Student thesis series INES nr 603

Potential Silvoarable Agroforestry Regions for *Corylus avellana* and *Juglans regia* in Scania, Sweden

Isabella Svensson

2023
Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

Isabella Svensson (2023).

Potential Silvoarable Agroforestry Regions for *Corylus avellana* and *Juglans regia* in Scania, Sweden

Bachelor’s degree thesis, 15 credits in Physical Geography and Ecosystem Science

Department of Physical Geography and Ecosystem Science, Lund University

Level: Bachelor of Science (BSc)

Course duration: *March* 2023 until *June* 2023

Potential Silvoarable Agroforestry Regions for *Corylus avellana* and *Juglans regia* in Scania, Sweden

Isabella Svensson

Bachelor thesis, 15 credits, in Physical Geography and Ecosystem Science

Supervisor:
Karin Larsson
Department of Physical Geography and Ecosystem Science, Lund University

Exam committee:
Oskar Löfgren
Department of Physical Geography and Ecosystem Science, Lund University
Ulrik Mårtensson
Department of Physical Geography and Ecosystem Science, Lund University

Acknowledgements

I would like to thank my supervisor Karin Larsson, for her guidance during my thesis work. Your advice, encouragement and feedback were invaluable throughout the progress of my thesis. Thanks to my examinators Oskar Löfgren and Ulrik Mårtensson, and my opponent Nicholas Asplin for your helpful comments. I also want to thank my friends for your patience and understanding during these months. Finally, thank you to my family and partner, Dario, for your unfailing support and for reminding me to take a break every now and then.

Abstract

Conventional agriculture in Sweden is facing challenges with low resilience to a changing climate and decreased biodiversity. Silvoarable agroforestry is an alternative land use practice that contain a woody perennial and crop in the same field. Trees on cultivated land break up large monocultures, increase biodiversity, creates functional diversity, and produces more commodities. This land use practice is being recognized as a method for the transition to a more sustainable agriculture. It is included in the new European Union Common Agricultural Policy (2023-2027), where farmers are eligible for subsides for their environmental and conservational efforts. Silvoarable practices are marginal in the Swedish context. It is relevant for farmers to know if they will be eligible for subsidies but also to guide policymaking and drive transition. This study aims to assess potential silvoarable agroforestry regions for two types of nut trees: *Corylus avellana* (common hazel) and *Juglans regia* (common walnut) in the county of Scania. Furthermore, to estimate the variation in suitability across these regions. Productive growth criteria were developed through literature review for the two species where annual precipitation, mean annual temperature, soil texture, soil depth, and soil moisture were found to be relevant criteria. Potential regions were identified using Boolean and fuzzy logic, where the Boolean analysis identified 3436.2 km^2 of cultivated land that could be suitable for *Corylus avellana* and 1616.6 km^2 of potentially suitable regions for *Juglans regia*. The fuzzy analysis identified 3864.2 km^2 of potentially suitable cultivated land for *Corylus avellana*, where 553.1 km^2 could be highly suitable (≥80% fuzzy membership). Using fuzzy logic, 1445.7 km^2 were identified as potentially suitable for implementing *Juglans regia*, where 14.6 km^2 could be highly suitable (≥80% fuzzy membership). Multiple opportunities are identified with implementing silvoarable agroforestry systems with *Corylus avellana* and *Juglans regia*, but the barriers need to be addressed for it to be beneficial. Stakeholders also need to be included. This study is limited to the available data and literature review, and only considers the potential implementation of *Corylus avellana* and *Juglans regia*. More field experiments are required to fully evaluate the suitability of silvoarable agroforestry systems in Scania. Future studies should consider what the suitability assessment would look like in a future climate projection and consider other types of trees and crop commodities.

Key words: Silvoarable agroforestry, *Corylus avellana*, *Juglans regia*, Suitability assessment, Scania

Table of Contents

1 Introduction

Swedish agriculture has low resilience to sudden changes of environmental conditions (Wiréhn, 2018). In 2018, Sweden experienced an extreme weather event that contributed to great yield losses, especially for the fodder production for livestock in Sweden. Swedish agriculture is not equipped to handle great heat stress and is vulnerable in a changing climate (Schaffer et al., 2019). The climate in Sweden is projected to become warmer and wetter, where the frequency of extreme weather events, together with increased periods of droughts and heavy precipitation are expected to increase (Wiréhn, 2018). Excessive soil moisture drowns crops as well as cause diseases. Warmer temperatures will not only cause droughts but also facilitate the northward expansion of weeds and pests (Wiréhn, 2018). This threatens to greatly enhance yield losses. Southern Sweden is projected to experience earlier springs, and with increasing temperatures might come to experience all-year-round growing seasons. This could be beneficial for agriculture regarding production and market contribution. Yet, these opportunities might be missed if the agricultural sector fails to adapt to the challenges (Wiréhn, 2018).

Agroforestry is a sustainable land use practise described as agriculture with trees (Mosquera-Losada et al., 2023). The practice contains a woody perennial (either tree or shrub) on the same land as either animals, or crops, or the two in combination (Mosquera-Losada et al., 2009). It is further distinguished as silvopastoral (woody perennial with animals) (Mosquera-Losada et al., 2009), silvoarable (woody perennial and crop), or agrosilvopastoral (woody perennial in combination with animals and crops) (Reisner et al., 2007).

Agroforestry systems (AFS) are more widespread in tropical regions compared to temperate. This is in part due to farmers' reluctance of implementing trees on arable land as they fear resource competition and yield reductions (Vaccaro et al., 2022). Since the introduction of modern agricultural practices, the use of AFS has become less important and not considered as an economically beneficial land use practice in the European context. It has been left out of policy making and environmental efforts (den Herder et al., 2017). Because of this, more research has been conducted on tropical AFS. In temperate regions, there has been historic systems of silvopastoral agroforestry including animal grazing in natural woodlands and orchard cropping, and silvoarable AFS including alley cropping and home gardens (Schaffer et al., 2019).

den Herder et al. (2017) estimated that 8.8% of all agricultural land in Europe consists of AFS. Out of the 154000 km^2 of agroforestry only 3580 km^2 is counted as silvoarable practices, the remaining 150420 km^2 are silvopastoral (den Herder et al., 2017). The current European AFS are dominated by broadleaved woodlands, and grasslands with sparse trees, olive groves and grazed fruit orchards (den Herder et al., 2017). The most famous agrosilvopastoral practices in Europe, are the *Dehesas* of Spain, and the *Montados* of Portugal. These AFS are oak trees intercropped with cereal and livestock (Reisner et al., 2007). Spain and Portugal together with France, Greece, Italy, Romania, and Bulgaria have the largest extent of agroforestry within Europe (den Herder et al., 2017).

Agroforestry in Sweden covers 1.1% of Sweden's territorial area. This translates to 15.2% of the agricultural land (den Herder et al., 2017). Historic Swedish agroforestry include forest grazing (Schaffer et al., 2019) and wooded meadows (Gunnarsson, 2010). The traditional Sami practices of reindeer forest grazing are considered as silvopastoral agroforestry and are still in practice in the North of Sweden and Fennoscandia today (Schaffer et al., 2019). Silvopastoral AFS cover 4636 km^2 in Sweden. Silvoarable practices are marginal in comparison, covering 20 km^2 (den Herder et al., 2017) (Figure 1). The most common silvoarable AFS in Sweden are wooded meadows with fruit trees (Gunnarsson, 2010).

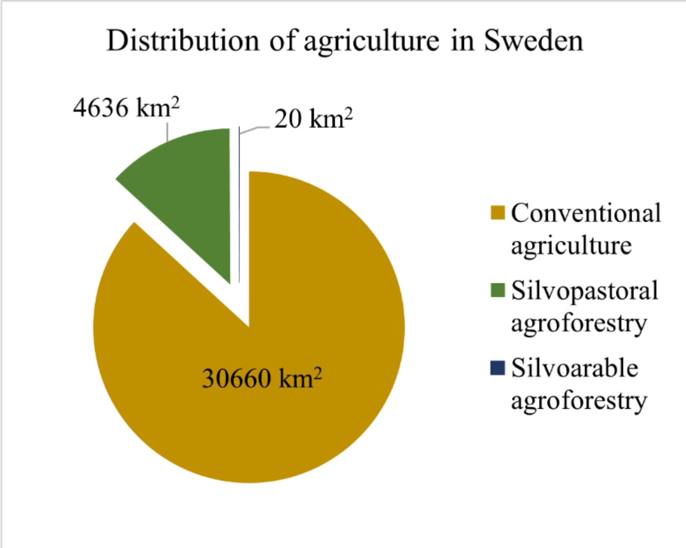

Figure 1. Pie chart of agricultural distribution in Sweden, split between conventional agriculture, silvopastoral and silvoarable agroforestry. The numbers are from den Herder et al. (2017).

Silvoarable AFS is beneficial for arable production and contributes to multiple ecosystem functions. AFS increases biodiversity (Reisner et al., 2007) and has a greater functional and structural diversity than conventional agriculture and forestry (Torralba et al., 2016). Implementing trees on cultivated land breaks up large monocultures. Introducing trees will alter the microclimate's temperature, radiation, and humidity. This can create new habitats on lands that were previously treeless (Mosquera-Losada et al., 2023), for different species of insects (Pardon et al., 2020) and birds (Vlahova, 2020), that do not live in open areas. AFS could have a positive effect over conventional agriculture and forestry on erosion control and soil fertility as conventional agriculture contributes to marginal ecosystem services (Santiago-Freijanes et al., 2021). Nutrient leaching from mineral fertilizers could be mitigated by tree roots extending further in the soil layer than crop roots, retrieving nutrients (Reisner et al., 2007) and contributing to increased water accumulation (Wiréhn, 2018). Trees on cultivated land can function as green corridors for wildlife, and windbreaks that protect the crops in windy locations (Schaffer et al., 2019). Provisioning ecosystem services are enhanced by silvoarable agroforestry where intercropping with trees generates more commodities, e.g., fruits, nuts, and berries, than monocultures (Reisner et al., 2007). AFS has shown to produce higher yields than monocultures when the system is fully developed (Schaffer et al., 2019). In addition to the forementioned benefits, trees on cultivated land can potentially increase carbon sequestration through storage in soil and biomass. AFS are being recognized as a means to adapt to, and mitigate climate change (Schaffer et al., 2019).

The new European Union Common Agricultural Policy (CAP), in effect from 2023 to 2027, will subsidise climate change action, together with environmental and conservational efforts taken by farmers in member states (European Commission, n.d.). This includes changing production methods to appropriate management strategies such as agroforestry. Through promoting more silvoarable practices, the CAP aims to reduce greenhouse gas emissions, increase carbon sequestration, conserve natural resources, and enhance water resilience (European Commission, 2022). Furthermore, Sweden has committed to 16 environmental quality objectives as part of the effort to meet the global targets of Agenda 2030 (Naturvårdsverket, n.d.). Changing the agricultural production method could, according to the Swedish Environmental Protection Agency (Naturvårdsverket), contribute to four of the environmental objectives:

i) Reduced climate impact,
ii) A varied agricultural landscape,
iii) Zero eutrophication,
iv) A rich diversity of plant and animal life.

For areas where agroforestry is not widely implemented there is an opportunity for farmers to introduce and apply AFS and novel practices to the agricultural landscape (den Herder et al., 2017). It is relevant to assess where silvoarable agroforestry can be implemented, moreover if the land can be eligible for subsidies within the CAP. It is essential to map the extent of potential areas so that agroforestry takes place in decision making to guide policy development and implementation (den Herder et al., 2017).

Reisner et al. (2007) made a study estimating potential target regions for silvoarable agroforestry across Europe. Target regions were determined by considering European cultivated land, together with areas of potential tree growth and areas at risk of soil erosion, nutrient leaching, and low biodiversity. This study was conducted with coarse data (1-kilometer (km) resolution) and thus provided an overview of potential silvoarable agroforestry locations across Europe. The study did not consider regional and local landscape differences. Target regions in Sweden were found exclusively in north-eastern Scania for *Prunus avium* (wild cherry) for mitigating nutrient leaching (Reisner et al., 2007).

In Sweden, Scania is a region that accommodates a substantial amount of intensively cultivated land. These lands have issues with decreased biodiversity and will be vulnerable in a changing climate (Wiréhn, 2018). Hence, it is an appropriate region to consider the potential implementation of silvoarable AFS. The trees can provide resilience of the system, increase biodiversity, and generate higher functional and commercial diversity with long-term increased production. Certain trees are recognized to work well in temperate agroforestry (Pardon et al., 2020; Reisner et al., 2007; Vlahova, 2020). This study will consider two species of trees, one native to Scania and one non-native, that are suitable for silvoarable AFS: the native common hazel (*Corylus avellana*) and the non-native common walnut (*Juglans regia*).

1.1 Aim

The aim of this thesis is to assess:

i) Where are the potential silvoarable agroforestry regions in Scania for:
    a. *Corylus avellana*, and
    b. *Juglans regia*?
ii) What is the variation in suitability across these regions?

1.2 Hypotheses

I. Scanian cultivated land is suitable for implementing silvoarable AFS with *Corylus avellana* and *Juglans regia*.
II. As *Corylus avellana* is native to Scania, more suitable areas will be identified than for *Juglans regia* that is non-native (Weiss, 2022).
III. By using finer spatial resolution geodata, more suitable silvoarable agroforestry regions can be identified in Scania compared to previous studies on European level by Reisner et al. (2007).

2 Background

2.1 Tree species

Two species of nut trees were selected to be assessed for suitability in the Scanian landscape: *Corylus avellana* and *Juglans regia*. Productive growth requirements for *Corylus avellana* and *Juglans regia* were based on literature review.

2.1.1 *Corylus avellana*

Corylus avellana (*C. avellana*) or common hazel is a deciduous tree, widespread in Europe and a naturally occurring tree in the Scanian landscape (Allegrini et al., 2022). *C. avellana* is characterized by root shoots, taking on a shrubby form, and grows between 3-10 m in height (Weiss, 2022). The tree is a monoecious plant with catkins (male) and female flowers, pollinated by wind (Allegrini et al., 2022). The fruit of *C. avellana* is the hazelnut. This is a nutrient rich nut containing unsaturated fatty acids (Allegrini et al., 2022), essential amino acids, fibres, vitamins, and minerals (Weiss, 2022). The commodity has a high economic value and can be consumed unripe, ripe, dried, or processed (Allegrini et al., 2022). For a newly planted tree it will take 4-6 years to produce nuts. Once the tree is productive, the nuts can be harvested between August and September (Weiss, 2022). The tree is also multifunctional (Allegrini et al., 2022) where the husks of the nut can be used as biofuel and bio-charcoal (Weiss, 2022).

C. avellana is a resilient tree that can tolerate different climate conditions (Allegrini et al., 2022). It flowers between February and April (Weiss, 2022), but is not sensitive to frost (Hicks, 2022). The catkins can survive temperatures below -27 °C, and the female flowers are tolerant to -40 °C (Weiss, 2022). As the tree is naturally adapted to Scania, it is well accustomed to the vegetation period (Hicks, 2022).

