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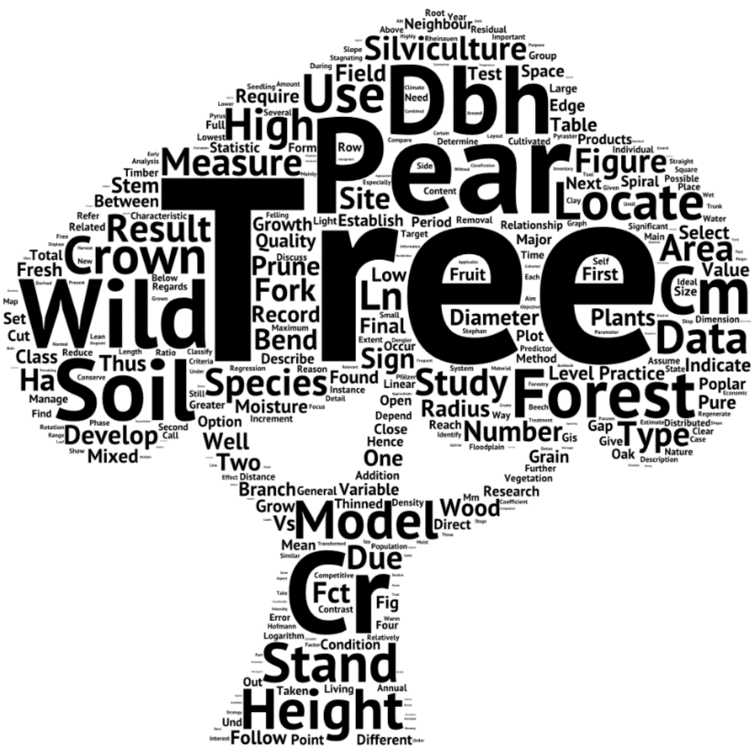
SILVICULTURAL PRACTICES FOR WILD PEAR



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Swedish University of Agricultural Sciences
Master Thesis no. 242
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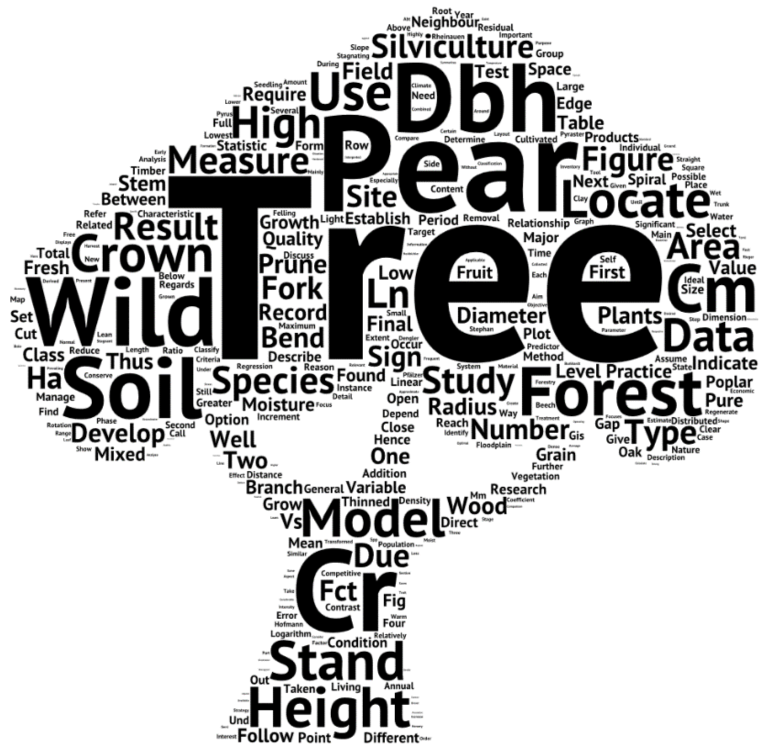

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Large wild pear at edge next to field (DBH: 96 cm, Height: 25.2 m)

ABSTRACT

The research objective is to construct a model for crown radius (CR) based on DBH and significant quantifiers for wild pear *(Pyrus pyraster)*, using regression analyses, to develop guidelines for silvicultural practices for wild pear. To establish the model empirical data of a wild pear population in Western Germany was collected. Site measurements include prevailing vegetation, soil characteristics, location and neighbouring trees. Tree measurements include DBH, height, crown radius and quality characteristics: living branches, forking, bending and spiral grain. 52 trees have been measured of which 41 have been used for modelling purposes. Selection criteria for the model are residual plots and coefficient of determination (R^2). In order to find a linear relationship, (semi-) logarithmic transformations of the dependent and independent variables have taken place. A backward variable elimination from a full model was used to find significant predictors. The logarithmic model is selected best as residual plots show a homoscedastic distribution and follow a normal distribution around the zero-line. The R^2 of 0.6101 gives an indication of a significant relationship. The final relation can be formulated as: $CR = e^{(0.61388*\ln(DBH)-0.75029)}$, where CR in m and DBH in cm. No other independent variables than DBH have been significant. From the derived model, tree spacing and number of stems per ha can be calculated at any DBH. Based on collected data and the model silvicultural guidelines for a pure and two mixed wild pear stands including planting density and layout, pruning, thinning and regeneration cutting are established.

Keywords: Wild pear, Pyrus pyraster, crown radius, silviculture guidelines

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1 INTRODUCTION

Silviculture refers to “the art of producing and tending a forest; the application of knowledge of silvics in the treatment of a forest; or the theory and practice of controlling forest establishment, composition, structure and growth” (Smith et al., 1997). For almost all European tree species and forest types, silvicultural practices have been established, tested and discussed in very detail. Wild pear (*Pyrus pyraster*) so far has not attracted a lot of attention from a silvicultural point of view, especially for the production of high value timber almost no recommendations exist.

Due to a variety of reasons a raising interest for wild fruit trees in the production of high value timber can be noted. Aspects as traditional silvicultural systems, agroforestry in temperate regions [1] and climate change as well as biodiversity conservation have shifted the focus to rare or scattered indigenous tree species. This is a result of increasing importance of close-to-nature forestry and decreasing interest in monocultures with a focus on wood production only. Thus advantages and disadvantages of pure and mixed wild pear stands will be discussed in this study. In addition to that, possible options for incorporating wild pear in agroforestry systems are included.

Silvicultural practices require a solid scientific foundation including descriptions of suitable sites and growing conditions, individual tree growth, forest stand development, climate and a large number of additional information. This study aims at collecting empirical data for the development of a silvicultural program for wild pear. Moreover the development of a model for individual tree growth and stand density is a major focus of the study. This information finally is required to discuss silvicultural practices including planting density, pruning and thinning operations as well as the final regeneration cutting for pure and mixed wild pear stands.

The first section of the thesis report describes the wild pear species, its differentiation from cultivated pear and gives an overview of current silvicultural practices as well as a detailed research hypothesis. The second section of the report summarizes the material and methods used, explaining statistical methods, study area and design of measurements. Thirdly the results from the field work are displayed including results

[1] Agroforestry projects focusing on valuable broadleaf species in Germany: http://www.agroforst-iww.uni-freiburg.de/index.php/de/publikationenb

from statistic models. In the discussion the results are transferred to silvicultural guidelines.

1.1 Species description

Wild pear (*Pyrus pyraster*) belongs to the Rosaceae family. There are various descriptions of the species, but some of these include questionable information, possibly because the species can be difficult to identify and distinguish from cultivated pear. Moreover wild pear trees are relatively rare (Stephan et al., 2003; Dengler, 1992; Grosser, 1999) and receive little attention in research and forestry practice. Despite this, there are efforts made for a more detailed description of the species (Wilhelm, 1998) and certain facts can be summarized in general terms.

Wild pear is a light demanding species (Stephan et al., 2003; Hofmann, 1993; Mayer, 1992), although literature describes a range from semi to high light demand. The species has a deep root system (Hofmann, 1993; Mayer, 1992) and thrives on or tolerates a wide range of site conditions. Based on the deep root system, wild pear is drought-resistant as well as moisture tolerant (Hofmann, 1993; Dengler, 1992). The species has relatively low competitive ability, especially competition with beech *(Fagus sylvatica)* is often fatal for pear (Stephan et al., 2003). Literature describes wild pear as competitive mainly on dry sites with low water supply, due to the deep-root system which is able to access deep ground water levels (Hofmann, 1993).

Figure 1 *– Uprooted wild pear, showing deep-root system*

The growth of wild pear is slow and trees can reach ages of more than 150 years (Dengler, 1992). The shape of the trees depend on the location, in favourable growing conditions the trees have a slender form with a rising crown (Stephan et al., 2003), and in less favourable situations one-sided or extremely low crowns frequently occur. The trees rarely reach a height greater than fifteen meters and a diameter at breast height (DBH) of more than 50 cm (Dengler, 1992).

The wood of wild pear is highly appreciated and hence a reason for economic utilization of the species (Abt and Hochbichler, 2013; Abt et al., 2014; Dengler, 1992;

Grosser, 1999). The 'gross' density[2] of wild pear wood is approximately 0.74 g/cm³ at 12-15% wood moisture, comparing to 0.69 of oak and 0.72 of beech (Grosser, 1999). There are various uses of the heavy and strong wood that is light to dark red-coloured (Dengler, 1992; Grosser, 1999), for instance it is used for the production of music instruments and as veneer. The prices of wild pear wood are high, in 2010 the average price per m³ was 357 €, the maximum reached 1808 € in Austria (Abt and Hochbichler, 2013).

The reproduction of wild pear is mainly vegetative (Hofmann, 1993) and the flowers are insect pollinated (Stephan et al., 2003).

Wild pear covers theoretically a large range of growing locations, in West, Central, East and Southeast Europe, from low elevations up to approximately 850 m above sea level in the Alps (Dengler, 1992; Mayer, 1992).

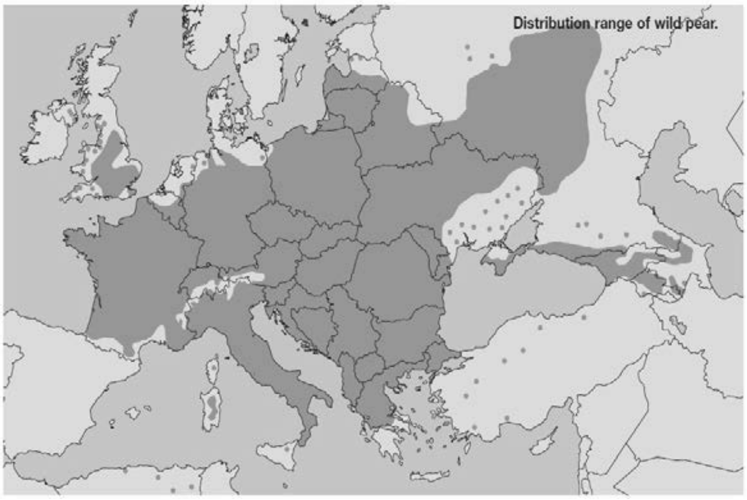


Figure 2 *- Distribution of wild pear (EUFORGEN, 2003)*

Problems of the species are the low competitive ability combined with the high economic value of the wood, which together are a major reason for the scattered occurrence (Grosser, 1999). Moreover natural regeneration is endangered by browsing, and hybridizations with cultivated pears are frequent (Stephan et al., 2003) which results in a further loss of genetic material.

There is no European-wide protection status for wild pear (Stephan et al., 2003), however some countries have taken independent steps to conserve genetic resources, mainly through ex-situ breeding projects.

1.1.1 Growing requirements, site and forest types

There is not a great quantity of scientific data on the sites where wild pear mainly occurs. However Hofmann described populations of wild pear on Muschelkalk, Buntsandstein and calcareous Zechstein. Moreover the soil range is relatively wide

[2] Gross density = density based on the volume including the pore volume

from fresh to calcareous, only not on extremely acid soils (Hofmann, 1993). Other sources include that wild pear favours warm and nutrient-rich soil types, on relatively shallow calcareous soils and elevated floodplain soils (Dengler, 1992). In addition to that a general description refers to warm, low elevation areas up to 300 m above sea level as optimum growing condition (Mayer, 1992).

Wild pear populations can be found at field and pasture edges, at former grazed pastures, anthropogenic forest edges, natural forest edges and in slope forests (Hofmann, 1993). This is underlined by other sources pointing at the fact that wild pears are often located in small groups in formerly used forests, as for instance coppice forests or forest pastures (Määttänen and Holderegger, 2007).

Mixtures of wild pear are related to forest types of beech and oak (Hofmann, 1993; Määttänen and Holderegger, 2008; Türk, 1999). Sunny, warm slope forests with not too dense mixed hardwood species from lowland to mid-alpine elevations are often characterized as growth habitats of wild pear. Specifically the forest types *Carici-Fagetum primuletosum* for dry, warm beech forests on slopes, G*eranio-peucedanetum cervariae* on warm, south exposed Muschelkalk slopes, *Ligustro-prunetum* at anthropogenic forest edges as well as *Quercetum pubescenti-petraeae* for exceptional habitats in warm oak forests have been identified on the one hand (Hofmann, 1993; Türk, 1999). On the other hand, there is evidence that wild pears occur in forest types at river-floodplains with hardwood species, for instance in the forest type of *Querco-ulmetum* in warm and wet climates (Stephan et al., 2003; Türk, 1999).

1.1.2 Brief history of pear cultivation for fruit production

Due to its long tradition of domestication, a clear differentiation between wild and cultivated pear is difficult. Therefore an introduction in the domestication of wild pear seems to be appropriate to clarify the origin of the current form of wild pear in Europe. The domestication of wild fruit trees is the process of changing the reproductive biology of the plants (Zohary et al., 2012). This is achieved by a shift from sexual to vegetative reproduction by rooting twigs, use of suckers or grafting. Based on desired fruit treats, individuals are selected and duplicated to produce genetically identical saplings (Zohary et al., 2012). Historically, due to this so-called clonal cultivation, fruit trees have undergone only a few sexual cycles since their cultivation in contrast to other agricultural crops. Hence the difference between cultivated pears and their wild progenitors is considerably low. This explains the occurrence of cultivated pears only in similar growing conditions as their wild ancestors and the frequent hybridizations (Zohary et al., 2012).

Taking a closer look at the arrival of wild pear *(P. pyraster)* to Europe the date is estimated in the time during a warm period around 5000 to 2500 BC (Aas, 1999). In contrast to that, the cultivated form *(P. communis)* came only with a “second-wave” of domesticated fruits after for instance olives, dates, figs and grapes to Europe dating back to approximately 1000 BC. The cultivated form was derived from *P. pyraster* in central Europe, yet there is uncertainty when the domestication took place. Some sources speak of domestication already since the Neolithic period (Hofmann, 1993; Aas, 1999), however definite evidence only exists since the Roman and Greek time (Zohary et al., 2012). Since then cultivated pears have been used for fruit production and contributed most to fruit supply in temperate regions next to apples.

1.1.3 Wild pear characteristics

There are several identification criteria to distinguish wild pear *(P. pyraster)* from cultivated pear *(P. communis)*. Hence a lot of research has been carried out to identify quantitative criteria based mainly on leaf and fruit traits (Hofmann, 1993; Aas, 1999; Rotach and Baume, 2004; Paganová, 2009). The statistical analysis of a number of morphological measurements has resulted in a relatively unambiguous characterisation of wild versus cultivated pear based on several traits. Most important and significant are the combination of fruit traits based on colour, taste and size (Rotach and Baume, 2004). An identification solely based on leaf traits bears an error percentage of 20–40%, however is often the only applicable method in the field due to the lack of fruits. The identification based on leaf traits serves a merely descriptive purpose, and four traits have been identified to result in a reasonable method for an indication.

Trait	Wild pear		Cultivated pear
Twig	Usually Thorns		No Thorns
Leaf			
Length	< 5cm	5 – 7 cm	> 7cm
Width	< 5cm		> 5cm
Shape	Orbicular		Elliptical
Ratio Leaf Length/Width	≈ 1		Significantly > 1
Hairs at underside	Not dense white-hairs		Dense hairs
Length of petiole	(< 6cm)		(> 6cm)
Ratio Length petiole/Length Leaf	≈ 1		< 1
Fruit			
Size (Length)	≤ 3cm		> 3cm
Shape	Round		Longer
Ratio Length/Diameter	≈ 1		Usually > 1
Ratio Length of stalk/Length of Fruit	≈ 1		Significantly < 1
Diameter of Stalk	≤ 2mm		> 2mm
Taste	Astringent		Well-tasting
Colour	Never red		Partly red

***Table 1**- Differentiation criteria wild and cultivated pear (adapted from Rotach and Baume, 2004)*

They are the combination of length of leaves, length of the petiole, the ratio of length of leaf and width of the leaf and the occurrence of thorns on twigs as described in table 1(Rotach and Baume, 2004). Table 1 summarizes several of the important traits included in the identification of wild pear and could be used in the field. The majority of the studies point out that more research is needed to identify more significant differences and thus clearer differentiation criteria. To further penetrate into this topic requires genetic analysis and is not the scope of the current study.

Based on the criteria stated in the table above wild pear can be identified by orbicular (i.e. essentially circular) leaves without (dense) hairs at the petiole. Moreover, the fruits are apple-shaped with an astringent taste and never red. Following these traits the distinction between wild and cultivated pear can be made in the field.

1.1.4 Current silvicultural practices

Descriptions of silvicultural practices for wild pear are quite rare even though the timber is of high economic value. Some publications include general terms for the use of wild pear as stating the rotation period of 50 - 70 years and extensive felling due to high prices on wood market (Kleinschmit and Stephan, 1997). The age assumption at final felling is neither further explained nor based on any empirical data.

In more detailed fashion there are descriptions from two different contexts which are relevant to some extent. First is the example of a silvicultural description from a south European context in Catalonia for the closely related *Pyrus communis* (Coello et al., 2013), however the publication is not scientific proven and lacking references. For a descriptive purpose some major ideas are stated here. The description refers to southern European forests dominated by oak, beech and chestnut. The first step for establishing a pear plantation is to choose planting material from similar sites which are healthy and well-developed. Secondly, soil preparation in two perpendicular directions to break compact soil layers is required. Moreover in the production of high-quality wood pruning and thinning is essential, which should take place at an intermediate intensity. Pruning is described as frequent (annual or every second year) but moderate. Thinnings refer to the removal of trees shading Future Crop Trees (FCT) including the possibility to create income from intermediate thinnings.

Another example is taken from the silviculture of mixed stands in Austria. There are different forest types in which wild pear could be used for additional value timber production (Hochbichler et al., 2013). Mixing wild pear for wood production in selection forests seems applicable for the following mixtures on slope forests from 100 to 350 m elevation:

- Oak-hardwood forests including species as *Acer plantanoides, Tilia cordata, Sorbus spp.* and wild pear on rather dry to fresh soil types
- Noble hardwood forests including species as *Acer plantanoides* and *pseudoplantaoides* , *Tilia cordata, Sorbus spp*. and wild pear on rather dry to fresh soil types
- Beech-oak-hardwood forests, this in beech dominated forests to add value by mixing with hardwoods as wild pear, though very limited to locations where beech has low competitive capacity on relatively fresh to relatively dry sites limited by water availability

The main idea is to include a mixture of 20% - 60% of wild pear in medium-sized to large groups into the stand. The groups should cover larger areas in the stand of about 500m² -5000 m² and the planting density for the whole stand is set at 2000 to 4200/ha depending on whether intensive pruning is included or not. Thus indicating a planting density of 3 x 1.3 m, respectively 2 x 1.2 m (Hochbichler et. al, 2013). For wild pear a target diameter of 60 cm is assumed, the selection silviculture aims at high quality wood including branchless trunks with great dimensions. The final crown width is assumed to be 12 m (10-14) and resulting in a total of 70 crop trees per ha. The average rotation period is set at 70-90 years, requiring intensive treatment and constant release of FCT’s.

Another upcoming trend in forest management is the QD – strategy. The strategy aims at the production of high-quality timber, and could to some extent be relevant for the silviculture of wild pear. The qualification - dimensioning forest management strategy consists of four stages:

The establishment phase defined as the first year after germination until seedlings have overgrown the competing vegetation, requires low interference.

The qualification phase defined as competition between trees including mortality, height growth and self-pruning, requires low interference including removing wolf-trees, start favouring vital FCT.

The dimensioning phase including a clear bole of 25% of desired final height, (self-) pruning, development of crown to create diameter growth, requires strong interference including pruning and organizing the distribution of FCTs.

The maturation phase in which the crown and diameter growth decrease, stem reaches goal diameter and the establishment of following generation begins (Rieger, 2004; Hettesheimer et al., 2009; Wilhelm and Rieger, 2013).

This strategy is assumed to not be applicable completely for wild pear and fruit trees due to the low competitive ability and mostly individual scattered trees. It is assumed that more intensive management in early stages is required, which could be legitimated by high wood prices and gene conservation efforts.

1.2 Research objective

There are several objectives included in this study. First and overall the main goal is to find approaches for suitable site-specific silviculture for wild pear in the given context. In addition to that generalizations for the silviculture of wild pear in a global sense are aimed at. This could include aspects as gene conservation and a possible increase of the use of wild pear related to climate change.

More specifically the following objectives are elaborated during the research:

- To compile an overview of the occurrence of wild pear in western Germany
- To analyse dimensions of wild pear trees in relation to neighbouring trees (Height, DBH, crown radius)
- To develop a silvicultural strategy in order to guarantee the conservation of the genetic material of the species

1.2.1 Research Hypotheses

A research hypothesis should be a tentative proposition with unknown validity, specifying a relationship between two or more variables (Kumar, 2011). The specific hypothesis for this research is:

There is a causal relationship between crown radius and diameter at breast height of wild pear that can be statistically tested and is described below (for natural regenerated or planted trees in the study area).

$$H_0 = CR = \alpha * DBH + \beta$$

where CR = Crown radius, DBH = Diameter at Breast Height.

The elaborated research hypothesis is that next to DBH also height and the location of the wild pear trees possibly influence the crown radius (H_1).

$$H_1 = CR = \alpha * DBH + \beta * Height + \gamma * Location + \varepsilon$$

Where CR = crown radius, DBH = diameter at Breast Height, Height = total height in m and location = edge or forest.

$$H_2 = \text{Number of stems per ha} = 10{,}000/(CR^2 * \pi)$$

for a crown radius based on the model from H_0 or H_1.

Hence the crown radius of wild pear can be used to indicate the maximum number of stems per ha assuming crown expansion without competition (Hein, 2007; Hemery, 2005). This is one of the most relevant silvicultural tools for high-quality wood production focusing on maximum DBH increment.

2 MATERIAL AND METHODS

2.1 THEORETICAL MODEL DEVELOPMENT

The research objective is to construct a model for crown radius based on DBH for wild pear. Hence an overview of the statistical approach for the modelling is regarded necessary. Several basic statistical concepts are used in the modelling.

The basic statistical concepts in forest modelling involve two primary objectives of statistical methods which are the estimation of population parameters and testing of hypotheses about these parameters (Husch et al., 2003). In a statistical sense the population is a collection of individuals belonging to a defined group, as for instance all pear trees located in the study area. Some basic population parameters are the variance, which is determined as the average squared deviation of individuals from the mean (σ^2) (Weisberg, 1985; Husch et al., 2003; Burkhardt and Tomé, 2012). Closely related is the standard deviation which is defined as the square root of the variance (σ). A third population parameter is the standard error of the mean, defined as standard deviation of the mean (Husch et al., 2003).

