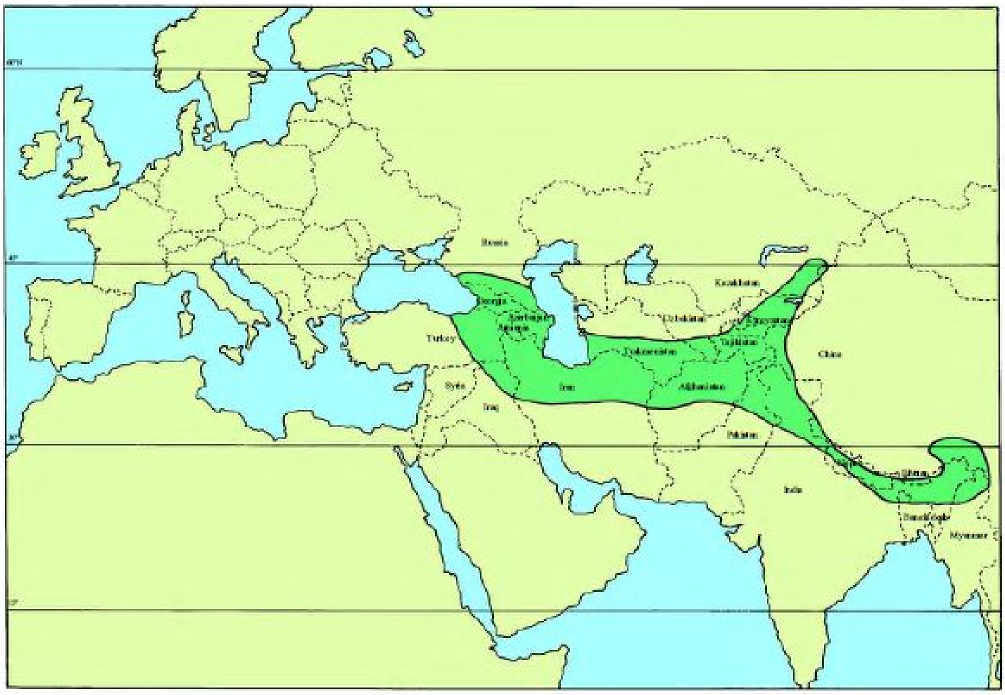


Figure 1. Natural range of Persian walnut

(McGranahan and Leslie 1991, in Hemmery 2000)

Black walnut

Due to the cultivation peculiarities of *J. regia*, in some cases attention was shifted towards other members of *Juglans* genus, such as black walnut (*Juglans nigra* L.) which is a non-native tree species in Europe (*Aradhya et al. 2007*) (*Fig. 2*). Desired characteristics such as better stem shape, limited phototropism, stronger apical dominance and temporary tolerance of stagnant water (*Coelho et al. 2008*) has made it a preferred species for high quality timber plantations in countries like Romania (*Nicolescu, 1998*), Great Britain (*Russell&Hemmery, 2004*) and Czech Republic (*Šálek&Hejcmanová, 2011*).

Figure 2. Natural range of black walnut
(Williams, 1990)

Hybrid walnut

The introduction of *Juglans x intermedia* was made some decades ago (1977), when interspecific hybrid progenies had been created specifically for timber production (*Germain,1989*). The crossing (*J. nigra* ♀ *x J. regia* ♂) was (and is) done in open pollinated seed orchards in France, between a high performance black walnut clone, surrounded by Persian walnut pollinator trees (*Fady et al. 2003*). Two most common hybrids between black walnut and Persian walnut are NG23 and NG38 and as the acronym suggests, the mother tree was *J. nigra*. The acronym "NG" stands for *nigra* (from *Juglans nigra* L.) indicating the mother tree, while the two digits indicate the tree number (location) in the orchard. Of course there are other hybrids and crossings (e.g. *J. major x J. regia*), but these two mentioned varieties are more commonly used and also addressed in this research.

J. intermedia combines the good stem shape and apical dominance of black walnut with the wind tolerance and valuable timber of Persian walnut (*Coelho et al. 2008*). The hybrids are more vigorous the first years after planting, as compared to common walnut, having at the same time at stronger apical dominance (Table 1.). Moreover, hybrids have a higher resistance to diseases (*Coelho et al. 2008*) and tolerate late spring frosts better than the parents (*Charrier et al. 2011*). Overall, the *intermedia* hybrid is a good compromise between growth rate and resilience to damaging factors, and its management is not particularly problematic, as long as its site and climatic conditions are fulfilled.

Table 1. Main characteristics of interest in walnuts plantation establishment

	Water requirements	Sensitivity to temporarily stagnant water	Active limestone sensitivity	Wind sensitivity	Drought sensitivity	Phototropism
Persian walnut	High	High	Low-Medium	Medium	Low-Medium	High
Black walnut	High	Low-Medium	Medium	High	Medium-High	Low-Medium
Hybrid walnut	High	Medium	Low	Medium	Low-Medium	Medium

Establishment of hybrid walnut

The hybrid might prove superior growth capacity, but to fully exhibit its potential certain conditions should be fulfilled. Optimum edaphic conditions are deep, fertile, well drained soils, with pH values between 5.5 and 8.5 (hybrid walnut tolerates active limestone), while pessimum development and survival is on clayey and sandy soils. Regarding temperature requirements hybrid walnut thrives in areas with mean annual temperatures between 9.5 and 12 degrees, depending on walnut variety (NG23 is better suited to colder areas). The optimal precipitation regime is generally over 800 mm/year, recorded as rain fall (*Mohni et al. 2009, Coelho et al. 2008, Moya et al. 2019*). After choosing the 'right' hybrid for the 'right' site conditions, the next important step is related to establishment practices and tending operations.

It is known that walnuts have a higher sensibility to wind compared to other species (*Heiligmann &Schneider, 1974; Heiligmann&Schneider, 1975; Ashby et al. 1979*) and so the *J. ×intermedia* hybrid. Despite its higher frost tolerance, hybrid walnut may also get affected, especially unlignified shoots and recently flushed foliage.

Beside fertilization, mulching and chemical weed control, more sources confirm the advantages of interplanting the walnut with other tree/shrub species. They key aspects are related with the N-fixation capacity of certain shrub species (*Elaeagnus umbellata* Thunb., alder species) and with the favourable micro-climate created by these (*Fady et al. 2003;Clark et al, 2008; Pelleri et al. 2013; Moya et al. 2019*).

Aim and research questions

When cultivating newly introduced tree species, or hybrids, it is important to find out what are the optimum and limiting conditions for their growth. The field experiment was established in 2015 (*Skovsgaard et al. 2015*) on a site with large variation in site conditions. The chosen varieties of hybrid walnut are NG23 and NG38. These are compared in terms of survival, early growth and stem quality. Furthermore, the influence of presence and absence of companion nurse trees and nurse shrubs is investigated. The effects of different levels of fertilization and weed control on the development of the hybrids is also tested.

By analyzing data collected during five growing seasons, and by reviewing relevant literature for supporting or contradicting evidence, it is the purpose of this work to answer following questions:

- Which of the two hybrids is better suited for cultivation in southwest Sweden?
- What treatments encourage a good stem development in the early stage? What treatments don't influence the development, or influence it in a less desirable way and should be therefore avoided?
- Do differences in growth rate between hybrids influence the quality of the stem?

.

2. Materials and methods

Trees from the experimental plot have been measured and outcomes have been compared with results from reviewed literature. The visits to field trials in the UK and Denmark has to be mentioned as another source of information in the elaboration of this project.

The experiment is located in southwestern part of Sweden (northwest of Västra Karup, Båstad municipality) and was established in 2015 on former agricultural land (Table 2.). More details about the experiment are provided in the establishment report (*Skovsgaard et al. 2015).*

Table 2. Location of the experiments

Code	Country	County	Location	coordinates	Altitude
J-01	Sweden	Skåne	Västra Karup, Påarp	56.4166° N, 12.7192° E	≈ 90 m ASL (WGS84)

The area of the field trial is divided into two separate, nearby sites (I and II) and each site is further separated into four blocks (*Fig. 3*). Considering the design and layout differences between the two sites, the word “blocks” is used onwards even if it is not statistical blocks defined in literature (*Hinkelmann&Kempthorne, 1994*). This term is used with the meaning of “geographical blocks”.

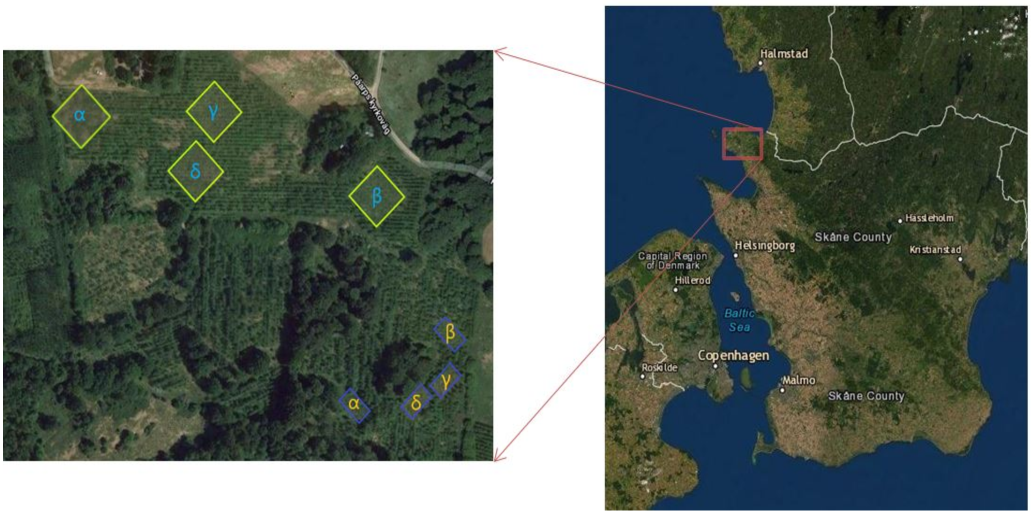


Figure 3. Satellite map and experimental layout of the experiment

(https://satellites.pro//Sweden_map#56.416658,12.719282,17 – accessed 16.03.2020)

Prior to plantation, soil samples from central part of each of the plots have been analysed and an overview of characteristics of interest can be seen in *Table 3.*

The values of soil variables are considered representative both for smaller and larger blocks. For site I, they are representative because of smaller area of the blocks, and of lower variation of soil conditions within respective area. For site II, because of the higher elevation which determines a relative homogeneity in site conditions.