C. avellana can adapt to most soil conditions (Allegrini et al., 2022), but favours deep, well-drained soils (Weiss, 2022). The tree is sensitive to waterlogged soils and requires a clay content below 35%. Moreover, it favours soils that are rich in humus content (Weiss, 2022). *C. avellana* prefers alkaline conditions but is not constrained by acidic soils, and it can also grow well in soils that are nitrogen rich (Hicks, 2022).

According to Hicks (2022) *C. avellana* can be found at altitudes between 0-1000 m.a.s.l. Allegrini et al. (2022) even found species located at an altitude of 1700 m.a.s.l.

2.1.2 *Juglans regia*

Juglans regia (*J. regia*) or common walnut is a nut tree that can be found across several parts of Southern Europe (Wani et al., 2016). The tree's native range is the Mediterranean (de Rigo et al., 2016), and it does not occur naturally in Scania. *J. regia* is a single stemmed tree, that grows to a height of 12-15 m (Weiss, 2022). The tree is monoecious with catkins and female flowers. However, the catkins and female flowers bloom at different times, thus it is not self-pollinating (Wani et al., 2016). *J. regia* is wind pollinated and can pollinate, and be pollinated by, all species within the *Juglans* genus (Weiss, 2022). The fruit of *J. regia* is the walnut. Walnuts are a valuable commodity as they are highly nutritious with fatty acids, vitamins, proteins, and minerals (de Rigo et al., 2016). When the tree has been planted as a seedling it will give fruit after 10-15 years and will live to be 100 years old. If the tree was planted as a grafted plant, it will give fruit after 3-5 years, but this will only grow to be 30-50 years. When the tree has become productive, the walnuts can be harvested in October (Weiss, 2022).

J. regia is sensitive to late spring frost, damaging the flowers. The tree blooms from the middle of May to June, depending on the variety (Weiss, 2022). When the tree is dormant it can survive -30 °C. However, *J. regia* requires a vegetation period of minimum 170 days (Weiss, 2022).

Soils that are well drained, and moderately humus rich are preferable for *J. regia* (Weiss, 2022). Soil pH is optimal between 6-7.5 (de Rigo et al., 2016) and clay content below 35% (Wani et al., 2016) as *J. regia* cannot grow in waterlogged conditions (Weiss, 2022).

J. regia is tolerant to high altitudes, between 1000-3000 m.a.s.l. (Orwa et al., 2009).

3 Study area and Data

3.1 Study area description

The study area is the county of Scania in southernmost Sweden (Figure 2), extending over 11356 km^2. Scania is neighboured by Halland and Kronoberg county to the north and Blekinge county to the north-east. The remaining study area borders the Baltic Sea in the south-east and Öresund to the west.

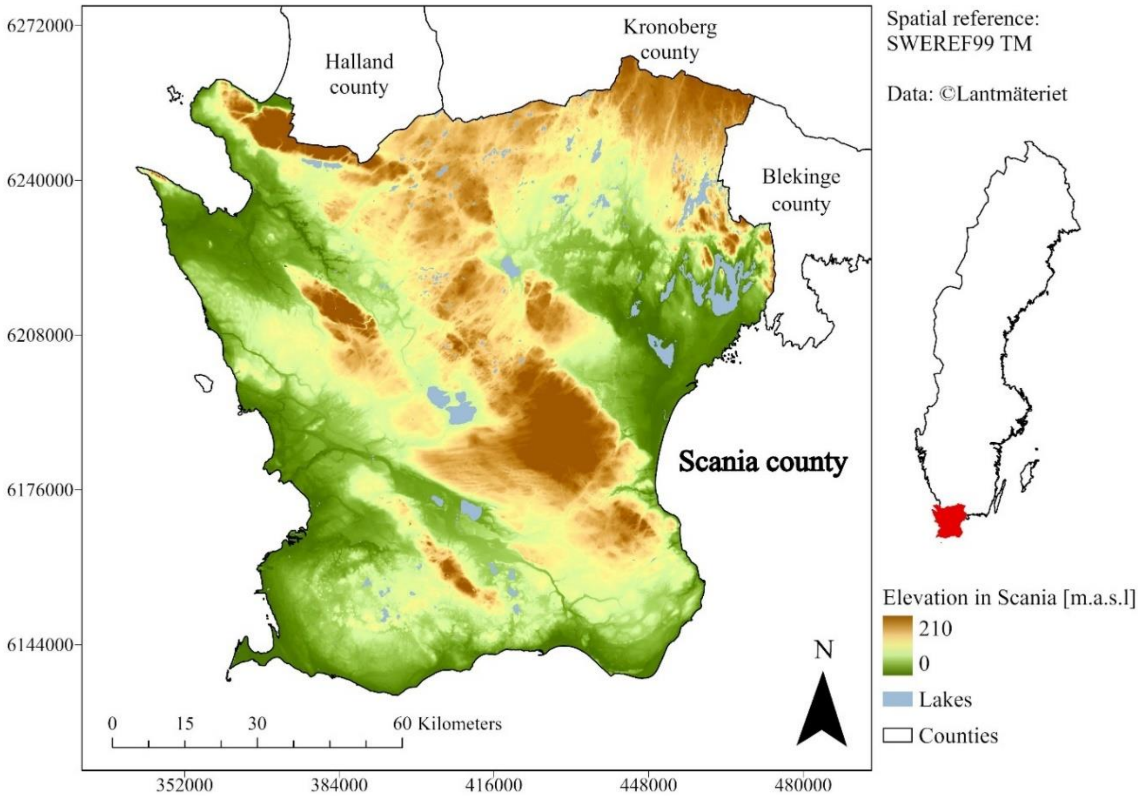

Figure 2. Study area of Scania, with elevation in meters above sea level [m.a.s.l.] ranging from low elevation (green) to high elevation (brown). The neighbouring counties of Halland, Kronoberg, and Blekinge are delineated in black against a white background.

The geomorphology of Scania is heterogenous. It is characterized by the Fennoscandian Shield extending down from the north, where the bedrock consists of gneiss and granites (Sveriges Geologiska Undersökning [SGU], 2017). A rift zone reaches diagonally across the county, north-west to south-east. This zone has experienced tectonic activity, creating the characteristic horsts of Scania, e.g., Söderåsen (Erlström et al., 1997), with the highest elevation of 210 m.a.s.l. (Länsstyrelsen, 2006) (Figure 2). South of the rift, the bedrock consists of sedimentary rocks (SGU, n.d.). The majority of the county is covered by a soil layer over 100 meters deep (Länsstyrelsen, 2006). The most prominent soil type is till of varied clay content (SGU, 2000), where the most fertile soils are used as cultivated land. The cultivated fields are concentrated to the south-western part of Scania (Figure 5). Here, fine-grained, and nutrient rich soils of high lime content, are accumulated. This contrasts the coarser, relatively nutrient poor tills to the north-east (Länsstyrelsen, 2006). The cultivated land of Scania covers 4284 km^2, i.e., 38% of the territorial area (Figure 5).

The county experiences a mean annual precipitation of 805 mm and mean annual temperature of 8 °C (Persson et al., 2012). The spatial distribution of annual precipitation and mean annual temperature for the recent years 2018-2022, are visualised in Figure. 3 and Figure 4 respectively.

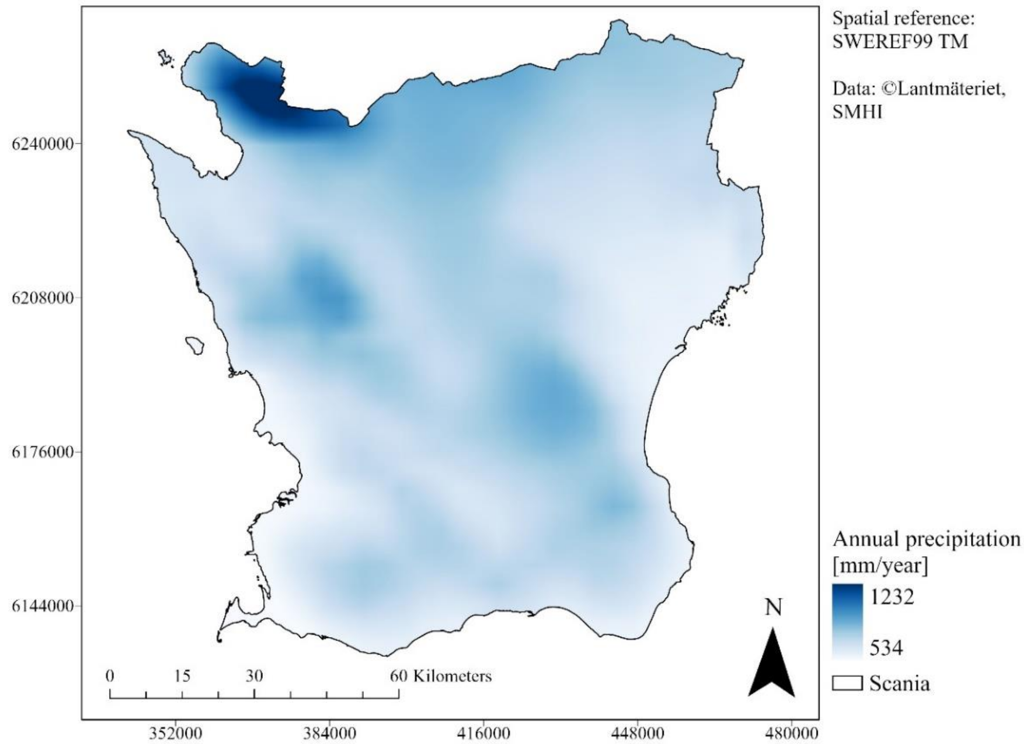

Figure 3. Spatial distribution of annual precipitation [mm/year], averaged over the years 2018-2022. The dataset was resampled from 4-km resolution to 10-meter resolution using bilinear interpolation. County boundaries are also visualised (Scania).

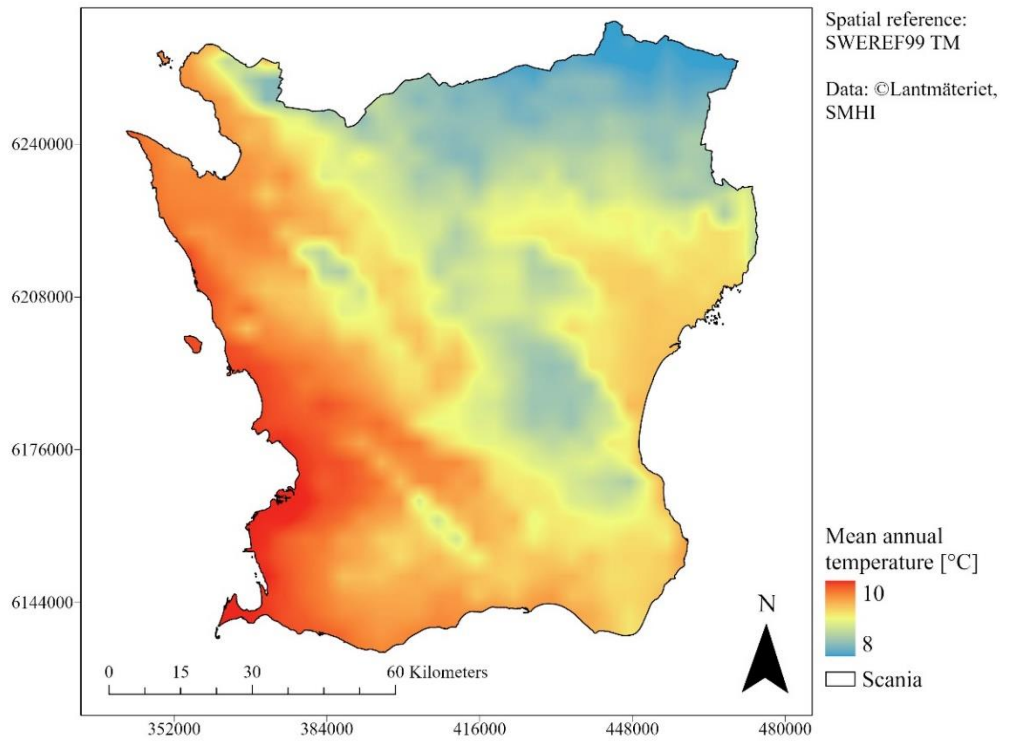

Figure 4. Spatial distribution of mean annual temperature [°C], averaged over the years 2018-2022. The dataset was resampled from 4-km resolution to 10-meter resolution using bilinear interpolation. County boundaries are also visualised (Scania).

3.2 Administrative boundaries data

The administrative boundaries for Sweden and Scania were retrieved from the General map provided by the Swedish Surveying and Cadastral Agency (Lantmäteriet). The data was from 2022 and downloaded in vector format.

3.3 Cultivated land delineation data

Data for the distribution of cultivated land was retrieved from the Swedish Board of Agriculture (Jordbruksverket). The dataset of agricultural blocks (Jordbruksblock) was from 2021 and was downloaded in vector format. The agricultural blocks are unique agricultural fields that contain different agricultural practices: cultivated land, cultivated land with permanent grass, cultivated land with permanent crops, pasture, unknown, other land use, and wetlands.

Spatial information on forested and open land cover was retrieved from the General map provided by Lantmäteriet. The datasets were from 2022, classified, and in vector format.

Figure 5 shows the land cover distribution in Scania for cultivated, forested and open land. In the north-eastern part of the county, forest is the prevailing land cover. Cultivated land dominates the south-western part of Scania, and some parts of the north-east. Open land includes agricultural fields and the practices mentioned above, data not defined as cultivated land is visualised in grey (Figure 5). For the scope of this study only areas defined as cultivated land by Jordbruksverket were considered. Each unique cultivated field is the smallest area that the results will be estimated on.