The model development for crown radius based on DBH makes use of regression and correlation analyses. In theory, regression and correlation analyses evaluate the relationship of two or more variables and state the type of relationship (Husch et al., 2003). In fact, regression analyses is used to quantify a relationship between a dependent variable and one or more independent variables which are also called predictors (Weisberg, 1985; Husch et al., 2003). This essentially includes an assumed cause-and-effect relationship in which changes in the predictor result in expected average changes in the dependent variable (Weisberg, 1985; Husch et al., 2003).

To be able to identify whether this cause-and-effect relationship is statistically significant different measures are available. The measure of the degree of the relationship for a whole population is called the correlation coefficient p, implying that if the coefficient is 0, there is no correlation but when it is 1 there is a perfect correlation (Fox, 2008). For samples from the whole population most often the squared value of the correlation coefficient (R^2) is used, called the coefficient of determination. The R^2 can be interpreted to indicate the percentage of variation in one variable that is associated with the other variable (Husch et al., 2003).

A possible cause-and-effect relationship can be formulated based on a mathematical expression fitting observations in a graphic form: $\mathrm{y = a + bx}$ where b = slope (regression coefficient), a = intercept (Weisberg, 1985; Husch et al., 2003). Some of these relationships can be transformed into linear form by logarithmic transformation, for instance: $y = ax^b$ can be transformed to $\log(y) = \log(a) + b * \log(x)$ (Husch et al., 2003). The most common and easiest form to find the relationship is called linear regression. When applying linear regression analyses, it fits a straight line to the recorded data at the best position by calculating the slope and intercept. The optimal position of the line is where the sum of the squared deviation from the recorded y-values from regression line is a minimum; this is called the least squares method (Husch et al., 2003).

To test a hypothesis as formulated under the research objective, various statistical options exist. An appropriate method is a test of significance. For tests of the difference between two measures involving continuous-type variables that follow a normal distribution, the T-test can be used. This test evaluates the “possibility of occurrence of difference between two means, a null hypothesis is always implied in the test, although not always explicitly stated” (Husch et al., 2003). The null hypothesis would always be that the two means come from same population and there is no difference (Husch et al., 2003). When using the T-test for an independent categorical variable, that is not continuous, but qualitative, the use of dummy variables becomes necessary. In this study the use is restricted to dichotomous dummy variables, indicating that there are only two values (0 and 1) (Weisberg, 1985). Through this, it is possible to include for instance location or soil type in a linear model.

As indicated above, in some cases transformations of the recorded data can be desirable. When models are fitted to data, a common transformation is to take the natural logarithm (ln) of both sides of the prediction equation, so that still a linear regression is possible. This transformation often reduces the heterogeneity of variance (Burkhardt and Tomé, 2012). However the predictors are desired in arithmetic units and a retransformation of the fitted equation often results in bias. The use of the natural log often underestimates the dependent variable, hence a correction is required, the retransformation estimator has been established as $\hat{y} = e^{\hat{\mu}} * e^{\frac{\hat{\sigma}^2}{2}}$,where $\hat{y}$: estimated mean in arithmetic units, $\hat{\mu}$: estimated mean of y for a given level of x after logarithmic transformation, and $\hat{\sigma}^2$: estimated variance about the fitted regression after logarithmic transformation (Burkhardt and Tomé, 2012).

In order to fit a model to the recorded data variable selection of significant variables is often a necessary step. To select variables included in the final model, a backward stepwise approach can be used (Weisberg, 1985), this means that a full model including all variables of interest is established and afterwards stepwise reduced until solely significant predictor variables remain.

In linear full models also interactions between variables are considered. Two variables interact in determining a dependent variable if the partial effect of one depends on the value of the other. There are differences in interpreting possible interactions between quantitative and qualitative predictors, for instance the interaction between a quantitative and a qualitative variable means that the regression surfaces would not be parallel (Fox, 2008). Thus an interaction between DBH and location or height and location would mean that different slopes of the regression line in different locations are present.

Based on several reasons, the statistical concept of linear regression is regarded as appropriate for finding a possible relationship between crown radius and DBH, although also non-linear models of this relationship exist (Hasenauer, 1997).

Larger crown sizes generally result in higher rates of growth for trees of given species, due to the direct relationship of crown size to the photosynthetic capacity of trees (Hemery, 2005; Burkhardt and Tomé, 2012; Attochi and Skovsgaard, 2014).Hence, crown size has been identified and used to model the diameter increment and vice versa (Husch et al., 2003; Dubravac et al., 2013; Attochi and Skovsgaard, 2014). This information can be incorporated in forest management descriptions especially thinning guidelines, determining the growth space for trees or general growth models (Krajieck et al., 1961; Burkhardt and Tomé, 2012, Attochi and Skovsgaard, 2014). A specifically interesting aspect is that the crown projection area based on the crown radius allows calculating the land area required for optimal tree development for the production of high-quality timber (Attochi and Skovsgaard, 2014). It has been acknowledged that crown sizes for open-grown trees (OGT) represent the empirical maximum for certain tree dimensions as for instance DBH (Krajieck et al., 1961; Hasenauer 1997; Burkhardt and Tomé, 2012). Most commonly data from OGTs is collected and used for developing silvicultural approaches. In this study however, the data collection is taken in both, open and closed forest conditions. Possibly a location effect on the crown development can be found.

As the research hypothesis refers to the use of the crown radius – DBH relationship the relationship has to be established and tested. In order to do so, the collected data from the field work is analysed with the help of the open-source statistic program R. R is a GNU-licensed statistical program, which can be ideally used for analysing forestry datasets (Robinson and Hamann, 2011).

The main function for the statistical data analysis in R is the “summary” function for linear models. The function “summary” computes and returns a list of summary statistics of the fitted linear model given, most important ones are summarized below (from R):

- (Weighted) residuals
- Coefficients, giving columns for the estimated coefficient, its standard error, t-statistic and corresponding p-value
- Degrees of freedom
- R^2, the “fraction of variance explained by the model”
- Adjusted R^2, the above R^2 statistic ‘adjusted’, penalizing for higher p
- Significance for each coefficient

In environmental science the test criterion is commonly set to 95% (or 0.05). The main method used to find a suitable model for the crown radius has been a backward variable selection. First a full model was set up, including all predictor variables which might be of importance. In a sequential approach, the least significant predictor was removed from the model until solely significant predictors remain.

Full model without transformation (as formulated in R):

CR = DBH + Height + Location + DBH:Height + DBH:Location + Height:Location

Logarithmic full model (as formulated in R):

ln(CR) = ln(DBH) + ln(Height) + Location + ln(DBH):ln(Height) + ln(DBH):Location + ln(Height):Location

Semi-logarithmic full model (as formulated in R):

CR = ln(DBH) + ln(Height) + Location + ln(DBH):ln(Height) + ln(DBH):Location + ln(Height):Location

The major aim of this method was to create an applicable and practical model for silvicultural purposes. Selection criteria for the most ideal model can be various, in this study the focus is on the residual plots as well as the coefficient of determination (R^2). In order to find the most linear relationship based on residual plot interpretation, semi-and logarithmic transformations of the dependent and independent variables has taken place.

The model development focuses on the data recorded for crown radius and DBH.

2.2 Study area

The main method to establish a model is an inventory of wild pear population in West-Germany in the federal state of Rhineland-Palatinate, where a sufficient number of trees is available. These trees have been recorded before in the run of the establishment of a seed orchard. The focus is to acquire data to test the research hypotheses as well as gaining descriptive insights of the forest type and surrounding.

The study area belongs to the forest office called "Pfälzer Rheinauen" located in western Germany in the province Rhineland-Palatinate. The forest districts in which a certain number of wild pear trees are located are called "Hördter Rheinauen" and Speyer.

The green dots indicate the location of the wild pear trees based on the GPS data tracked by a Garmin hand device. The map is created with the help of the free-online tool, GPS-visualizer. As possible to see, the study

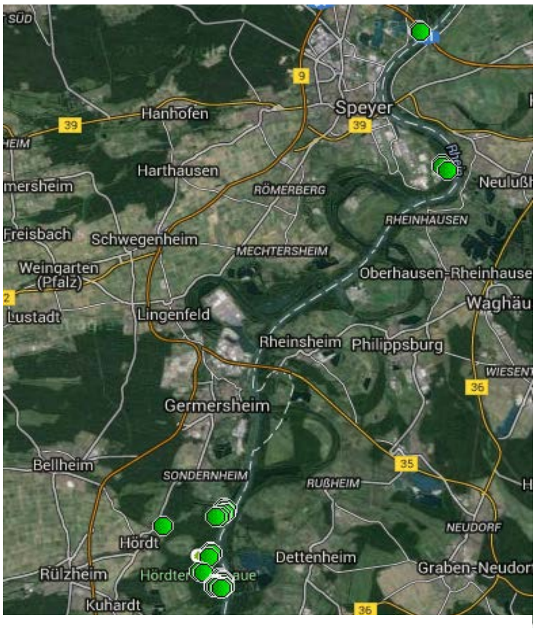


Figure 3 *- http://www.gpsvisualizer.com/map?output_google*

area borders one of the largest connected forest areas in Western Europe, the Pfälzer Wald, which is connected to the Vosges Mountains on the French side of the border.

More in detail, it reveals that the wild pear trees are located directly at Rhine floodplain areas at the border of the federal states Rhineland Palatinate and Baden-Württemberg, which are at this specific location separated only by the Rhine (Fig.3). The management history of these areas with regards to the wild pear is largely unknown, in recent years no specific focus has been placed on the species.

The climate of Rhineland-Palatinate is temperate, the annual temperature in the study area is around 10°C (Fig. 4), and the annual precipitation is ranges between 500 and 800 mm (Fig. 5). The red square indicates the location of the study population.

The temperature during the vegetation period from May to September ranges from 17.5°C to 20°C (Fig. 6). Precipitation during the vegetation period ranges from 200 to 400 mm. For the temperate zone this are relatively high average temperatures and low precipitation values (Fig. 7). The climate data is based on the period of 1981 to 2010.

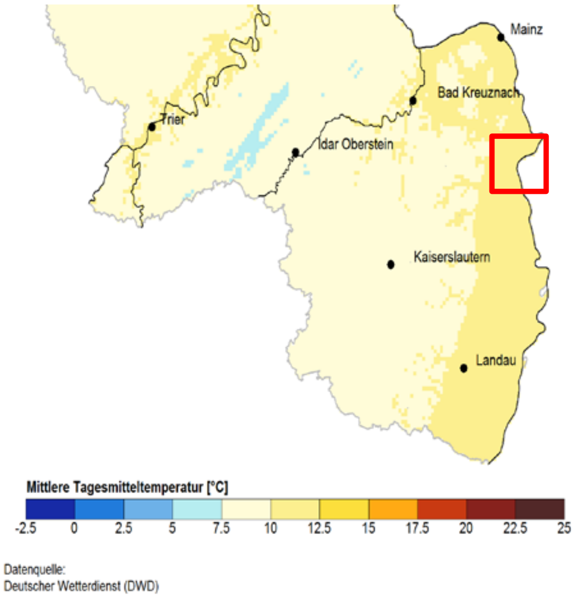


Figure 4 *- Annual temperature (http://www.kwis-rlp.de/uploads/tx_userdownload/LT_kalJahr_1981-2010_DWD.png)*

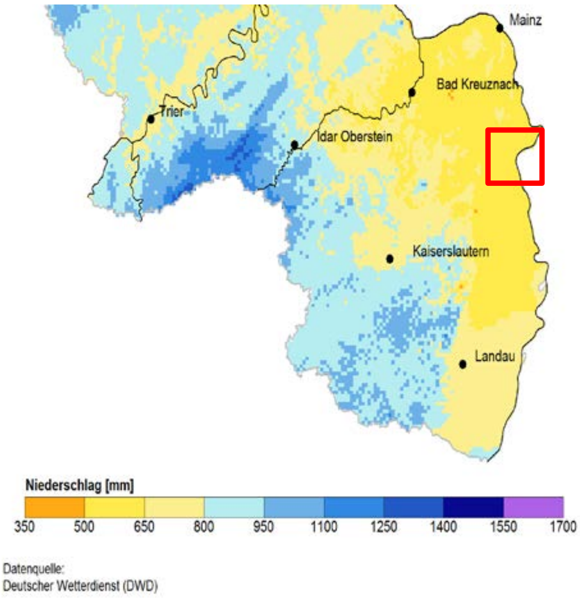
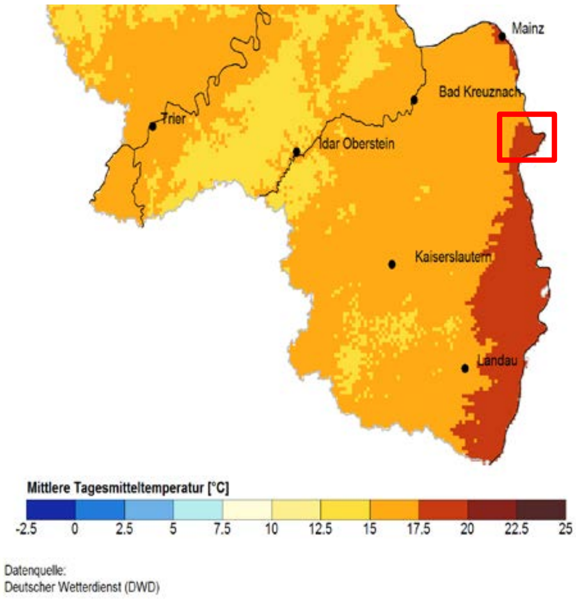


Figure 5 *- Annual Precipitation in mm (http://www.kwis-rlp.de/uploads/tx_userdownload/N_metJahr_1981-2010_DWD.png)*



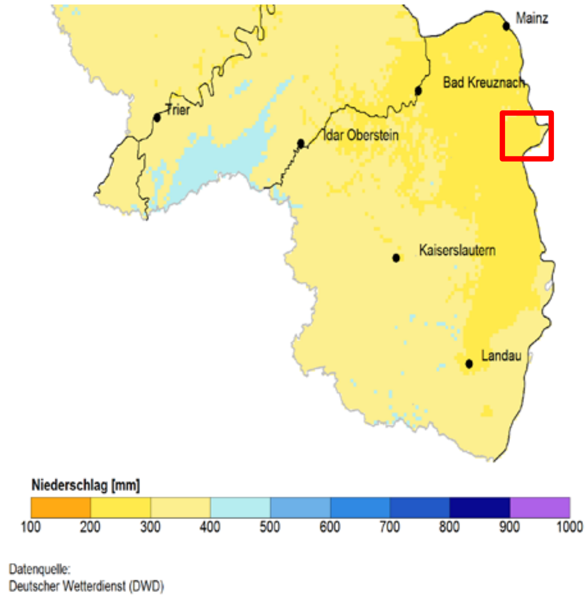


Figure 6 *-Temperature during vegetation period (May to September) (http://www.kwis-rlp.de/uploads/tx_userdownload/LT_fVZ_1981-2010_DWD.png)*

Figure 7 *- Precipitation during vegetation period (May to September from) (http://www.kwis-rlp.de/uploads/tx_userdownload/N_fVZ_1981-2010_DWD.png)*

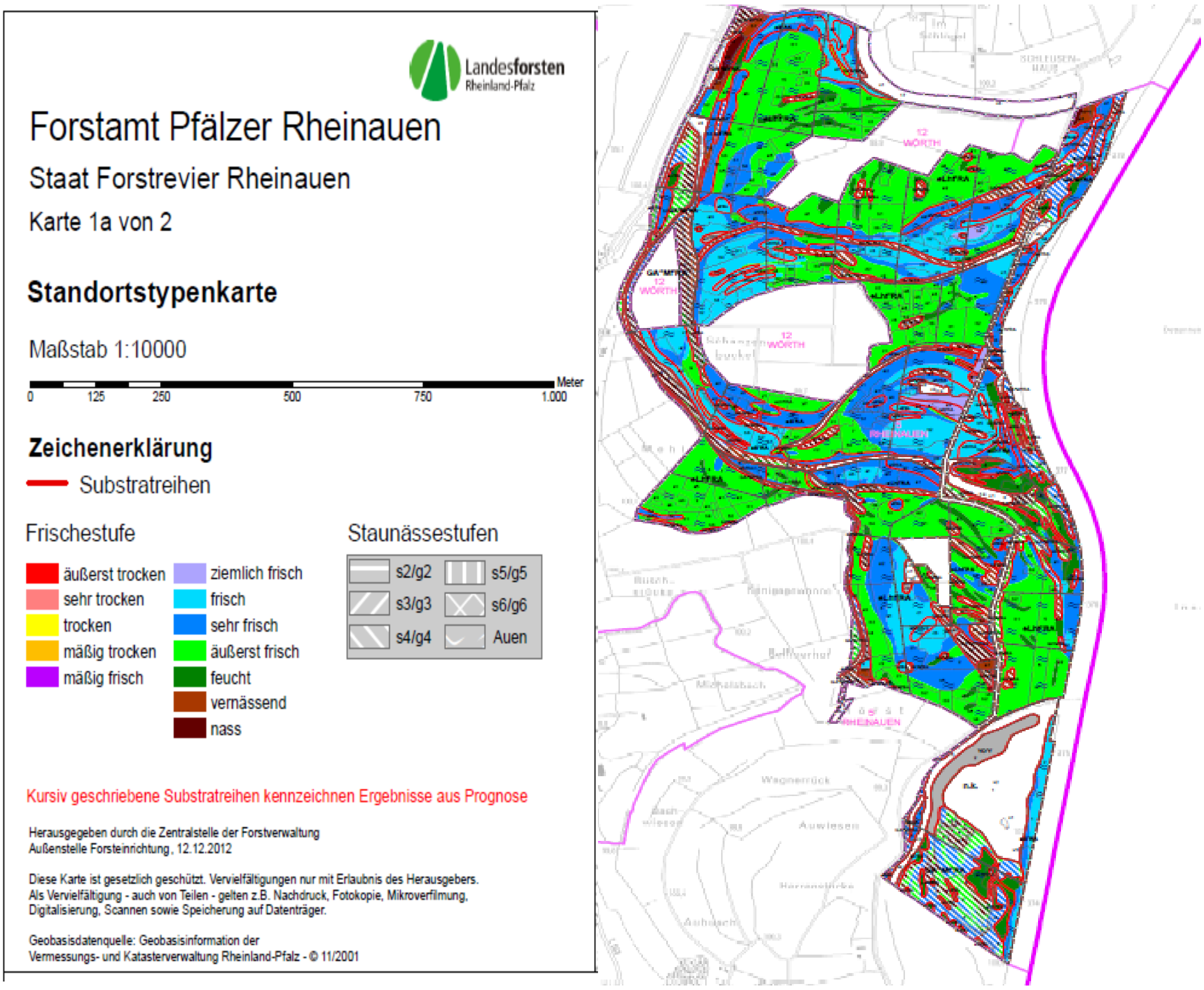


Figure 8 *– Soil freshness of forest district Pfälzer Rheinauen*

The main soil characteristic in the forest district is a high level of freshness. The majority of soils are classified as fresh (light blue), highly fresh (blue) and extremly fresh (light green) (Fig.8). Moreover the character of the soil includes a high loam content with a high freshness. On other parts the soil is classieifed as moist to wet due to a high groundwater level. The soil in the study area is described in the result section more in detail.

The tree species compostion of the Pfälzer Rheinauen is the following (based on personal communication with forester A. Vogelgesang, 7 April 2015):

Species	**Per centage**	**Growth Phase**
Ash *(Fraxinus excelsior)*	20.5%	50% maturation phase, 27% diemensioning phase, 21% qualification, 1% establishment phase → Result from Ash dieback
Beech *(Fagus sylvatica)*	20.1%	35% maturation, 30% dimensioning, 28% qualification
Sycamore *(Acer pseudoplatanus)*	14.8%	24% maturation, 39% dimensioning, 29% qualification
Poplar *(Populus spp., mainly P. tremula and P. alba)*	11.5%	66% maturation
Pedunculate oak *(Quercus robur)*	8.9%	70% maturation, 19% dimensioning, 3% qualification, 7% establishment
Alder *(Alnus glutinosa)*	4.2%	-
Hornbeam *(Carpinus betulus)*	4.0%	-
Norway maple *(Acer plantanoides)*	3.8%	-
Willow *(Salix spp.)*	3.1%	-
Other species	~ 1%	-

Table 2 *– Species composition in the study area*

The major part of the study area is a floodplain hardwood forest type.

2.3 SITE MEASUREMENTS

The site describes the relationship of the growth of forest trees and their environment (Husch et al., 2003). The environmental factors can be categorized in four types (from Husch et al., 2003):

- Edaphic: includes soil depth and texture, as well as moisture and drainage (in this study reflected by soil field measurement and GIS data analysis of soil properties)
- Climatic: includes temperature, precipitation and length of the growing season (in this study not directly measured, descriptions of long-term observation under the study area section)

- Topographic: altitude, slope angle, position (in this study recorded as GPS location of wild pear trees)
- Competition: includes the competition with other trees and vegetation (in this study quantified by neighbouring trees and location as well as prevailing vegetation)

2.3.1 Prevailing vegetation

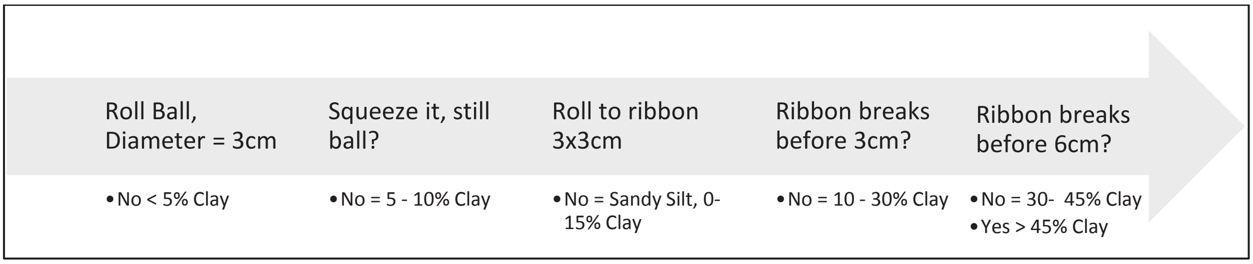
To establish a descriptive picture of the forest surrounding in which the wild pear populations are located dominating tree species in the canopy cover were recorded. The three nearest neighbour trees were identified by species. The species composition is an important parameter in describing forest stands (Husch et al., 2003).

2.3.2 Soil

To be able to classify the growing location of the wild pear trees, major soil characteristics were measured using a field test. In addition to that, available GIS data from the local forest research station was used to gain further insights.

The soil texture field test works the following way and is based on experiences from other field works (based personal communication with Jens Peter Skovsgaard, January 2015). The field tests refers to taking a small soil sample and perform an analysis based on the performance of the soil when treated in a systematic way.

The first effort is to quantify the clay content in wet or “non –organic” soils.



To identify whether the current soil type is silt the soil is examined by the following characteristics: shiny look, mushy feel, in spring: dry and dusty.

The third character of the soil would be coarse sand (0.2 – 2mm). Based on the coarse sand contents on mm-sheet: < 50% coarse sand, > 50% coarse sand or > 90% of coarse sand.

As the study site is located close at the Rhine floodplain forests, a high clay content is expected.