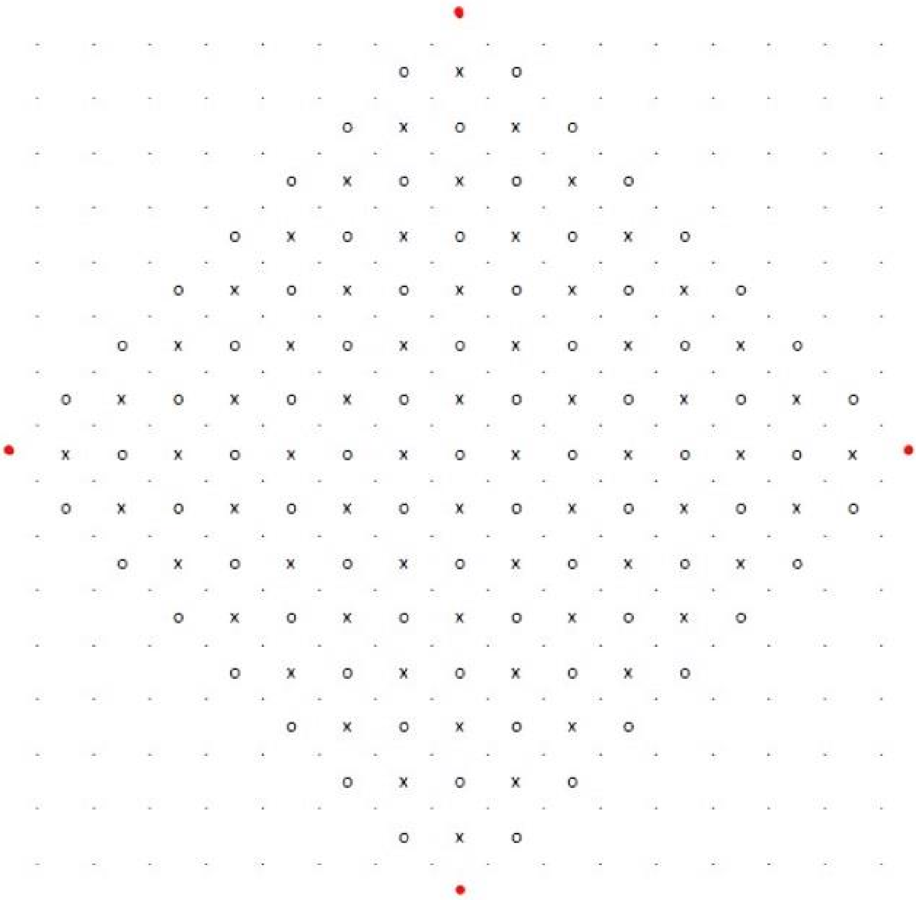
Table 3. Soil characteristics in 2015 across the experiment (*Skovsgaard et al. 2015)*

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	8	8	8	10	8	8.5	5.5
Silt (2-63 μm, %)	29	21	23	24	29	27	28,5	41
Sand (63-2000 μm, %)	62	71	69	68	61	65	63	53.5
pH ($CaCl_2$)	4.5	4.6	5.1	4.7	5	4.4	6	6.3
C/N	11.6	9.4	11.3	10	12.3	11.5	8.3	11.9
CEC (meq/100 g)	9.9	8.6	7.9	8.4	14.8	10	16.6	28.3
BS (%)	14.1	29.1	43	25	48.6	20	91.4	98.8

The hybrid walnut seedlings have been planted in a square pattern at a distance of approximately 4.25 x 4.25 m. Each walnut was planted at a 45º angle to poplar (*Populus trichocarpa* Torr. & A.Gray) nurses rows. The spacing of poplar nurse trees is 3x3 m and in blocks without nurse trees they have been removed. Autumn olive nurse shrubs have been planted in a similar pattern as walnuts, at the crossings of diagonals between poplar rows (*Fig. 4*). In those blocks where both nurses are present, autumn olives in the row are interleaved with nurse trees.

The distance between a nurse shrub and a neighbouring poplar is 2.12 m, same distance being measured between a walnut tree and a nurse shrub in its proximity.

a)



b)

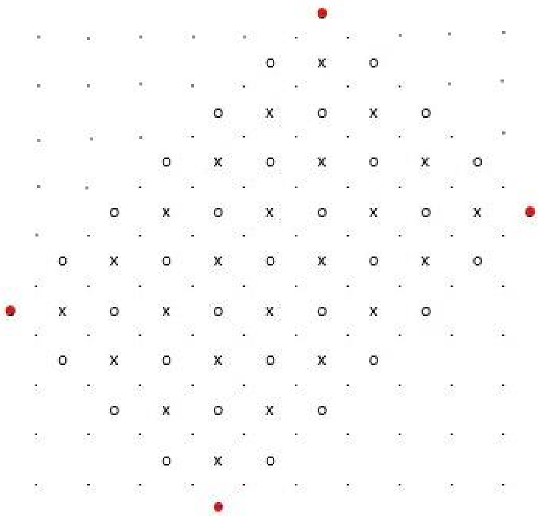


Figure 4. Spatial distribution of the δ blocks

a) δ large; b) δ small, with a combination of autumn olive (o) and western balsam poplar (·). Walnut trees are marked with (x) and nurse shrubs in block's corners with (●)

(Modified from Skovsgaard et al. 2015)

In order to test the nurse's effect, four different combinations of nurse shrubs (Shrubs) and nurse trees (Trees) have been tested in geographically separate blocks (*Table 4.*). Each combination was replicated twice: once in large blocks and once in small blocks. To remove the edge effects, the blocks were surrounded by a buffer area with nurse trees or without (as inside the block).

Table 4. Treatment differences between blocks (*Skovsgaard et al. 2015)*

Block	Nurse trees	Nurse shrubs
α	No nurse trees	No nurse shrubs
β	No nurse trees	Autumn olive
γ	Western balsam poplar	No nurse shrubs
δ	Western balsam poplar	Autumn olive

Within each block (Block), the treatments are defined as a combination of walnut variety (Variety), weed control (Weed) and fertilization (Fertilization). Two hybrids were tested in this experiment (*Table 5.*). It has to be mentioned that NG38 seedlings delivered for planting were in the 80-100 cm height class, and NG23 transplants were in the 60-80 cm class. Weed control treatments consisted in application of glyphosate, on an 80 cm radius around the tree (2 m^2). For fertilization, the chosen dose of 25 g N per tree was considered to be optimum, as indicated by *Goodman et al. 2014*. Another experiment testing hybrid walnut in Denmark, indicated that a high amount of fertilizers (<100 g N) kills the walnuts.

Table 5. Overview of treatments within the blocks (*Skovsgaard et al. 2015)*

Treatment	Walnut variety	Weed control	Fertilization
A	NG23	No weed control	No fertilization
B	NG23	No weed control	25 g N
C	NG23	Glyphosate	No fertilization
D	NG23	Glyphosate	25 g N

E	NG38	No weed control	No fertilization
F	NG38	No weed control	25 g N
G	NG38	Glyphosate	No fertilization
H	NG38	Glyphosate	25 g N

The large blocks containing 64 trees have been installed in a 2^3 factorial design with the treatment levels (*Table 5.).* There, each treatment was replicated eight times in an 8 x 8 Latin square (*Figure 5. a)*). For small blocks, the combination of treatments have been replicated three times, and have been randomly distributed within the block (*Figure 5. b)*).

a)

G	C	H	F	D	E	B	A
F	E	B	G	A	C	H	D
E	G	D	C	B	F	A	H
D	H	G	A	E	B	F	C
A	B	F	D	C	H	G	E
C	F	A	E	H	G	D	B
H	A	C	B	G	D	E	F
B	D	E	H	F	A	C	G

b)

C	E	C	B	F	E
H	A	H	F	D	E
D	G	F	G	B	A
G	C	A	F	D	B

Figure 5. Overview of treatments within the blocks

a) δ large and b) δ small
(Modified from Skovsgaard et al. 2015*)*

2.1. Field measurements

Measurements and assessments of different parameters were carried out. Initial measurements (2015-2017) of walnut seedlings' height and diameter at breast height (DBH) have been supplemented in 2020 with a series of "quality" assessments.

Forking occurrence was noted when the forking branches were of similar diameter and were inserted in the stem at the same height. Therefore, as part of the field inventory, forking occurrence, forking height and forking angle have been recorded, and as for "knottiness" - thickest branch angle, thickest branch diameter and height of insertion in the stem. Also, a total number of branches per stem and damages of the top bud which could lead to a poor stem shape have been noted.

The height in spring 2020 (autumn 2019) was measured at the highest living point, using the mEssfix measuring rod. To identify the top of the tree in spring 2019 (autumn 2018), a tracing down on the main stem measured in 2020 helped to identify the "scar" or the point where the apical bud flushed.

Angle of forking stems and angle of thickest branch was considered to be the angle determined by the central axis of the branch (fork) and the azimuth axis passing through the branch's (fork's) insertion point. The angle was measured with a half circle protractor, in centesimal degrees (*Fig. 6)*.

Figure 6. Measuring thickest branch angle

46 degrees. Red line represents the central axis of the branch.

Photo: Original

For diameter measurements of branches, forks and stems was used a digital caliper. To ensure a higher accuracy and consistency of measurements, each measurement was done twice (cross calipering) and the mean value was rounded to nearest unity (mm) (*Fig. 7*).

a)   b)

c) 

Figure 7. Measuring stem diameter

(a) above and (b) below thickest branch. Diameter of the thickest branch (c). Can be noticed the influence of branch on stem diameter below the thickest branch (b).

Photo: Original

To measure the height of the fork or of the thickest branch, a foldable ruler was fixed on a mEssfix telescopic measuring rod (*Fig. 8*). For branches or forks at a height lower than 1,53 m, readings were done on the foldable ruler, while for heights over 1,53 m the telescopic measuring rod was used.

a)

b)

Figure 8. Measuring thickest branch height and height to the forking point.

(a) thickest branch height– 215 cm, and (b) height to the forking point - 112 cm

Photo: Original

To analyze whether there is any difference between walnut types in terms of branching, or if treatments have any influence on it, for each stem was recorded the number of branches over 3 cm in length. This value represents the length of the shortest branch observed. If the inferior threshold would be considered at 2 cm length, the counted number of branches would be the same. If a higher value would be chosen (5 cm), then a certain number of branches would be omitted. Only branches emerging from the stem have been counted, as they are the ones which are likely to generate knots in the wood.

Regarding data filtering, each individual seedling was attributed to one of these groups: forking trees, multi-stem (re-sprouts) trees and single stem trees. Forking trees are in a separate group than multi stem seedlings, as stem is branching at >50 cm from the ground. Unlike forking, the tendency to generate more than one stem appears closer to ground level, usually up to 10 cm.