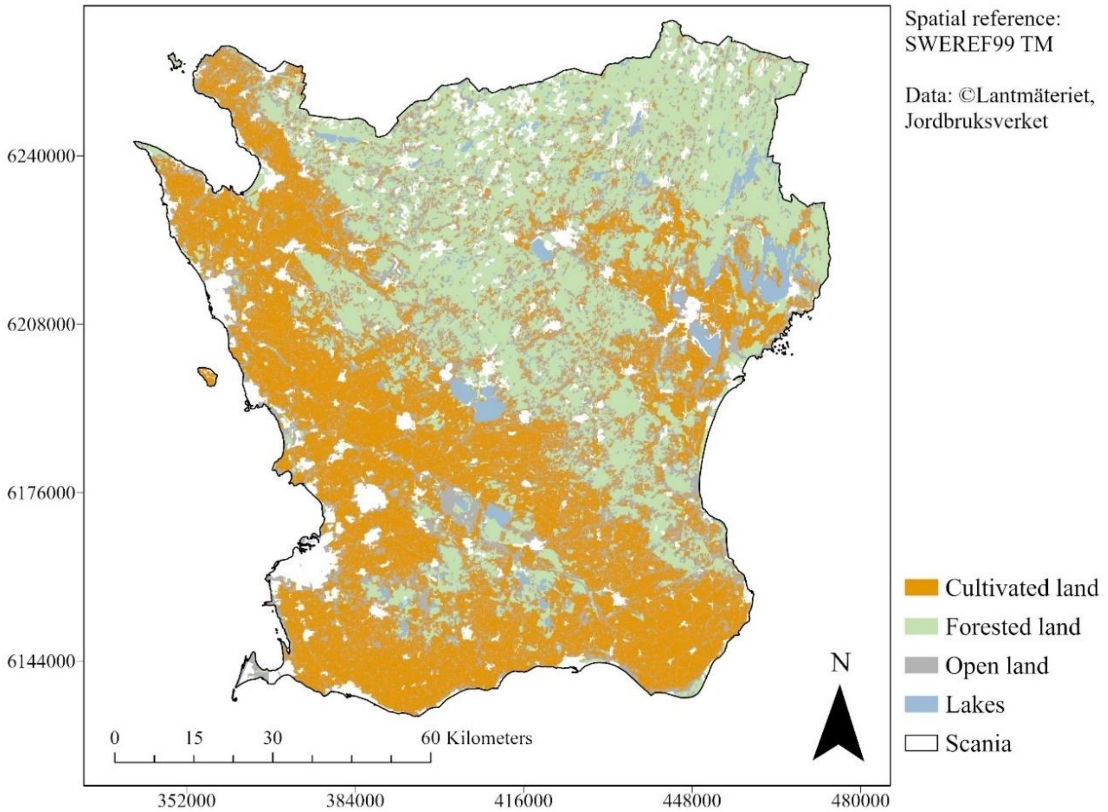

Figure 5. Land cover map of Scania divided into cultivated land used for suitability assessment, forested land, and other open land. Lakes and county boundaries (Scania) are also visualised.

3.4 Productive tree growth data

Productive tree growth for *C. avellana* and *J. regia* is not constrained by the annual minimum and maximum temperatures in Scania. Temperatures do not go beyond the minimum and maximum temperature tolerances for the two species (Sveriges Meteorologiska och Hydrologiska Institut [SMHI], 2018). The average annual dates for late spring frost in Scania are between April 1 and May 1 (SMHI, 2017). Late spring frost in Scania is therefore not a limiting variable for the vitality of *C. avellana* and *J. regia*. The requirement for growing days per year is also met for both species in Scania where growing days are between 210 to 240 days/year (SMHI, 2023).

Soil conditions that do not limit productive tree growth in Scania are humus content, clay content, and soil pH. Humus content and soil pH exceeds species' tolerance levels on Scanian cultivated land. Clay content is <35% across Scania (Jordbruksverket, 2015b).

Topography is not a limiting variable for *C. avellana* and *J. regia* in Scania as the altitude (0-210 m.a.s.l.) is low and cultivated land is not located on steep slopes. Topography was only used for visualisation purposes.

3.4.1 Climate data

The necessary climate data include:

i) Annual precipitation (mm/year)
ii) Mean annual temperature (°C)

The gridded precipitation and temperature data - PTHBV were retrieved from the SMHI as NetCDF (Network Common Data Form)-files for the years 2018-2022. The files were converted into raster format, in 4-km resolution. Temperature data showed mean annual temperature, based on daily averages. Precipitation data contained annual precipitation.

3.4.2 Soil conditions data

Classified soil texture data was retrieved from Jordbruksverket from the map collection of soil properties (Matjordens egenskaper). The dataset was from 2015 as TIFF (Tagged Image File Format), in 25-meter resolution.

Data on soil depth was given in meters (m) from the soil depth model (Jorddjupsmodell) and provided by SGU. Soil depth data was from 2015, and in raster format as TIFF, in 10-meter resolution.

Data on soil moisture was provided by Naturvårdsverket as an index (Markfuktighetsindex_NMD) in raster format as a TIFF-file, in 10-meter resolution. The soil moisture index ranges from dry (0) to wet (240) (Figure 6). The dataset was from 2019.

3.4.3 Topography data

Elevation data was retrieved from Lantmäteriet. The national elevation model (Markhöjdmodell) GRID 50+ NH from 2020 was used. The tiles were downloaded as TIFF-files in 50-meter resolution. Elevation is given in m.

4 Methodology

To identify potential silvoarable areas for the selected species in Scania, a multicriteria suitability assessment was conducted in ArcGIS Pro (version 2.7.0) (ESRI Inc, 2020). The method for locating areas of potential tree growth was developed by Reisner et al. (2007), who concluded that productive tree growth was limited by:

i) Climate,
ii) Soil conditions, and
iii) Topography.

In my study, suitability was assessed using both Boolean and fuzzy logic. A literature review was conducted through Web of Science to develop the species' criteria for productive growth. There is only limited research conducted on silvoarable AFS in Sweden. Therefore, data for productive tree growth in Scania was found using a combination of scientific articles and "The Nut Farmer's Hand Book (Nötodlarens Handbok)" (Weiss, 2022), a guide to nut farming in the Swedish landscape.

4.1 Productive tree growth criteria

Five limiting variables for productive tree growth in Scania were identified for the *C. avellana* and *J. regia* (Table 1).

Table 1. Productive tree growth criteria for C. avellana and J. regia.

Criteria	Unit	*C. avellana*	*J. regia*	Source
Annual precipitation	mm/year	>600	>700	Weiss (2022); Wani et al. (2016)
Mean annual temperature	°C	3.5-14.6	9.2-15	Hicks (2022); Orwa et al. (2009), Weiss (2022)
Soil texture	Classified	Tolerant to: Sandy loam, Sandy clay loam, Silt loam, but prefers: Loam	Tolerant to: Sandy loam, Sandy clay loam, Silt loam, but prefers: Loam	Allegrini et al. (2022); Wani et al. (2016)
Minimum soil depth	m	0.6	1	Hicks (2022); Wani et al. (2016)
Soil moisture	Index	Tolerant but prefers: Medium-low	Tolerant but prefers: Medium	Weiss (2022), Hicks (2022); Wani et al. (2016), Orwa et al. (2009)

4.2 Data processing

The datasets were resampled for harmonisation purposes to the finest resolution input dataset, i.e., 10-meter resolution. The climate datasets (annual precipitation and mean annual temperature) were downloaded and averaged over the past five years (2018 to 2022) and resampled from 4-km resolution to 10-meter resolution using bilinear interpolation. The raster dataset for soil texture was resampled from 25-meter to 10-meter resolution using nearest neighbour interpolation (Table 3).

Soil moisture index was reclassified from, but guided by, the original classification made by Naturvårdsverket (2019b) (Figure 6) according to Table 2. Naturvårdsverket describes the index is a combination of depth to ground water table and the soil topographical wetness index (STI). Depth to ground water table is considered more important for soil moisture and weighted higher. The STI is a modification of the topographical wetness index (TWI), so that also the soil's permeability is considered. Figure 6 shows the correlation between the five soil moisture categories determined through field sampling in the Swedish national forest inventory and the soil moisture index values (Naturvårdsverket, 2019b).

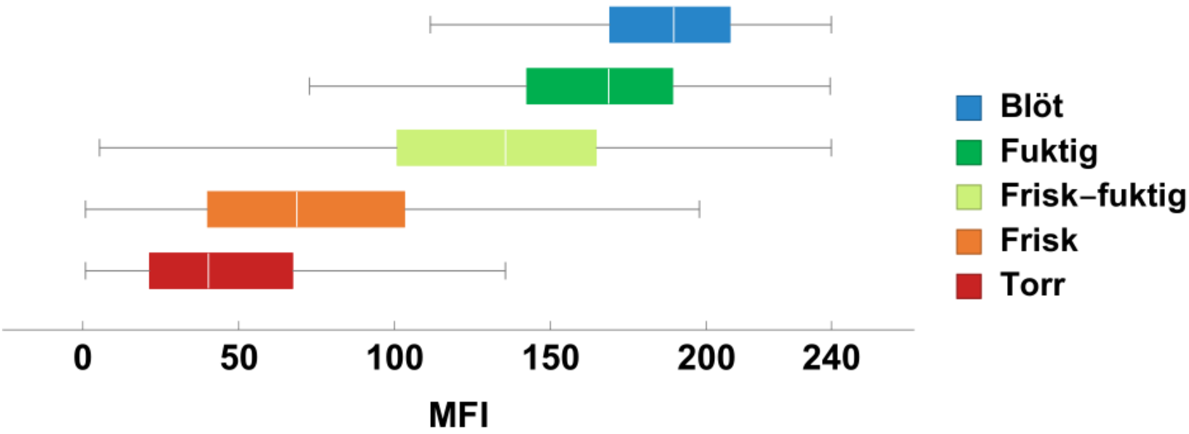

Figure 6. Soil moisture index (0-240) is divided into five categories: Blöt (Wet), Fuktig (Moist), Frisk-fuktig (Fresh-moist), Frisk (Fresh), and Torr (Dry). The graph is developed by Naturvårdsverket (2019b), where the white line indicates the median of the values, where 50% of the values are within the boxes and 90% are within the whiskers (Naturvårdsverket, 2019b).

As both *C. avellana* and *J. regia* are tolerant to relatively dry and wet conditions (Hicks, 2022; Orwa et al., 2009; Wani et al., 2016; Weiss, 2022), limits for too dry and too wet conditions had to be determined. It was reasoned that soil moisture conditions are very low at indexes from 0 to 20 and very high at indexes from 210 to 240 (Table 2). At indexes <20 the species might be subject to drought stress and require more irrigation. Indexes >210 indicate very wet conditions which both species are sensitive to as they cannot survive in waterlogged conditions (Weiss, 2022). The reclassification is visualised in Figure 7.

Table 2. Reclassification of soil moisture index further developed from the classification Naturvårdsverket (Figure 6). Low indicates dry conditions and High indicates wet conditions.

Soil moisture index	Classification
0-20	Very low
20-45	Low
45-105	Medium-low
105-145	Medium
145-170	Medium-high
170-210	High
210-240	Very high

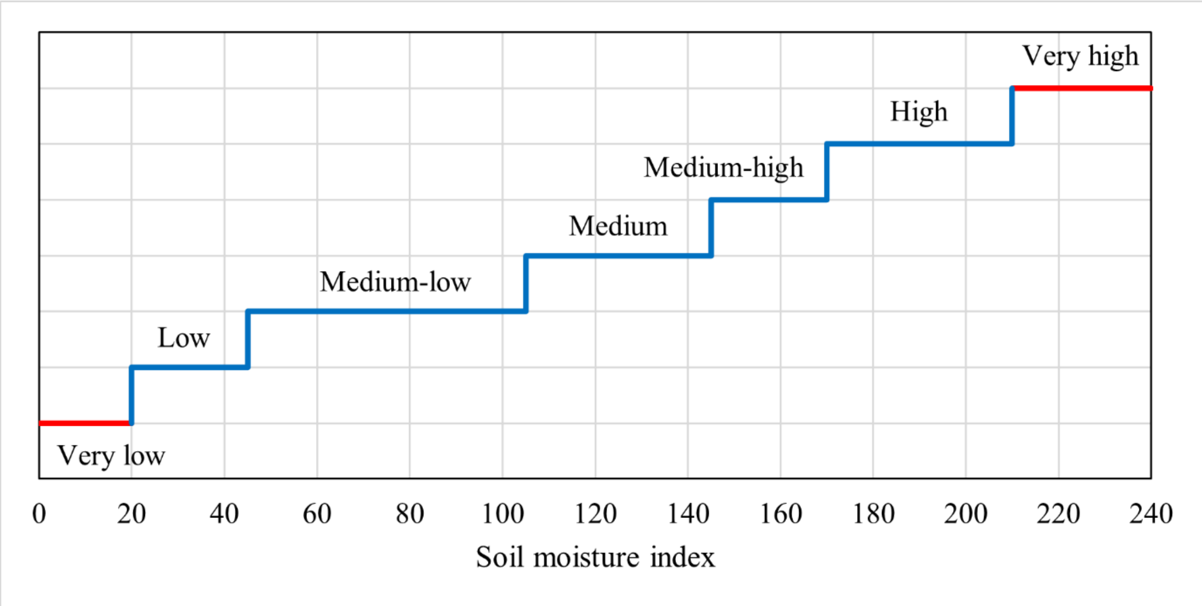

Figure 7. Reclassification of soil moisture index according to the limits set in Table 2. The red lines (Very low and Very high) illustrate soil moisture conditions that are too dry and too wet for productive tree growth for C. avellana and J. regia.

All datasets were projected to SWEREF99 TM and are summarized in Table 3.

Table 3. Datasets used for identifying potential silvoarable regions with units, datatype, original resolution, and resampled resolution.

Dataset	Unit	Datatype	Original resolution	Resampled resolution	Resampling method
Administrative boundaries	Classified	Vector	-	-	-
Cultivated land	Classified	Vector	-	-	-
Annual precipitation	mm/year	Raster	4*4 km	10*10 m	Bilinear
Mean annual temperature	°C	Raster	4*4 km	10*10 m	Bilinear
Soil texture	Classified	Raster	25*25 m	10*10 m	Nearest neighbour
Soil depth	m	Raster	10*10 m	10*10 m	-
Soil moisture index	Index	Raster	10*10 m	10*10 m	-

4.3 Identifying potential silvoarable agroforestry regions

The potential regions for implementing silvoarable AFS with *C. avellana* and *J. regia* were identified where all criteria of Table 1 were met for each species. In ArcGIS Pro, the analysis was initially conducted using Boolean logic. To gain higher spatial variability and identify regions of various suitability, the analysis was further developed using fuzzy logic. The raster datasets in Table 3 were used as input variables for creating logical conditions.

4.3.1 Boolean logic

The variables were reclassified using Boolean logic (1 or 0) for each species (Table 4) according to the criteria in Table 1.

Table 4. Boolean reclassification (1 or 0) of input variables for C. avellana and J. regia.

Boolean value	Annual precipitation	Mean annual temperature	Soil texture	Soil depth	Soil moisture index
C. avellana:					
1	≥600 mm	3.5 - 14.6 °C	Sandy loam; Sandy clay loam; Silt loam; Loam	≥0.6 m	20 - 210
0	<600 mm	<3.5 or >14.6 °C	All other soil textures	<0.6 m	<20 or >210
J. regia:					
1	≥700 mm	9.2 - 15 °C	Sandy loam; Sandy clay loam; Silt loam; Loam	≥1 m	20 - 210
0	<700 mm	<9.2 or >15 °C	All other soil textures	<1 m	<20 or >210

The reclassified layers were overlaid for both *C. avellana* and *J. regia*. Potential silvoarable agroforestry regions were identified using zonal statistics, where cultivated land functioned as the zone parameter. The majority statistics type was used to calculate the output cell value, where "1" indicated suitable and "0" indicated not suitable.