2.3.3 Location

The actual location of the wild pear trees is an important classifier for the development of the crown diameter. Hence a classification for the most frequent locations has been established during the inventory. The following classes have been identified and the trees classified accordingly:

- Forest
- Forest, next to Forest Road
- Forest edge at field
- Forest edge at dam
- Forest edge next to gap
- Gap

The study location is located next to a dam separating the floodplain from other terrains, therefore the somewhat surprising classification, forest edge at dam occurs.

2.3.4 Neighbouring trees

If applicable and not removed due to earlier silvicultural operations, the distance to three closest neighbour trees and their cardinal direction in relation to the wild pear tree was measured by compass and Vertex.

In addition to that height and DBH as well as species of the neighbouring trees was recorded to create an approximate picture of the surrounding forest type.

2.4 Tree measurements

In total 52 wild pear trees were measured. Not all are used for modelling purposes as they had to be classified according to their health status (dead/ decaying trees with no alive shoots excluded), prior events (dead trees leaning into crown), missing measurements due to location (water next to tree). After this selection, finally 41 trees are considered in the result section. In addition to that, GIS data from state forest inventory was used as well as an old data set containing information from an earlier inventory of the same wild pear trees, which had been measured in 1988 for gene conservation purposes.

For all trees UTM coordinates were recorded with a Garmin hand device. In addition to that the known history including silvicultural treatments as pruning or release operations was summarized. Moreover obvious stem defects as cavities, broken branches et cetera have been recorded.

2.4.1 DBH and Height

The diameter at breast height was measured by calliper in two perpendicular directions in cm at breast height (1.3 m).

Following aspects have to be considered when measuring the DBH (from Husch et al., 2003):

- When tree is on slope or uneven ground → DBH measured on uphill side
- When tree is leaning → DBH measured parallel to lean on high side of the tree
- When tree has limb, bulge or other abnormality at breast height → Diameter measured above abnormality
- When tree is forking below breast height → Diameter measured of each stem separately
- When fork occurs a breast height or slightly above → Diameter measured below enlargement resulting from fork
- When tree has a buttress that extend higher than 1 m → Diameter commonly measured at fixed distance above top of buttress, for instance 30 cm

The total height of each tree was recorded by Vertex, this means the distance along the axis of the tree stem between the ground and tip of the tree (Husch et al., 2003). Hypsometers as the Vertex usually assume that trees are straight and not leaning, hence trees leaning away from point of observation will be underestimated (Husch et al., 2003). In contrast to that, trees leaning towards point of observation are logically overestimated, to minimize the error in height estimations the point of observation should be chosen in a way that the trees lean to the right or left (Husch et al., 2003).

For several trees data from a prior inventory from the year 1988 was available, which allowed the calculation of annual growth. The annual growth can be calculated as: $Annual\ growth = (DBH_{present} - DBH_{old})/n_{years}$. The results from this equation give an indication to the time required to produce high-quality timber.

2.4.2 Crown radius

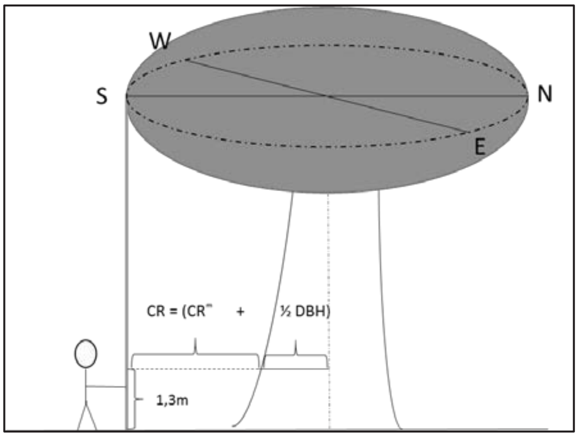


***Figure 9** – Crown measurement*

The crown is an essential part of the tree on which the growth depends. Crown dimensions can be used for modelling of height and/or diameter increment of individual trees and mortality at any point of time (Husch et al., 2003; Dubravac et al., 2013). The crown radius is usually measured by projecting the perimeters vertically to the ground and taking the radius of this projection. In general field measurement of crown radii is difficult due to the irregular shape of crowns (Husch et al., 2003; Burkhardt and Tomé, 2012). However, there are various options how to quantify the crown radius, discussions focus mainly on where to locate the centre of the crown and the quantity of radii necessary to give a reliable result. In latest literature, it has been agreed that four radii are sufficient (Attocchi and Skovsgaard, 2014; Hemery et al., 2005). The crown diameter based on the radius in this case is regarded to be circular, although other forms are also discussed in literature (Burkhardt and Tomé, 2012; Dubravac et al., 2013). One way to carry out the field measurement is for instance to first take the widest radius of the crown and make a second measurement at a vertical angle (Husch et al., 2003).

In this study, the method chosen in order to record the crown radius was that four radii in cardinal directions (N, W, S and E) are taken with help of Suunto clinometer, Vertex and a pole (Fig. 9). The Suunto clinometer was used to find the exact vertical position under the most outreaching part of the crown. Afterwards the pole has been placed at this position and the distance to the stem at 1.3 m height was measured by Vertex. The process was performed clockwise starting north. Finally the average was calculated: $CR = \frac{CR_N + CR_E + CR_S + CR_W}{4} + \frac{DBH}{2}$, adding half of the DBH, as the centre for the crown projection area is assumed to be the centre of the stem.

2.4.3 Quality characteristics

2.4.3.1 Lowest living branch

The lowest living branch (LLB) is often taken as a measure for the crown base and is a sign for vital and competitive crown. Following for instance the QD-strategy for commercial purposes the crown base should be at about 25% of desired final height. This is required to ensure a clear, branch-free bole for value production. Ideally this should be achieved by self-pruning to enable optimal crown development at dimensioning phase (Hettesheimer et al., 2009; Rieger, 2004; Wilhelm and Rieger, 2013). Moreover a clear bole is important for high-quality wood production and the determination of other features as time to reach target diameter and number of FCTs (Hein, 2007).

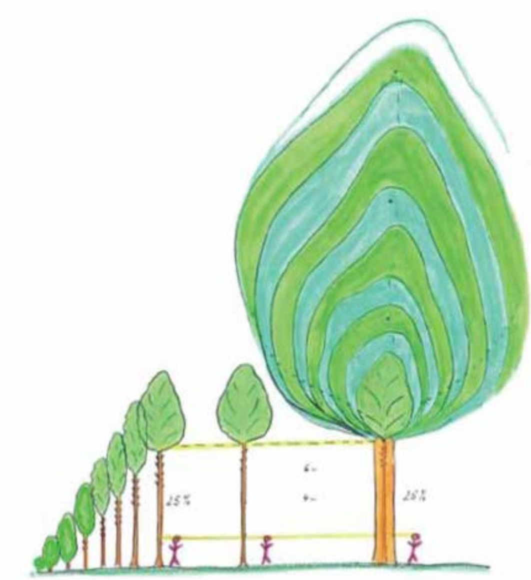


Figure 10 *– Lowest Living branch as crown base for ideal crown development (Wilhelm and Rieger, 2013)*

In order to measure height of the lowest living branch, the mEssfix-tool, a telescopic stick, was used to reache the lowest living branch on the upper side where it is attached to the stem. In case the LLB is out of reach of the maximum height of the telescopic stick (8 m), the height was measured by Vertex.

2.4.3.2 Forking

Forks reduce the wood quality due to formation of unwanted reaction wood. An example of forks reducing the quantity of straight and highly priced wood are tensile forks: described as a stem fork without notch stress

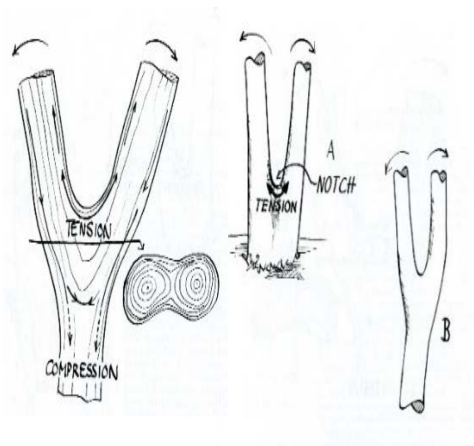


Figure 11 *– Tensile fork (Mattheck, 1991)*

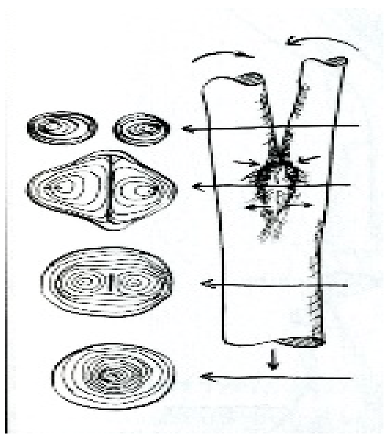


Figure 12 *– Compression fork (Mattheck, 1991)*

(Mattheck, 1991), indicating two or more stems bending away from each other. It features in a mechanical sense a “shape-optimized component with a very good fail-safe ratio”, in contrast to this positive mechanical aspect the wood quality requirements of equally shaped annual rings are strongly disturbed by the occurrence of a tensile fork. Due to the fact that the tension-loaded section connecting the two (or more) stems consists of annual rings is running from one stem into the other (Mattheck, 1991).

Another example of forks reducing the wood quality are compression forks: described as divided stems pressed together by strong formation of reaction wood (Mattheck, 1991) to reduce the contact stress by surface enlargement. Including that as soon as a circular shape is reached, the tree rings form a nearly plane contact area (Mattheck, 1991). Regarding the strength of the two described fork types, compression forks are inferior to tensile forks. Compression forks are mainly found in dense stands which force divided stems and branches to grow straight to receive sufficient light, tensile forks in dense stands would result in lower height and loss of light, and thus they are found in wider and more open stands (Mattheck, 1991).

The height of forks was measured by the mEssfix-tool, reaching into the lowest point of the fork, as this is the most objective way to measure fork height. However one has to be aware that the reduction in high-quality wood reaches further down into the trunk. In case the fork have been higher than the maximum reach of the tool (>8 m) the height of the fork was measured by Vertex.

2.4.3.3 Bending

Bending stresses are an internal resistance of trees to flexure, a combination of tensile and compressive stresses distributed of the cross-section of the tree (Mattheck, 1991). Trees have different ways to reduce unnecessary loads for instance if the centre of gravity of crowns is not over the root stocks (Mattheck, 1991). In addition to that the tree stem generally develops a mechanical structure to handle the force of the vertical moving load of its crown as well as the horizontal wind forces (Smith et al., 1997).

Bending is a different type of reaction of trees to their growing circumstances than leaning, however the differentiation is difficult in the field. Hence all trees deviating from vertical were considered to be bending.

There are different reasons for bending of trees which are summarized in the following:

- Negative geotropism/gravitopism describes the self-correction of counter-gravity growth, angiosperms are “pulled” in position by the formation of tension wood
- Phototropism directing the tree towards light, moreover it is a light-intensity indicator
- Apical dominance which is the manifestation of the dominance of the leading shoot (Mattheck, 1991)

The result of the bending is “adaptive growth” explaining the shaping of trees adapted to the external conditions. In case of geotropism due to evenly distributed light, trees minimize bending by placing the crown directly over the centre of the root stock, resulting in straight and non-bending trunks. In case of phototropism light comes most often only from one direction. This reduces the geotropic growth, hence trees to some extent “accept” bending (Mattheck, 1991). Generally bending stress is greatest at the tree base due to an anchor function of the roots above which movement of the trunk creates the greatest force (Smith et al., 1997). More vigorous tress with a higher metabolism create therefore more wood at the trunk bottom as a reaction to the heavy because bigger crown (Smith et al., 1997).

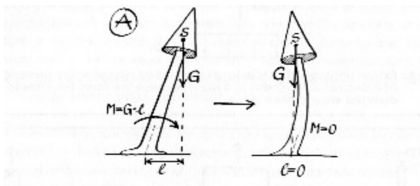


***Figure 13** - Bending as quality treat (Mattheck.*

Bending was measured in the following way: a meter scale is place on the forest floor, at 1.3 m, 3 m and 6 m distance from the place of germination the corresponding height of the stem was measured, in case the height of the tree outreaches the height of the mEssfix tool (8 m), the bend has been classified as slight. Moreover the cardinal direction of the bending was noted.

2.4.3.4 Spiral grain

The “significant geotropic corrections followed by internal bending stresses are accompanied by twisted growth which is called spiral grain” (Mattheck, 1991). There are two factors which generally contribute to the occurrence of spiral grain. The first is a response to bending stresses on slopes:

- Non-circular stems under bending loads tilt out of plane to increase flexibility, trunks with rectangular cross-section tip over if bent in direction of highest stiffness → combined bending and twisting to release mechanical energy, due to reaction wood at upper side of stem (Mattheck, 1991)
- Geotropic processes cause significant difference in axial length of concave and convex sides of the stem, twisted growth reduces the stress between annual rings → longer part of tree is bent around shorter part until ends are closer (Mattheck, 1991)

The second is a different factor why spiral grain occurs on upright trees: to some extent due to genetic reasons. The main assumption is that trees twist to reduce risk of splitting possibly explained by formation of small scale reaction wood (Mattheck, 1991). Trunks get an oval shape and therefore a twist develops to release stress. Moreover spiral grain might guarantee a more even distribution of upward flow of water and nutrient even if parts of root system are ineffective (Mattheck, 1991). Regarding the wood of trees spiral grain reduces the quality. In addition to that, spiral grain notches promote end-splitting after final felling (Mattheck, 1991).

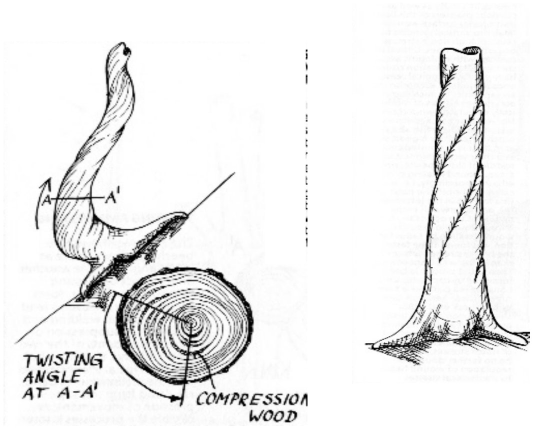


***Figure 14** – Spiral Grain on slopes and on straight planes (Mattheck, 1991)*

3 RESULTS

3.1 SITE AND FOREST TYPE

3.1.1 Prevailing vegetation

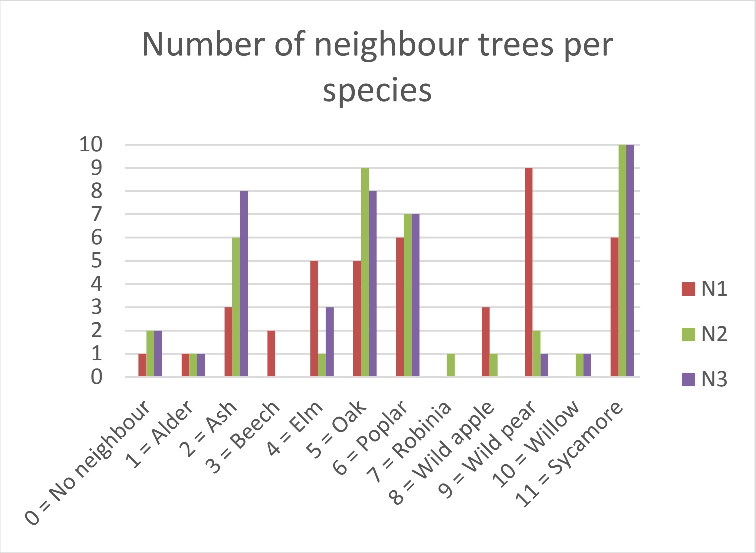
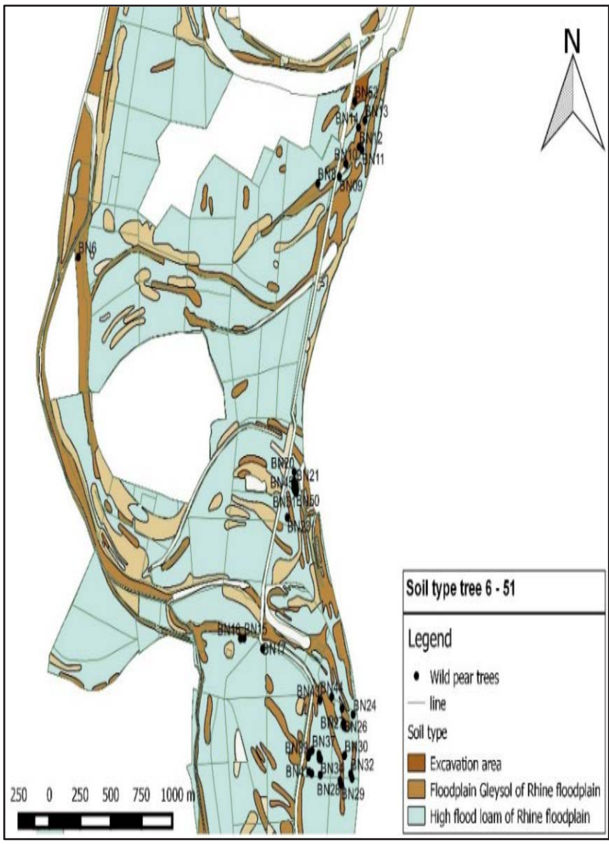


Figure 15 *– Number of neighbour trees per species*

The general forest type has been classified as mixed hardwood floodplain forest. The recordings for the direct neighbour trees revealed the following species distribution. The greatest number of closest neighbour trees is wild pears. This indicates that wild pears occur in small and relatively dense groups. In the direct proximity of wild pear trees also four tree species are commonly found in the study area: sycamore (*A. pseudoplatanus),* pedunculate oak (*Q. robur*), poplar *(Populus spp.*) and ash (*F. excelsior*). Poplar occurs in the same number as closest neighbour as in the more distant categories N2 and N3. For the other three species, the number increases with increasing distance. Interestingly, also elm (*Ulmus laevis*) can be found in a relatively high number as direct neighbour of wild pear trees. Next to these a variety of trees common in floodplain forests as alder (*A. glutinosa*), wild apple (*M. sylvestris*) and willow (*Salix spp.*) can be found. Some individual beech (*F. sylvatica*) and robinia (*R. pseudoacacia*) complete the species recorded. The "no neighbour" column indicates that wild pear trees are located in a gap with at least 15 m distance from the nearest tree.

3.1.2 Soil

The soil was classified in two ways: a field measurement indicating the substrate of the soil as silt, sand or clay and the percentage of the respective substrate were recorded. In addition to that, GIS data provided by the forest research station and collected GPS locations of the wild pear trees were used. The results of the GIS analysis are three maps based on soil type, soil moisture and stagnant soil moisture.



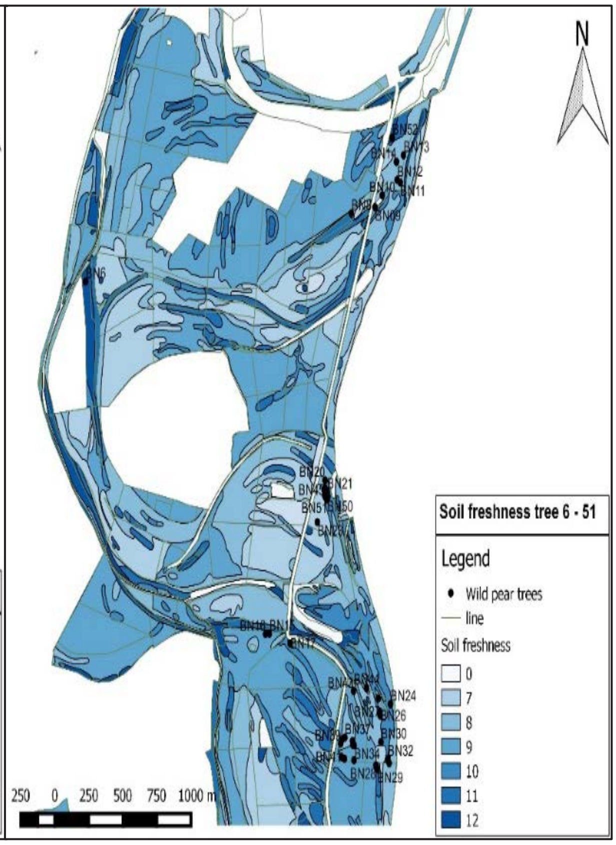


__Figure 16__ – Map soil type tree 6 - 51

__Figure 17__ – Map of soil freshness tree 6 - 51

Soil freshness	Explanation
0	Not mapped
7	Fresh
8	Highly Fresh
9	Extremely Fresh
10	Moist
11	From moist to wet
12	Wet

__Table 3__ – Explanation for map soil freshness

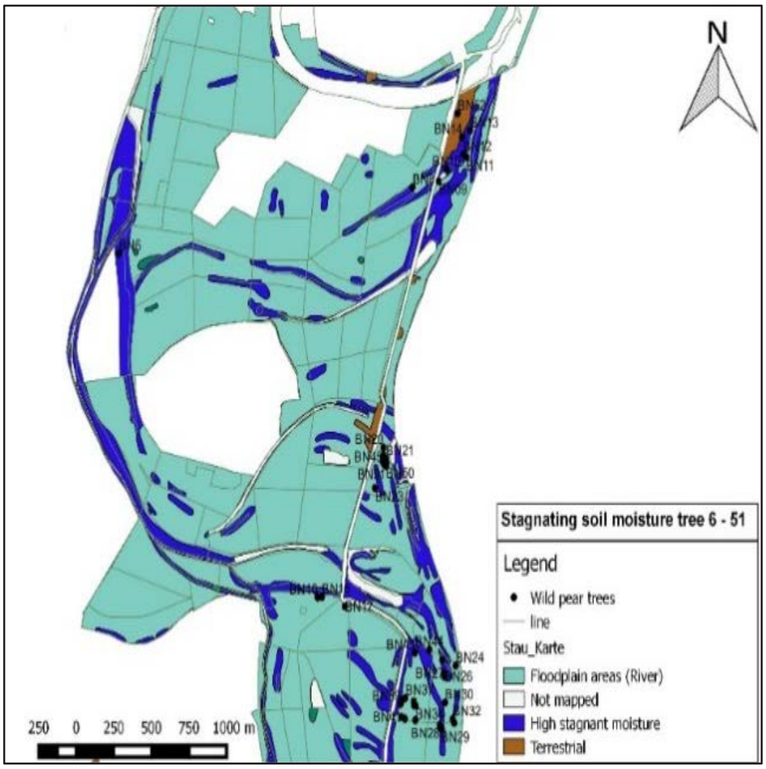


__Figure 18__ – Stagnating soil moisture tree 6 – 51

The location of the wild pear trees in the study area are widely spread, therefore only the trees 6 – 41 are displayed here[3]. When analysing the maps more in detail, a certain edge effect might be found referring to the location of the trees at the margins of respective soil types. However this detail is not further pursued in this study and leaves room for further investigation.