Further, in order to assess survival rate each tree was classified as being dead or alive, based on the presence of green buds, or on cambial activity. For trees with no clear signs of vegetation, the condition was verified by making a small incision in the bark. For two transplants in the experiment, there are some reasonable doubts about their status and they were omitted from all analyses.

In 2020 all trees with dieback, or damages of the top caused by various factors have been noted.

From living and single stem trees, were chosen “Future crop trees”. This subgroup comprised only the trees appreciated to hold the highest potential to produce timber of high quality and value. Future crop trees were separated in three classes, noted with I, II, III. The difference between these classes is mainly in terms of height at the moment of measurement and height change during last growing season, but a series of qualitative traits such as stem straightness and the number of branches have also been considered.

- Class I - height > 2,1 m in spring 2020 and height change > 50 cm since spring 2019. No damages, no bending, no tilting
- Class II - height > 2,1 m in spring 2020 or height change > 50 cm since spring 2019. Damages accepted, stem is bending or tilting
- Class III - height < 2,1 m in spring 2020 or height change < 50 cm. No damages, no bending, no tilting

2.2. Data computation and analyses

Data was analysed in R version 3.5.1 (2018-07-02). Noteworthy that in this program the interactions between factors are marked with ’’*’’ symbol.

A series of tests and analysis have been performed, depending on investigated parameter. For binomial variables (e.g. survival, forking, damaged top), the optimal solution was obtained running a chi-square test. For the other variables, the parametrical test ANOVA was used to identify significant factors, their level of significance as well as the differences between mean values of it. In addition to ANOVA, a stepwise backwards elimination of least significant factors contributed to the final results of the analysis.

The multi-stem trees have been eliminated from the analysis. One of the reasons for this step was the difficulty of cross calipering their stems. Trees with an uncertain condition have not been considered for the test as they might skew the results and provide inaccurate estimates, thus, two transplants were omitted from all analyses as their status was unclear.

The succession of steps that have been followed, as well as important details that have been considered for the analysis, are mentioned accordingly for each variable in the following paragraphs.

The percentage difference between total number of planted trees and the dead ones was considered the *Survival Rate* for the given period of 5 years. An analysis of factors influencing the mortality, was not considered to provide reliable results because of the low number of values.

Frequency of forking and damaged trees

Prior to the analysis of forking trees a data filtering was done, to remove dead trees, and multi-stem ones. For a number of 40 forking trees, was also tested to what extent previously recorded damages (2015-2017) had an effect on the forking frequency. Effects of Trees were considered, as walnut seedlings have been under their influence during the most sensitive development stage.

It was also tested to what extent the top damages were related to site fertility and location (sheltered/exposed), and to Variety (NG23, NG38).

Forking height

The model for the fixed effects in the analysis, using Block as random factor, was (with the notation from the package "lmer" in R):

$$\textit{Forking height} = \textit{Trees} + \textit{Variety} * \textit{Fertilization} + (1|\textit{Block})$$

After backwards elimination, the analysis of ''raw'' forking height values indicated the significant effect of Variety. It was also indicated that damages occurred during first vegetation season after plantation were the causal effect of an increased forking tendency. Considering the confounding effect of Variety, with the differences in height at the moment of planting, other alternatives were considered.

Therefore, in an attempt to rectify this inconvenience, the difference between forking height and the height in autumn 2015 was analyzed. But in some cases the dieback was very severe. This reduced the height of the highest living point (after dieback), below the height of seedlings in autumn 2015. Thus, the differences between the two heights came out negative and the results of this analysis are not reported.

Consequently, the next step was to analyze the coefficients between forking height and height in the autumn 2015. In other words, the forking height was divided by the height of walnuts in autumn. These coefficients had subunit values, but positive and therefore this was the analyzed data set.

Forking angle

In order to test only for the aforementioned effects, the random effect of Block was part of the model, to exclude potential influences of the site.

Height change

Was calculated as the difference between heights values measured in two consecutive years.

Before the analysis, soil variables were screened, being considered possible covariates. Based on a simple linear regression, N and Silt were included as covariates.

In blocks with nurse shrubs as companion, the effects of the nurse bushes were not considered and Shrubs have been excluded from the model.

The last year when the influence of nurse trees was taken into account, was 2017. The reason behind this is that poplar trees have been cut in spring 2018. Consequently, the fixed effect of Trees was excluded from the analysis of height change in 2018 and 2019.

A number of 58 trees with undamaged top from the moment of planting until the moment of last measurement have been analyzed. A consequence of this reduction of the data for the analysis is the restriction of using the Latin square design. The undamaged trees were found in both sites, site I and site II which have a different experimental design. A drawback of this situation is that random effects occurred on certain rows, or columns in the Latin square (for site I) could not be specified in the model.

Considering these findings, it was decided to run a covariance analysis for undamaged trees, using the model:

*Height change = Covariates + Trees +Variety*Fertilization*

This model was applied both for undamaged trees since the moment of planting, and for damaged ones. It has to be mentioned that four trees which had damages occurring in 2020, have been included in the analysis of undamaged trees, as the height was not affected by those damages.

Diameter at breast height

This parameter was not analyzed for the entire five year period because of the lack of data from the previous years. A number of 225 single stem trees that reached the breast height in spring 2020 was considered for the analysis.

Thickest branch angle, thickest branch diameter and height, and number of branches

For each parameter, the same model was applied, containing *Trees+Variety*Fertilization* as main factors of influence. Though, after removal of least significant ones (one at a time) the model differed as reflected by the significant variables.

292 single-stem (no forking, no re-sprout) and living trees were considered only.

Future crop trees

A number of 54 trees showcasing high potential to turn into a high quality stem, depending on different variables was tested using a chi-square test.

3. Results

3.1. Survival rate

The overall rate of living trees at the end of five growing seasons was calculated to be 96.9%. The analysis show that survival did not significantly depended on any of the factors of interest. However, the recorded mortality was different between hybrids. Seven NG23 walnuts were dead, all with damages in at least one year since have been planted. The NG38 variety registered four dead trees and damages occurred during first vegetation season were noted only for one walnut.

3.2. Frequency of forking and frequency of trees with damaged leading shoot

The only significant factor for the forking frequency was Fertilization (χ^2 =6.430, p-value=0.011). Trees and Variety proved to have an insignificant effect on this variable, with a p-value of 0.676 and 0.736 respectively. Values of forking frequencies, as well as the share of the total number of trees are presented in *Table 6.*

For forked trees, damages occurred before bud burst in 2016 produced the most forking trees. Out of a total number of 40 forking trees, 15 have been damaged between flushing time in 2015 and flushing time in 2016. If it is to include trees with this type of damages, and those that have been damaged in subsequent years, the number raises to 28. The significance of this type of damages is supported by the results of chi-square test. (χ^2= 21.95, p-value = 0.001236).

Table 1. Forking frequency depending on fertilization levels

Fertilization	Forking		
	No	Yes	Total
25 g N	142	28	170
	42.8	8.4	51.2
No fertilization	150	12	162
	45.2	3.6	48.8
Total	292	40	332
	88.0	12.0	100

The frequency presented as number in top line, as frequency percent in bottom line.

The main factors that caused a higher occurrence of top damages are site conditions and Variety. Site's influence is supported by a χ^2 = 24.998 and a p-value <0.001, while Variety's effects by a χ^2 = 10.507 and a p-value = 0.001189.

From 339 trees, 54 were recorded as being damaged on the top of the terminal shoot (*Table 7.*). Out of the damaged walnuts, more than half of them were distributed across site comprising small blocks. Five years after planting, nearly 1/3 of the total number of trees planted there presented damages. Across the site comprising large blocks, the share and the number of damaged trees is smaller compared to the site containing small blocks. Over the area of large blocks, a higher number of trees have been planted, but despite this, only 11% of them are damaged. In large blocks are distributed 46% of the total number of damaged trees.

Table 2. Damages frequency depending on site

Site	Damage		
	No	Yes	Total
Large	225	25	250
	66.4	7.4	73.8
Small	60	29	89
	17.7	8.5	26.2
Total	285	54	339
	84.1	15.9	100

The frequency presented as number in top line, as frequency percent in bottom line.

Besides location, the walnut variety was also statistically significant in terms of influence on frequency of damaged trees. Out of the total number of 169 NG23 trees planted, 16 of them have had a damaged top. From 170 NG38 trees, 38 of them presented damages on the top (*Table 8.*).

Table 3. Damages frequency depending on walnut variety

Walnut type	Damage		
	No	Yes	Total
NG23	153	16	169
	45.1	4.7	49.8
NG38	132	38	170
	39	11.2	50.2
Total	285	54	339
	84.1	15.9	100

The frequency presented as number in top line, as frequency percent in bottom line.

3.3. Forking height

Initial analysis of means (ANOVA) indicated that Variety was the most influential factor, with a p-value <0.001 **.**

The analysis of differences between height of the fork and height in autumn 2015 did not revealed any significant effects of any of the factors.

An alike situation showed the analysis of coefficients. The influence of Fertilization (p-value= 0.09896) brought up no significant influence using the significance level 0.05.

3.4. Forking angle

Analysis of variance did not show any statistically significant effects, of any of the considered variables.

3.5. Height change

For change in height, first are going to be presented the effects of each of the factors, by year in a tabular format. For the undamaged trees, below *Table 9*, every factor is going to be presented more in depth.

Trees with undamaged leading shoot

Starting with the year by year analysis of the change in height, can be observed that site conditions play the most important role (*Table 9.)*.

The concentration of N was significant for the first three years of the trial, its effect beginning to diminish for height growth in 2018 and being insignificant in 2019. The proportion of the other soil variable (Silt) influenced the height significantly and negatively in 2018 and had a marginally significant (and negative) influence during the previous year.

Experimental factors do not follow a certain pattern of distribution. The difference in height-change response between blocks with or without nurse trees was significant only in the third year after planting. A clear significant effect of the walnut type was noticed only on the change in height that occurred during the growing season prior to last measurements. For the same year was recorded a significant interaction between Variety and Fertilization.

Even though there is not a certain pattern in the distribution of analysed variables, a general shift is observed from soil variables towards experimental factors with the passage of time.

Table 4. Effect of analysed variables on height change of undamaged trees

Year	Intercept	N	Silt	Trees	Variety	Fertilization	Variety* Fertilization	n	R^2
2015	8.51	0.0266 **						58	0.153 **
2016	17.01	0.0700 ***			-10.96 •	-17.77 ***		58	0.348 ***
2017	104.08	0.2583 ***	-2.4521 •	-17.46 *		-49.52 ***		58	0.598 ***
2018	80.37	0.0719 •	-2.4749 *					58	0.110 *
2019	47.35				92.90 ***		-72.90 *	58	0.305 ***

The value for each factor represents the estimate coefficient. N and Silt are continuous variables. For Trees is the difference between No nurse trees and Western balsam poplar, for Variety is the difference between NG38 and NG23 and for Fertilization is the difference between No fertilization and 25 g N

Levels of significance, based on ANOVA outputs are as follow: • represents a p-value < 0.10, * p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

To continue with each of the factors, the effects of soil variables are presented first. The N and Silt concentrations have had a significant effect. The higher N concentration and a more sheltered location in site II contributed to a mean total height of 368.6 cm. This value was significantly higher than the mean total height of 183.5 cm reached in site I. In the chart below *(Fig. 9 a))* can be seen the fluctuation of the mean changes in height over the years, on the two site conditions.