4.3.2 Fuzzy logic

Fuzzy logic was used to identify cultivated fields with low to high suitability for implementing silvoarable agroforestry with *C. avellana* and *J. regia*. Fuzzy membership values were estimated using linear functions (Equation 1) for mean annual temperature, soil texture, and soil moisture index. In Equation 1, *a, b, c*, and *d* are membership breaking points. Annual precipitation and soil depth were given crisp Boolean limits (1 or 0) as the criteria were minimum values (Table 1) and not ranges.

$$\mu_A(x) = \begin{cases} 0 & d \leq x \leq a \\ \frac{x-a}{b-a} & a < x < b \\ \frac{d-x}{d-c} & c < x < d \\ 1 & b \leq x \leq c \end{cases} \qquad x \in X \qquad \text{(Equation 1)}$$

The mean annual temperature criteria for each species were given fuzzy membership values between 1 and 0. Temperature for full fuzzy membership (1) was estimated as the range midpoint + 10% (Table 1). The increase from the midpoint was based on the reasoning that productive tree growth is favoured by warmer conditions (Allegrini et al., 2022; Wani et al., 2016; Weiss, 2022). The functions are therefore skewed towards the higher temperatures (Figure 8 and Figure 9). No fuzzy membership (0) was given at the minimum and maximum values of each species' temperature range. *C. avellana* follows the linear fuzzy membership function according to Figure 8. Fuzzy membership was estimated from a = 3.5 °C to b, c = 9.96 °C, and to d = 14.6 °C. The linear fuzzy membership estimation for *J. regia* is visualised in Figure 9, where fuzzy membership was estimated from a = 9.2 °C to b, c = 13.31 °C, and to d = 15 °C.

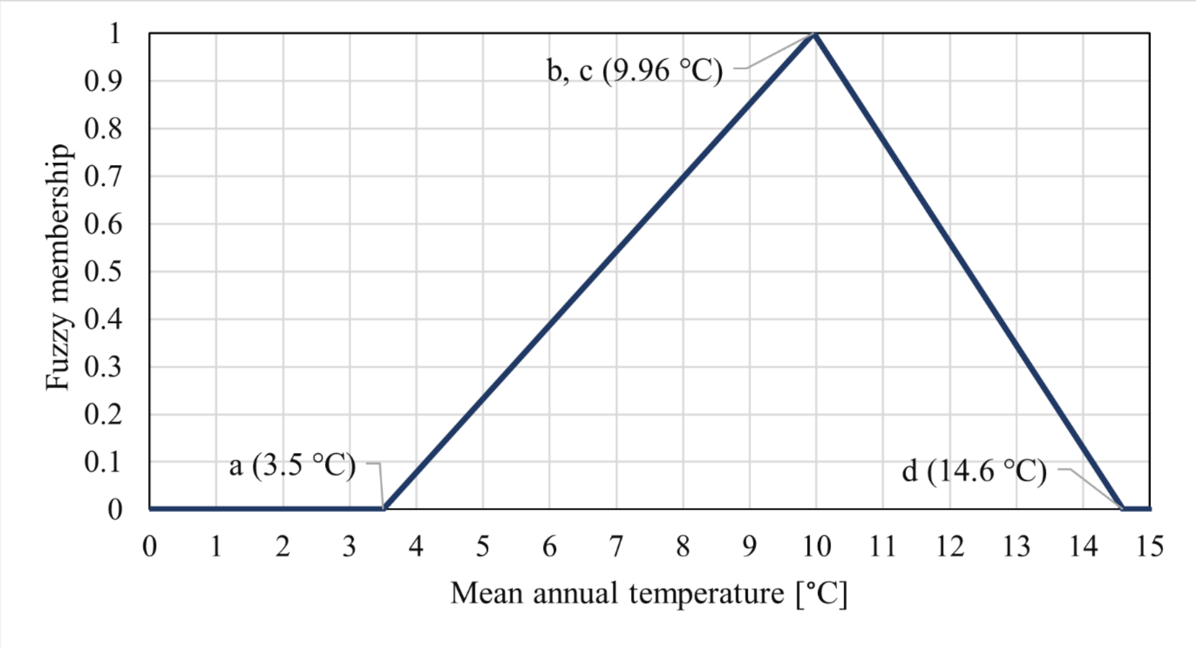

Figure 8. Graph of linear fuzzy membership against mean annual temperature criterion for C. avellana. Full fuzzy membership (1) is reached at b, c, where the mean annual temperature is 9.96 °C. There is no fuzzy membership at a and d, for mean annual temperatures ≤3.5 °C or ≥14.6 °C.

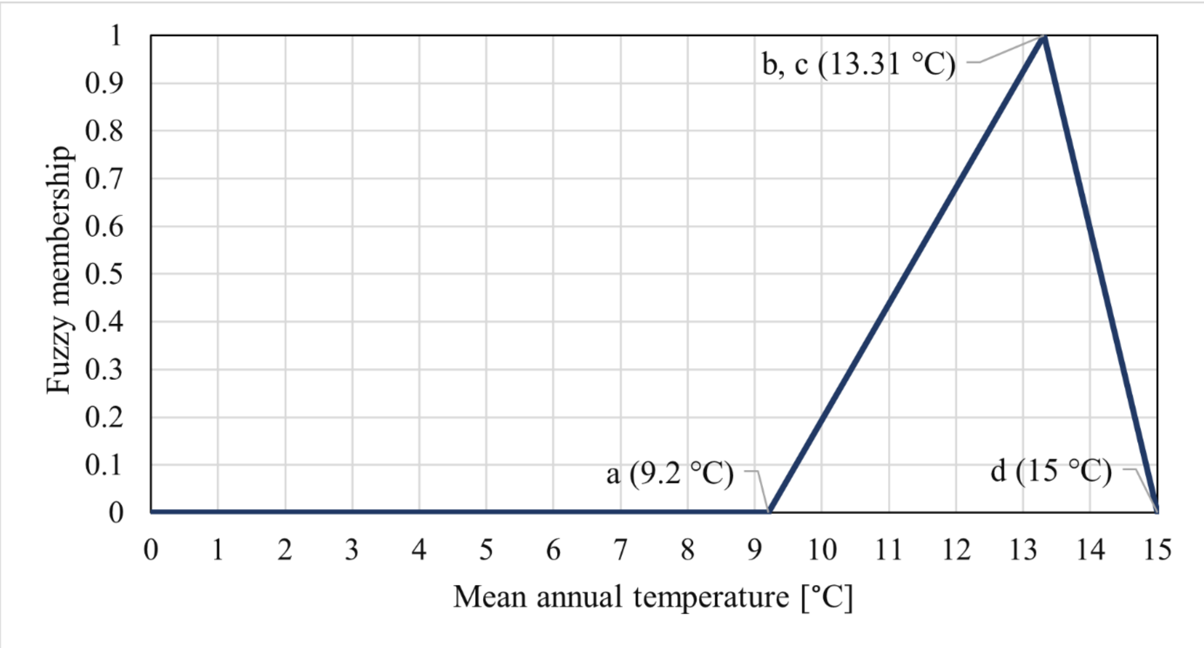

Figure 9. Graph of linear fuzzy membership against mean annual temperature criterion for J. regia. Fuzzy membership equals 1 at b, c, where the mean annual temperature is 13.31 °C. Fuzzy membership equals 0 at a and d, for mean annual temperatures ≤9.2 °C or ≥15 °C.

Soil texture criterion is the same for *C. avellana* and *J. regia* (Table 1). Based on the criteria, fuzzy membership values were given to different soil textures (Table 5). Full fuzzy membership is met for soil texture where b, c = Loam (Figure 10).

Table 5. Fuzzy membership values for different soil textures. Fuzzy membership ranges from 0 (no membership) to 1 (full membership).

Soil texture	Fuzzy membership
Sand	0
Loamy sand	0
Sandy loam	0.33
Sandy clay loam	0.67
Loam	1
Silt loam	0.5
Silt	0
Sandy clay	0
Clay loam	0
Silty clay loam	0
Silty clay	0
Clay	0

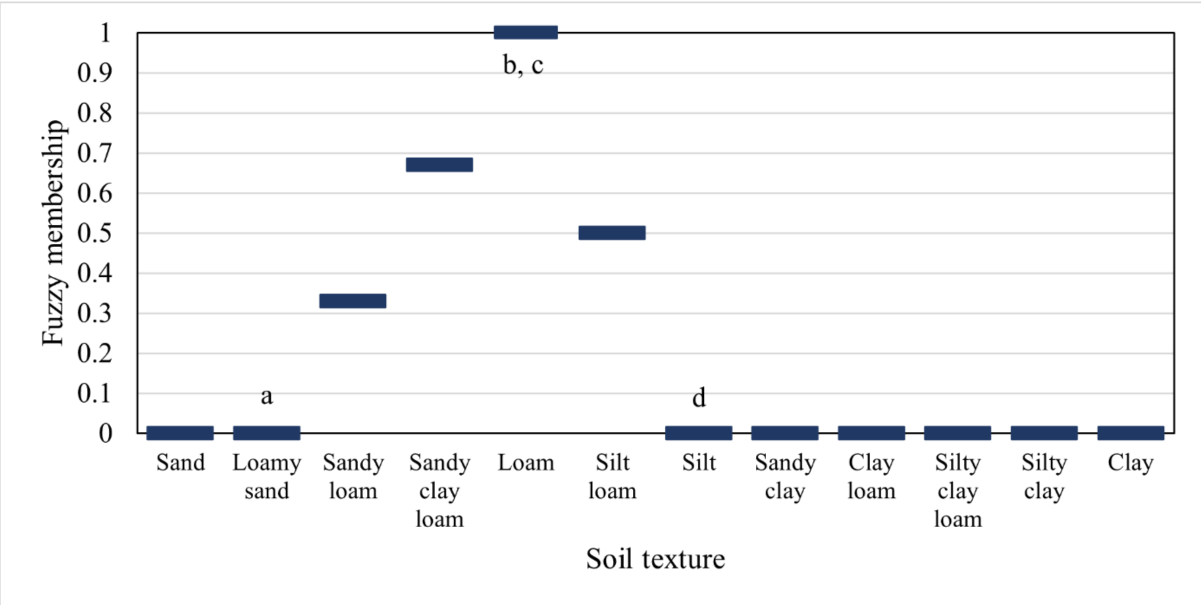

Figure 10. Fuzzy membership values for soil texture criteria for C. avellana and J. regia. Full fuzzy membership (1) is met at b, c, where soil texture is loam.

Soil moisture index has continuous values between 0 and 240, but *C. avellana* and *J. regia* has optimal productive growth criteria in ranges (Table 2), where b and c have different values, but both have full fuzzy membership (Table 6). The linear fuzzy membership functions are visualised in Figure 11 for *C. avellana* and Figure. 12 for *J. regia*.

Table 6. Variable inputs to Equation 1 (a-d) of soil moisture indexes (SMI), showing linear fuzzy membership for each SMI.

Variable	SMI *Corylus avellana*	SMI *Juglans regia*	Fuzzy membership
a	20	20	0
b	45	105	1
c	105	145	1
d	210	210	0

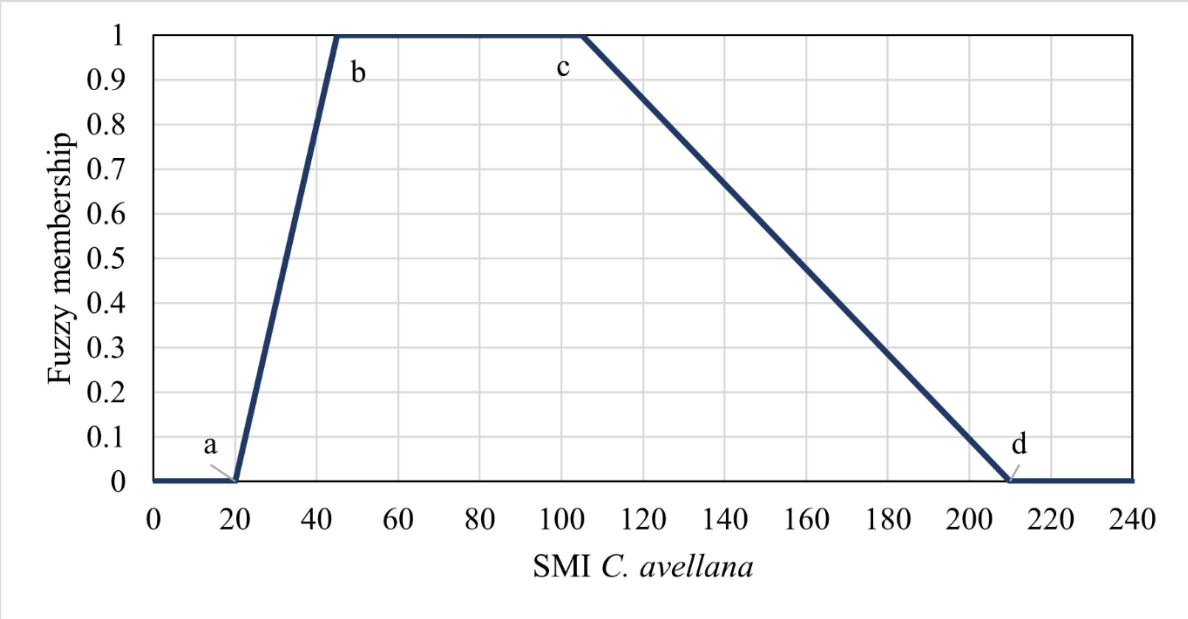

Figure 11. Linear fuzzy membership function against soil moisture index (SMI) criteria for C. avellana. Fuzzy membership equals 1 between b (SMI 45) and c (SMI 205). No fuzzy membership (0) is reached at a (SMI 20) and d (SMI 210).