The GIS data describes the soil type summarizing soils originating from identical substrates with comparable soil development and dynamics as well as similar biological, physical and chemical characteristics as one soil type. This procedure aims at providing similar circumstances for the roots of the trees. The characteristics of the soil types are quantified, with regards to the nutrient cycle, by soil physical and chemical inventories as well as, if possible, stagnating and groundwater level (Anweisung, 1996)

The number of trees per soil type reveals that by far most trees are found on soils classified as high flood loam of the Rhine floodplain (29 of 41). Second soil type on which wild pear trees occur is a floodplain gleysol of the Rhine floodplain (6). Due to either lack of GPS data for the exact location, or wild pears outside the inventoried soil areas, some of the trees are not mapped (4). One tree is located on a soil classified as excavation area.

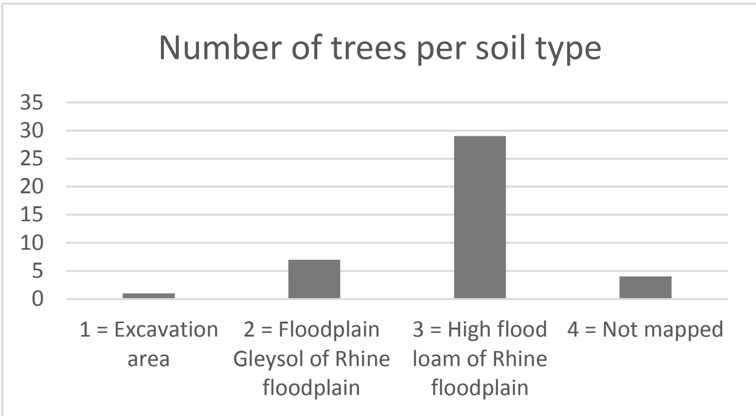


***Figure 19** – Number of trees per soil type*

The soil moisture is based on the relation of climatic hydrological balance (precipitation and temperature), geographical climate (influence of relief) and the ability of the vegetation to store water in the soil. In addition to that supplemental water is taken into account (Anweisung, 1996).

The classifications moist, from moist to wet and wet indicate locations with top-soils characterized by very high ground or stagnating water levels during the vegetation period. The major criteria for soils in this category is the duration of the high water

[3] Maps for trees 1-5 can be found in the appendix

level, in contrast to the stagnating water level, where merely the height of the water level is decisive (Anweisung, 1996).

More detailed, moist locations are characterized by a water consumption of the vegetation (>3 mm/day) which is completely covered by capillary water rising to the primary root area (<60 cm below surface) from the stagnating groundwater.

Locations which are classified as moist to wet have a stagnating groundwater level of 20 to 40 cm below surface during the vegetation period.

Locations which are classified wet have a stagnating groundwater level above 20 cm below surface during the vegetation period (Anweisung, 1996).

The number of trees per soil moisture class indicates that most wild pear trees can be found on highly fresh (9), extremely fresh (10) and moist (12) locations. Clearly for the given study area the wild pear seems to have an optimum under these soil conditions.

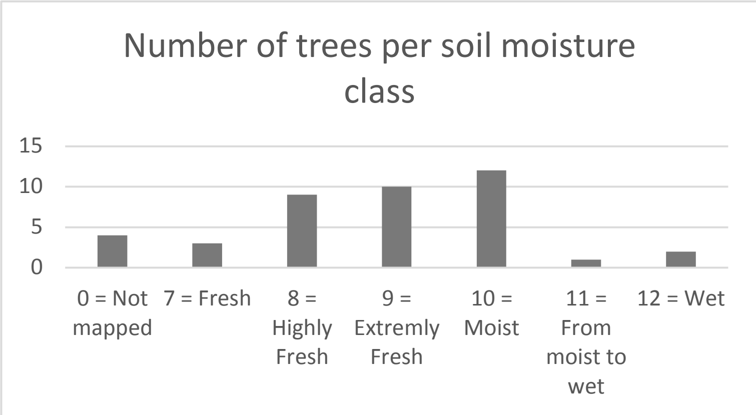


Figure 20 *– Number of trees per soil moisture class*

The GIS data shows that the level of stagnating soil moisture is mainly related to floodplain areas (26). Several trees can also be found in areas with a high stagnant moisture (7) as well as on dry soils (4) (called terrestrial). This supports the findings from the soil field measurement and indicates that wild pear performs well on soils with a high groundwater level.

The stagnant soil moisture, referring to the groundwater level, is grouped in several categories. The relevant categories are floodplain areas, areas with high stagnant moisture and terrestrial areas. The high stagnant moisture

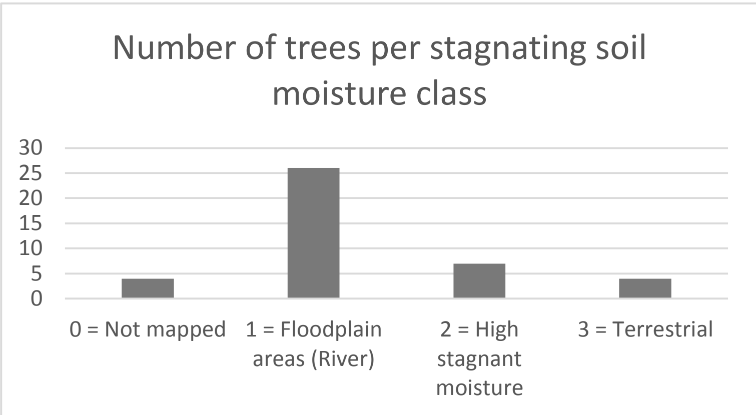


Figure 21 *– Number of trees per stagnating soil moisture class*

refers to a situation where the water level is 25 to 0 cm below surface level for a period of 4 to 7 months per year (Anweisung, 1996).

The field measurement indicates that overall a high clay content was found in the study area for the location of the wild pear trees. The vast majority of wild pear trees is located on soils with an estimated clay content of more than 30%. Only seven of the 41 pear trees are located on soils with a lower clay content. This indicates that wild pears prefer soils with a high clay content. The data clearly supports the results from the GIS data underlining that most wild pear trees are found on soils with high loam content.

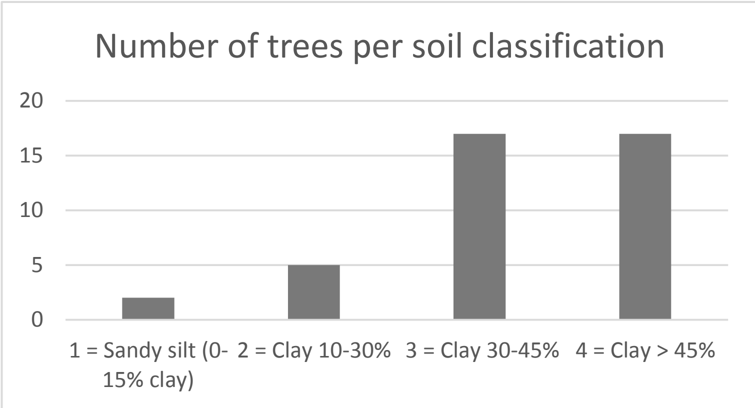


Figure 22 *- Number of trees per soil classification*

3.1.3 Location

The location is an important factor when it comes to modelling and discussing the crown dimension of a tree. As outlined above, open-grown trees have a different crown development than trees in close competition. Hence describing the growth situation for each individual tree is essential. In this study, the classes are forest, forest edge next to road in a closed forest, forest edge next to field, -dam, - gap and gap. The single class with most individuals is forest (20). One individual was next to a dam for flood prevention, two next to fields and six next to forest roads. The distinction between forest edge next to gap and gap is based on a minimum distance of 15 m for the closest neighbour for the classification as gap. However some trees at the edge next to gaps have almost similar growing conditions regarding competition. For modelling purposes, the classification

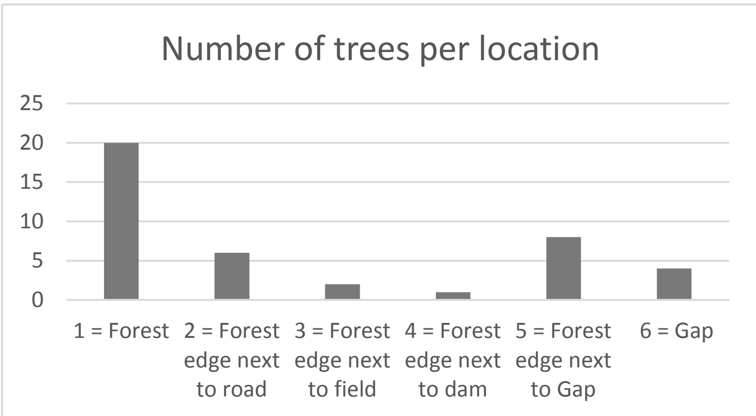


Figure 23 *– Number of trees per location*

could be simplified in trees inside the forest including individuals in the forest and next to forest roads (26), and trees in edge and gap situation with less competition (15).

3.1.4 Neighbouring trees

Neighbouring trees were recorded in order to describe the direct surrounding of the inventoried wild pear trees. One measure taken are cardinal directions of the neighbour trees from the wild pear tree. In total, most neighbour trees of all categories (N1, N2, and N3) are located in the North of the wild pears (37). Equally distributed are trees in the South and West (30) whereas in the East only 21 neighbour trees can be found. These numbers might indicate, that wild pear has a certain level of phototropism as most trees are in the North and the pear trees focus the growth in the direction where most sunlight is available. However from this values, there does not seem to be a strongly significant relationship and more data is needed.

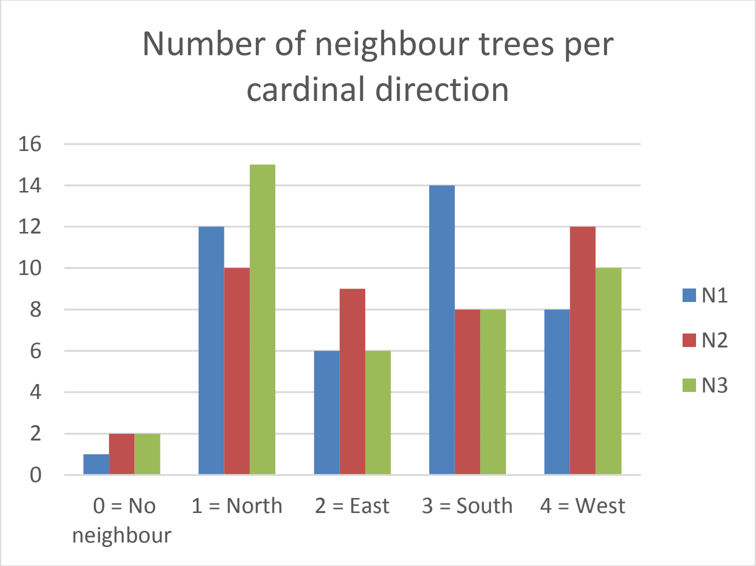


Figure 25 *– Number of neighbour trees per cardinal direction*

The second graph describes the height/DBH relationship of the neighbour trees versus the distance from the wild pear tree. The h/d ratio is an indicator for the stability of the trees, a ratio around 70 is considered to be stable, and values above that indicate that instability might occur. The majority of the neighbour trees have a decent stability;

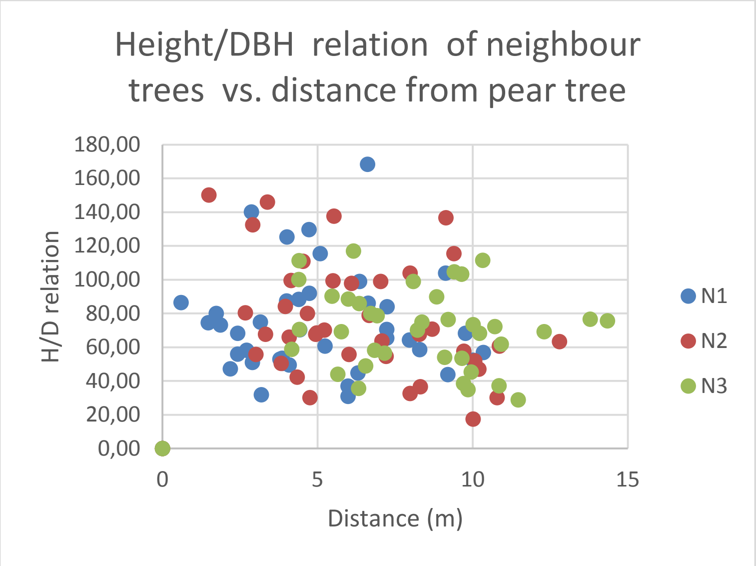


Figure 26 *– Height/DBH relation of neighbour treees vs. Distance from pear tree*

however several trees clearly might be susceptible to storm events, as they have an h/d ratio of more than 100. Mostly trees in direct proximity of the wild pears are somewhat more instable, than the trees further away. This might indicate that the direct neighbour needs to achieve a certain height quickly, and only then can focus of DBH increment. The explanation could be that crowns of wild pear are not easy to interfere with for other species, and only after reaching a greater height as the wild pear, the crowns can expand and generate a greater DBH increment.

To identify whether there might be a relationship between dimensions of the wild pear trees and the nearest neighbour based on the distance from the wild pear, the following graph indicates this relationship for different tree species. There are several interpretations obtained from the graph. First neighbouring sycamore trees have a clearly smaller DBH (4-6 times) than wild pears. Oaks have a greater DBH than wild pears of approximately the double, indicating that wild pears are able to survive in direct proximity of large oaks. Last but not least, the DBH relationship of closely neighbouring wild pear trees with the measured individuals is around 1, indicating that the DBH variation in close surroundings for the species is low.

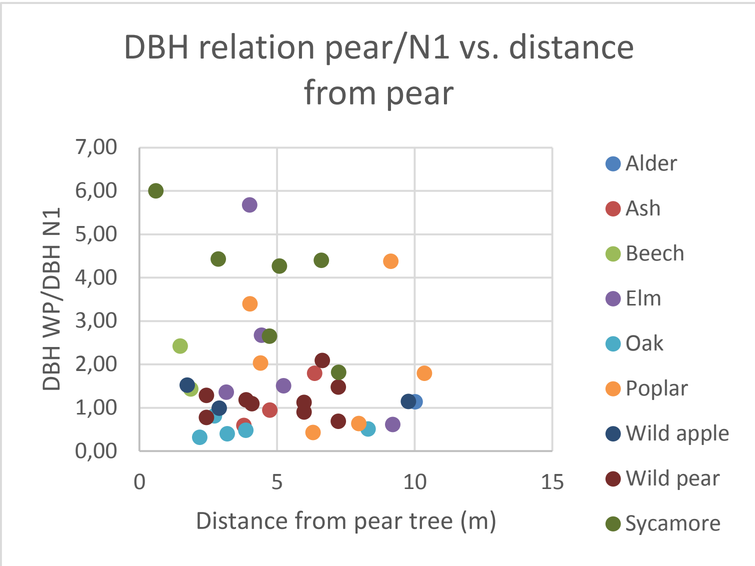


***Figure 27** – DBH relation/N1 vs. Distance from pear*

3.2 Tree measurements

For modelling purposes, quantitative data of the individual trees is needed. DBH, height and crown radius are the most important parameters, but also data on exterior wood qualities as height of lowest living branch (crown base), forking, spiral grain and bending are recorded and displayed below.

3.2.1 DBH and Height

The results for DBH and height measurements are displayed by including qualitative variables as location, soil classification, soil type, soil moisture and soil stagnating moisture. This is done in order to possibly identify patterns based on the qualitative variables. Moreover the annual average increment could be derived from the earlier data set in comparison with the new recordings.

The frequency of the diameter and height classes is displayed as histograms. The DBH frequencies follow roughly a normal distribution. Due to the random sampling and the relatively low number of individuals, in diameter class 30-40 cm there is a slight under-representation of trees. Trees with a DBH less than 10 cm are not represented in this study. The mean of the DBH for the population is 39 cm (Min.: 17 cm – max. 78.5 cm), the standard deviation from the mean is 15.5 cm.

For the height distribution mainly the same as for DBH holds true. In low height classes below 10 m only one tree was recorded. Most individuals had a height between 15 and 20 m. The mean of the height for all trees is 17.8 m (Min.: 9.9 m – max.: 31.6 m), with a standard deviation of 5.2 m from the mean.

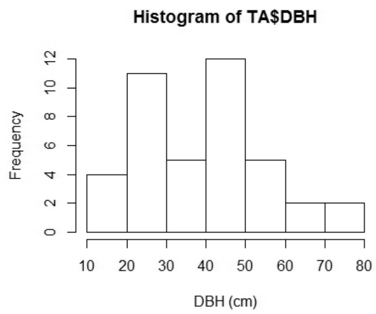


Figure 28 *– Histogram of DBH*

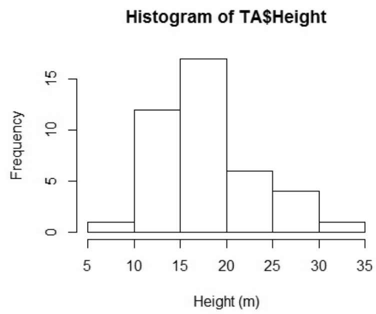


Figure 29 *– Histogram of Height*

The height of the individual trees is plotted against the respective DBH based on the growth location in Figure 31. It is evident that in this study trees in more open locations as forest edge next to dam, -gap and in gaps have small dimensions whereas the data from closed locations indicates large wild pear trees. Thus there might be two sub-groups in the data, trees in closed forest and in open conditions.

A second graph (Fig. 32) shows the height - DBH relationship based on the soil classification from the field measurement. Most trees no matter of which dimension are located on soils with high clay contents. For trees with greater DBH a lower clay content, or even sandy silt indicates a somewhat greater height in comparison with the clay content of >45%. However it does not reveal a clear trend to identify a more ideal soil class for the height and diameter development.

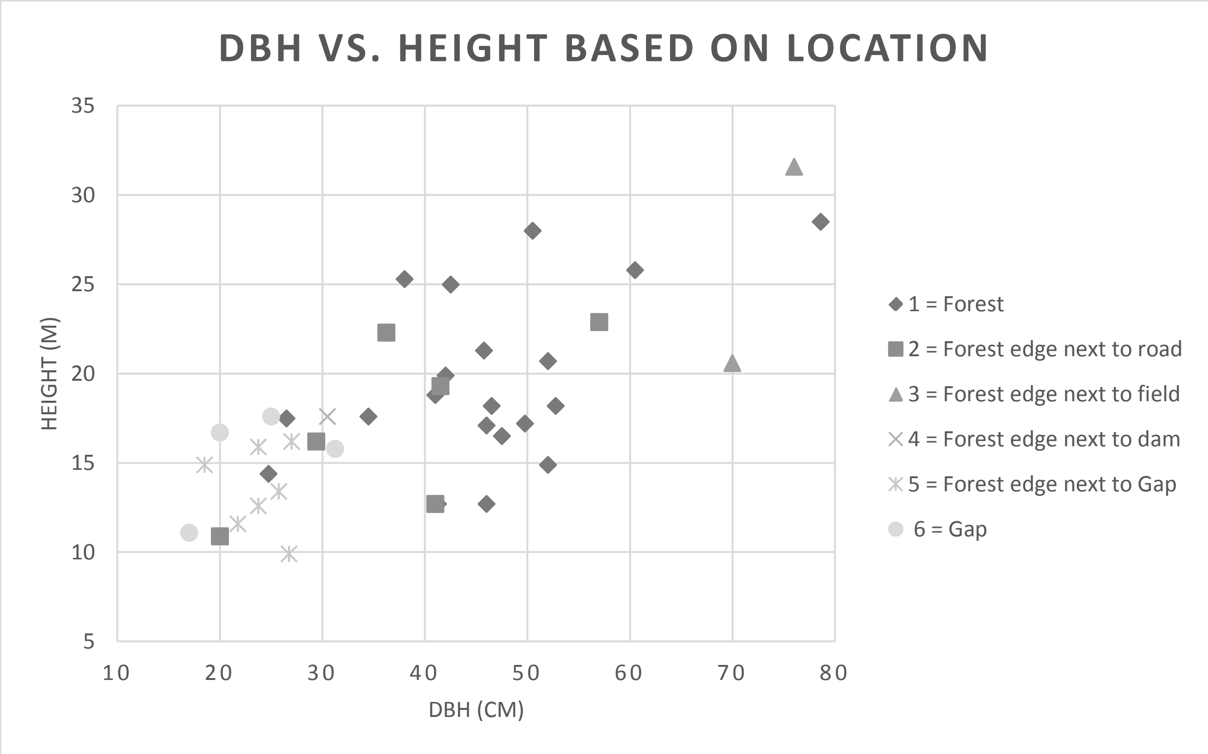


Figure 31 *- DBH vs. Height based on Location*

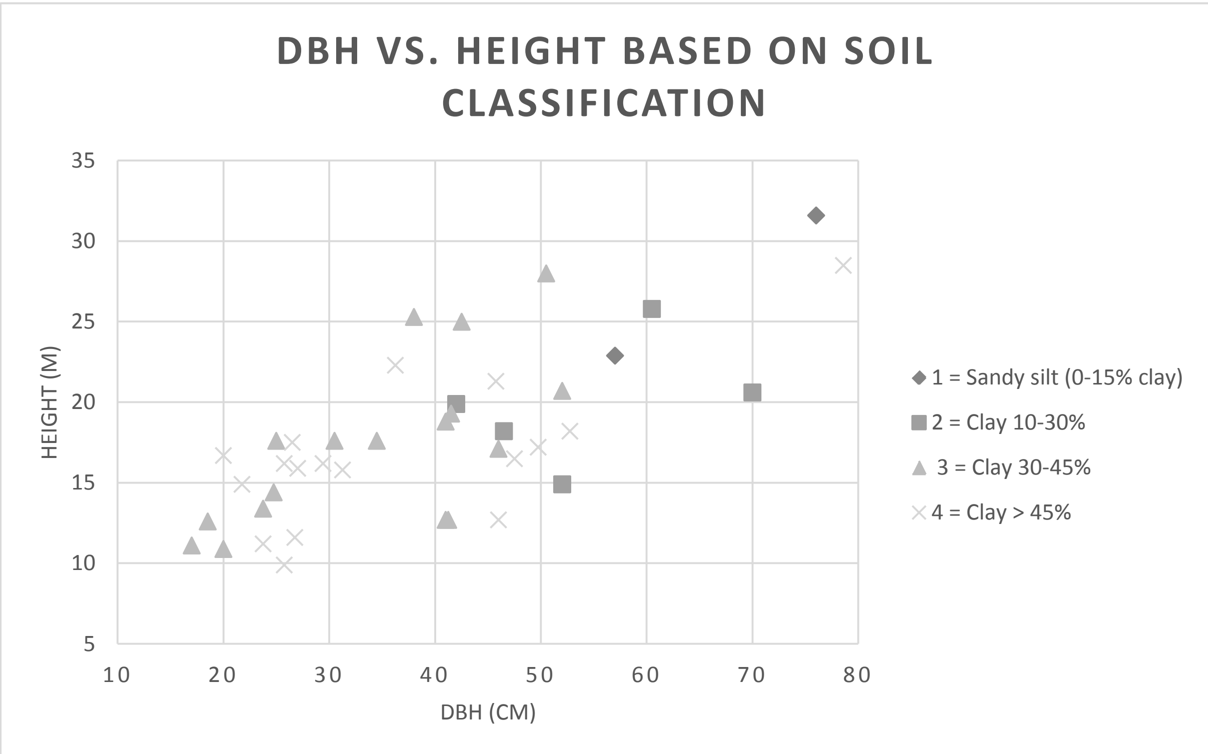


Figure 32 *– DBH vs. Height based on soil classification*

The following three graphs are based on the provided GIS data from state forest inventories. The majority of trees from all dimensions is found on high flood loam soils of the Rhine floodplain (Fig. 33). In DBH classes above 40 cm the trees located on this soil type have a greater height than the trees located on floodplain gleysols. The soil type excavation area solely occurs once, thus no comparison can be made. For statistical modelling the unequal distribution of locations most probably does not allow significant interpretations, but has not been tested.