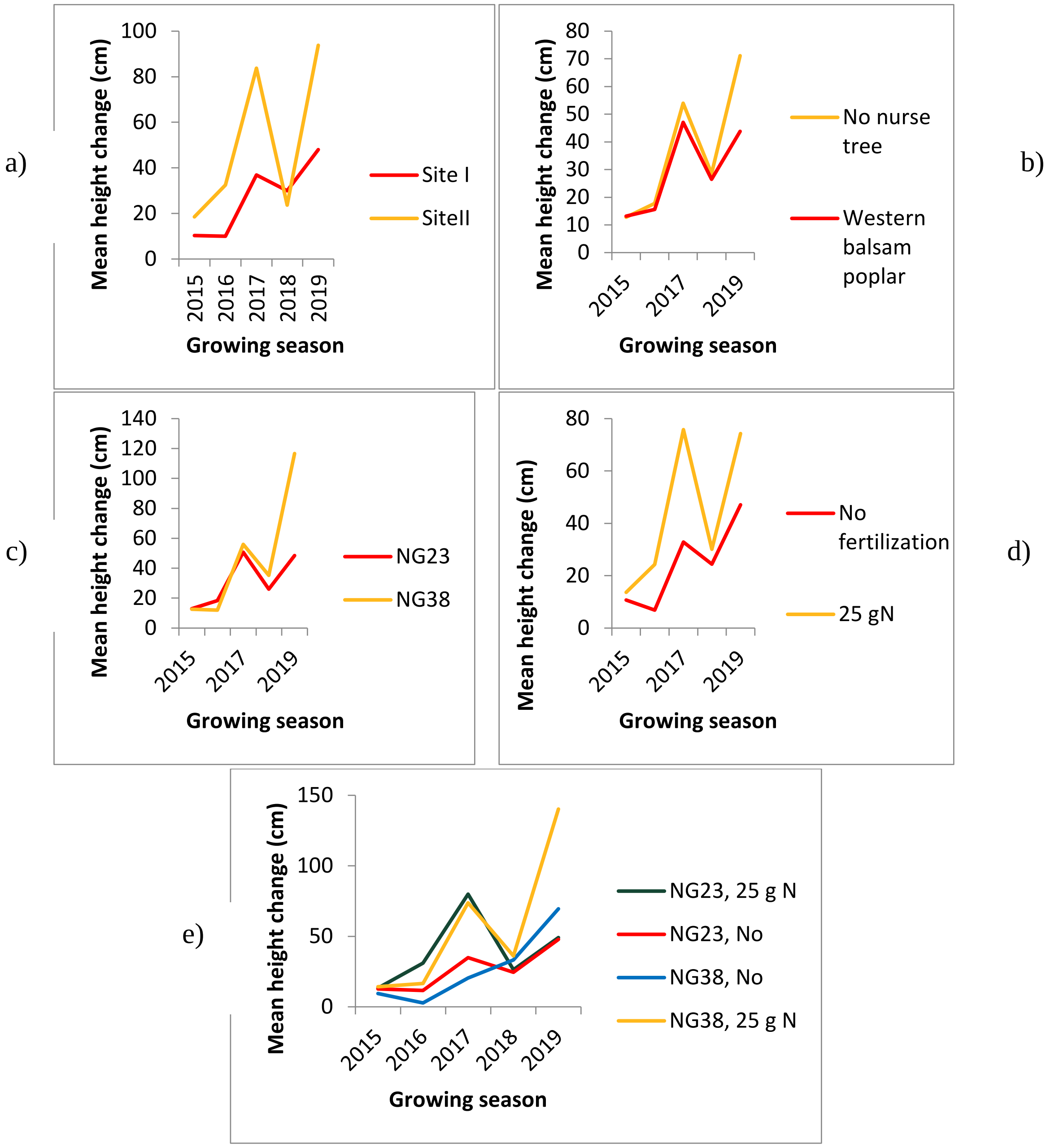


Figure 9. Mean height change with explanatory variables, by growing season

Moving on with the other investigated factors, can be observed that the influence of nurse trees on the height change was significant and negative. Mean total height reached by walnuts in autumn 2017 in blocks with trees as companion nurses was 178.7 cm. In blocks without nurse trees, walnut hybrids reached a mean total height of 191 cm. The difference increased in subsequent years (*Fig. 9 b)*), but as the poplars were removed from the stand in 2018 it cannot be accounted as the effect of presence/absence of nurse trees.

Variety had also a significant effect as the mean change in height was lower for NG23 compared to NG38. The mean value of total height in 2020 was 225.8 cm for NG23 and 342.2 cm for NG38. The total height change was also different between hybrids. After five growing seasons NG23 had a mean value of 156.6 cm while the hybrid NG38 had a mean value of 232.5 cm.

The year by year fluctuations are presented in *Fig. 9 c)* and can be seen that NG23 is showcasing a better height change only during first two vegetation seasons, later on being outcompeted by NG38.

The significant influence of Fertilization is illustrated in *Fig. 9 d)* where the mean values of the height change response over the five growing seasons are represented, both for fertilized and unfertilized walnuts. It can be noticed how the change in height of the fertilized trees follows an ascending trend from the very first growing season, while for unfertilized transplants it takes one more year until they register a positive height change.

In *Fig. 9 e)* is showcased the significant interaction (*Table 9.)* between Variety and Fertilization. Even though the difference between NG38 and NG23 was not significant in terms of height change for most of the years, in 2019 NG38 had a change in height substantially higher than NG23. Can be also noticed that even unfertilized NG38 transplants change their height positively, at a higher rate than fertilized NG23.

An additional remark is related to the positive and higher change in height of NG23 walnuts during first three years, as compared to NG38 trees. Albeit the height change of NG23 transplants is vigorous for the first three years, by 2020 is outcompeted by NG38 saplings.

At the end of five vegetation seasons the inter-hybrid differences in terms of height change are considerable, fertilization treatments enlarging only the intra-hybrid height change differences.

Trees with damaged leading shoot

Trees with dieback at the leader shoot in one or more years after planting, in following paragraphs referred to as “damaged trees”, had a mean total height in 2020 of 183.5 cm in large blocks and 356.9 cm in small blocks.

There were no differences between the mean total height of undamaged and damaged trees growing in large blocks. Insignificant differences (9.1 cm) were found between undamaged and damaged trees located in small blocks.

No significant differences were found between the height change in 2015, 2016, 2017 and 2019. A marginally significant difference between the change in height of undamaged and of damaged trees was found in 2018 (p-value=0.0605, estimate coefficient=6.2 cm, multiple R^2=0.015).

The analysis indicated that soil variables influenced significantly the height change response during four vegetation seasons. The difference between these factors and Fertilization lays in the temporal distribution of their effects (*Table 10.).* While Silt had a negative and significant influence during the last four years of the trial period, Fertilization had a significantly and positive effect during first four years. N concentration also exhibited significant control of the growth, but without continuity over the years.

The effect of Trees is indicated as being significant only for the change in height that occurred during 2017. Variety had a barely significant influence in 2017, while its effect on growth in 2018 was significant. The combined effects of the hybrids and fertilization (Variety*Fertilization) was significant only in 2018.

For the damaged trees, the transition towards experimental variables is more visible, with exception of year 2019.

Table 5. Effect of analysed variables on height change of damaged trees

Year	Intercept	N	Silt	Trees	Variety	Fertilization	Variety* Fertilization	n	R^2
2015	10.29	0.0202 ***				-2.98 ***		223	0.126 ***
2016	41.14	0.1537 ***	-1.7220 **			-12.55 ***		202	0.428 ***
2017	143.79	0.4615 ***	-5.4246 ***	-15.07 ***	9.20 •	-42.73 ***		216	0.592 ***
2018	54.61		-1.0569 **		-8.71 *	-14.55 **	21.86 ***	176	0.112 ***
2019	149.96	0.1900 ***	-5.0759 **					224	0.050 **

The value for each factor represents the estimate coefficient. N and Silt are continuous variables. For Trees is the difference between No nurse trees and Western balsam poplar, for Variety is the difference between NG38 and NG23 and for Fertilization is the difference between No fertilization and 25 g N

Levels of significance, based on ANOVA outputs are as follow: • represents a p-value < 0.10, * p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001.

3.6. Diameter at breast height

Fertilization have had statistically significant influence on the DBH (p-value <0.001). Trees growing on fertilized spots had a mean diameter of 28.4 mm, being 8.7 mm larger than mean diameter of unfertilized walnuts, which was 19.7 mm. The difference between fertilized and unfertilized trees indicated in *Table 11*. shows a higher level of significance as compared to Variety.

The effect of Variety is also significant, with a p-value of 0.03709. NG38 had in 2020 a significantly larger diameter compared to NG23 hybrid. The estimated mean value indicated a difference of 3.5 mm between the two varieties, NG38 having a mean DBH of 25.8 mm and the NG23 hybrid 22.3 mm.

Table 6. Significance level of different factors for DBH

Intercept	Variety	Fertilization	n
26.60	3.5 *	-8.7 ***	225

The value for each factor represents the estimate coefficient. For Variety is the difference between NG38 and NG23 and for Fertilization is the difference between No fertilization and 25 g N.
Levels of significance, based on ANOVA outputs are as follow: • p-value less than 0.10, * p-value less than 0.05, ** p-value less than 0.01, *** p-value less than 0.001.

3.7. Thickest branch height

Was significantly dependent on fertilization application. The difference between the height of the thickest branch of fertilized walnuts, and the height of thickest branch of unfertilized ones was 16.9 cm (*Table 12.).*

Table 7. Significance level of different factors for thickest branch height

Intercept	Fertilization	n
110.84	-16.9 ***	292

The value for each factor represents the estimate coefficient. For Fertilization is the difference between No fertilization and 25 g N.
Levels of significance, based on ANOVA outputs are as follow: • p-value less than 0.10, * p-value less than 0.05, ** p-value less than 0.01, *** p-value less than 0.001.

3.8. Thickest branch diameter

Mean value of thickest branch diameter was 16.9 mm for NG23 and 18.9 mm for NG38. The diameter of thickest branch for unfertilized trees was 14.6 mm.