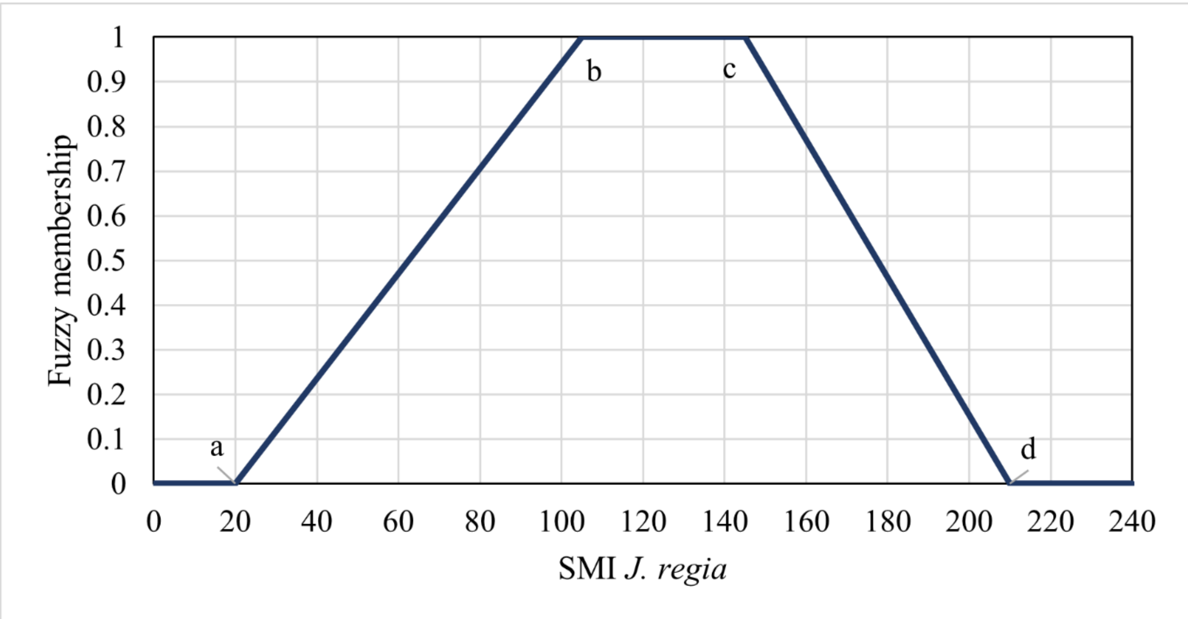

Figure 12. Linear fuzzy membership function against soil moisture index (SMI) criteria for J. regia. Full fuzzy membership (1) is reached between b (SMI 105) and c (SMI 145). Fuzzy membership equals 0 at a (SMI 20) and d (SMI 210).

The fuzzy membership layers were overlaid using weighted sum. The variables were weighted equally based on the assumption that all criteria are equally limiting for productive tree growth. The weighted layer with fuzzy memberships was multiplied with the crisp membership layers (annual precipitation and soil depth). Zonal statistics, where cultivated land was the zone parameter, was used to identify potential silvoarable agroforestry cultivation fields of different suitability. The mean statistics type was used to calculate the mean suitability for each cultivated field.

Based on the reasoning that a fuzzy membership value <0.5 (50% membership) indicates low adherence to criteria developed in Table 1, suitability was classified and ranked according to Table 7. Low suitability is reached between 50% to 65% fuzzy membership, medium suitability between 65% to 80% membership, and high suitability at ≥80% membership.

Table 7. Suitability classification based on fuzzy membership value. Fuzzy values below 0.5 (50% membership) were classified as not suitable, and fuzzy values above or equal to 0.8 (80% membership) were classified as high suitability.

Fuzzy membership	Suitability classification
0-0.5	Not suitable
0.5-0.65	Low suitability
0.65-0.8	Medium suitability
0.8-1	High suitability

5 Results

5.1 Suitability assessment for *Corylus avellana*

The suitability assessment of each variable for *C. avellana* is visualised in Figure 13. Annual precipitation (Figure 13A) is compliant to the criterion (Table 1) in most of the county; it is too low only in the south-western region and parts of the east. Mean annual temperature (Figure 13B) meets the temperature criterion for *C. avellana* throughout the county, generating high suitability. Soil texture (Figure 13C) does not meet the criterion on much of the cultivated land. Regions of high suitability, where soil texture is loam, are concentrated in the south-western region, and parts of the north-eastern. Soil moisture index (Figure 13D) complies to the criterion for medium suitability for much of the cultivated land, and high suitability in southern Scania. Figure 13E illustrates suitability with soil depth as variable input. Generally, soil depth meets the suitability criterion for *C. avellana* in Scania, apart from some regions in the north-west.

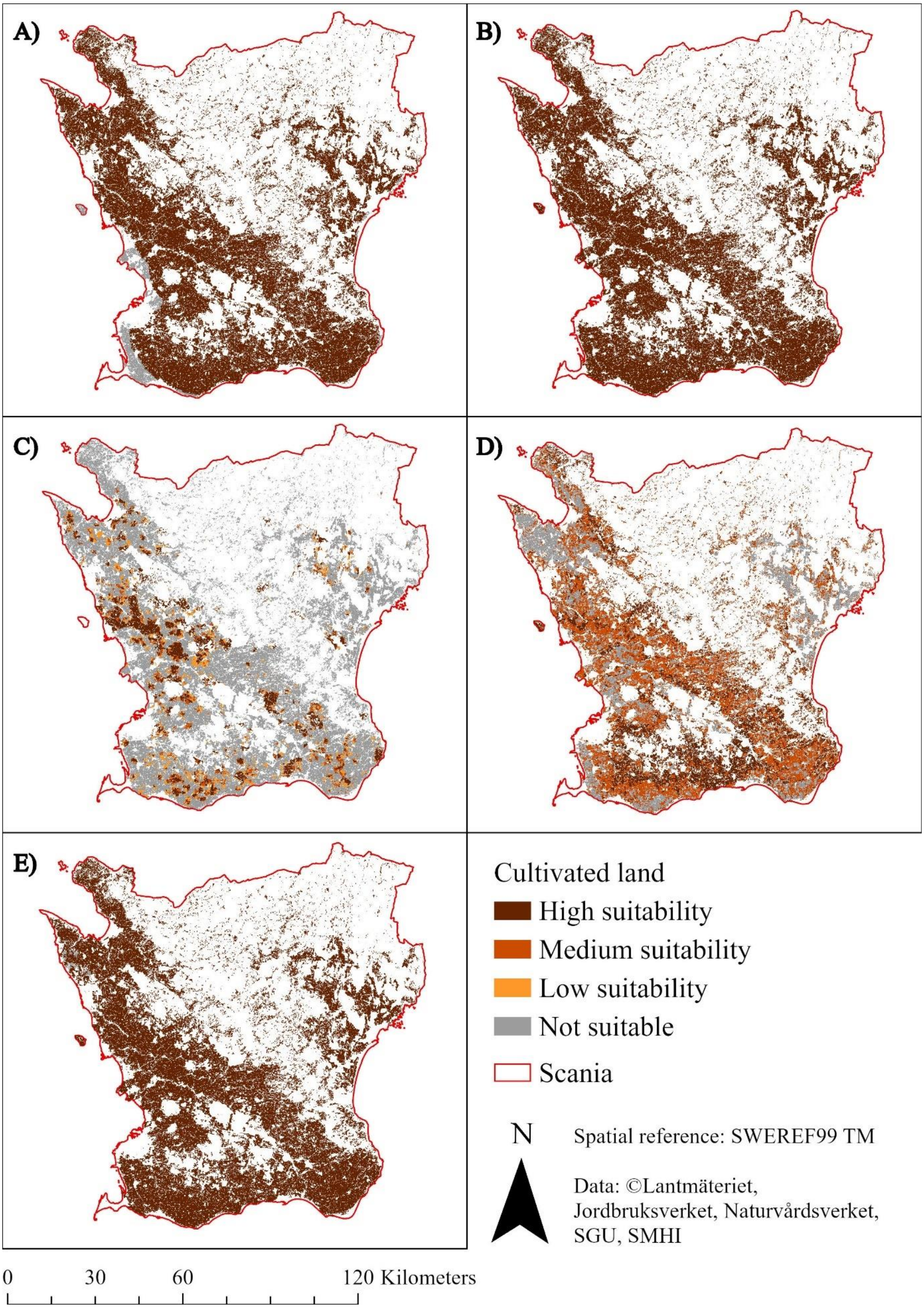

Figure 13. Suitability assessment for C. avellana where the criterion was met for each variable: A) Annual precipitation, B) Mean annual temperature, C) Soil texture, D) Soil moisture index, E) Soil depth.

5.2 Suitability assessment for *Juglans regia*

J. regia was assessed for suitability according to each variable in Figure 14. Annual precipitation (Figure 14A) is below 700 mm/year around the western, southern, and eastern borders of the county. Annual precipitation exceeds the critical limit on cultivated land inland. Mean annual temperature (Figure 14B) reach the criterion for low suitability throughout much of the cultivated land. Not suitable areas based on temperature input can be identified in the centre of Scania and the north-eastern parts. Regions of high suitability where soil texture (Figure 14C) is loam are accumulated in the south-western region, and scattered parts cultivated land in the north-east. Soil moisture index (Figure 14D) reaches the criterion for high and medium suitability throughout most of the county. Soil depth (Figure 14E) meets the minimum criterion of 1 m across the county apart from some regions in the north-west.

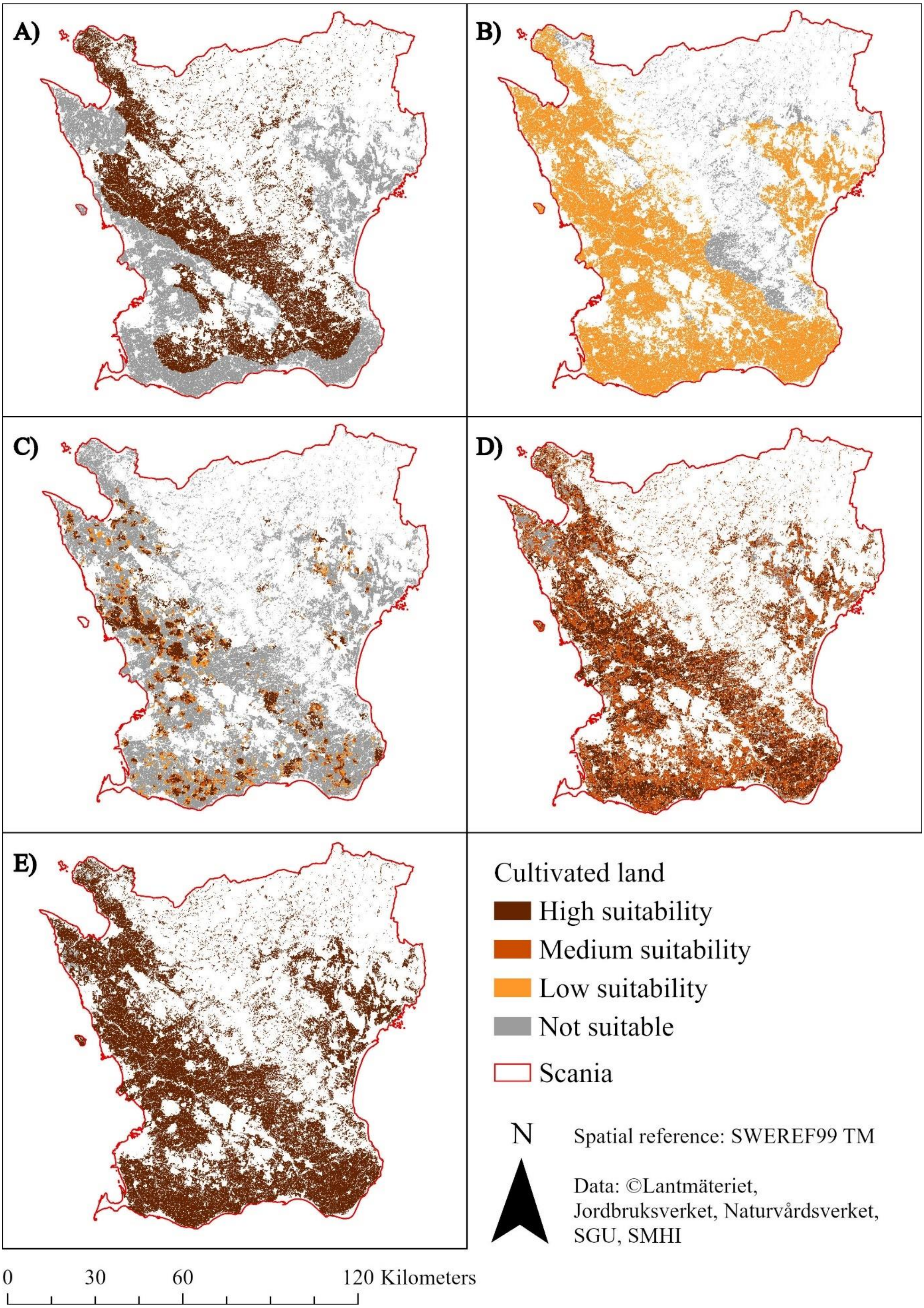

Figure 14. Suitability assessment for J. regia where the criterion was met for each variable: A) Annual precipitation, B) Mean annual temperature, C) Soil texture, D) Soil moisture, E) Soil depth.

5.3 Potential silvoarable agroforestry regions for *Corylus avellana*

Potential silvoarable agroforestry regions for implementing *C. avellana* were identified with Boolean and fuzzy logic according to Figure 15. The Boolean suitability assessment (Figure 15A) identifies suitable regions for *C. avellana* across most part of cultivated land in the county. Suitability is limited on the western border and part of the north-east according to the Boolean assessment. Figure 15B identifies potential silvoarable regions for *C. avellana* through fuzzy suitability assessment, where the identified regions meet the criteria of low, medium, and high suitability. High suitability regions are scattered on cultivated lands, mainly in the south-western part of the county.