The DBH and height relationship for the different soil moisture classes is displayed in Figure 34. Trees with a lower DBH than 40 cm show a relatively equal distribution of height among all soil moisture classes, only the wet soil class is not represented. Trees with larger dimensions (DBH > 40 cm) can be found on soils ranging from fresh to wet conditions, and seem to achieve somewhat greater heights on extremely fresh sites, than on the moist and wet soils.

The stagnating soil moisture is strongest represented in the floodplain areas next to rivers over all DBH and height dimensions (Fig. 35). More or less the same as for the soil moisture classes holds true, for a DBH greater than 40 cm, trees on floodplain areas might have a slightly greater height than trees on soils with a high stagnant moisture or on terrestrial locations. However the data for comparing these effects is insufficient as only four trees of the study population are located on terrestrial sites.

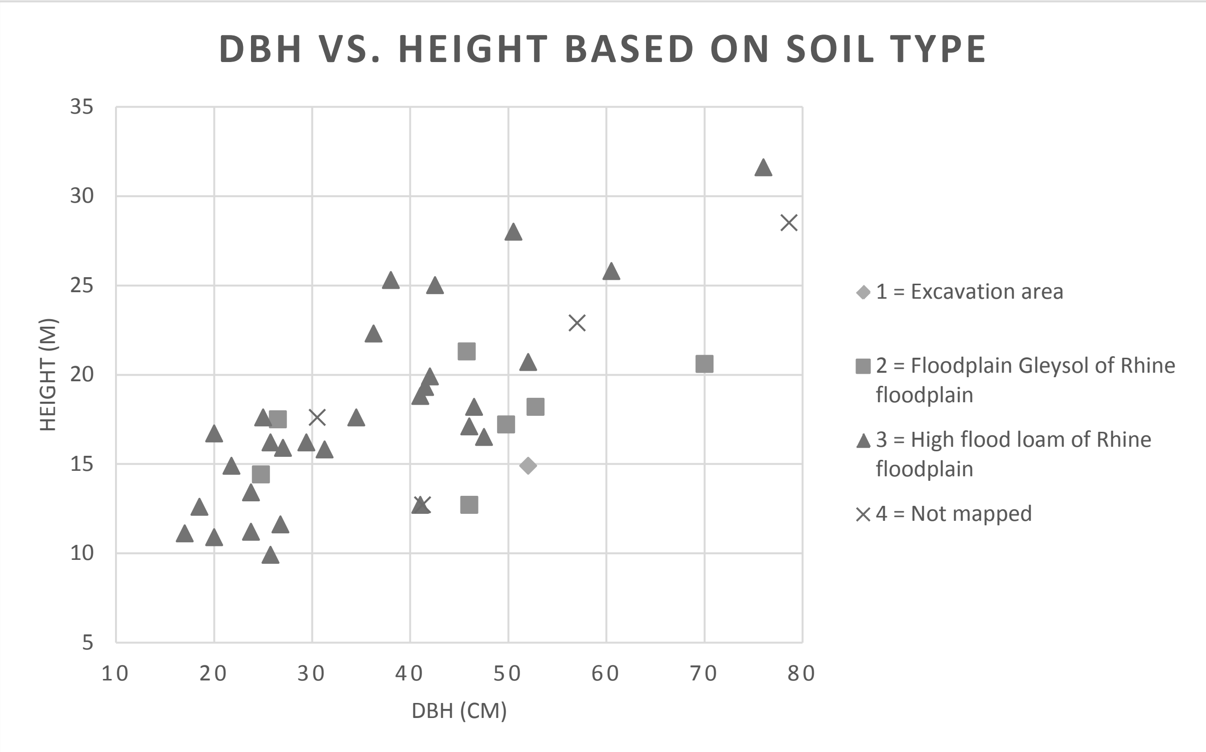


Figure 33 *– DBH vs. Height based on soil type*

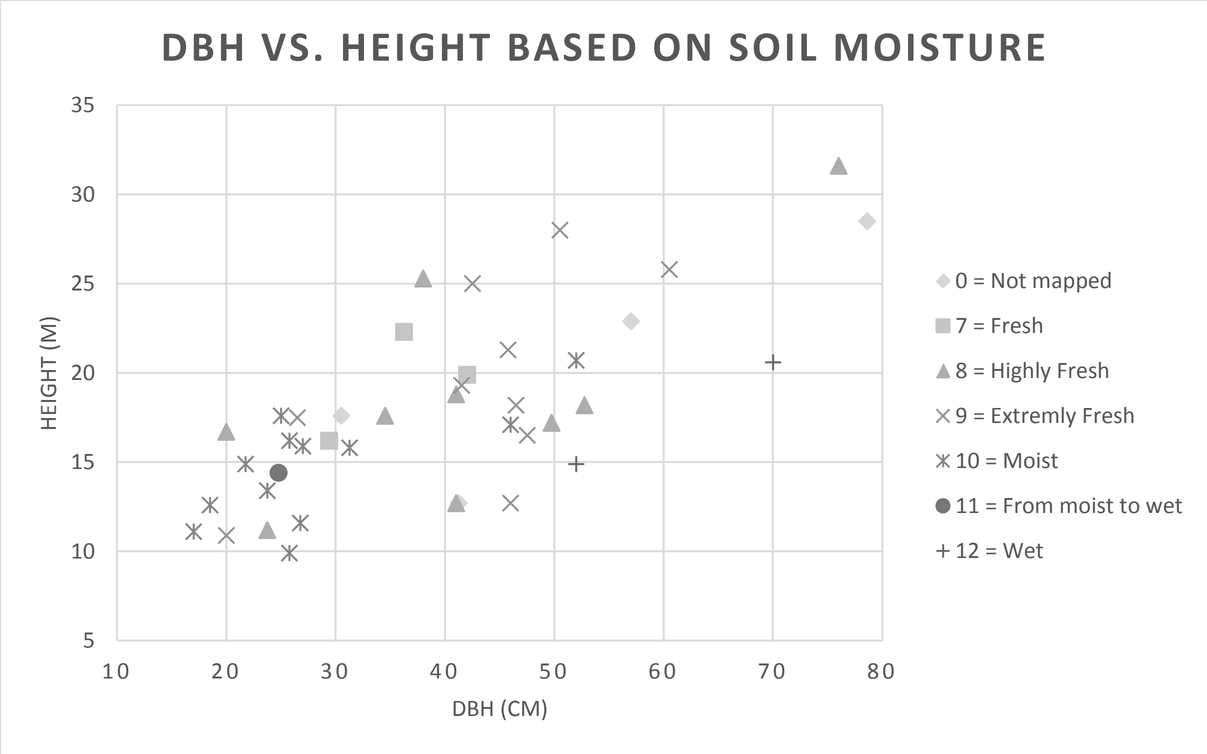


Figure 34 *– DBH vs. Height based on soil moisture*

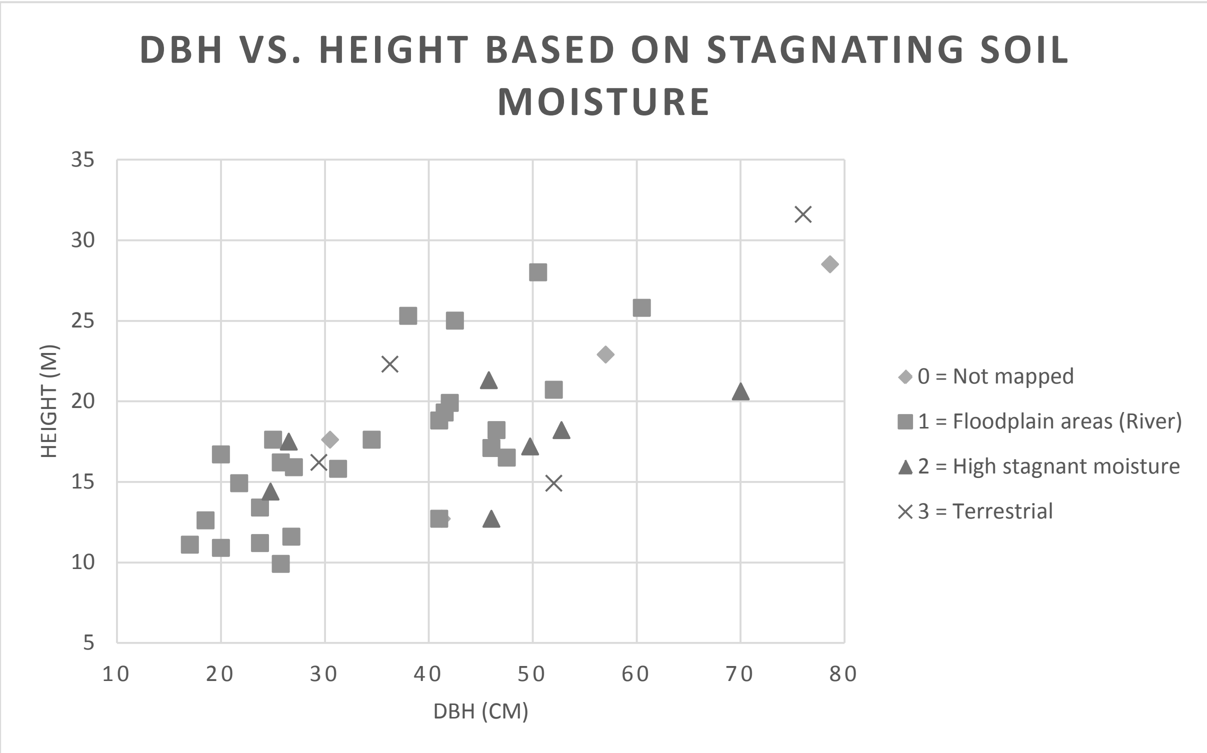


Figure 35 *– DBH vs. height based on stagnating soil moisture*

One important parameter to indicate the development of trees is the annual DBH increment. For this study, 18 trees have recordings from the earlier inventory. Thus for the period from 1988 to 2015 it is possible to calculate the annual average DBH increment. Overall, the growth is slow and the increment low as expected for the species. A maximum of 0.3 cm per year could be reached. The majority of wild pear trees has an average increment of 0.1 to 0.2 cm per year which is stable over all DBH classes. There cannot be any statements made about the growth in different growing locations due to the low number of trees measured twice.

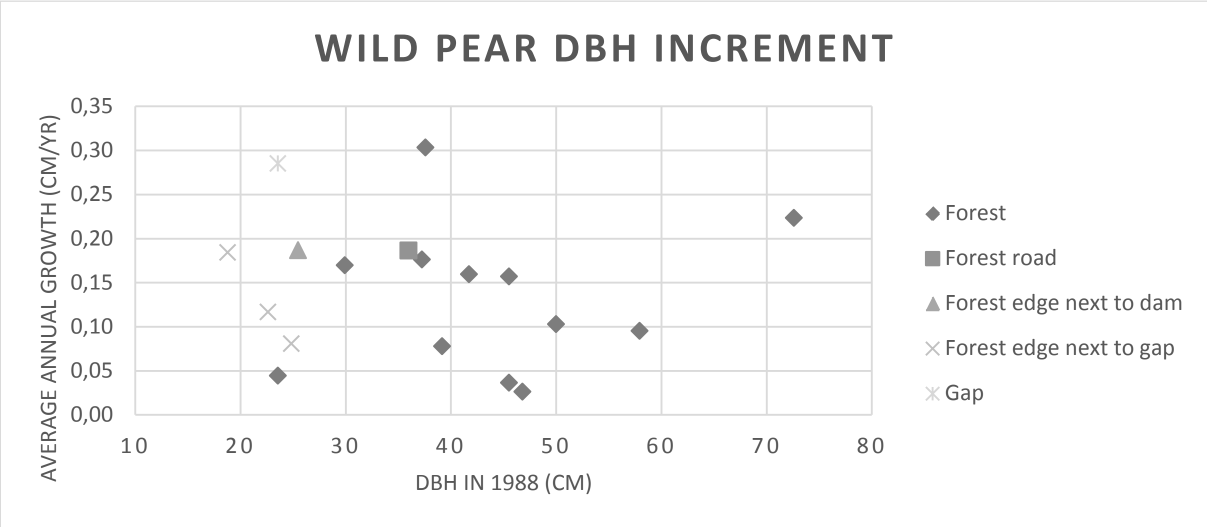


***Figure 36** – Wild pear DBH increment*

3.2.2 Crown Radius

As pointed out, the crown radius (CR) is an important measure to be able to develop silvicultural strategies as thinning regimes based on the stand density.

The histogram of the distribution of crown radii shows a normal distribution for sizes from two to eight meters. The mean of the crown radius is 4.4 m with a standard deviation of 1.3 m. The minimum recorded crown radius is 2.2 m and the largest 7.2 m.

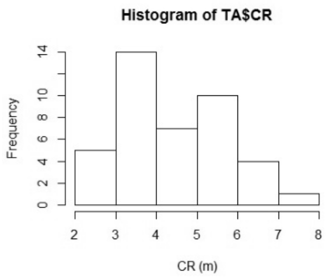


***Figure 37** – Histogram of crown radius*

As well as for DBH and height, also for DBH and crown radius, graphs with qualitative parameters have been established. For the CR – DBH model development the analysis of the following graphs is of uttermost importance.

The CR increases with increasing DBH, as expected from the literature review. Trees with a smaller CR are found in lower DBH classes, whereas trees with a greater DBH have a greater CR (Fig. 38). Interestingly, trees with small crown dimensions are represented in this study in more open conditions (edge/gap), in contrast to that large trees are found inside the forest. This needs to be interpreted carefully, the low number of data recordings might be one reason for this. In addition to that, the forest history is largely unknown, hence changes in the location are not represented, only the current state. This for instance makes it impossible to know whether trees which are now in the forest have prior developed in gaps or edges. However for modelling purposes the location factor should be included and statistically analysed.

To identify parameters for the CR - DBH relation, also the soil classification from the field measurements might be of interest. The graph (Fig. 39) however does not reveal any clear trend, trees with both small and large CR are found more or less equally distributed among all soil classes. Thus an inclusion of soil class as a parameter does not seem necessary.

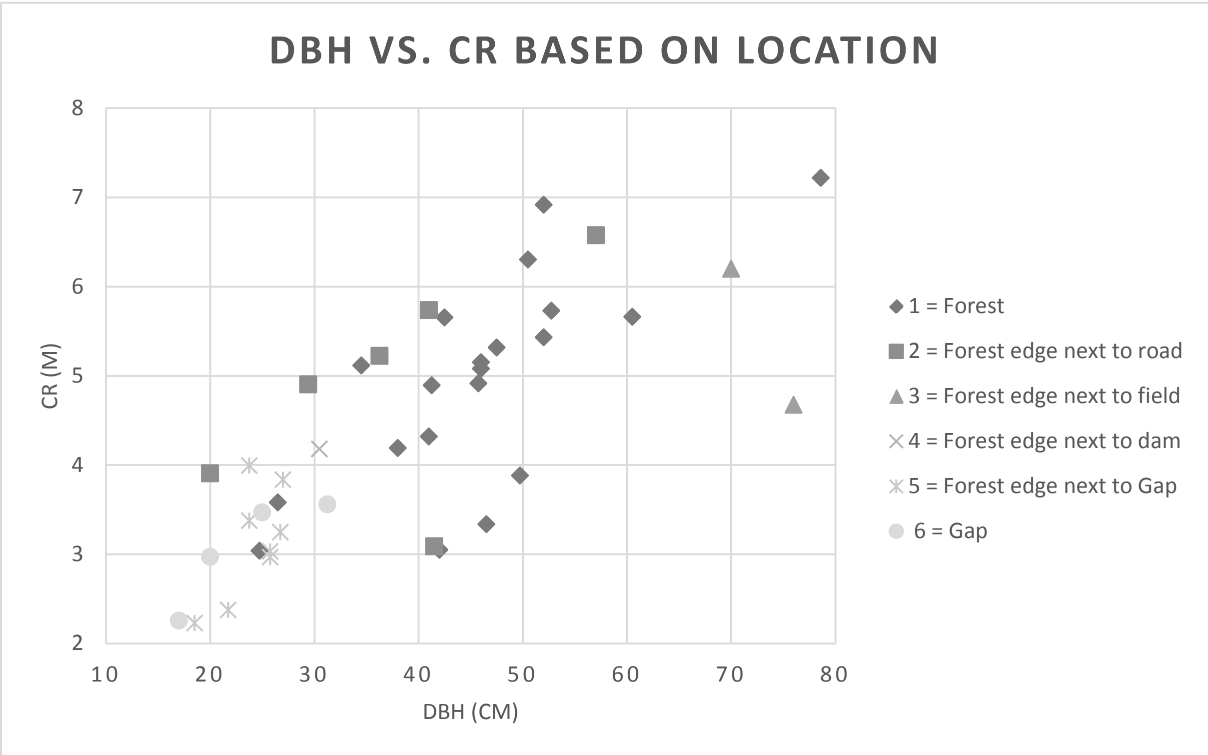


Figure 38 *– DBH vs. CR based on location*

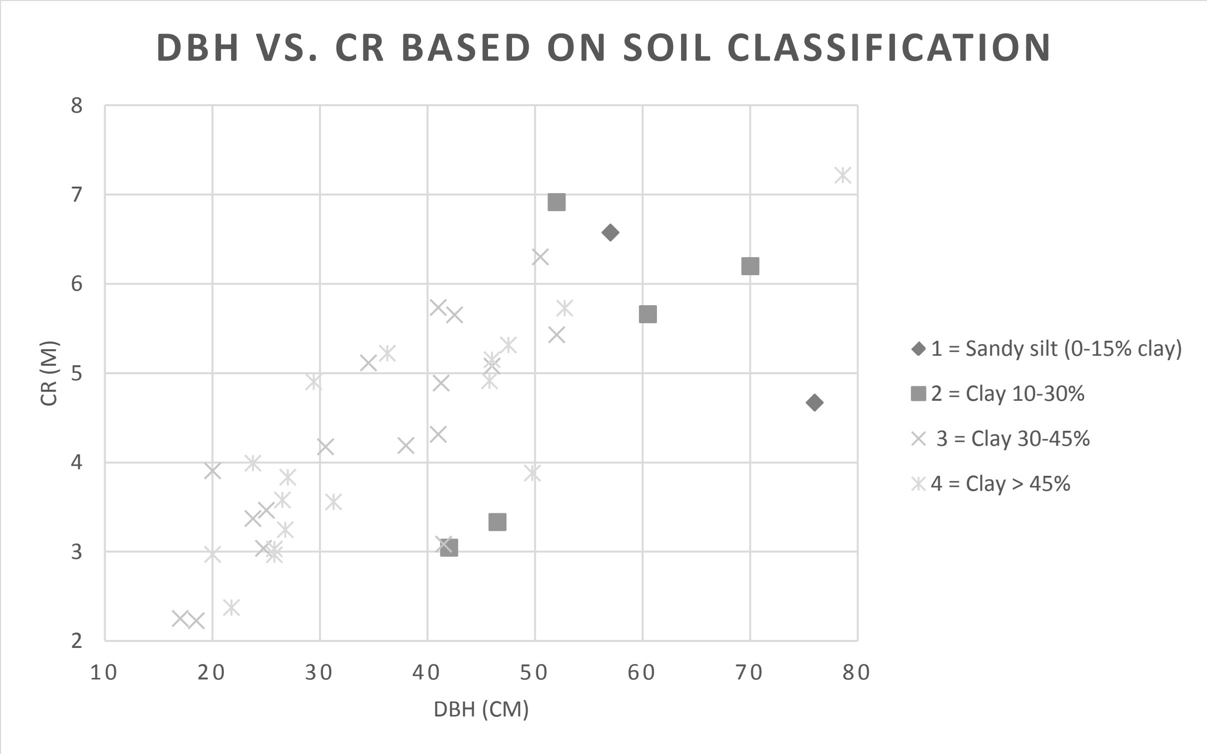


Figure 39 *– DBH vs. CR based on soil classification*

The soil type taken from the GIS inventory data is plotted for the CR and DBH relation (Fig. 40). A similar interpretation as for DBH and height can be taken from this graph. Most trees are located on high flood loam soils and floodplain gleysols of the Rhine floodplain. There is not a clear differentiation of CR-size between the two soil types.

The soil moisture displayed for CR and DBH does not reveal a clear trend or pattern (Fig. 41). Trees with smaller CR and DBH are found on moist locations, whereas larger trees are more frequent on fresh to extremely fresh sites. However there are no clear differences in CR-size when trees have the same DBH for any of the soil moisture classes. Hence the soil moisture is not regarded as a necessary parameter in the modelling.

The third parameter from the GIS data which could be relevant is the stagnating soil moisture (Fig. 42). The graph shows the CR in relation to the DBH for the three different stagnating soil moisture classes. In contrast to the height - DBH relation, the graph might indicate that trees on terrestrial sites have a slightly greater CR than trees in floodplain areas or sites with high stagnant moisture. As in this study there are only four recordings of terrestrial sites, this indication cannot be further pursued, more data is required. Based on this analysis, the stagnating soil moisture does not seem to be relevant for further modelling.