Fertilization treatments lead to a 45% larger diameter of the branch, as compared to No fertilization. The difference between mean diameter of thickest branch of fertilized trees and the mean diameter of trees that received no fertilizaton is 6.6 mm (*Table 13*.). Fertilized walnuts have had a mean diameter of the branch of 21.2 mm, while the mean value for unfertilized trees was 14.6 mm.

Table 8. Significance level of different factors for thickest branch diameter

Intercept	Variety	Fertilization	n
20.26	1.9 ***	-6.6 ***	292

The value for each factor represents the estimate coefficient. For Variety is the difference between NG38 and NG23 and for Fertilization is the difference between No fertilization and 25 g N.
Levels of significance, based on ANOVA outputs are as follow: • p-value less than 0.10, * p-value less than 0.05, ** p-value less than 0.01, *** p-value less than 0.001.

3.9. Thickest branch angle

Based on an alpha-value of 0.05, this variable was not influenced at a significant level by any of the analysed factors. Though, ANOVA displays the barely significant effect of Variety with a p-value=0.08195. The mean value for the angle of thickest branch is 36.6º for NG23 and 34.1º for NG38. The value of the estimate coefficient is 2.43.

3.10. Number of branches

The mean number of branches for NG23 was higher than for NG38 (10.5 versus 9.6). Fertilization with 25 g N showed a 50% increase in number of branches. In the control group, the average value of 7.9 was significantly lower than in fertilized one, for which were counted 12.3 branches on average.

Table 9. Significance level of different factors for the number of branches

Intercept	Variety	Fertilization	n
12.7	-0.9 *	-4.4 ***	292

The value for each factor represents the estimate coefficient. For Variety is the difference between NG38 and NG23 and for Fertilization is the difference between No fertilization and 25 g N.
Levels of significance, based on ANOVA outputs are as follow: • p-value less than 0.10, * p-value less than 0.05, ** p-value less than 0.01, *** p-value less than 0.001.

3.11. Future crop trees

The frequency of future crop trees was under the control of Variety. The number of NG38 walnuts was only one third of the assigned trees to be kept in the future. This represants only half of the number of NG23 trees (*Table 15*). The difference between hybrids was significant (χ^2=7.26, p-value = 0.007036), NG23 walnuts representing the highest proportion of potential crop trees (36 out of 54).

Table 10. Frequency of future crop trees depending on Variety

Walnut type	Future crop trees		
	No	Yes	Total
NG23	133	36	169
	39.2	10.6	49.8
NG38	152	18	170
	44.9	5.3	50.2
Total	285	54	339
	84.1	15.9	100

The frequency presented as number in top line, as frequency percent in bottom line.

4. Discussion

Survival rate

Five years after the establishment, the survival rate was as high as 96.9% and was not significantly dependent on analyzed factors. Even though, the recorded mortality was different between hybrids. Might be the case, as noted by (*Hemmery, 2000*) that the size of seedlings at the moment of planting is strongly correlated with later death. In the respective research was observed that dead trees were significantly smaller, both in terms of diameter and height. As presented by (*Skovsgaard et al. 2015*), NG23 transplants were in the height class 60-80 cm, while NG38 in 80-100 cm, so smaller size seedlings seem to be more prone to register higher mortality. However, this observation should be taken with care, as the sample of dead trees was very small.

Overall, the survival rate is in line with the ones observed across other experiments and supports the hypothesis that examined factors had no influence on it. In a black walnut plantation, *Bohanek&Groninger 2003* indicated a survival rate between 94 and 98%. The same authors concluded that survival is positively influenced by lower planting densities. Similar values of survival rates were recorded in a hybrid walnut trial in Great Britain by *Clark&Hemery, 2010*. In the respective experiment, five years after planting survival both for NG38 and NG23 had a 100% establishment success, confirming therefore the lack of influence of Variety. In another experiment from Great Britain *Hemery, 2000* reported no significant effects of treatments on the survival rate of the walnut seedlings but was recommended to plant seedling with a height of at least 60 cm. The insignificant effect of fertilization was specified in another black walnut plantation, where the survival rate was 90% regardless of treatments (*Jacobs et al. 2005*).

Considering other experiments involving walnut trials, there is an agreement upon the higher survival rate of the hybrids created for timber production, compared to Persian walnut, or other hybrids occurring naturally (*Fady et al. 2003; Clark&Hemery, 2010*).

Frequency of forking trees, forking height and frequency of damaged trees

The chi-square test indicated that Fertilization was the only factor of interest with a significant influence on the forking frequency. In addition to this, a significantly larger number of trees forked as a consequence of damages produced only between bud burst in 2015 and bud burst in 2016.

The formulated hypothesis trying to explain this situation was that increased nutrients uptake might determine the production of a large shoot which may be surprised unlignified by early autumn frosts. Next growing season, the response of the damaged tree would be to generate new shoots from sub-apical buds and if the buds are at the same height on the stem, a fork will occur.

The field trial indicated that walnut trees damaged during the first growing season, encouraged by Fertilization, will turn into forked trees. Forking tendency was reported to be favoured by fertilization not only for broadleaves but for conifers as well (*Espinoza, 2009*). It is thought to be the response of the tree, to shift the biomass production from the stem and direct it towards branches, with the increased availability of nutrients (*Goodman et al. 2010*). In the case of current research, it is clear that forking trees are dividing the resources between two branches, division triggered by damages occurred during the first vegetation season.

Special care at the moment of planting, the optimum dosage of fertilizer, fencing to prevent browsing damages are few of the measures that can be taken to avoid damages of the leading shoot and reduce the forking occurrence.

The limitation represented by the sample size of only 40 trees does not allow for an unquestionable conclusion regarding causal factors of forking. However, a high management intensity has been linked to a higher propensity to increase branches and stem deformities, including stem forking (*Espinoza, 2009*).

The same hypothesis, claiming that large availability of nutrients will make the shoot more prone to damages, was tested for damaged trees and the results support it only partly. It was indicated by the analysis that favourable growing conditions (site) increased significantly the number of trees damaged at the top. The highest number of walnuts with top damages was recorded in small blocks, where the concentration of N as well as of other minerals was higher than in large blocks. The part that does not support the hypothesis is the lack of a significant influence of Fertilization, the frequency of damages not depending on this treatment.

The investigation in literature did not provide an unequivocally answer in regards to which of the two hybrids performs better when it comes to top damages. Most of the publicly available information about hybrids' frost sensibility is coming from countries located on the European side of the Mediterranean basin. In spite of different climate conditions, compared to Baltic or Nordic countries, the experiences gained there after many years of trials, the availability of information as well as similarities between tested hybrids, pleaded for the inclusion of the respective information in the current research. Thus, two studies investigating cold resistance of walnuts in Central France concluded that

NG38 appeared particularly resistant to cold (*Poirier et al. 2004*), having the longest dormancy period and flushing the latest (*Charrier et al. 2011*). Research from Spain indicates that hybrids show a frost resistance that is in between black walnut and Persian Walnut (*Guàrdia et al. 2013a*). Another Spanish study reported that growth (DBH) of the hybrids was not correlated with a higher presence of frost damages (*Guàrdia et al. 2013b*). *Coelho et al. 2008* indicate that hybrids are flushing later and are therefore less prone to late frosts damages. The same authors mention that NG23 is better suited to colder areas, but “colder areas” probably refer to the Mediterranean countries. A more comprehensive study including trials in five countries from Europe, mentions that NG23 (and another hybrid) was the least affected by late spring frosts (<5% of the trees), as compared to Persian walnut (*Fady et al. 2003).* An interesting result was presented by *Díaz&Fernández-López, 2005* who concluded that among tested varieties, there was moderate genetic heritability to late frost damages

Height change

Firstly, few explanations will be presented, to provide a better understanding of the analysis and results. Secondly, the influence of different factors on the height change is going to be presented.

The height change analysis of undamaged trees is more relevant, as it is tested strictly for the growth of the leading shoot. Usually, the response of the trees with a damaged top is to produce a new shoot, from a sub-apical bud. This growth is generally more vigorous than that of the apical shoot. If all trees were analyzed together the result could be deceiving, because it would be analyzed the development of a side branch, not of the leading shoot. Moreover, if the aim of the plantation is to produce high-quality timber, it is less likely to select a tree with a stem crooked because of a side branch taking over.

Because of practical and economic reasons, no rhizology studies have been carried out. Therefore, the interaction in the rhizosphere between the roots of walnuts and the roots of the nurse shrubs could not be confirmed or infirmed. But because of the distant location from autumn olive bushes, it was hypothesized that the roots of the walnuts could not exploit the nitrogen-fixing capacity of the roots of the shrubs. It was also considered that the local climate determined by the nurse shrubs and the microclimate under the influence of nurse trees, cannot vary to a large extent. These were the main considerations that determined the omission of the fixed effect of Shrubs from the analysis.

Regarding the outcomes of the analysis, it can be observed a low value of R2 in s *Table 9* and *Table 10*. This means the fit of the model is not the best and there could be a couple of explanations for this. Firstly, the large year to year variation both in growing conditions and the response of the trees does not allow for a better prediction of the height change using the chosen model. Secondly, maybe other explanatory variables should be included to enhance the fit of the model.

In terms of site conditions, the higher elevation, the exposure to wind, as well as mesic site conditions of large blocks seems to be detrimental to a positive height change. A higher wind speeds lead to a higher transpiration rate, which correlated with the dry site conditions, will influence the water balance of the seedlings, generating water stress (*Heiligmann and Schneider, 1974; Heiligmann and Schneider, 1975; Ashby et al. 1979*).

On the other hand, small blocks in a more sheltered location, with a higher moisture content of the soil show a very strong, positive influence on the height change. The N concentration of soil samples taken in some of the blocks (delta small), was almost six-fold higher compared to large blocks and also contribute to the impressive total mean heights and mean changes in height.

Nurse companions are reported to have a beneficial effect on the growth and development of the main species, although the magnitude of the response usually depends on species and site conditions (*Moya et al. 2019*; *Clark et al. 2008*). In an experiment from northern Italy, the growth rate of walnuts could not be sustained over time, due to the competition of inter-planted poplars (*Pelleri et al. 2013*) In another trial in France the growth of walnut both in height and diameter was greater than in monocultures (*Becquey&Vidal, 2006*). It is important therefore the choice of nurses so that is matching the growth rate with one of the main species.

An interesting outcome is the significant effect of Trees, only in 2017. During the first two growing seasons, the walnut trees could have lower requirements for nutrients, water, and other resources. But as soon as their development started to take a faster pace, the competition with nurse trees might be an impediment to their growth. Probably this effect would have been until 2020 if poplars would have not been removed in 2018.