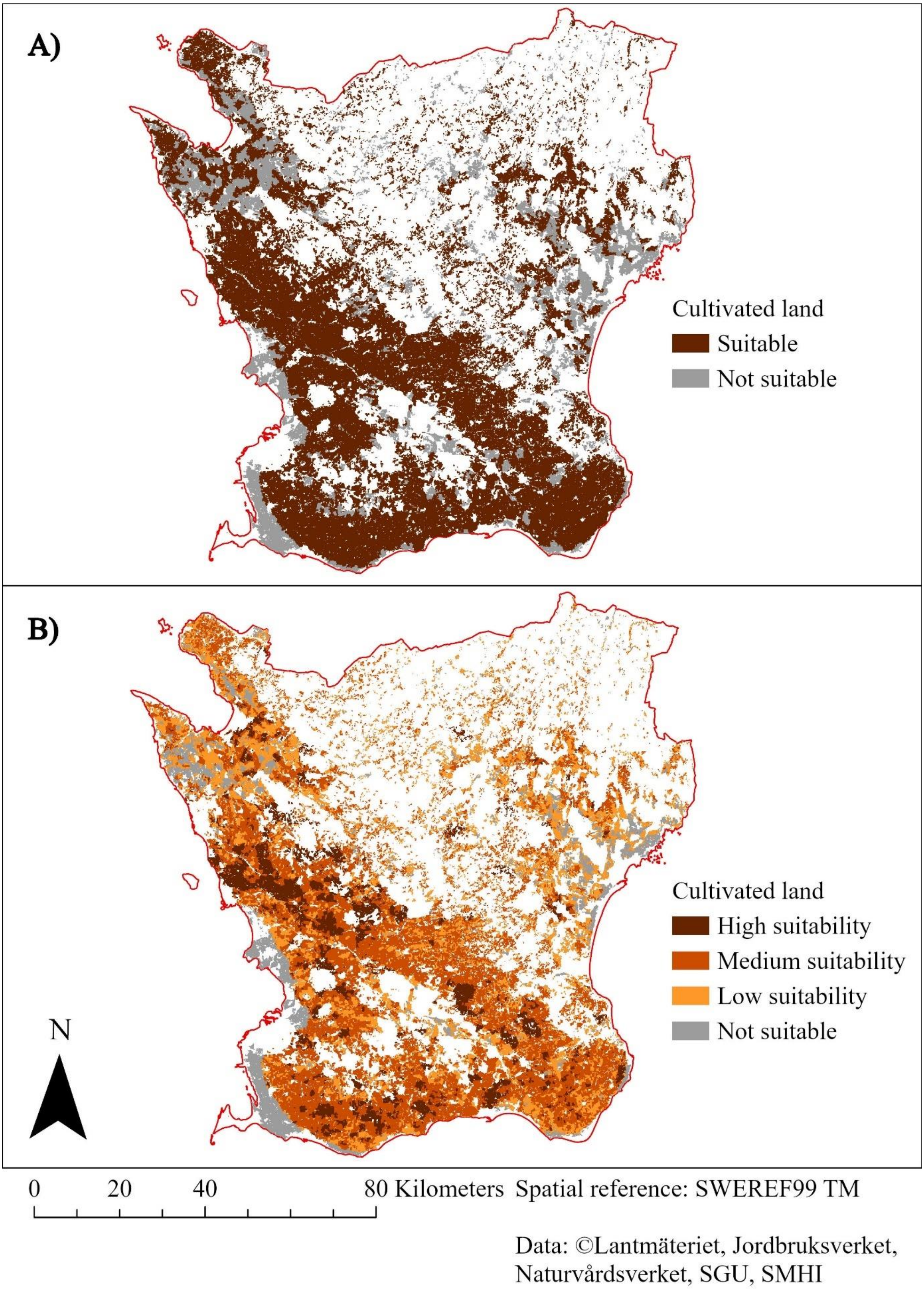

Figure 15. Potential silvoarable agroforestry regions for Corylus avellana in Scania, where A) show Boolean suitability, and B) show fuzzy suitability.

5.4 Potential silvoarable agroforestry regions for *J. regia*

Potential regions for implementing *J. regia* in AFS are identified in Figure 16. Figure 16A show regions assessed using Boolean suitability where suitable regions extend diagonally from the north-west to south-east, and part of the south. Suitability is limited around the western and southern borders, and the north-eastern part of the county according to the Boolean assessment. The fuzzy assessment (Figure 16B) mainly identifies low to medium suitable agroforestry regions for *J. regia*. High suitability is identified in a few isolated regions in the western part of the county.

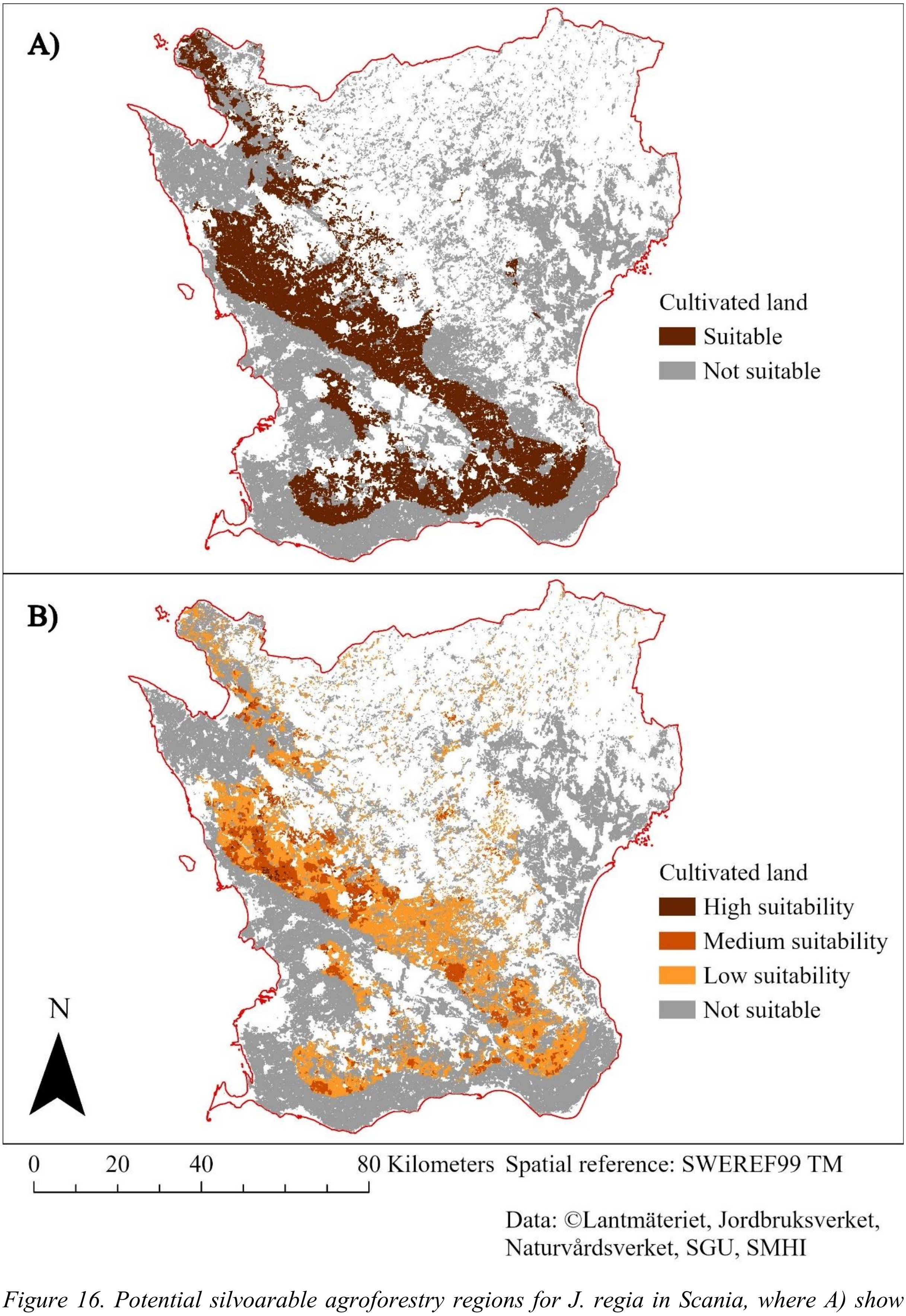

Figure 16. Potential silvoarable agroforestry regions for J. regia in Scania, where A) show Boolean suitability, and B) show fuzzy suitability.

5.5 Comparison of suitability

The extent of suitable regions for implementing *C. avellana* and *J. regia* are shown in Table 8. The total extent of cultivated land is 4283.9 km^2, where the Boolean assessment for *C. avellana* shows that 3436.2 km^2 (80.2%) of the cultivated land is suitable. The fuzzy assessment of *C. avellana* generated a slightly higher total suitability of 3864.2 km^2 (90.2%), where 553.1 km^2 (12.9%) is cultivated land of high suitability. However, most regions (48.1%) are of medium suitability. Fuzzy suitability assessment identified 10% more total suitable regions compared to the Boolean method. The Boolean suitability assessment identified, 1616.6 km^2 (37.7%) of the cultivated land as suitable for *J. regia.* The fuzzy method identified 1445.7 km^2 (33.7%) of suitable cultivated land, where 14.6 km^2 (0.3%) is of high suitability. Mostly low suitability regions are identified (25.5%). The fuzzy method identified 4% less suitable areas than the Boolean suitablility assessment for *J. regia*.

Table 8. Area [km^2] of cultivated land with Boolean (Not suitable, Suitable) and fuzzy (Not suitable, Low, Medium, High) suitability categories for C. avellana and J. regia. Total suitability is the sum of classes that meet the suitability criteria.

Suitability	Not suitable	Suitable	Low suitability	Medium suitability	High suitability	Total suitability
C. avellana:						
Boolean	847.7	3436.2	-	-	-	3436.2
Fuzzy	419.7	-	1252.2	2058.9	553.1	3864.2
J. regia:						
Boolean	2667.3	1616.6	-	-	-	1616.6
Fuzzy	2838.2	-	1094.2	336.9	14.6	1445.7

The suitability variation for the two assessment methods (Boolean and fuzzy) are visualised in pie charts (Figure 17) for the two species.

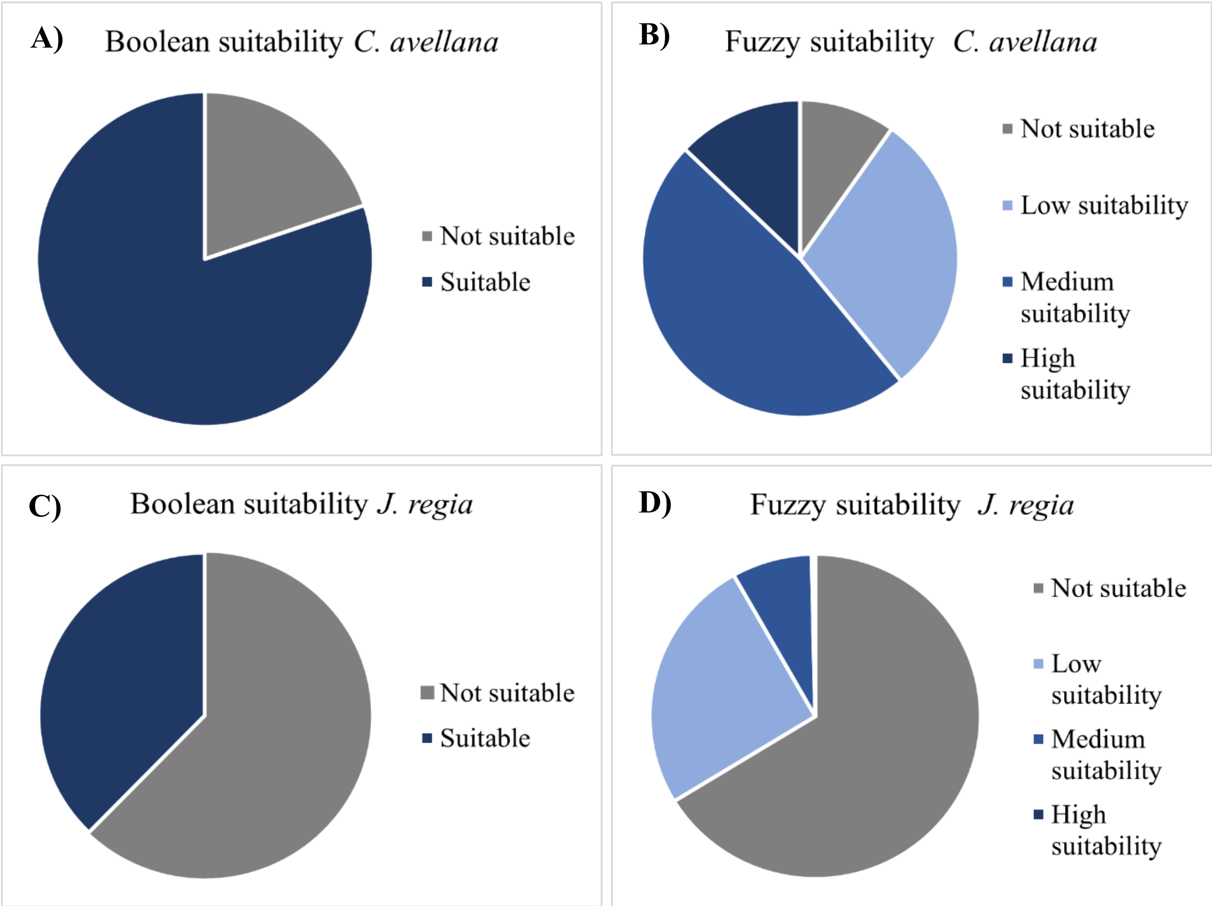

Figure 17. Pie charts showing the suitability distribution from Table 8, where A) shows the Boolean suitability distribution for C. avellana, B) shows the fuzzy suitability distribution for C. avellana, C) and D) show Boolean and fuzzy suitability distribution for J. regia respectively.

The fuzzy membership distribution of the identified potential cultivated fields is visualised in histograms (Figure 18 and Figure 19). Identified regions suitable for *C. avellana* (Figure 18) follows a near normal distribution, where values <0.5 (50% membership) account for little of the distribution. Most of the distribution is between fuzzy membership values 0.62 and 0.8. At values >0.8 (80% membership) the cell count significantly decreases. Figure 19 shows the similar distribution of cell count against fuzzy membership for potential regions for *J. regia*. The highest cell count is where fuzzy membership is close to 0. The rest of Figure 19 follows a bell-shaped distribution with the highest cell count between fuzzy values 0.5 and 0.6.

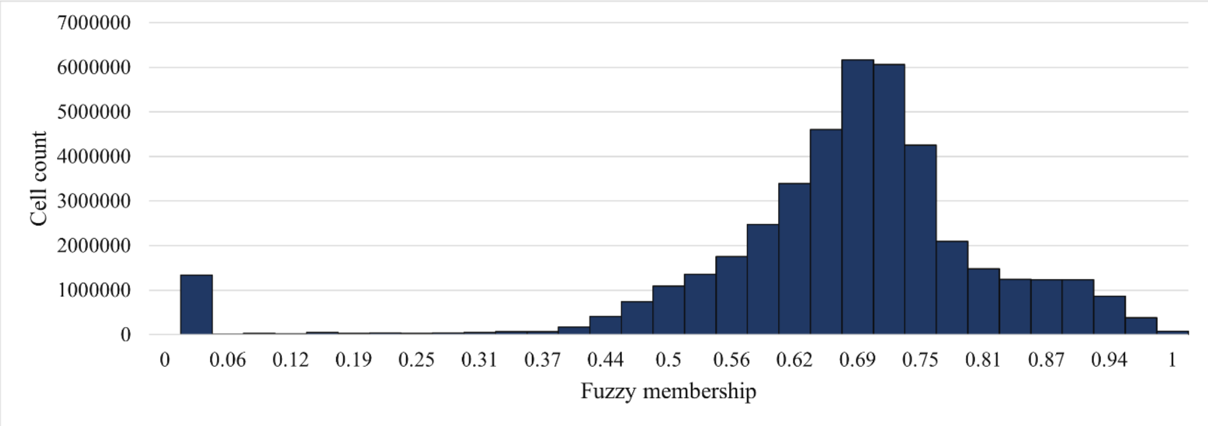

Figure 18. Histogram of cell count against fuzzy membership value for potential regions for C. avellana.