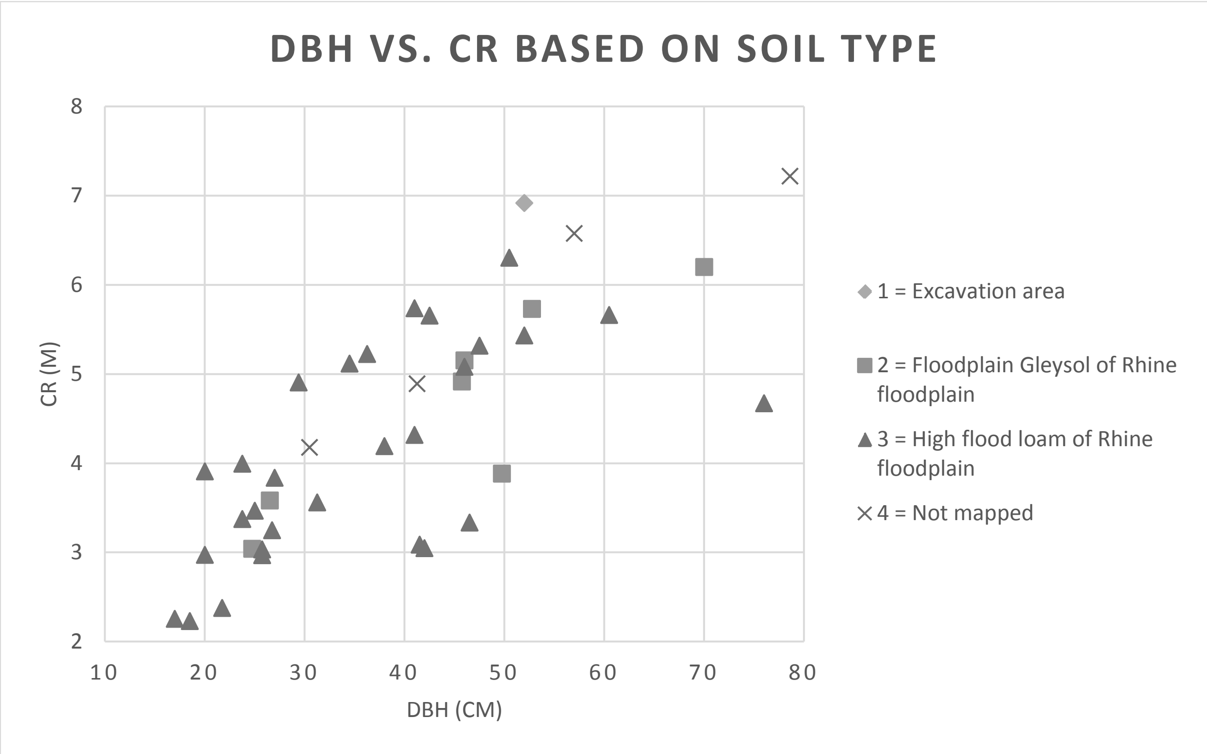


Figure 40 *– DBH vs. CR based on soil type*

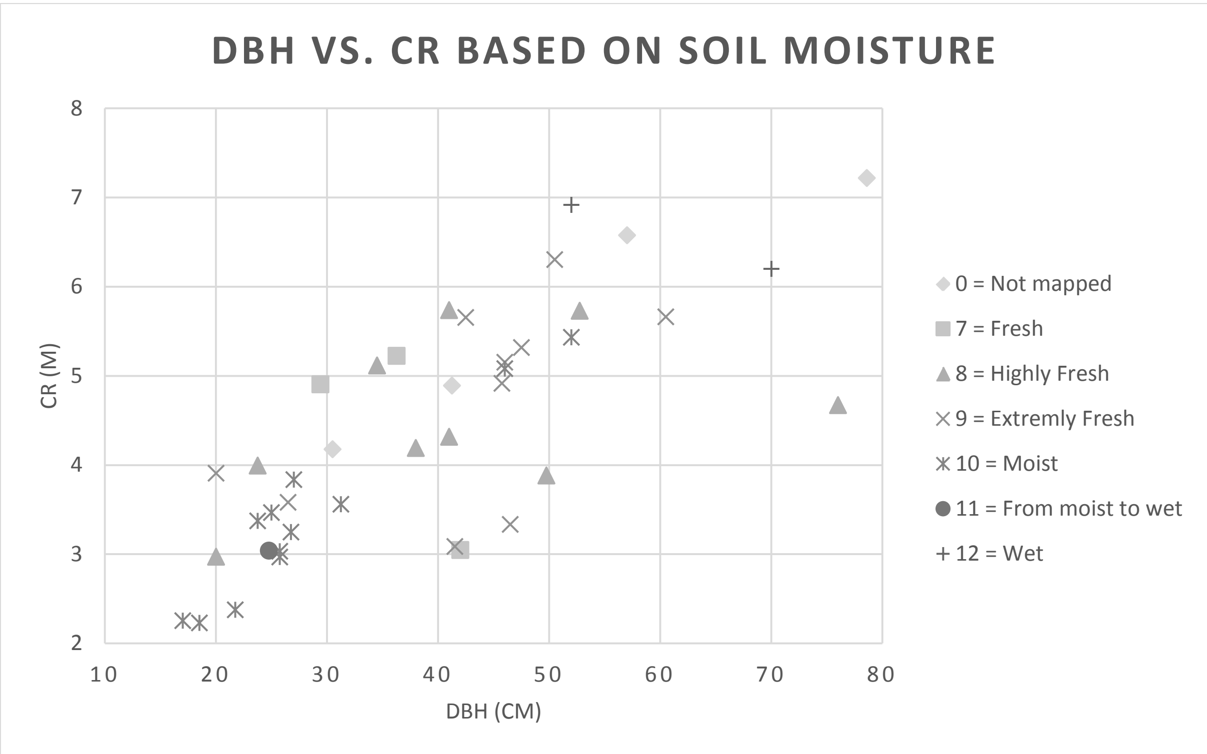


Figure 41 *– DBH vs. CR based on soil moisture*

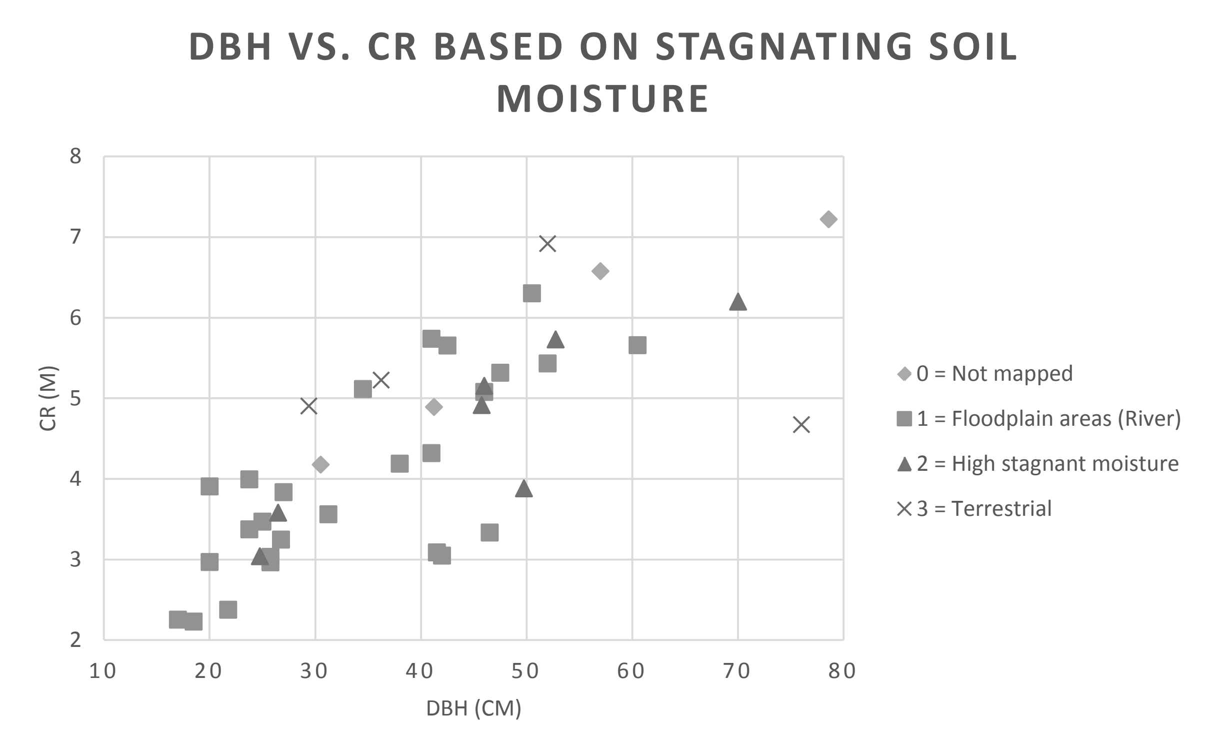


Figure 42 *– DBH vs. CR based on stagnating soil moisture*

3.2.3 Quality characteristics

The quality characteristics include the lowest living branch (crown base), forking, bending and spiral grain. To some extent measurements have been not performed as described in the method section, hence the validity might be questioned.

3.2.3.1 Lowest Living branch

An important measure for the clear bole of a tree which is desired for high-quality timber production is the height of the lowest living branch. The graph displays the height of the lowest living branch against the total height of the tree. Several trees seem to have a crown base at the ground level, this is the result from a measurement error. Trees in gap and edge conditions had epicormics, which have been recorded and reduced quality of the data. Overall, there still is a trend visible that higher trees have their crown base at a

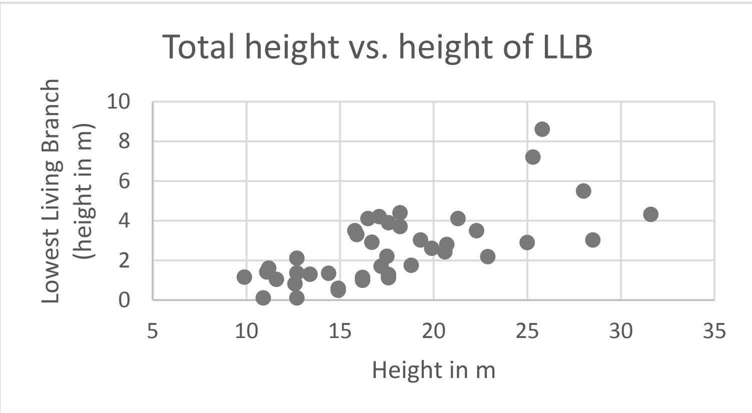


Figure 43 *– Total height vs. height of Lowest Living Branch*

greater height. Due to the inconsistent data, the lowest living branch is not further included in the modelling.

3.2.3.2 Forking

The importance of forking for the wood quality with regards to the production of high-quality timber has been pointed out. Especially reaching straight trunks of 3 m or ideally 6 m is a major target for the silviculture of wild pear. 13 of the 41 trees had a fork. The height of the fork is displayed against the total height of the tree. For quality production purposes especially forks below 3 m and 6 m are negative, in the study population only three wild pears had a fork below 4 m height. All other forks have a height above 6 m, although several are very close, which still might result in a value loss of the trunk as the forks reach further

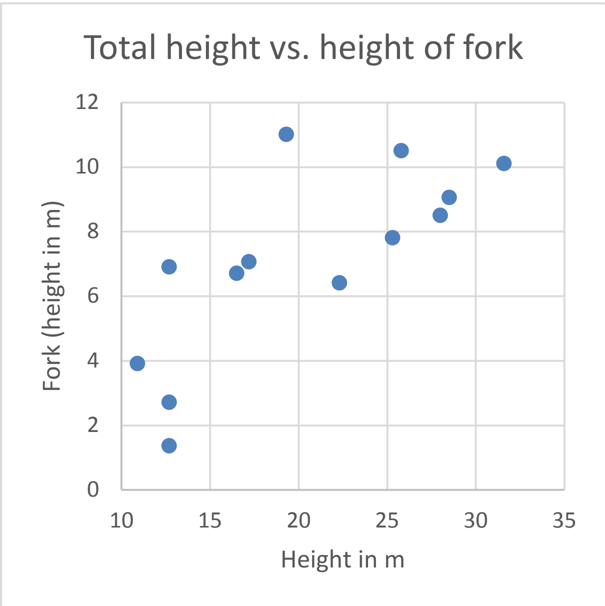


Figure 44 *– Total height vs. height of fork*

Figure 45 *– Wild pear with fork*

down.

3.2.3.3 Bending

Bending is a quality characteristic which reduces the value of the timber due to the reduction of straight wood. The study recorded the quantity and direction of trees bending. Overall, more trees are bending (26) than straight (15). Most of the bending trees are classified as slightly bending, in total seven trees are strongly bending, most of them south (5).

The majority of slightly bending trees leans south as well (14). Hence bending is clearly a factor which needs to be incorporated in silvicultural strategies for wild pear.

Moreover the fact that most trees are bending south could be an indication for a certain level of phototropism.

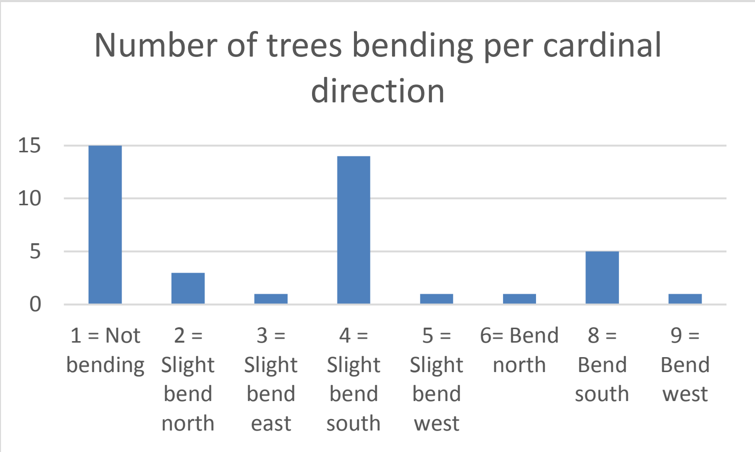


***Figure 46** – Number of bending trees per cardinal direction*

***Figure 47** – Bending wild pear*

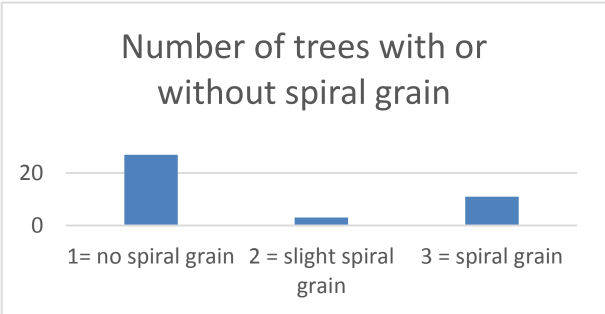


***Figure 48** – Number of trees with or without spiral grain*

3.2.3.4 Spiral grain

Spiral grain is related to the formation of reaction wood and thus reduces the wood quality. Overall the majority of trees did not have signs of spiral grain (26). If the trees showed spiral grain, mostly it was a clear and strong (11). Only four trees had signs of slight spiral grain. As spiral grain can result from growing location or genetics, the inclusion of spiral grain in silviculture is important, but the prevention per se difficult. Clearly, spiral grain needs to be a quality sign and trees which are twisting and form spiral grain need to be removed in thinning operations.

3.3 MODEL DEVELOPMENT

The model development for crown radius was carried out using the open-source statistic software R. The detailed output results of the software including residual plots can be found in the appendix.

Not only the displayed models have been tested, a variety of predictors had been included. However for reasons of practicality, only the most relevant models are shown. For instance a model based on biggest CR in relation with DBH and location has been tested to find a possible edge effect[4].

Basically three full models have undergone an F-test. A simple linear one without transformation, a full logarithmic model with transformation of dependent and independent variable and a semi-logarithmic with only transformed predictor variables. For all transformations the natural log (ln) has been used.

Regarding the inclusion of a categorical predictor variable as location, a dichotomous dummy variable has been used. To test the effects of location the different recorded locations have been summarized as “Forest” including forest trees and trees in the forest next to roads as well as “Edge” for all locations with a clear edge or gap effect. “Edge” has been set 0 and “Forest” 1.

The results from the stepwise variable selection can be found in the table below.

Full Model	**Linear Model**	**Logarithmic Model**	**Semi-Logarithmic Model**
Data	Pfälzer Rheinauen	Pfälzer Rheinauen	Pfälzer Rheinauen
DBH	Significant	Significant	Significant
Height	Not sign.	Not sign.	Not sign.
Location	Not sign.	Not sign.	Not sign.
DBH:Height	Not sign.	Not sign.	Not sign.
DBH:Location	Not sign.	Not sign.	Not sign.
Height:Location	Not sign.	Not sign.	Not sign.
Adjusted R^2	0.5716	0.6101	0.6054
Variance (σ^2)	0.7049	0.0356	0.6492
Formula after F-test	CR= 0.06474*DBH + 1.86768	$CR = e^{(0.61388 * \ln(DBH) - 0.76810)}$	CR = 2.5953*ln(DBH) - 4.9190

Table 4 *– Results from modelling*

[4] Find the results in the appendix

All three models reveal that solely the DBH is a significant predictor for the CR. Neither height nor location or the interactions have shown a significant relationship. The intercept and slope of the final models has been determined for further purposes of developing silvicultural practices. This means that the research hypothesis H_0 can be accepted, whereas the research hypothesis H_1 is rejected.

Not only because of the highest coefficient of determination, but also due to the distribution of residuals, is the logarithmic model regarded best among the three. The residual plots show a clear homoscedastic distribution, there is no apparent trend present. Moreover they follow a normal distribution around the zero-line. In addition to that the Normal-QQ plot indicates that especially around 0 the theoretical quantiles follow a normal distribution. The R^2 of 0.6101 gives an indication of a significant relationship. For the logarithmic transformation bias, as pointed out above the variance has to be taken into account, for the constructed model it is 0.0356. The retransformation has to be corrected by: $\frac{\sigma^2}{2} = 0.01781$. The final relation can thus be formulated as:

$$CR = e^{(0.61388*\ln(DBH) - 0.76810 + 0.01781)} = e^{(0.61388*\ln(DBH) - 0.75029)}$$

Where CR in m and DBH in cm.

For field measurements including all uncertainties due to random sampling, the result is satisfying and can be used for further analysis. The non-significance of the location factor is to some extent counter-intuitive, as an influence of crown competition respectively free development would have been expected. The relatively low number of observations in addition to the unknown history of the stand development can to some extent explain this result. Trees which have been recorded in gaps might have been in closed forest situations and vice versa.

For complimentary reasons data of open-grown pear trees on different sites from a prior study has been tested, however due to major uncertainties including comparability of species, site and genetic origin the results are not included for silvicultural recommendations[5].

[5] Find the result of the modelling including Austrian data in the appendix.

4 DISCUSSION

The discussion focuses on interpreting the results from the field study as well as including further thoughts on silvicultural practices for wild pear.

The validity of the following silvicultural practices is reserved to a narrow forest type, as the described floodplain forests are not very large in size and relatively rare in central Europe. Only in conditions similar to the study area the descriptions hold true. This means the applicability is limited to sites characterised by a highly fresh to moist soil with a high clay content (more than 30%) and a high groundwater level resembling soil characteristics of a high flood loam soil close to rivers. The climatic conditions are restricted to the temperate zone with an average annual temperature of about 10°C and an annual precipitation of 500 to 800 mm. Moreover rather closed forest conditions in contrast to open situations are required for the silvicultural practices. However with slight modifications and application of further knowledge of the site, also other growing conditions might profit from the proposals on silviculture presented.

4.1 SILVICULTURAL TREATMENTS IN MIXED AND PURE WILD PEAR STANDS

For the production of high quality wood from wild pear four main features for could be pointed out (Hein, 2007):

- Target diameter at point of final felling set by forest manager
- Rotation period in which the target diameter should be reached
- Number of future crop trees per ha
- Height of clear bole

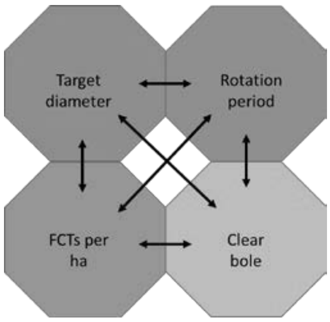


***Figure 49** – Features for high quality wood production*

By determining the target diameter the number of crop trees at final felling and the required time (rotation period) can be calculated. All of the four features are interlinked between each other. In the present study there are two major shortcomings to employ this concept to the full extent. The target diameter for wild pear can be set, also the number of FCTs can be determined. However the rotation period cannot be analysed due to the lack of information on age of the wild pear trees. Due to nature conservation in the study area as well as required complicated annual ring analysis it was not possible to determine the age of the recorded trees. For the wild pear species with slow growth, the determination of annual rings based on age-driller is almost impossible. Second major shortcoming for a description of a full silvicultural practice for wild pear is the lack of information on the height of the clear bole, i.e. the correct measurement of the height of the crown base. Thus the silvicultural descriptions are limited to density and distance functions, which nevertheless allow an appropriate description of silvicultural practices for wild pear.

As pointed out, for silvicultural considerations tree spacing is of major importance for crown development.

The model as major goal of the study assumes a logarithmic relationship between crown dimensions (crown radius or crown diameter (CD)) and DBH. Other studies have pointed out similar results, however only one has focused on pear species. The result from the other study is displayed in the table below for comparative reasons:

Species	Author	Type of model	Data	Formula	R^2
Pyrus spp.	Abt and Hochbichler	Logarithmic	Selected open-grown trees	$CD = e^{(0.853*\ln(DBH)-1.177)}$	0.964
Pyrus pyraster	Asbeck	Logarithmic	Random sampling	$CR = e^{(0.61388*\ln(DBH)-0.75029)}$	0.6101

Table 5 *– Comparison of crown dimension models for pear*

As the mathematic relation between diameter and radius is simple, the results of this two studies could be used as comparison. However it has to be pointed out that the data from Abt and Hochbichler is from a completely different site type and open-growing conditions which have been selected carefully, also explaining the extraordinary high R^2 value. Moreover the species are not wild pear per se, but pear species which have been cultivated to some extent. The most significant reason is that the genetic material is from a different origin than the one included in the present study.

The absolute comparison indicates that in lower diameter classes, the deviation between the two studies is greater than in larger diameter classes.

This might be explained by the highly fertile floodplain-river sites in contrast to the less fertile sites from the Austrian study. Also less data from the smaller diameter classes is available for the present study. However in the greater DBH classes the results are relatively comparable, supporting the developed model.

DBH (cm)	CR - Asbeck	CR - Abt
20	2.97	1.98
30	3.81	2.80
40	4.55	3.58
50	5.21	4.34
60	5.83	5.06

Table 6 *– Absolute comparison of CR*

From the derived model, the theoretical tree spacing and number of stems per ha can be calculated. Tree spacing calculations have been for instance described in Hemery et al., 2005. The maximum occupied space can be calculated by the crown of each tree at any mean diameter assuming no overlap:

The number of stems= 10000m²/space per tree (m²) at a given DBH.

The space per tree $= CR^2 * \pi$. Hence based on $CR = e^{(0.61388*\ln(\mathrm{DBH}) - 0.75029)}$, the following theoretical numbers can be developed:

This includes a diameter of 3 cm for young trees to give an indication of the number of stems shortly after stand establishment. However one has to be careful operating an extrapolation of the model to this kind of extreme values. The most reliable range of the model is from 17 to 78.5 cm DBH, as for the upper and lower extremes presented in the table no data has been recorded. Still assuming that the model is correct, the figures can give a first indication towards the silviculture of wild pear.

DBH (cm)	CR (m)	Space occupied per tree (m²)	No. of trees per ha
3	0.93	2.70	3705
10	1.94	11.84	845
20	2.97	27.72	361
30	3.81	45.60	219
40	4.55	64.92	154
50	5.21	85.39	117
60	5.83	106.81	94
70	6.41	129.06	77
80	6.96	152.05	66

Table 7 *– Space per tree and number of trees/ha based on model*

To set a target diameter strongly depends on the wishes of the forest manager. In this study for further silvicultural consideration the target diameter is set at 60 cm. There are two major reasons for the selection, first from a practical point of view most sawmills would be able to handle stems of this diameter, secondly for greater diameters the upper limit of the recorded data is reached. Hence an extrapolation would be necessary which might result in less reliable results. Risk considerations could also lead to the decision for lower target diameters, but largely economic considerations as calculation of net present value (NPV) and demands of the forest manager are responsible for the selection. Based on the numbers derived from the developed model, a maximum of 94 FCT per ha at DBH 60 cm is appropriate for wild pear under the given conditions.

For comparative reasons the same numbers are given for selected tree species (from Hemery et al., 2005):

Species	**DBH (cm)**	**Crown radius (m)**	**Space occupied per tree (m²)**	**No. of trees per ha**
Fraxinus excelsior	60	6.5	132.2	76
Populus	60	6.35	116.3	86
Acer pseudoplatanus	60	5.95	111.2	90
Quercus spp.	60	5.55	96.5	104
Prunus avium	60	5.5	95	105

Table 8 *– Comparison of other tree species CR, Space and number per ha (from Hemery et al., 2005)*

This indicates that the result of 94 FCT’s per ha for a CR of 5.83 m at 60 cm diameter is a realistic calculation, however the numbers from Hemery et al. are based on trees from different growing conditions. Comparing them directly with the result from the present study would be misleading. Assuming that the crown radius of wild pears increases in open conditions a maximum of approximately 90 trees/ha is close to optimal. This maximum is based on assuming a square lattice and circular crowns, if the trees would be arranged in a different spacing layout, possibly more individuals would fit per ha.