Despite a lower change in height, a number of 46 NG23 transplants were undamaged, while only 12 NG38 walnuts manage to grow without top damages. An interpretation of this situation could be that a small number of NG38 seedlings grew undamaged in spots with favourable conditions. There they reached larger heights, and this resulted in a skewed distribution of the heights. On the other hand, the higher number of undamaged trees indicates the NG23 hybrid copes better with a higher variability (including low fertility) of site conditions.

A literature review indicates that differences in growth rate and total height between the two hybrids have been observed in other field trials as well. In an experiment from Great Britain were found similar results, both in terms of total height values and height change. The difference between the total height of NG38 (318 cm) and NG23 (290 cm) was not found to be significant, but the change in height between these hybrids was statistically significant.

Also in Germany, one of the trials with different hybrids and provenances indicates that at the age of seven, NG38 performed the best in terms of total height (*Online reference 1*). The height of NG23 walnuts was lower, but the difference between the height of NG38 and the height of NG23 trees was not as large as in the current experiment.

Regarding the significant influence of Fertilization, few remarks can be made. For the fertilized trees the change in height follows an ascending trend from the very first growing season, while for unfertilized transplants it takes one more year until they register a positive height change. The conclusion is therefore that Fertilization may minimize transplantation shock by reducing nutrient stress while contributing to a significant increase in height change response (*Jacobs et al. 2008*). Even though it is very important the type of fertilizer, the amount (too large dosage kills the plants), as well as the way of administration, as was found across three black walnut experiments in the United States (*Jacobs&Seifert, 2004, Goodman et al. 2010*).

Despite the positive and encouraging tendency of fertilized walnut trees to grow significantly better, the chart and the analysis indicate their incapability to maintain a positive and consistent change in height for more than three years. During the 2019 growing season, the tree is changing the height at the same rate as in 2017. One possible explanation could be represented by the nutrients' leaching, as forewarn by *Jacobs&Seifert, 2004,* or by different partitioning of resources and shifting biomass production towards other parts of the plant (e.g. branches) (*Goodman et al. 2010*).

This hypothesis should be taken with care, as is not the aim of this research to investigate nutrients' uptake, and in order to clarify this situation, further research is required.

As mentioned previously, walnut transplants do dot transplant well and fertilization might reduce nutrients stress (*Jacobs et al. 2008*) and it might take a while until root to shoot ratio comes in balance (*Clark&Hemmery, 2010*). As presented in the establishment report (*Skovsgaard et al. 2015*) the seedlings delivered differed substantially (and significantly) by height: NG38 seedlings were in the 80-100 cm height class, while NG23 seedlings were in the 60-80 cm class. A larger root to stem ratio of NG23 might boost their height change for the first years, but as soon as NG38 seedlings establish and the root system is in balance with above-ground parts, they will change the height at a higher rate than NG23.

In regards to different analyses of undamaged and damaged trees, one might ask: if the mean total height and the height change from year to year do not vary significantly between the two categories, why to create two separate groups?

The aim to produce high-quality timber, from valuable broadleaved tree species, can be fulfilled only by promoting the individuals with the highest potential both in terms of qualitative and quantitative characteristics. A height change analysis, on two different levels of damages, indicated no significant differences in the yearly height change, nor in the mean total height after five growing seasons. What was indicated in turn, is the ratio of the number of damaged to undamaged trees, which was 233:58 in this experiment. It was also observed that the cohort of undamaged trees remained pretty stable along the trial period. From the initial number of 64 undamaged trees, only six were presenting damages or forking/re-sprout tendency by the spring of 2020. The injured walnuts, do not easily overcome the damages and tend to respond by producing new shoots from sub-apical buds, and this generally leads to forking. Albeit the height change does not vary significantly in comparison to undamaged trees, the stem form plays at least an equally important role in the production of valuable timber.

Based on these findings, it can be postulated that for the purpose of high-quality timber production, only undamaged trees should be the focal point of management actions, as they the highest chances to produce a quality bole.

Diameter at breast height

Considering the significant effect of Variety, one can ask whether it is the higher genetic potential of NG38, or it is the influence of a larger height of the same hybrid at the moment of planting. In spring 2015, delivered NG38 seedlings were in the 80-100 cm size class and NG23 transplants in 60-80 cm class. This definitely represented an advantage, as NG38 trees reached breast height. Considering the mean total height as well can be stated that NG38 has a better development in terms of height and diameter change as compared to NG23, at least during the first five years after establishment.

A discussion about the positive effect of fertilization treatments on the development of seedlings would be redundant, as the statistically significant influence of fertilizers' application was already discussed in *Height change* sub-chapter and is discussed at large in extant literature (*Ponder 1998, Jacobs&Seifert, 2004, Jacobs et al. 2005*). Just to summarize, fertilization treatments contributed significantly to the differentiation of trees in terms of DBH.

Thickest branch height, thickest branch diameter, thickest branch angle

As Variety was excluded from the model to remove the potential influence of different heights at the time of planting, Fertilization turned out to be the most influential factor, as indicated in *Table 12*. For fertilized saplings, the thickest branch was positioned higher than the thickest branch of unfertilized ones. This can be translated into a larger height of the stem clear of branches, which is a positive outcome in the context of high quality (and value) timber production.

Fertilization not only increases the height of the insertion for the thickest branch, but also the diameter of it.

Not part of the model, but strongly and positively correlated with thickest branch diameter, was the diameter of the stem below the thickest branch *(Fig. 10)*. The explanation for this is that the tree adapts its crown architecture to different environmental conditions, in a way that provides optimal resistance to destabilizing factors, but at the same time assures optimum uptake of resources *(Fig. 11)*. In other words, a tree with a thin stem will not be able to support the weight and the growth of a thicker branch, and a tree with a thick stem will need thicker branches, with more leaf biomass to support its development.

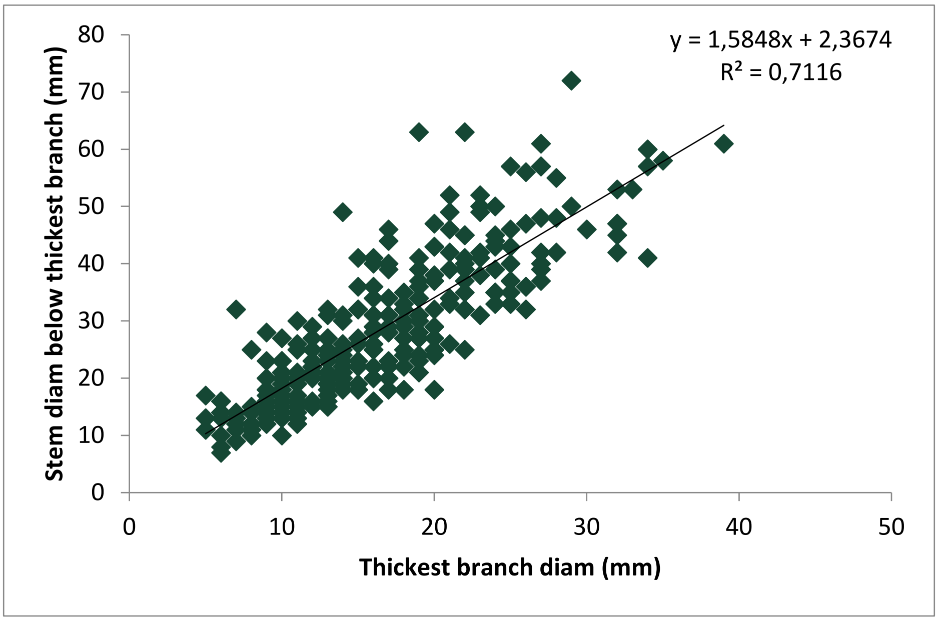
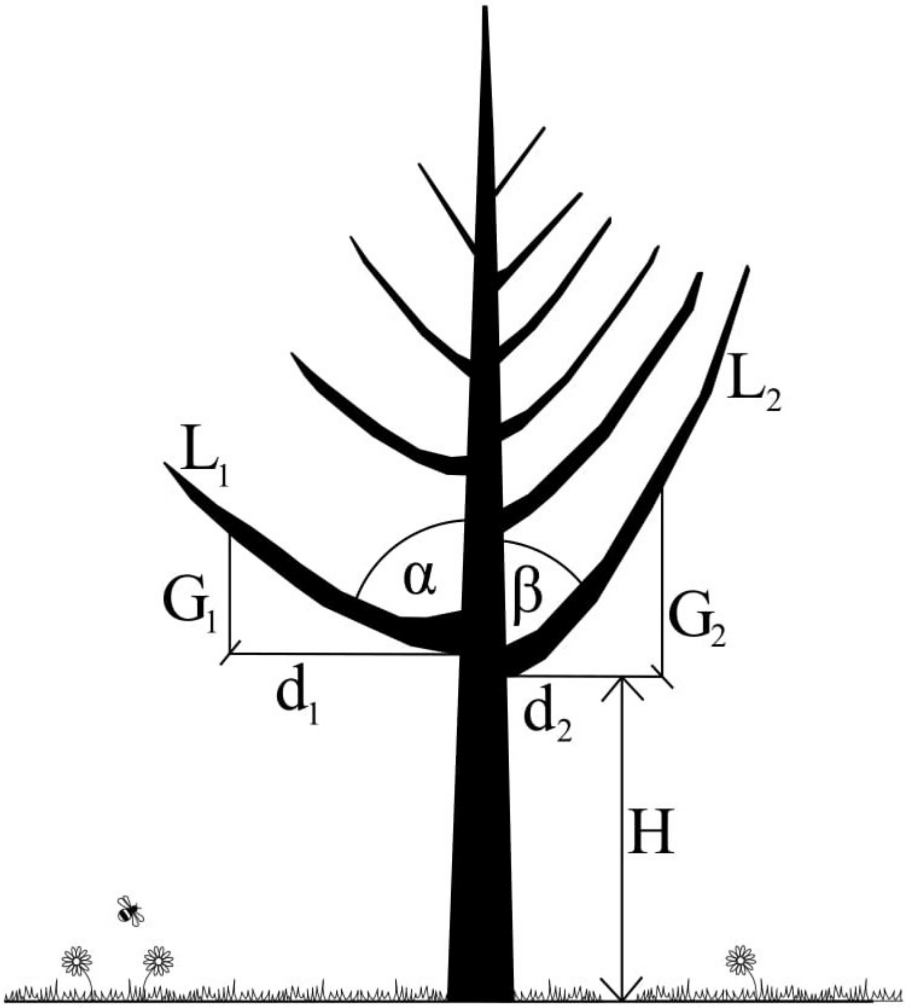


Figure 10. Correlation between stem and thickest branch diameter

In different studies, allometric equations describe the same strong correlation between branch diameter and stem diameter, but also between other characteristics. The wide majority of them describe different correlations, but mostly for coniferous species (*Mäkinen&Colin, 1998, Mäkinen&Hein, 2006, Weiskittel et al. 2007*). However, there have been found some researches investigating different correlations for broadleaved tree species. *Mäkinen, 2002* found out that the branch angle is dependent on sunlight exposure. The same author reported also that trees with a larger diameter will tend to develop branches with smaller angles (*Mäkinen et al. 2003*).