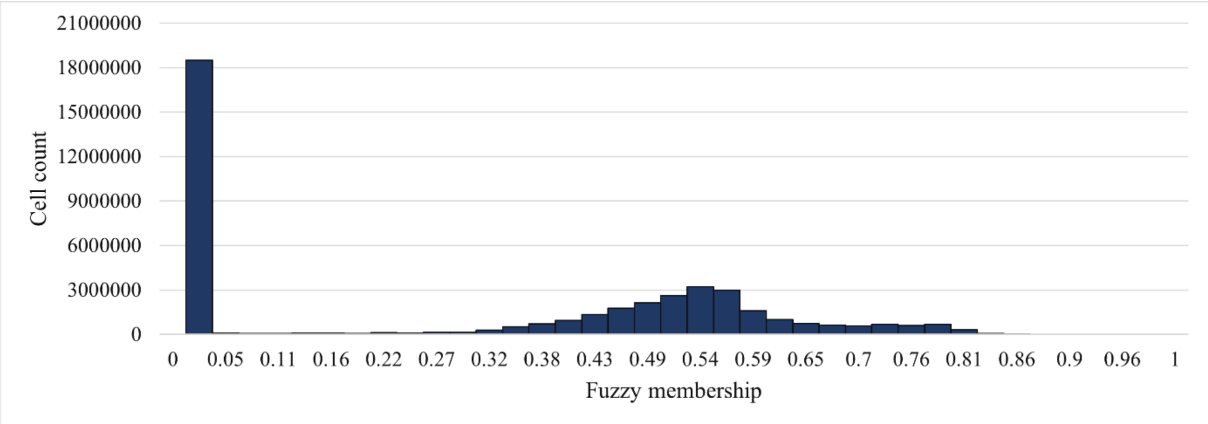

Figure 19. Histogram of cell count against fuzzy membership value for potential regions for J. regia.

6 Discussion

6.1 Suitability assessment

The analysis considered five limiting variables for productive tree growth for *C. avellana* and *J. regia* within the intensively cultivated areas in Scania. Suitability was assessed using both Boolean and fuzzy logic approaches to identify potential silvoarable agroforestry regions for *C. avellana* and *J. regia*.

Annual precipitation is more limiting for *J. regia* (Figure 14A) than for *C. avellana* (Figure 13A), as the former requires 100 mm more of annual precipitation. This is one of the main attributes as to why *J. regia* is not suitable to a larger extent in Scania compared to *C. avellana*.

The mean annual temperature in Scania is well-suited for *C. avellana* (Allegrini et al., 2022). All cultivated land (Figure 13B) meets the ranking of high suitability. In general, Scania is colder than the native regions for *J. regia* (Paz-Dyderska et al., 2021) which lowers the suitability (Figure 14B). This affects the overall suitability (Figure 16B) and causes most of the membership to only meet the criterion of low suitability. However, the low suitability is also in part due to the skewed membership function for temperature when fuzzy values were estimated (Figure 9). As this was based on the reasoning that productive tree growth is favoured by warmer conditions, more cultivated fields fell outside the temperature criteria for any higher suitability for *J. regia.*

Soil texture is the most limiting variable for *C. avellana* (Figure 13C). The tree is most productive on loam soils, which do not exist across all cultivated land in Scania. However, where the soil texture is loam, it attributes to the high suitability regions seen in Figure 15B. Soil texture criteria were the same for the two species. The overall suitability of *J. regia* (Figure 16B) is raised from low to medium suitability in regions where soil texture meets the criterion for suitability.

Soil moisture index becomes interesting as it meets the criteria of medium and high suitability for both species on several fields of cultivated land (Figure 13D and Figure 14D). However, as *C. avellana* prefers less (medium-low) soil moisture, it has less suitable areas than *J. regia*. As *J. regia* requires medium soil moisture, the criterion is generally met in most parts of the cultivated land. *C. avellana* is more sensitive than *J. regia* to waterlogged conditions, but more resilient to drought as it requires less precipitation and prefers lower soil moisture (Hicks, 2022; Weiss, 2022).

Soil depth is largely not a limiting variable for the potential agroforestry regions for the two species. Scania has deep soils where most of the cultivated land already exists, apart from a few regions in the north-west.

6.2 Potential silvoarable agroforestry regions

More regions of potential AFS with *C. avellana* were identified than with *J. regia* (Figure 17). The Boolean approach identified 3436.2 km^2 (80.2%) of suitable cultivated land for *C. avellana* and 1616.6 km^2 (37.7%) for *J. regia*. The fuzzy approach identified 3864.2 km^2 (90.2%) for *C. avellana* and 1445.7 km^2 (33.7%) for *J. regia*. The fuzzy method identified 10% more suitable areas for *C. avellana* (Figure 17B) but 4% less suitable areas for *J. regia* (Figure 17D). This can be attributed to an overall lower adherence from the input data to the cirterion in Table 1 for *J. regia*. As the species is non-native to Sweden it does not meet the climate criteria as well as *C. avellana*. Eventhough the majority of the land is found to be not suitable for *J. regia* where 62.3% was identified as not suitable according to Boolean assessment (Figure 17C), and 66.3% according to the fuzzy analysis (Figure 17D), there are still extensive areas which could be suitable for implementing *J. regia.* 1094.2 km^2 meet the low suitability criterion and 336.9 km^2 meet the medium ranking. 14.6 km^2 are highly suitable for implementing *J. regia*. Where *J. regia* is not suitable, there is the opportunity to implement *C. avellana*.

This study identified more suitable regions for implementing silvoarable AFS than Reisner et al. (2007). Reisner et al. (2007) considered the genus *Juglans* but found no regions of productive tree growth within Scania, which can be attributed to limited data availability and low-resolution data (1-km resolution). Using higher resolution datasets (10-meter resolution), this study identified several regions in Scania that met the criteria for productive tree growth for *C. avellana* and *J. regia*. Scanian cultivated land could potentially be considered as well-suited for implementing silvoarable agroforestry with *C. avellana* and *J. regia*, especially in regions of high suitability. It should be noted though, that some input datasets, mainly annual precipitation and mean annual temperature, were resampled into a higher resolution (Table 3). Nevertheless, other important criteria datasets had considerably higher spatial resolution compared to the previous study by Reisner et al. (2007).

6.3 Evaluation of method

The method was initially an exclusively Boolean approach as developed by Reisner et al. (2007). However, Boolean logic, with its crisp criteria limits, cannot capture any variability within the suitability ranges. Thus, the method was further developed using linear fuzzy membership functions and weighted sum overlay. Based on the reasoning that adherence to criteria for optimal productive tree growth generated high suitability, the suitability was ranked. The lower limit for low suitability was set at a fuzzy membership value of 0.5 (50% membership). The limit could have been set at a lower value e.g., 0.3, and that would have generated more suitable regions for both *C. avellana* (Figure 18) and *J. regia* (Figure 19). However, that would identify regions with an overall lower compliance to the criteria. It was therefore justified to use a relatively high limit for suitability.

The fuzzy analysis used weighted sum as overlay method. All variables were weighted equally, based on the assumption that each variable is equally limiting for productive tree growth. However, this assumption was made due to lack of data and information to assess if any criteria were more limiting than others and would affect the suitability for each species. Such an assessment would have required significantly more biological and agronomical expert knowledge. With that expertise, the method could have been advanced to define more appropriate weights to the input variables. Since annual precipitation and soil depth remained as crisp Boolean memberships the results became non-suitable where the criteria for the two were not suitable (0). Another approach would have been to use the overlay method of fuzzy AND, however, this becomes very restrictive as it assigns the minimum value to the output cell from all input raster sets. That would generate no to low suitability for regions in the fuzzy output layer, even though the regions are considered suitable in the Boolean assessment. The weighted sum was therefore considered more appropriate.

It would be interesting to consider other variables that might be limiting for productive tree growth, such as wind, and seasonality. One could consider the mean annual temperature during summer and during winter separately for temperature criteria instead. It can also be considered a weakness of the method that detailed information on the physical criteria for different species productive growth in silvoarable AFS is not readily available. The productive tree growth criteria (Table 1) developed in this study, are general growth requirements and not specified for silvoarable agroforestry.

It can be considered a shortcoming of the method to not have used higher spatial resolution input datasets for annual precipitation and mean annual temperature. These layers were downloaded in very low spatial resolution (4-km) and resampled to a finer resolution (10-meter) using bilinear interpolation. However, this study wanted to consider Swedish developed climate data for the most recent years available for the suitability assessment. The only datasets readily available that met those requirements were the ones provided by SMHI for the years 2018-2022.

6.4 Opportunities with implementing silvoarable AFS

Scania is projected to experience changes in environmental conditions with droughts and flooding due to heavy precipitation. On cultivated land, this will cause erosion, drowned crops, and soil compaction (Wiréhn, 2018). Introducing trees on cultivated land in Scania can protect crops and preserve yields during rapid changes of environmental conditions (Crews et al., 2018). The tree roots help facilitate infiltration and can limit erosion (Mosquera-Losada et al., 2018). As the soils are prevented from becoming waterlogged, the crops could have a higher chance of survival (Smith et al., 2013). More water could also be retained within the system and can help improve soil structure as well as limit the risk of water stress during droughts (Crews et al., 2018).

Biodiversity is increased when monocultures go from treeless fields to having trees (Mosquera-Losada et al., 2023). Even though *J. regia* is not a native species, it will serve a purpose of breaking up and diversifying monocultures and could potentially create microhabitats for species, not the least insects (Pardon et al., 2020), that do not live in open areas. An increased insect population could also attract birdlife to these fields (Vlahova, 2020). Large monocultures of high suitability should be targeted for best implementation effects.

There are now opportunities for farmers to get financial support for their environmental and conservational efforts, within the new CAP (European Commission, n.d.). These subsidies could give further incentives for a transition into silvoarable agroforestry (Mosquera-Losada et al., 2023). Farmers have the opportunity to introduce novel silvoarable practices in Scania, that can serve as an adaptation method to changing environmental conditions.

According to Wiréhn (2018) Scania is projected to have growing days all-year-round in a future climate. As crops and vegetation are fertilized by atmospheric CO_2, in combination with an accelerated phenological development due to higher temperatures it might be very beneficial if farmers in Scania decide to plant *C. avellana* and *J. regia* on their land during the coming years. This could increase the cultivated fields' resilience to challenged conditions in a future climate (Wiréhn, 2018).

Our diets will probably have to change in order to feed a growing population in a sustainable way (Parodi et al., 2018). Nuts are recognised as key commodities in sustainable diets as they require less processing and are rich in nutrients (Springmann et al., 2018). Implementing AFS with *C. avellana* and *J. regia* can introduce locally produced commodities such as hazelnut and walnuts to the Swedish market that is normally heavily reliant on import of these goods (Allegrini et al., 2022; Paz-Dyderska et al., 2021). When the systems are fully implemented it can potentially generate higher yields per land equivalent ratio (LER) than monocultures (Smith et al., 2013). This might be the case particularly in rapid changes of environmental conditions as fields will not be limited to one type of commodity.

6.5 Barriers for implementing silvoarable AFS

Silvoarable AFS are time-demanding implementations that can become more labour intensive for farmers when the system complexity increases (Schaffer et al., 2019). Adding a woody component to a current crop system will require more management. It is therefore important to design systems with enough space between the trees to allow for machinery, e.g., alley-cropping (Crews et al., 2018). Farmers can be reluctant because of the forementioned challenges, together with fear of yield reductions (Vaccaro et al., 2022). Research and education on which crops grow well together in an intercropped system is therefore very important, together with financial support through subsidies (Schaffer et al., 2019).

It also takes decades for systems to be fully established in order to evaluate the effects in the landscape (Schaffer et al., 2019).

Other barriers for implementation include risk of insects, diseases, and allelopathy that would inhibit the productivity of AFS with *C. avellana* and *J. regia*. Both *C. avellana* and *J. regia* are generally healthy put can be prone to certain fungi (Allegrini et al., 2022; Weiss, 2022) and bacterial diseases if the soil moisture conditions are too wet (Weiss, 2022). *C. avellana* also faces the issue of the nut weevil, *Curculio nucum*, that attacks the nut and reduce yields. However, an option to using pesticides to combat the nut weevil, is using fungi and nematodes (Weiss, 2022). All trees within the *Juglans* genus have allelopathic tendencies as they exhibit the substance juglone, mainly from the roots. When the chemical oxidises, it becomes poisonous to other vegetation. However, this is not an acknowledged issue in silvoarable AFS systems with *J. regia* (Weiss, 2022). Weiss further states that the substance juglone does not impede the growth of intercropped vegetations if the requirements for light and water are met.

There also needs to be a market for Scanian nut commodities for AFS to be a viable option to conventional agriculture. Environmental efforts aside, there needs to be enough market interest to incentivise changing agricultural management systems and not proceed with business as usual (Schaffer et al., 2019). Changing diets (Springmann et al., 2018) might drive market demand, but this need to be further investigated.

A paradigm shift is required for AFS to reach widespread establishment, to mitigate the environmental footprint of agriculture. There needs to be a change in how we view agriculture, and education on alternative practices to promote agroforestry (Schaffer et al., 2019). Promotion of conventional agriculture has made it difficult for farmers to gain permission to plant trees on cultivated land (Schaffer et al., 2019). This will change with new CAP, i.e., with adjusted rules for subsidies (European Commission, 2022). Nevertheless, it might not be enough if farmers still have a fear of low yields and limited resources. Examples and case studies are important for promoting change. Participatory research projects might be very important in these efforts, and economic incentive necessary.

6.6 Limitations of the study

Presently there is not enough data to evaluate performance of silvoarable AFS in Sweden. As the concept of agroforestry gains more traction, more research will be conducted, and more examples will be available. But currently, only evaluation through literature review based on studies in other areas is available.

There is also the case of farmers incentive to implement AFS, that is key for these system's development. This study does not consider any stakeholder participation when looking at suitable areas, which might be a main limiting factor.

This thesis does not consider implementation of AFS with *C. avellana* and *J. regia*. As discussed in the previous section, this process is time consuming and will vary between the two species. There was also no field measurement data that could be used to evaluate the suitability of *C. avellana* and *J. regia* in this context as the full establishment of these systems can take decades.

This study did not consider what type of crop that should be intercropped with *C. avellana* and *J. regia* respectively. This is a very important factor for the productivity of the AFS (Crews et al., 2018), and it needs to be thoroughly evaluated and researched. However, this did not fit within the timeframe of this thesis work.

6.7 Future studies

The method of this study allows for more tree species to be included in the analysis. It would be interesting to consider species that are non-native to Scania today but would become interesting in a changing climate. Future studies should also consider a future climate projection, as it is evident that *J. regia* would be more suitable in a warmer climate with higher precipitation.

Other studies should also consider looking at the market situation, and what other commodities are of interest from trees and shrubs. Reisner et al. (2007) already identified some regions suitable for the implementation of *Prunus avium* (wild cherry) in the context of mitigating nutrient leaching. Perhaps there is a market for berries and other fruit trees where Scania provides optimal growth conditions.