4.1.1 Mixed or pure stands

The question of mixed or pure forest stands for high-value timber production is complicated and much discussed among scientists. Growth and yield comparisons between pure and mixed species stands is complicated and rarely exist in practice. Most indications are taken from statistic models which show a variety of results (Agestam et al., 2005) and focus on coniferous species. Therefore it is not exactly feasible to select only a mixed or a pure stand in the further discussion.

Reasons which clearly would favour a pure stand are the lower skills required for management and the more systematic silvicultural approach. In case of wild pear, mixed stands could offer a reduction of risk due to reduced spreading of forest pests to which species of the rosacea family are susceptible. Moreover the long rotation period of wild pear might lead to an interest in intermediate income from thinnings from other tree species. For a detailed comparison of pure or mixed stands of wild pear in terms of growth and yield as well as economic income, more information and resources are required. Due to the mentioned reasons it is regarded viable to discuss both options in the following a pure stand of wild pear and a mixed stand.

Based on the recorded data a mixture of poplar and wild pear is considered to deliver an interesting option for the silvicultural practice. The poplar species might vary, but most frequent in the study area were asp (*Populus tremula)* and silver poplar (*Populus alba)*, thus in the following it is referred to these two species. The first reason why poplar is selected is that it occurs frequently as a neighbour tree of wild pear in the suitable growing conditions. In addition to that it is equally numbered in the vicinity of wild pears no matter of the distance. This leads to the conclusion that both species can thrive in close as well as more distant neighbour ship conditions without outcompeting each other. The fact that poplar is a light-demanding species which would not lead to heavy shading effects on wild pear contributes to the selection of poplar. Secondly from an economical point of view it is an advantage that poplar is fast growing. This gives the option of several rotations in gaps between the wild pear trees which deliver additional and more frequent income in contrast to pure stands. This based on the management goal of pulp or biomass for poplar. Thirdly, poplar can regenerate in a vegetative way, hence after harvesting there is no essential need for repetitive planting, but the sprouts can be used. Fourth based on descriptive observations from the field work, only few wild pears with poplar as neighbours formed epicormic branches, the highest quantity of epicormics was found with oaks as neighbours, the lowest with sycamore. As pointed out a higher level of complexity of silvicultural treatment is required to manage a mixed forest stand.

4.1.2 Stand establishment

The planting density of pure or mixed stands is decided based on practical concerns as availability of planting material, machine or manual planting options and economic considerations by the responsible forest manager. Due to risk of browsing and high costs of planting material, fencing of the planting area is considered necessary depending on the quantity of game in the respective area. Timing of the stand establishment depends on the ground water level situation, in the described forest type high water or flooding situations might be present, which are inadequate for stand establishment. The size of wild pear stands should be restricted to rather small areas, for pure stands a range from 0.5 to 1 ha is regarded appropriate, for mixed stands the areas might be bigger. This size is chosen due to the fact that wild pear does not form large, pure connected stands under the recorded conditions, but rather occurs in small to medium-sized groups.

There is a large variety of options for planting density and layout, first a more classical option for a pure stand is discussed. A square lattice is assumed as planting layout referring to planting in straight lines with a fixed planting density. The theoretical number of seedlings in a pure wild pear stand per ha would be 3086 with a planting density of 1.8 x 1.8 m. This spacing is based next to aspects of practicality on the optimal distance at target DBH of 60 cm assuming a circular crown projection. The root collar diameter could have a range from 1 to 3 cm, which can be discussed and adapted to the specifics of available planting material and is not necessarily authoritative, but other broadleaved species seedlings have similar diameters (Johnson et al., 1986). For a pure stand, the maximum number of FCTs as derived from the CR model of 94 per ha could be achieved.

In mixed stands of wild pear and poplar even more options for planting density and layout exist.

Species	Number of rows	Seedlings per row	Total
Wild Pear	16	50	800
Poplar	34	50	1700

Table 9 *– Seedling numbers for mixed row planting*

The first option would be based on economic and practicality issues, assuming row planting of wild pear and poplar on a square lattice. This has the advantage of easy access for harvesting and intermediate operations in the stand. A greater distance between the rows could result in a reduced number of required seedlings, moreover if a fast-growing species as poplar is included; the early growth will close the canopy faster than in a pure wild pear stand. Thus a planting density of 2 x 2 m with a total of 2500 seedlings is regarded appropriate. This would mean in a square lattice 50 planting rows in total. To avoid total removal of wild pear rows at an early stage, it is optimal that every third row is wild pear and in between two rows of poplar. This is based on the modelled 3 m CR of wild pear trees at a DBH of 20 cm, which would be given the right space at this planting layout. However there are still enough wild pears for later selection. In addition to that, regarding a crown radius of approximately 6 m at 60 cm DBH, this planting layout has a total of 64 FCTs at final felling in theory.

Species	Number of plots	Seedlings per plot	Total
Wild Pear	13	64	832
Poplar	12	64	768

Table 10 – Seedling number per plot

The second option is more strongly based on ecological requirements of wild pear. As found in the study area, by far the greatest number of closest neighbour trees of a single species is wild pear. This indicates that wild pear occurs in groups in direct vicinity. Thus planting groups of wild pear mixed with groups of poplar delivers another option for establishing a heterogeneous stand. In close-to-nature forestry this is believed to be beneficial as a more spontaneous forest structure is created. The planting plots could have a size of approximately 20 x 20 m, with a planting density of 2.5 x 2.5 m. A lower planting density is chosen because in a plot of 400 m² only four FCTs at target DBH 60 cm could be left for final felling anyways (Fig. 50). Per planting plot 64 seedlings would be required and 13 plots of wild pear could be placed on a hectare plus 12 plots of poplar. Regarding the CR at target diameter, per plot of wild pear four FCTs could be kept until final felling, resulting in a total of 52 per hectare.

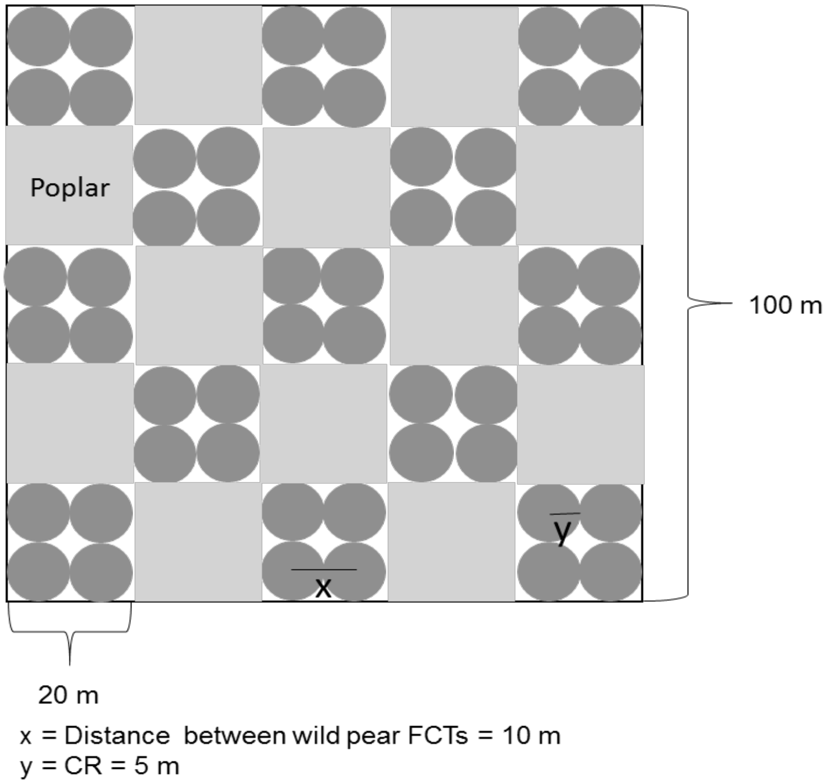


Figure 50 *–Spacing at final felling (DBH = 60 cm) for group planting of wild pear mixed with poplar, planting density 2.5 x 2.5 m*

4.1.3 Intermediate treatments

Intermediate treatments refer to silvicultural actions carried out in the time between stand establishment and regeneration cutting. They can include different options, in this study based on the aim of high-quality timber production; especially pruning and thinning are of interest.

4.1.3.1 Pruning

The production of high-quality timber requires branch-free wood at final felling. Most broadleaved species in contrast to coniferous have a self-pruning function, referring to the loss of dead branches. This self-pruning is of importance for the establishment of the stand as well as for the silviculture. At a dense, early development stage, wild pear is assumed to create a branch-free trunk of considerable height which forms the most valuable part for timber production in the long run. However, wild fruit tree species are among the broadleaved tree species which have a low or non-existent level of self-pruning and thus demand an exceptional and labour intensive silviculture for the production of high-quality timber. In addition to that, wild pear trees form epicormic branches, which need to be removed regularly. To go in detail of practical aspects of pruning as tools and methods is beyond the scope of this study[6]. The actual pruning layout is based on the demands and economic considerations of the responsible forest manager.

There are two ways of pruning discussed here, reflecting the options for stand establishment. Pruning is cost and labour intensive and thus commonly restricted to FCTs.

As pointed out, in dense stands a certain level of self-pruning of wild pear trees is assumed. The minimum requirement for branch-free size is 1/3 of the diameter of the final trunk (Springmann et al., 2011). For a target diameter of 60 cm, this means pruning has to take place the latest at a DBH of 20 cm. This is a classical form of pruning and removes mainly dead branches. Following the first removal of dead branches, occurring epicormics have to be removed at regular intervals. The pruning height needs to be considered based on the growth of the individual trees. For high-quality production a minimum of 3 m branch-free trunk at the final felling is required. In case of straight and vigorous trees, the next recommended height is usually 6 m, high-pruning in exceptional cases can reach up to 12 m. For wild pear high-pruning is most probably not relevant due to the low total heights. Most important is to only prune to a maximum of 1/3 of the final height to create a large living crown for

[6] Practical recommendations: Springmann et al., 2011 or Smith et al., 1997

maximum DBH increment at a later stage. In the discussed stand establishment options, this form of pruning could be especially applied in the pure wild pear stand.

In stands which do not necessarily have dense situations due to wider spacing, earlier pruning also of living branches can be carried out. For wild pear the first pruning operation could already take place at a DBH of 5 to 10 cm, to maximize the quantity of branch-free wood at final felling. Especially the formation of strong branches competing with the main shoot and leading to formation of unwanted reaction wood could thus be minimized. However at this early stage almost no quality signs of young trees are visible, hence pruning would be required on a large number of trees, which is certainly more cost and labour intensive. On the other hand more high-quality wood per individual tree could be achieved. Economic considerations are needed to support the selection of one or the other pruning method. The height of the pruning in this option is restricted by the total height of the trees, but as in the other pruning option, it should never exceed 1/3 of the final height. Also when applying this pruning option, possible epicormics need to be removed regularly. The second described pruning method could especially be applied in a group planting layout as described for mixed stands.

4.1.3.2 Thinning and spacing

In the production of high-quality timber from broadleaved tree species usually a two-step strategy comparable to QD-strategy (Hein, 2007) is implemented:

- First stage: self-pruning and development of quality signs at reduced DBH increment in early age to reach clear bole with good wood properties
- Second stage: release of FCTs and strong DBH increment in short time

The general idea for the thinning regime of both pure and mixed wild pear stands is a selection system. This refers to an early selection of FCTs based on their individual quality aspects as vigour, straightness, bending and forking. Straight and vigorous trees should be selected, bending and forking trees removed. After the selection of FCTs the silviculture focuses on creating growing conditions close to optimum, including a gradual removal of competitors for free crown development and thus maximal DBH increment. The thinning intensity and timing depends on the forest manager and individual tree and stand development. The descriptions here can give theoretical indications based on the available knowledge and should be only used as guidelines.

For a pure stand the implementation of a selection system would mean to let the wild pear develop quality signs as straightness and height growth before the first thinning operation. The first thinning is focused on the removal of bad quality trees with low vigour which hinder other trees in their optimal development. In the case of wild pear special attention has to be drawn to bending trees which could interfere with the growth of their neighbours. The DBH for a first intervention could have a range from 5 to 7 cm depending on the characteristics of the stand.

A second thinning is required at a DBH from 15 to 20 cm, including the selection of FCTs. Spacing and distribution of the FCTs should already be taken into consideration at this stage, the distance between trees should be 5 to 6 m. Approximately 350 trees per ha should be left.

At a DBH 35 to 40 cm the competitors of the FCTs should be removed and depending on their quality could already be sold as quality timber. About 160 trees per ha should remain. Following this a step-wise removal of competitors should take place, to finally have the number of desired FCTs with the defined target diameter per ha. Next to quality characteristics, spacing is the most important aspect to consider, thus at a target DBH of 60 cm, the distance between the FCTs should be 10 to 12 m. The developed model gives the appropriate CR per DBH and thus could be used as indication for the spacing.

For mixed stands, the selection system of FCTs as described above for the wild pear stands is also valid. Obviously the number of FCTs has to be adapted accordingly. In addition to the selection and spacing criteria for wild pear, additionally the development of the poplar rows or groups has to be taken into consideration. Ideally, the treatments for wild pear could to some extent be combined with the thinning and harvesting operations of poplar.

For instance, depending on the goal of the poplar management, it could be feasible that in combination with the first intervention in the pear groups at a DBH of 7 cm, the poplars are already harvested for biomass. However this option might not be the best practice, as the wild pears would be exposed to more open conditions, reducing self-pruning and increasing risks.

More ideally the poplars could be thinned at the same time of the first thinning of the wild pears and be harvested at the second intervention. The focus of the thinning should no matter the goal of the poplar be still to support the growth of the wild pear FCTs, thus a removal of competing poplars is required. Following the harvest of poplars their sprouting ability could be used, and a second generation of poplar could be established, depending on the canopy closure of the wild pear trees. If planted in groups, certainly more than one generation of poplar can be harvested during the rotation of the wild pear. In contrast to that with row planting this might be impossible due to the distance between the rows and a complete canopy closure of the wild pears.

To give more detailed and precise thinning recommendations, the respective stand development has to be taken into consideration. From a practical point of view, the thinning depends on the individual tree growth and thus should not be carried out in a solely schematic way. Therefore these recommendations should be reviewed based on further research and adapted accordingly.

4.1.4 Regeneration cutting

The regeneration cutting refers to the final removal of the FCTs. Designing the method of regeneration cutting includes the question of the establishment of the next generation. In other broadleaved tree species silviculture a gradual opening of temporary gaps in the stands allows the new generation to regenerate naturally. For wild pear this might be more complicated due to the mostly vegetative regeneration.

Vegetative regeneration has in contrast to regular seeding the possible disadvantage of instability as seedlings do not develop a full own root system. In contrast to that, it might offer an interesting option for the establishment of a new generation based on a coppice-like method, called stumping-back (Pope and Mayhead, 1994). After the FCTs have been harvested, it is assumed that sprouting from the stumps will occur. A few years after the sprouts have grown, quality signs can be detected. In case the sprouts show insufficient quality, they can be cut back to the stump and thus regenerate over. The lost time in contrast to directly planting after final cutting could be in economic terms compensated by the lower establishment costs, as no seedlings have to be purchased. Stumping back however is connected to rot issues which might occur, commonly it is accepted that higher stumps deliver a greater risk of rot than stumps cut close to the soil. There is no practical knowledge of the risk of rot for wild pear, more research is required to analyse the regeneration potential of this method for this tree species.

In contrast to focusing on natural regeneration, obviously there is also the option to replant the areas and establish a new generation of wild pear artificially after the final felling. However it is regarded realistic to be able to regenerate the stand naturally and thus prevent planting costs, if interest and research focuses on this issue.

The rotation period until the final cutting is assumed to be comparable to other wild fruit tree species as *Sorbus torminalis.* The best indication of the rotation period can be taken from the DBH increment measured in the field. The maximum annual DBH increment in the recorded trees is 0.3 cm. Assuming a target diameter of 60 cm, this would mean a required time of 200 years until final felling. The management history of the recorded trees is largely unknown, lately there has not been any management as releasing operations etc. taken place and the area is mainly designated for nature conservation, thus it is assumed that the described silviculture would lead to a shorter rotation period. Still more than 100 years are most probably required to produce valuable timber of the dimensions mentioned here. More data and tree ring analysis would be required to give more precise indications of the rotation period.

4.2 Alternative Practices for the use of wild pear

Despite the focus of this study to give recommendations for growing wild pear for high-quality timber, also alternative practices for the use of wild pear are shortly mentioned here.

Agroforestry systems have attracted a rising interest in temperate regions lately, especially as landscape elements as well as for the conservation of valuable broadleaf species. Wild pear might deliver an option for agroforestry practices in combination with the production of non-wood forest products. In case of agroforestry systems a highly intensive management focuses on a low number of trees combined with the production of biomass or fruits, nuts etc.

Wild pear could for instance be planted in combination with Salix species or hazelnut on soils with a high clay content and a high level of freshness. For example planting of only 100 trees per ha in a 10 x 10 m grid in tubes and intercropping them with Salix in between rows could generate interesting results. A constant income from biomass production would supplement the owner during the long rotation period of wild pear. In addition to that wild pear would grow in open conditions ensuring optimal crown development. Intensive management as constant pruning and supporting stability of the trees with staking is possibly needed to generate valuable timber.

Alternatively wild pear might be intercropped with hazelnut. Hazelnuts could deliver an extra income during the rotation period of wild pear. Additionally the shrubs might reduce the pruning intensity as they shade the trunks and thus prevent formation of epicormics to some extent. However, hazelnut shrubs might compete strongly with the wild pears especially at an early stage. This problem could be solved by regularly cutting the shrubs to ensure optimal growing conditions for the high-value trees.

5 Conclusion

Wild pear is an interesting species for the production of high-value timber. Different alternatives of silvicultural treatments are established and proposed based on the empirical data recorded. Especially guidelines for optimal spacing based on models of crown radius have been developed. More research and practical experiences are necessary to give detailed recommendations for silvicultural practices of wild pear. Based on the scattered and rare occurrence of the species it is regarded essential for the genetic conservation to develop economically profitable silvicultural systems. Due to the largely neo-liberal focus of current forest management, only if the species delivers beneficial values for forest managers the continued existence of wild pear in the forest landscape of today can be ensured.

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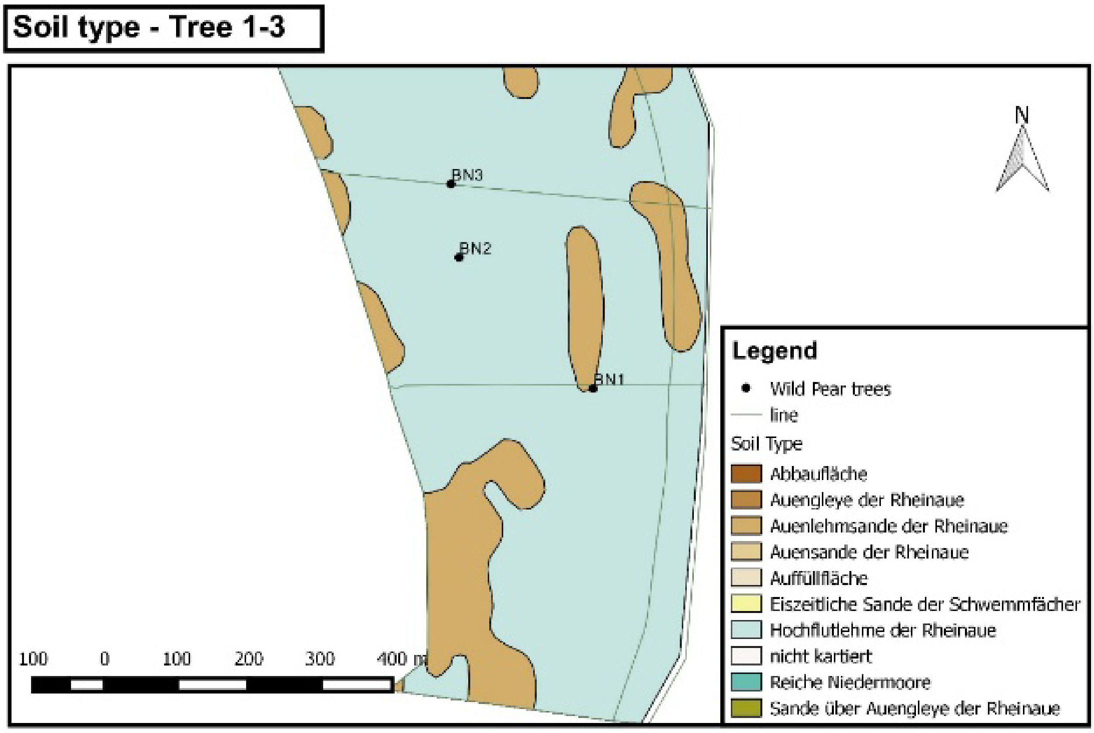
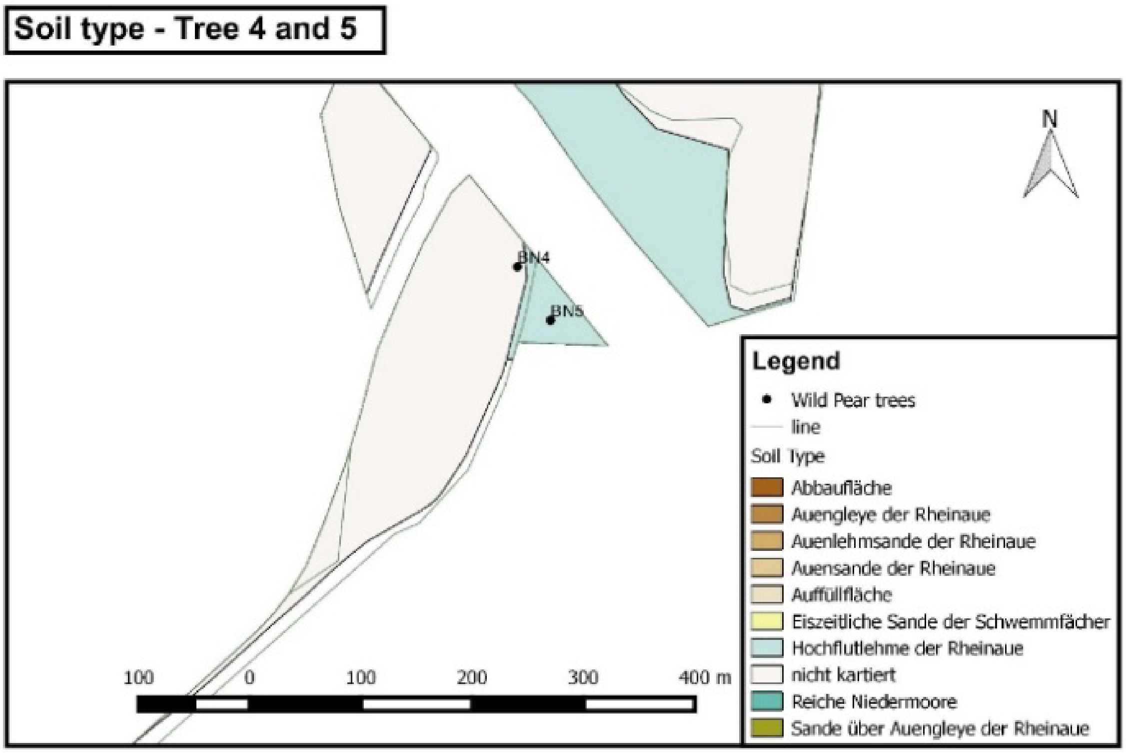
APPENDIX