If it is assumed that all branches are at equilibrium, the principle of moments can be applied. At the Thickest branch height H, the walnut generates a counter clock-wise moment M2 to support the side branch $L_{2,}$ and a clock-wise moment M1 to support L1. Thus, M1=G1d1 and M2=G2d2. Assuming that branch L1 and L2 weight the same (G1=G2) have the same diameter and M1 and M2 have a certain threshold (the support to the branch at a certain height on the stem being limited). Due to the fact that the branch L2 is inserted at a smaller angle ß, the result is that the torque d2 of G2 is smaller than d1 of G1. Therefore, L2 can grow more than L1.

Figure 11. Smaller angle branches have higer growth potential (Modified from Pang, 2014)

When it comes to walnuts, particularly to hybrid walnuts, little was analysed in terms of branching habits. Few pieces of research have been found relevant for the topic and the main findings are compared with the current experiment. One of the reviewed studies shows that when grown in mixture with Italian alder, the walnuts tended to develop lower angle of insertion and fewer branches (*Mohni et al. 2009*). *Díaz&Fernández-López, 2005* indicated that walnuts families whose bud flushed earlier had more apical branches. In an experiment from Great Britain was found that walnuts growing in monocultures developed thicker branches than the stem (stem to branch ratio 1:1.2) (*Clark et al. 2008*). In the same experiment was observed that branches inserted to a very acute angle were breaking under their weight (Clark, personal comm.). If the problems posed by wind damages are to be counted, it is clear that branches growing to a steep angle are not desirable on walnuts' stems.

Fertilization seems to encourage a detrimental branching habit for high-value timber production. Trees that received 25 g of N tended to develop branches at higher points on the stem, and therefore a higher proportion of the stem will be clear of branches. But in the same time, encourages the development of thicker branches, which not only shift the biomass from the stem (*Goodman et al. 2010*) but might represent an issue when it comes to tending operations (e.g. pruning) (*Mohni et al. 2009*, *Moya et al. 2019*).

Number of branches

An increase in the number of branches was also noticed by *Goodman et al. 2010*, who reported that fertilization usually contributes to the development of thicker branches and in higher numbers, compared to control treatments.

With a difference of one branch (0,9) between the two hybrids, Variety exerted a significant effect as well. It was indicated that NG23 tends to branch out more than NG38. The mean number of branches for the two hybrids was 10.5 and 9.6 respectively. Albeit significant, the difference of only one branch between the two hybrids seems to be in line with the research by (*Díaz&Fernández-López, 2005*)who reported that the number of branches as well as the apical dominance was not correlated with the genetic variance of tested walnuts. Might be the case as well that even at an early stage, the hybrids start to exhibit different branching tendencies, as observed by (*Pang, 2014*) who mentioned that in black walnut clone trials the number of branches was best predicted by the clone. In another trial involving fruiting walnuts, there have also been discovered differences between tested varieties regarding the numbers of branches (*Solar et al. 2011*).

In conclusion, the statement that fertilization increases the number of branches (by 50% in the case of this study) is as pertinent as can be. On the other hand, the (significant) difference of only one branch between NG23 and NG38 as well as the observation made by (*Díaz&Fernández-López*, *2005*), does not allow for an unequivocally link between the hybrid and the number of branches.

Future crop trees

A number of 54 future crop trees were assigned across the experimental plot. Out of this, only nine were assigned to Class I. Furthermore, out of these nine trees selected as showcasing the best characteristics, six were NG23 and three were NG38.

Class II, contained the highest number of trees. In this class, 27 trees were selected as having the potential to produce a high-quality stem. From this, the majority was again composed of NG23 walnuts (17) and a smaller share was represented by NG38 (10).

Lastly, Class III was in between Class I and Class II in terms of the number of trees. Normally, it would be expected to have more trees in inferior classes and fewer and fewer trees in superior classes due to more rigorous criteria of selection. Was not the case for this study, 18 trees being registered in this class. This number is supposed to represent a backup, or a reserve, in case if trees from Class I or Class II will lose their potential. Out of 18 walnuts in this class, 13 of them were NG23 and 5 of them were NG38.

Multi-stem trees

Have been excluded from all analyses, as the growth potential was divided among multiple shoots or branches.

However, the resprouting capacity in the walnut hybrids can be of interest and used to correct the stem shape. The capacity of walnut saplings to resprout allows for the stumping back treatment. This practice entails cutting the sapling back to the base, about 5–10 cm from the ground, during the dormant season. Following stumping, the seedling will develop a vigorous shoot that can reach a height above the perilous ground frost pocket. Other reasons for stumping are to enhance the shoot to root ratio and to promote vigorous and straight growth. It can also reduce the stress of walnut seedlings after planting and possibly increase survival rates. After stumping back, the singling (selection) of the resprouts has to be done (*Pope&Mayhead, 1994, Clark&Brocklehurst, 2011*).

Stumping back might represent an alternative to correct the stem shape of walnuts for instance in the site I, blocks alpha and gamma. Because of the windiness, mesic, and poor soil conditions, the height change, and the stem shape of walnuts growing there is not the most satisfying, and the stumping back can be tested.

5. Conclusion

After five vegetation seasons, the experiment provides information about the influences of establishment practices on the early development of two hybrid walnut varieties in southwest Sweden.

The establishment of both varieties was successful, with a survival rate of 96.9%. With lower planting density, the survival rate in this experiment is higher than the survival rate of species that are planted regularly, at higher densities. Considering the high water requirement of hybrid walnut, it is likely that the high amount of rainfall recorded in this area supports a higher survival rate and a better development. To confirm, or infirm this assertion more experiments involving hybrid walnut should be established, preferably on the east coast of Sweden where are recorded less precipitation. The suboptimal, or limiting conditions represented by the less abundant rainfalls, should provide information regarding areas where hybrid walnut can be cultivated with good results.

The effects of treatments varied from a positive influence on some of the analyzed variables to a negative or insignificant one. The effect of Weed control did not influence in any way the establishment success, neither the growth rate nor the characteristics of the stem.

As nurse shrubs were planted for their nitrogen-fixing capacity, it was considered that the distant location from the walnuts would not allow for the roots of the nurses and walnuts to interact after only a few vegetation seasons. Though their effect on *Thickest branch diameter* and *Thickest branch angle* was tested and turned out insignificant. In this case, their effect on stem quality was not as important as advertised in the reviewed literature. However, further investigation is required to remove any speculations.

Western balsam poplar nurse trees influenced the height change only in one year, in a negative way. As indicated by the analysis, the change in height of walnut trees found in blocks without nurse trees was significantly higher (with 17 cm) as compared to transplants growing in the blocks with poplars.

Fertilizers' application has proven in this experiment to have combined effects on the desired traits of the walnuts. Height change was significantly enhanced by the application of fertilizer. Alongside height change, the height of the thickest branch was also higher on fertilized walnuts. The drawbacks associated with this treatment, as indicated in this experiment lays in the negative influence on stem quality. Fertilization encouraged the damages that occurred on the leading shoot to turn into forks. Fertilization treatment also increased the diameter of the thickest branch, as well as the number of branches.

Regarding the walnut type, the height change rate pleads for NG38, as at the end of the fifth growing season reached a mean total height of 340 cm. This hybrid proved also to grow significantly less and thicker branches, as compared to the other variety of walnut.

Even though NG23 walnuts performed poorly in terms of quantitative variables as compared to the NG38 hybrid, the significantly higher frequency of future crop trees selected as well as the lower number of damaged trees plays for its consideration as an option in the establishment of a plantation with the purpose of high quality and value timber production.

Site conditions also proved a significant influence on the early growth of the walnuts. Better site conditions (high availability and accessibility of nutrients, balanced water supply, shelter from the wind) proved to support a higher rate of height change. This experiment also indicated that a higher growth rate is a prerequisite for damages of the leading shoot.

Damages occurred during the first growing seasons stick to the same trees, but the height change rate did not differ significantly in comparison to walnuts that presented no damages.

Considering the results of this work can be concluded that in southwestern Sweden both hybrids can establish and grow with good results. The NG38 hybrid proved to have a larger change in height, fewer and thicker branches, and a higher susceptibility to top damages. NG23 walnuts do not have a height change as large as of NG38 but had more and thinner branches. Among the future crop trees, NG23 were the majority. So, for the establishment of a plantation in southwest Sweden aiming to produce high-quality timber, NG23 is an option to be considered. It does not grow as fast as NG38 but the quality of the stem, higher resistance to (unidentified) damages recommend it for the establishment of plantations.

Fertilization treatments should be applied with moderation, as undesired branching habit is promoted. For future plantations, the nurse trees that accompanied hybrid walnuts in this experiment should be avoided as they will outcompete the main tree species.

References

Aletà, N. (2004). Current research in Spain on walnut for wood production. *UNITED STATES DEPARTMENT OF AGRICULTURE FOREST SERVICE GENERAL TECHNICAL REPORT NC*, *243*, 153.

Aradhya, M. K., Potter, D., Gao, F., & Simon, C. J. (2007). Molecular phylogeny of *Juglans* (Juglandaceae): a biogeographic perspective. *Tree Genetics & Genomes*, *3*(4), 363-378.

Ashby, W. C., Kolar, C. A., Hendricks, T. R., & Phares, R. E. (1979). Effects of shaking and shading on growth of three hardwood species. *Forest Science*, *25*(2), 212-216.

Bernard, A., Lheureux, F., & Dirlewanger, E. (2018). Walnut: past and future of genetic improvement. *Tree genetics & genomes*, *14*(1), 1.

Becquey, J. (1997). Les noyers à bois. *Forêt privée française*.

Becquey, J., & Vidal, C. (2006). Quels accompagnements ligneux choisir pour les plantations de noyer. *Forêt Entreprise*, *170*, 35-38.

Bohanek, J. R., & Groninger, J. W. (2003). Impacts of intensive management on black walnut (*Juglans nigra* L.) growth and bole quality at mid-rotation. *Forest science*, *49*(4), 522-529.

Charrier, G., Bonhomme, M., Lacointe, A., & Améglio, T. (2011). Are budburst dates, dormancy and cold acclimation in walnut trees (*Juglans regia* L.) under mainly genotypic or environmental control?. *International journal of biometeorology*, *55*(6), 763-774.

Clark, J., & Brocklehurst, M. (2011). Stumping in walnut. *Quarterly Journal of Forestry*, *105*(4), 275.

Clark, J. R., Hemery, G. E., & Savill, P. S. (2008). Early growth and form of common walnut (*Juglans regia* L.) in mixture with tree and shrub nurse species in southern England. *Forestry*, *81*(5), 631-644.

Clark, J., & Hemery, G. (2010). Walnut hybrids in the UK: fastgrowing quality hardwoods. *Quarterly Journal of Forestry*, *104*(1), 43-46.

Coelho, J., Becquey, J., & Gonin, P. (2008). Hybrid walnut (*Juglans× intermedia*) and common walnut (*J. regia*) for high quality timber. *Proy POCTEFA*, *93*(08), 5-12.

Díaz, R., & Fernández-López, J. (2005). Genetic variation at early ages for several traits of interest for timber-production breeding of *Juglans regia*. *Canadian journal of forest research*, *35*(2), 235-243.

Espinoza, J. A. (2009). Genetic and nutritional effects on stem sinuosity in loblolly pine (PhD dissertation, North Carolina State University). Available at: http://www.lib.ncsu.edu/resolver/1840.16/4296

Fady, B., Ducci, F., Aleta, N., Becquey, J., Vazquez, R. D., Lopez, F. F., ... & Paris, P. (2003). Walnut demonstrates strong genetic variability for adaptive and wood quality traits in a network of juvenile field tests across Europe. *New Forests*, *25*(3), 211-225.

Germain, E. (1990). Inheritance of late leafing and lateral bud fruitfulness in walnut (*Juglans regia* L.), phenotypic correlations among some traits of the trees. *Acta Horticulturae 284*, 125-134.

Goodman, R. C., Oliet, J. A., Sloan, J. L., & Jacobs, D. F. (2014). Nitrogen fertilization of black walnut (*Juglans nigra* L.) during plantation establishment. Physiology of production. *European Journal of Forest Research*, *133*(1), 153-164.

Guàrdia, M., Díaz, R., Savé, R., & Aletà, N. (2013a). Autumn frost resistance on several walnut species: methods comparison and impact of leaf fall. *Forest Science*, *59*(5), 559-565.

Guàrdia, M., Savé, R., Díaz, R., Vilanova, A., & Aletà, N. (2013b). Genotype and environment: two factors related to autumn cold hardiness on Persian walnut (*Juglans regia* L.). *Annals of Forest Science*, *70*(8), 791-800.

Hemery, G. E. (2000). *Juglans regia L.: genetic variation and provenance performance* (Doctoral dissertation, University of Oxford).

Hemery, G. E. (2004). Genetic and silvicultural research promoting common walnut (*Juglans regia*) for timber production in the United Kingdom. *Black Walnut in a New Century*, 137.

Heiligmann, R., & Schneider, G. (1974). Effects of wind and soil moisture on black walnut seedlings. *Forest Science*, *20*(4), 331-335.

Heiligmann, R., & Schneider, G. (1975). Black walnut seedling growth in wind protected microenvironments. *Forest Science*, *21*(3), 293-297.

Hinkelmann, K., & Kempthorne, O. (1994). Design and analysis of experiments (Vol. 1). New York: Wiley.

Jacobs, D. F., & Seifert, J. R. (2004). Facilitating nutrient acquisition of black walnut and other hardwoods at plantation establishment. *Black Walnut in a New Century*, 65.

Jacobs, D. F., Salifu, K. F., & Seifert, J. R. (2005). Growth and nutritional response of hardwood seedlings to controlled-release fertilization at outplanting. *Forest Ecology and Management*, *214*(1-3), 28-39.

Kelty, M. J. (2006). The role of species mixtures in plantation forestry. *Forest Ecology and Management*, *233*(2-3), 195-204.

Mäkinen, H. (2002). Effect of stand density on the branch development of silver birch (*Betula pendula* Roth) in central Finland. *Trees*, *16*(4-5), 346-353.

Mäkinen, H., & Colin, F. (1998). Predicting branch angle and branch diameter of Scots pine from usual tree measurements and stand structural information. *Canadian Journal of Forest Research*, *28*(11), 1686-1696.

Mäkinen, H., Ojansuu, R., & Niemistö, P. (2003). Predicting external branch characteristics of planted silver birch (*Betula pendula* Roth.) on the basis of routine stand and tree measurements. *Forest Science*, *49*(2), 301-317.

Mäkinen, H., & Hein, S. (2006). Effect of wide spacing on increment and branch properties of young Norway spruce. *European Journal of Forest Research*, *125*(3), 239-248.

Mohamed, A., Stokes, A., Mao, Z., Jourdan, C., Sabatier, S., Pailler, F., ... & Monnier, Y. (2018). Linking above-and belowground phenology of hybrid walnut growing along a climatic gradient in temperate agroforestry systems. *Plant and Soil*, *424*(1-2), 103-122.

Mohni, C., Pelleri, F., & Hemery, G. E. (2009). The modern silviculture of *Juglans regia* L.: a literature review. *Die Bodenkultur*, *60*(3), 19-32.

Fernández-Moya, J., Urbán-Martínez, I., Pelleri, F., Castro, G., Bergante, S., Giorcelli, A., ... & Homar-Sánchez, C. (2019). Silvicultural guide to managing walnut plantations for timber production. *Bosques Naturales*.

Nicodemus, M. A., Salifu, F. K., & Jacobs, D. F. (2008). Growth, nutrition, and photosynthetic response of black walnut to varying nitrogen sources and rates. *Journal of Plant Nutrition*, *31*(11), 1917-1936.

Nicolescu, N. V. (1998). Considerations regarding black walnut (*Juglans nigra*) culture in the north-west of Romania. *Forestry: An International Journal of Forest Research*, *71*(4), 349-354.

Pang, K. (2014). Crown ideotypes for genetically improved black walnut (*Juglans nigra* L.) clones under an intensive management regime in Indiana, USA.

Paris, P., Pisanelli, A., Todaro, L., Olimpieri, G., & Cannata, F. (2005). Growth and water relations of walnut trees (*Juglans regia* L.) on a mesic site in central Italy: effects of understorey herbs and polyethylene mulching. *Agroforestry systems*, *65*(2), 113-121.

Pelleri, F., Ravagni, S., Bianchetto, E., & Bidini, C. (2013). Comparing growth rate in a mixed plantation (walnut, poplar and nurse trees) with different planting designs: results from an experimental plantation in northern Italy. *Annals of Silvicultural Research*, *37*(1), 13-21.

Pelleri, F., Castro, G., Marchi, M., Fernandez-Moya, J., Chi-ararbaglio, P. M., Giorcelli, A., ... & Bidini, C. (2020). The walnut plantations (*Juglans* spp.) in Italy and Spain: main factors affecting growth. *Annals of Silvicultural Research*, *44*(1), 14-23.

Poirier, M., Bodet, C., Ploquin, S., Saint-Joanis, B., Lacointe, A., & Améglio, T. (2004, November). Walnut cultivar performance of cold resistance in south central France. In *V International Walnut Symposium 705* (pp. 281-285).

Pollegioni, P., Woeste, K., Chiocchini, F., Del Lungo, S., Ciolfi, M., Olimpieri, I., ... & Malvolti, M. E. (2017). Rethinking the history of common walnut (*Juglans regia* L.) in Europe: Its origins and human interactions. *PloS one*, *12*(3).

Ponder Jr, F. (1998). Fertilizer combinations benefit diameter growth of plantation black walnut. *Journal of Plant Nutrition*, *21*(7), 1329-1337.

Pope, S. J., & Mayhead, G. J. (1994). The effect of stumping back on the early growth of common walnut (*Juglans regia* L.). *Arboricultural Journal*, *18*(3), 299-306.

Russell, K., & Hemery, G. E. (2004). A new tree improvement programme for black walnut in the United Kingdom. *UNITED STATES DEPARTMENT OF AGRICULTURE FOREST SERVICE GENERAL TECHNICAL REPORT NC*, *243*, 134.

Šálek, L., & Hejcmanová, P. (2011). Comparison of the growth pattern of black walnut (*Juglans nigra* L.) in two riparian forests in the region of South Moravia, Czech Republic. *Journal of Forest Science*, *57*(3), 107-113.

Skovsgaard, J.P., Johansson, U., & Englund, J.-E. (2015). Hybrid walnut: Effects of nurse trees, nurse shrubs, weed control and fertilization on the survival and growth of different varieties of *Juglans x intermedia* in Sweden. SLU experiment no. 1220 at Påarp 19:6, Västra Karup district, Båstad municipality. Southern Swedish Forest Research Centre, *Field Experiments in Silviculture*, *Establishment Report*, 5, 1-15.

Solar, A., Osterc, G., Štampar, F., & Kelc, D. (2011). Branching of annual shoots in common walnut (*Juglans regia* L.) as affected by bud production and indol-3-acetic acid (IAA) content. *Trees*, *25*(6), 1083-1090.

Van Sambeek, J. W., & Garrett, H. E. (2004). Ground cover management in walnut and other hardwood plantings.

Weiskittel, A. R., Maguire, D. A., & Monserud, R. A. (2007). Response of branch growth and mortality to silvicultural treatments in coastal Douglas-fir plantations: Implications for predicting tree growth. *Forest Ecology and Management*, *251*(3), 182-194.

Weiskittel, A. R., Seymour, R. S., Hofmeyer, P. V., & Kershaw Jr, J. A. (2010). Modelling primary branch frequency and size for five conifer species in Maine, USA. *Forest Ecology and Management*, *259*(10), 1912-1921.

Williams, R. D. (1990). *Juglans nigra* L., black walnut. *Silvics of North America*, *2*, 391-399.

Online references:

- Bernhard Mettendorf (2008). *IG-Nuss*. Available at: http://ig-nuss.de/index_htm_files/858-Anbau%20von__%20Juglans-Hybriden.pdf [2020-05-17]
- Pirinoble (2008). *Hybrid walnut (Juglans x intermedia) and common walnut (J. regia) for high quality timber*. Available at: http://www.pirinoble.eu/docs/Hybrid%20walnut_final_10_07.pdf [2020-05-17]

- Pirinoble (2009). *Autecology of Common Walnut*. Available at: http://www.pirinoble.eu/docs/EN/Autecologie_Walnuts_Pirinoble.pdf [2020-05-17]
- CITES (2019). *Appendices I, II and III valid from 26 November 2019*. Available at: https://cites.org/eng/app/appendices.php [2020-05-17]

Acknowledgements

Special thanks to Nils Erik Norrby, Leonid Boganastiuc and Ewa Zuzanna Jastrzębska.