Appendix I – GIS maps for trees 1 – 5

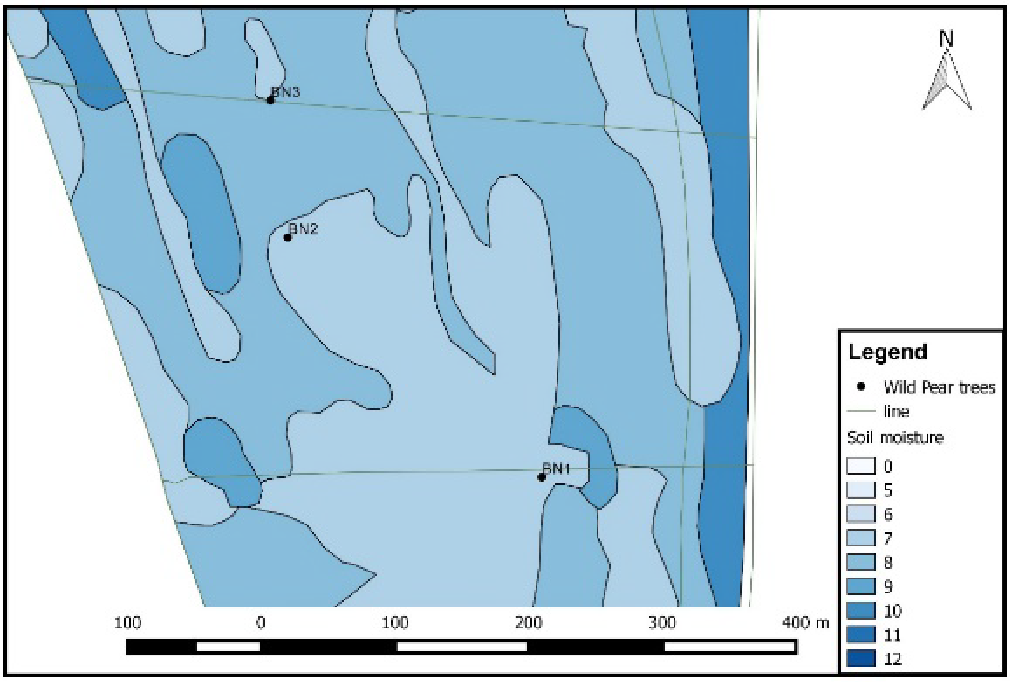
1.1. - Soil type



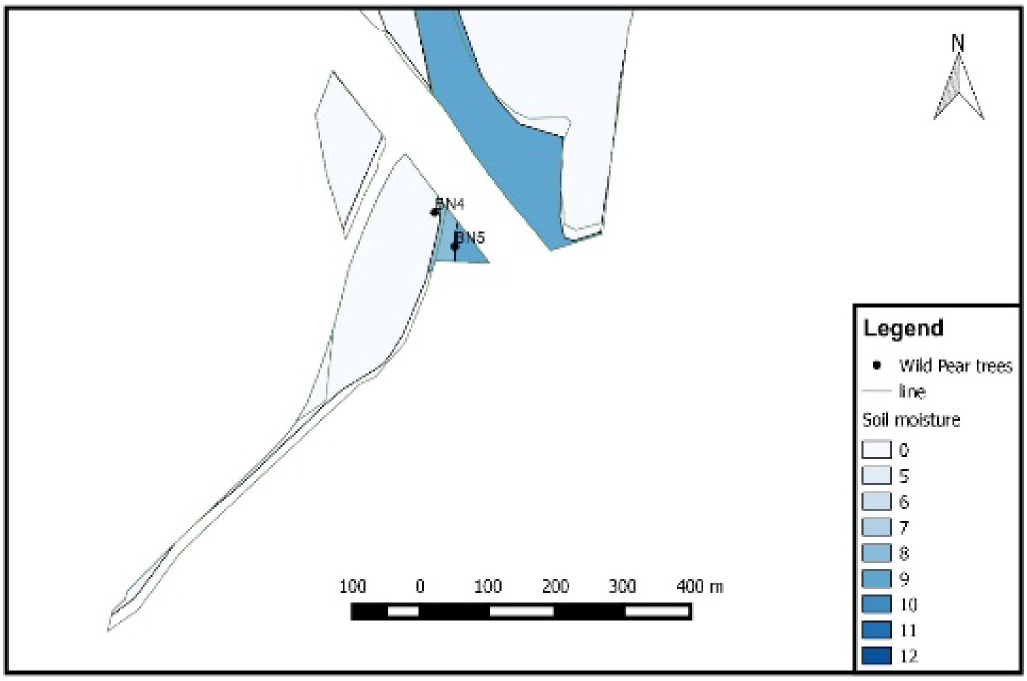


1.2. – Soil moisture

Soil moisture - Tree 1 - 3

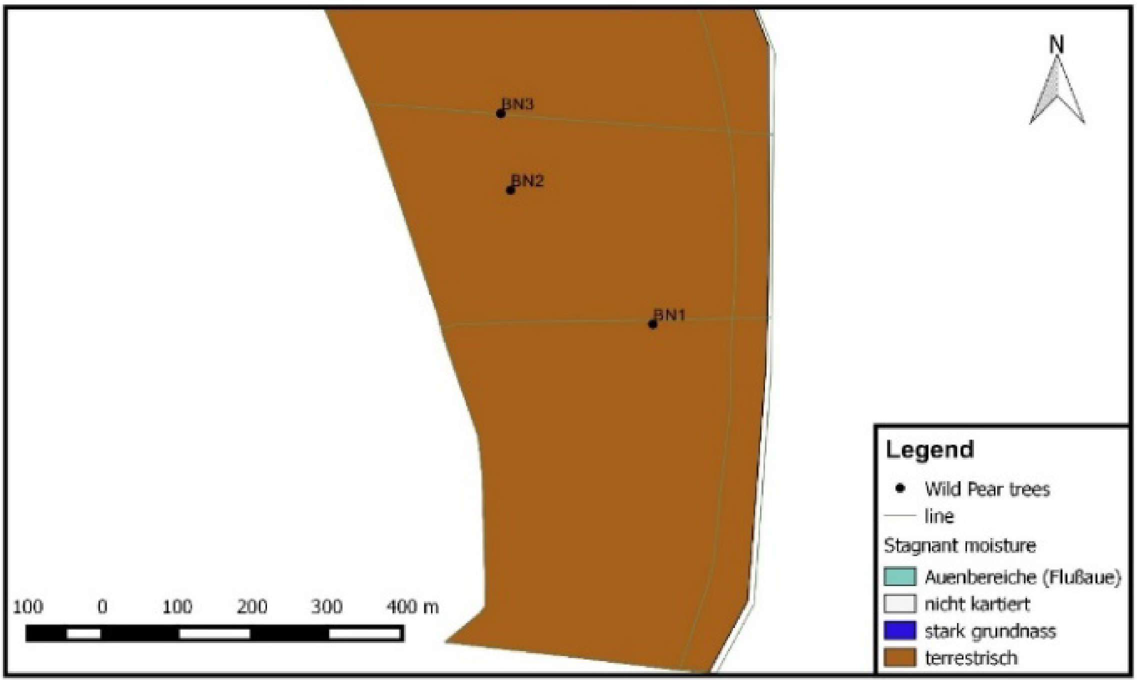


Soil moisture - Tree 4 and 5

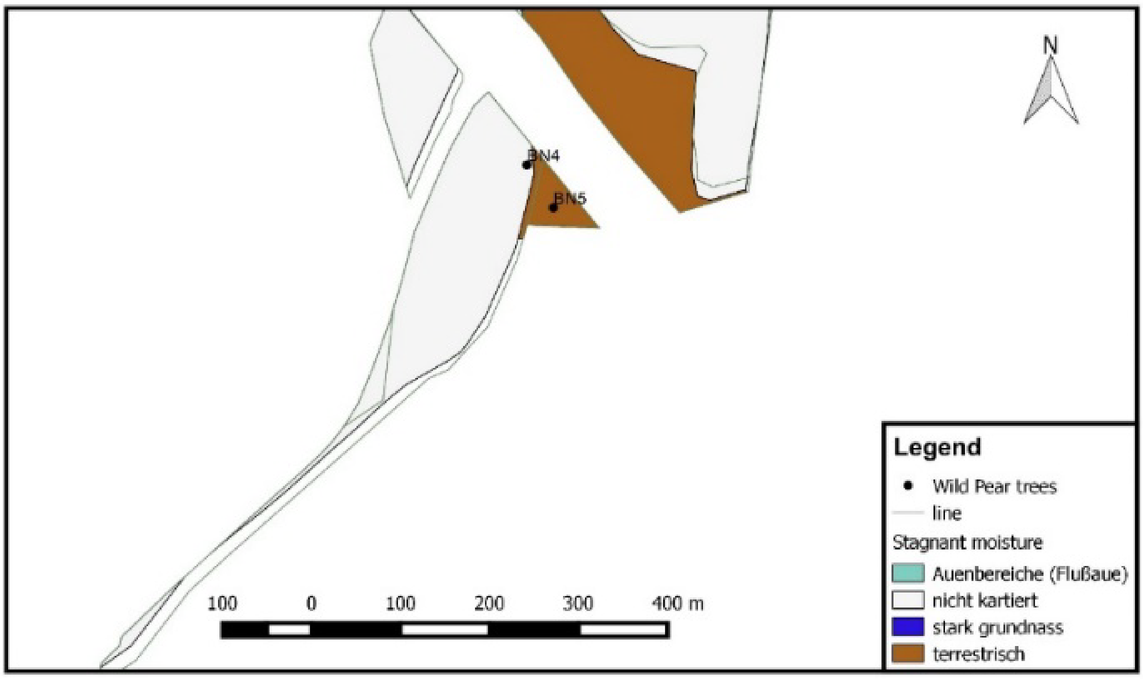


1.3. – Stagnant soil moisture

Stagnant moisture - Tree 1 -3



Stagnant moisture - Tree 4 and 5

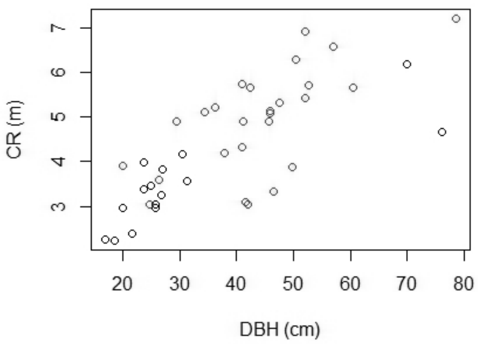


Appendix II – Modelling results based on data from Pfälzer Rheinauen

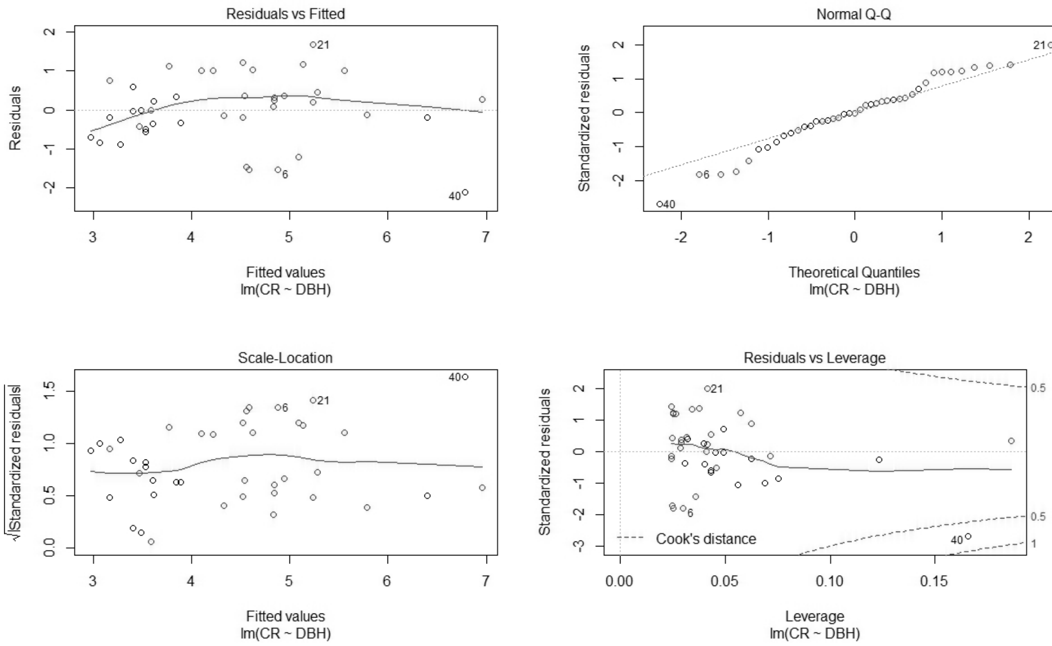
2.1. – Linear model for biggest crown radius - Biggest.CR = DBH + Location

```
Call:
lm(formula = Biggest.CR ~ DBH + Loc, data = Crb1)

Residuals:
    Min      1Q  Median      3Q     Max 
-4.3840 -1.2894 -0.0847  0.8607  8.5420 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)   3.7344     0.9282   4.023 0.000263 ***
DBH           0.0715     0.0241   2.967 0.005183 ** 
LocF          0.6651     0.7661   0.868 0.390802    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.152 on 38 degrees of freedom
Multiple R-squared:  0.2704,   Adjusted R-squared:  0.232 
F-statistic: 7.043 on 2 and 38 DF,  p-value: 0.002502
```

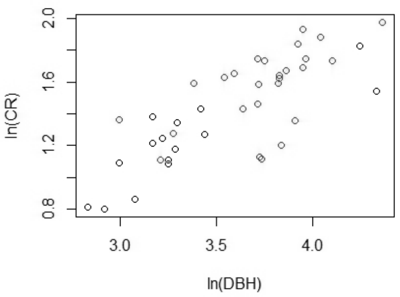
2.2. – Linear Model – LM6B – CR = DBH




```
Call:
lm(formula = CR ~ DBH, data = TA)

Residuals:
     Min       1Q   Median       3Q      Max 
-2.11508 -0.43113 -0.00317  0.44627  1.68358 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  1.86768    0.36932   5.057 1.05e-05 ***
DBH          0.06474    0.00878   7.373 6.63e-09 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.8609 on 39 degrees of freedom
Multiple R-squared:  0.5823,   Adjusted R-squared:  0.5716 
F-statistic: 54.36 on 1 and 39 DF,  p-value: 6.628e-09
```

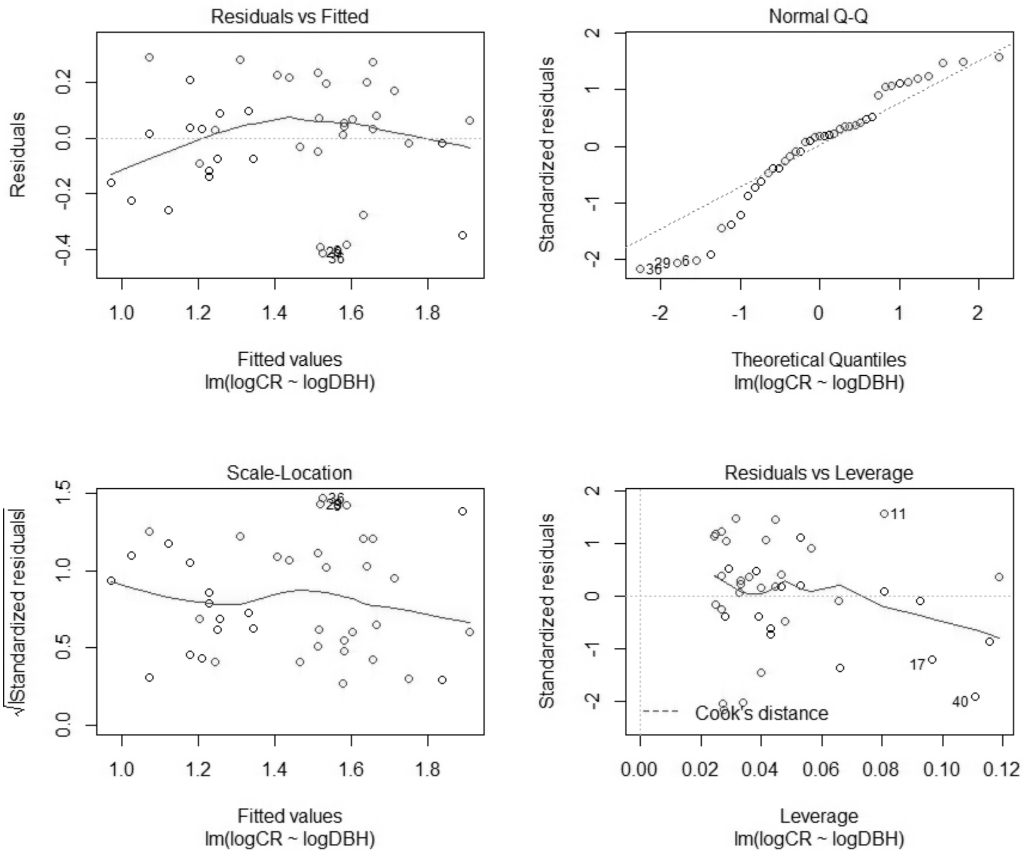


2.3. - Logarithmic-model – LLM1B – ln(CR) = ln(DBH)

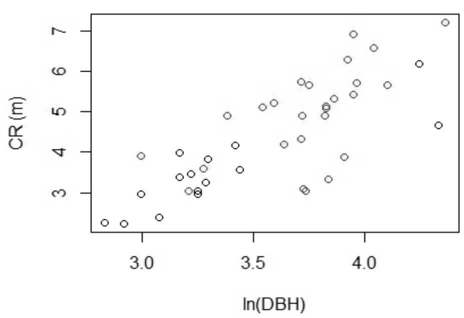



```
Call:
lm(formula = logCR ~ logDBH, data = TA)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.41206 -0.09029  0.03445  0.09974  0.29198 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept) -0.76810    0.27818  -2.761  0.00874 ** 
logDBH       0.61388    0.07698   7.974 1.02e-09 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.1935 on 39 degrees of freedom
Multiple R-squared:  0.6198,	Adjusted R-squared:  0.6101 
```

```
F-statistic: 63.59 on 1 and 39 DF,  p-value: 1.025e-09
```

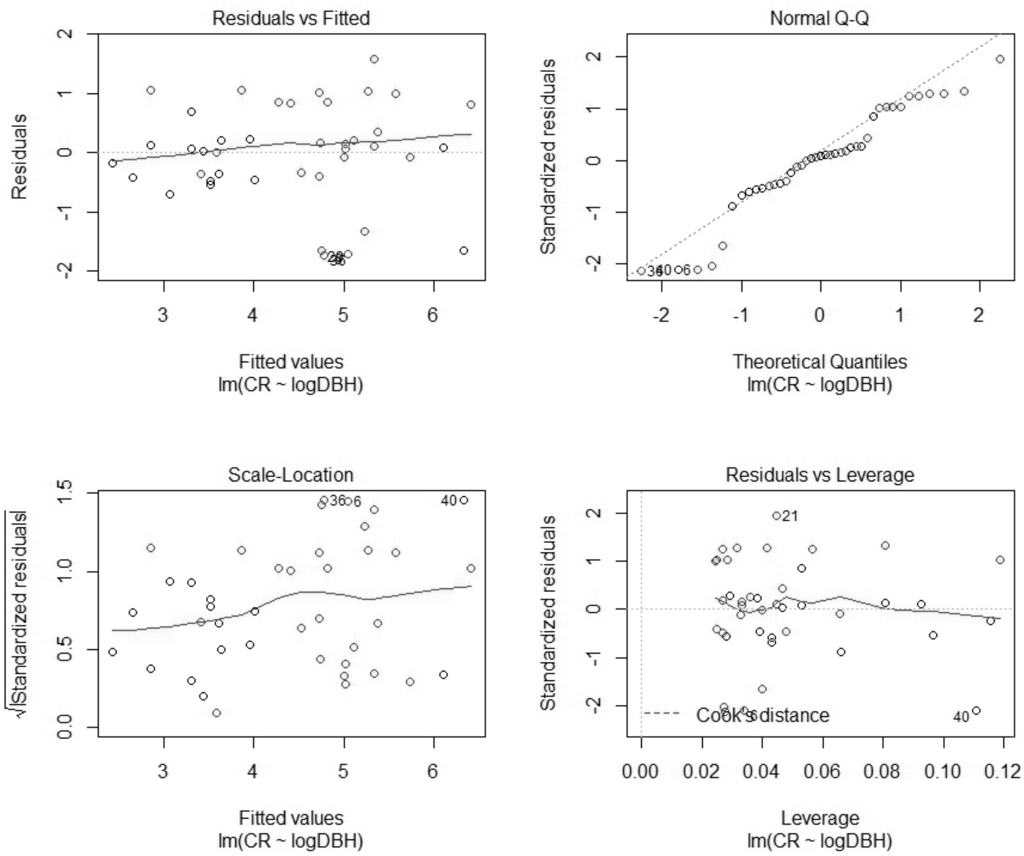


2.4. - Semi-logarithmic model – CR = ln(DBH)




```
Call:
lm(formula = CR ~ logDBH, data = TA)

Residuals:
    Min      1Q  Median      3Q     Max 
-1.7340 -0.4015  0.0718  0.6918  1.5817 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  -4.9190     1.1874  -4.143 0.000178 ***
logDBH        2.5953     0.3286   7.898  1.3e-09 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
Residual standard error: 0.8261 on 39 degrees of freedom
Multiple R-squared:  0.6153,   Adjusted R-squared:  0.6054
F-statistic: 62.38 on 1 and 39 DF,  p-value: 1.295e-09
```



Appendix III – Modelling results based on data from Pfälzer Rheinauen and Austria

3.1. – Result table for all full models

Full Model	**Linear Model –**	**Logarithmic Model –**	**Semi-Logarithmic Model**
Data	Pfälzer Rheinauen + Austria	Pfälzer Rheinauen + Austria	Pfälzer Rheinauen + Austria
DBH	Sign.	Sign	Sign
Height	Sign	Sign	Sign
Location	Sign	Not sign.	Not sign.
DBH:Height	Sign	Sign	Sign
DBH:Location	Not sign.	Not sign.	Not sign.
Adjusted R²	0.8306	0.9396	0.7717
Formula after F-test	CR=0.0972274*DBH +0.1020940*Height - 0.6209475*Location-0.0021375*DBH:Height +0.4283324 Forest = 0 Open-grown = 1	Ln(CR) = 0.91953*ln(DBH) + 0.10729*Height - 0.02492*ln(DBH):Height - 2.17052	CR = 1.20262*ln(CR) - 0.19016*Height+0.06319*ln(DBH):Height -0.74760