Something that should be investigated is what types of crops and trees work best together in intercropped systems. This can only be done through field experiments. Currently, the Swedish University of Agricultural Sciences (Sveriges lantbruksuniversitetet) has a field experiment in Southern Sweden called SITES Agroecological Field Experiment (SAFE) (Sveriges lantbruksuniversitet [SLU], 2023). The SAFE project consists of four cropping systems whereof one is a silvoarable alley cropping systems with apple trees and hedgerows (SLU, 2023). Similar small-scale projects could potentially be set up and monitored to assess compatibility between tree and crop.

Another interesting aspect that fell outside the scope of this study is what type of crop can be intercropped in the meantime while the AFS is establishing (Schaffer et al., 2019), as to minimize the yield reductions when the system is first implemented.

Additionally, more research needs to be done on how and if silvoarable AFS, and agroforestry in general, could contribute to increasing biodiversity for other vegetation, animals, and insects.

7 Conclusion

The aim of identifying the potential silvoarable agroforestry regions in Scania for *Corylus avellana* and *Juglans regia* was achieved. This confirmed the hypothesis (I) that Scania is suitable for implementing silvoarable AFS considering the five limiting variables of annual precipitation, mean annual temperature, soil texture, soil depth, and soil moisture.

This thesis also aimed to investigate the variation in suitability across these regions. Potential regions with high suitability were identified on 553.1 km^2 of cultivated land for *C. avellana* and 14.6 km^2 of cultivated land for *J. regia*. *C. avellana* had more regions of medium suitability (48.1%). *J. regia* had more regions of low suitability (25.5%) out of all the potentially suitable regions. The hypothesis (II) was confirmed as more overall suitable regions were identified for *C. avellana* than for *J. regia*. This is attributed to *C. avellana* being a native species and better suited to the current climate conditions in Scania.

By using finer spatial resolution this study could identify more potential regions for implementing silvoarable AFS than Reisner et al. (2007), thus confirming the hypothesis (III).

The study helped identify regions that could be suitable for implementing AFS with *C. avellana* and *J. regia* on Scanian cultivated land. These are regions that are potentially eligible for subsidies within the new CAP, and where farmers have an opportunity to introduce AFS to the landscape. This is relevant information to consider in decision making to help develop future implementation. Adding trees to previously treeless open areas will increase biodiversity, functional diversity, and commercial diversity.

8 References

Allegrini, A., Salvaneschi, P., Schirone, B., Cianfaglione, K., & Di Michele, A. (2022). Multipurpose plant species and circular economy: Corylus avellana L. as a study case. *Frontiers in Bioscience-Landmark*, *27*(1), Article 011. https://doi.org/10.31083/j.fbl2701011

Crews, T. E., Carton, W., & Olsson, L. (2018). Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. *Global Sustainability*, *1*, 18, Article e11. https://doi.org/10.1017/sus.2018.11

de Rigo, D., Enescu, C. M., Houston Durrant, T., Tinner, W., & Caudullo, G. (2016). Juglans regia in Europe: distribution, habitat, usage and threats. In J. San-Miguel-Ayanz, D. de Rigo, G. Caudullo, T. Houston Durrant & A. Mauri (Eds.), *European Atlas of Forest Tree Species* (pp. 103). Publication Office of the European Union

den Herder, M., Moreno, G., Mosquera-Losada, R. M., Palma, J. H. N., Sidiropoulou, A., Freijanes, J. J. S., Crous-Duran, J., Paulo, J. A., Tome, M., Pantera, A., Papanastasis, V. P., Mantzanas, K., Pachana, P., Papadopoulos, A., Plieninger, T., & Burgess, P. J. (2017). Current extent and stratification of agroforestry in the European Union. *Agriculture Ecosystems & Environment*, *241*, 121-132. https://doi.org/10.1016/j.agee.2017.03.005

Eichhorn, M. P., Paris, P., Herzog, F., Incoll, L. D., Liagre, F., Mantzanas, K., Mayus, M., Moreno, G., Papanastasis, V. P., Pilbeam, D. J., Pisanelli, A., & Dupraz, C. (2006). Silvoarable systems in Europe - past, present and future prospects. *Agroforestry Systems*, *67*(1), 29-50. https://doi.org/10.1007/s10457-005-1111-7

Erlström, M., Thomas, S. A., Deeks, N., & Sivhed, U. (1997). Structure and tectonic evolution of the Tornquist Zone and adjacent sedimentary basins in Scania and the southern Baltic Sea area. *Tectonophysics*, *271*(3), 191-215. https://doi.org/https://doi.org/10.1016/S0040-1951(96)00247-8

European Commission. (2022, December 1). *Common Agricultural Policy for 2023-2027*. https://agriculture.ec.europa.eu/system/files/2022-12/csp-at-a-glance-eu-countries_en.pdf

European Commission. (n.d.). *The common agricultural policy: 2023-27*. Retrieved April 20, 2023, from https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-2023-27_en#anewwayofworking

Gunnarsson, A. (2010). Wooded Meadow Gardening in Southern Sweden during the Past Centuries. *Acta Horticulturae*, *881*, 967-972. https://doi.org/10.17660/ActaHortic.2010.881.161

Hicks, D. (2022). Biological Flora of Britain and Ireland: Corylus avellana. *Journal of Ecology*, *110*(12) , 3053-3089. https://doi.org/10.1111/1365-2745.14008

Jordbruksverket. (2015a, November 11). *Matjordens egenskaper* [Dataset]. https://jordbruksverket.se/jordbruket-miljon-och-klimatet/kartor-med-information-om-svensk-akermark

Jordbruksverket. (2015b). *Nationell jordartskartering, Matjordens egenskaper i åkermarken* (Report 19). https://www2.jordbruksverket.se/download/18.4288f19214fb7ec78849af18/1441973777932/ra15_19.pdf

Jordbruksverket. (2021, January 1). *Jordbrukslock* [Dataset]. https://jordbruksverket.se/e-tjanster-databaser-och-appar/e-tjanster-och-databaser-stod/kartor-och-gis

Länsstyrelsen. (2006). *Odlingslandskapets geografiska förutsättningar*. Retrieved May 2, 2023, from https://www.lansstyrelsen.se/skane/besoksmal/kulturmiljoprogram/kulturmiljoprogram-skanes-historia-och-utveckling/kulturmiljoprogram-jordbrukets-landskap/odlingslandskapets-geografiska-forutsattningar.html

Lantmäteriet. (2017, January 1). *Markhöjdmodell, GRID 50+* [Dataset]. Geodata Extraction Tool. https://zeus.slu.se/get/

Lantmäteriet. (2022, January 1). *General map* [Dataset]. Geodata Extraction Tool. https://zeus.slu.se/get/

Mosquera-Losada, M. R., McAdam, J. H., Romero-Franco, R., Santiago-Freijanes, J. J., & Rigueiro-Rodróguez, A. (2009). Definitions and Components of Agroforestry Practices in Europe. In A. Rigueiro-Rodróguez, J. McAdam, & M. R. Mosquera-Losada (Eds.), *Agroforestry in Europe: Current Status and Future Prospects* (pp. 3-19). Springer Netherlands. https://doi.org/10.1007/978-1-4020-8272-6_1

Mosquera-Losada, M. R., Santiago-Freijanes, J. J., Rois-Díaz, M., Ferreiro-Domínguez, N., Rigueiro-Rodríguez, A., Aldrey-Vázquez, J. A., den Herder, M., Moreno, G., Pantera, A., & Pisanelli, A. (2018). Agroforestry in Europe: A land management policy tool to combat climate change. *Land use policy*, *78*, 603-613. https://doi.org/10.1016/j.landusepol.2018.06.052

Mosquera-Losada, M. R., Santos, M. G. S., Goncalves, B., Ferreiro-Dominguez, N., Castro, M., Rigueiro-Rodriguez, A., Gonzalez-Hernandez, M. P., Fernandez-Lorenzo, J. L., Romero-Franco, R., Aldrey-Vazquez, J. A., Sobrino, C. C., Garcia-Berrios, J. J., & Santiago-Freijanes, J. J. (2023). Policy challenges for agroforestry implementation in Europe. *Frontiers in Forests and Global Change*, *6*, Article 1127601. https://doi.org/10.3389/ffgc.2023.1127601

Naturvårdsverket. (2019a, March 19). *Markfuktighetsindex_NMD* [Dataset]. Metadatakatalogen. https://metadatakatalogen.naturvardsverket.se/metadatakatalogen/GetMetaDataById?id=cae71f45-b463-447f-804f-2847869b19b0#MDInfoTab

Naturvårdsverket. (2019b, March 19). *Rikstäckande information om markens fuktighet*. https://geodata.naturvardsverket.se/nedladdning/marktacke/NMD2018/ARTIKEL_Markfuktighetsindex_NMD.pdf

Naturvårdsverket. (n.d.). *Swedish environmental objectives*. Retrieved April 21, 2023 from https://www.naturvardsverket.se/en/environmental-work/swedish-environmental-objectives/

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R., & Simons, A. (2009, January 1). *Agroforestree Database: a tree reference and selection guide. Version 4.* https://apps.worldagroforestry.org/treedb2/AFTPDFS/Juglans_regia.PDF

Pardon, P., Mertens, J., Reubens, B., Reheul, D., Coussement, T., Elsen, A., Nelissen, V., & Verheyen, K. (2020). Juglans regia (walnut) in temperate arable agroforestry systems: effects on soil characteristics, arthropod diversity and crop yield. *Renewable Agriculture and Food Systems*, *35*(5), 533-549. doi:10.1017/S1742170519000176

Parodi, A., Leip, A., De Boer, I. J. M., Slegers, P. M., Ziegler, F., Temme, E. H. M., Herrero, M., Tuomisto, H., Valin, H., Van Middelaar, C. E., Van Loon, J. J. A., & Van Zanten, H. H. E. (2018). The potential of future foods for sustainable and healthy diets. *Nature Sustainability*, *1*(12), 782-789. https://doi.org/10.1038/s41893-018-0189-7

Paz-Dyderska, S., Jagodzinski, A. M., & Dyderski, M. K. (2021). Possible changes in spatial distribution of walnut (Juglans regia L.) in Europe under warming climate. *Regional Environmental Change*, *21*(1), Article 18. https://doi.org/10.1007/s10113-020-01745-z

Persson, G., Sjökvist, E., Åström, S., Eklund, D., Andréasson, J., Johnell, A., Asp, M., Olsson, J., & Nerheim, S. (2012). *Klimatanalys för Skåne län* (Report 52). https://www.lansstyrelsen.se/download/18.2e0f9f621636c84402730f3d/15288116359

25/LSTM-SMHI_2012_Klimatanalys%20f%C3%B6r%20Sk%C3%A5ne%20l%C3%A4n.pdf
Reisner, Y., de Filippi, R., Herzog, F., & Palma, J. (2007). Target regions for silvoarable agroforestry in Europe. *Ecological Engineering*, *29*(4), 401-418. https://doi.org/https://doi.org/10.1016/j.ecoleng.2006.09.020
Santiago-Freijanes, J. J., Mosquera-Losada, M. R., Rois-Diaz, M., Ferreiro-Dominguez, N., Pantera, A., Aldrey, J. A., & Rigueiro-Rodriguez, A. (2021). Global and European policies to foster agricultural sustainability: agroforestry. *AGROFORESTRY SYSTEMS*, *95*(5), 775-790. https://doi.org/10.1007/s10457-018-0215-9
Schaffer, C., Eksvard, K., & Bjorklund, J. (2019). Can Agroforestry Grow beyond Its Niche and Contribute to a Transition towards Sustainable Agriculture in Sweden? *Sustainability*, *11*(13), Article 3522. https://doi.org/10.3390/su11133522
Sveriges Geologiska Undersökning. (2000-present). *Quaternary deposits of Skåne*. Retrieved April 21, 2023 from https://resource.sgu.se/dokument/publikation/ba/ba55karta/ba55-karta.pdf
Sveriges Geologiska Undersökning. (2015, January 1). *Jorddjupsmodell* [Dataset]. Geodata Extraction Tool. https://zeus.slu.se/get/
Sveriges Geologiska Undersökning. (2017, November 1). *Sveriges berggrund*. http://resource.sgu.se/produkter/broschyrer/sveriges-berggrund-broschyr-nov2017-webb.pdf
Sveriges Geologiska Undersökning. (n.d.). *Sveriges berggrund*. Retrieved May 11, 2023, from https://www.sgu.se/om-geologi/berg/sveriges-berggrund/
Sveriges lantbruksuniversitet. (2023, March 1). *SITES Agroecological Field Experiement (SAFE)*. https://www.slu.se/en/departments/biosystems-technology/research-facilites/lonnstorp/safe-sites-agroecological-field-experiment/
Sveriges Meteorologiska och Hydrologiska Institut. (2017, March 20). *Genomsnittliga datum för den sista vårfrosten*. https://www.smhi.se/data/meteorologi/temperatur/genomsnittliga-datum-for-den-sista-varfrosten-1.4072
Sveriges Meteorologiska och Hydrologiska Institut. (2018-2022). *Griddade nederbörd-och temperaturdata - PTHBV* [Dataset]. https://www.smhi.se/data/ladda-ner-data/griddade-nederbord-och-temperaturdata-pthbv
Sveriges Meteorologiska och Hydrologiska Institut. (2023, May 3). *Vegetationsperiod*. https://www.smhi.se/kunskapsbanken/klimat/fenologi/vegetationsperiod-1.6270
Smith, J., Pearce, B. D., & Wolfe, M. S. (2013). Reconciling productivity with protection of the environment: Is temperate agroforestry the answer? *Renewable Agriculture and Food Systems*, *28*(1), 80-92. https://doi.org/10.1017/S1742170511000585
Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T. B., Rayner, M., & Scarborough, P. (2018). Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *The Lancet Planetary Health*, *2*(10), e451-e461. https://doi.org/https://doi.org/10.1016/S2542-5196(18)30206-7
Torralba, M., Fagerholm, N., Burgess, P. J., Moreno, G., & Plieninger, T. (2016). Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. *Agriculture, Ecosystems & Environment*, *230*, 150-161. https://doi.org/https://doi.org/10.1016/j.agee.2016.06.002
Vaccaro, C., Six, J., & Schob, C. (2022). Moderate shading did not affect barley yield in temperate silvoarable agroforestry systems. *Agroforestry Systems*, *96*(4), 799-810. https://doi.org/10.1007/s10457-022-00740-z

Vlahova, V. (2020). The role of hazelnuts (Corylus avellana L.) for the sustainability of the agroecosystem. *New knowledge Journal of science*, *9*(4), 77-84.

Wani, S., Hussain, A., Ganie, S., Munshi, A., Lal, E., & Gupta, R. C. (2016). Juglans regia – a review. *International Journal of Latest Research in Science and Technology*, *5*, 90-97.

Weiss, P. (2022). *Nötodlarens handbok*. Hälsingbo Skogsträdgård HB.

Wiréhn, L. (2018). Nordic agriculture under climate change: A systematic review of challenges, opportunities and adaptation strategies for crop production. *Land use policy*, *77*, 63-74. https://doi.org/10.1016/j.landusepol.2018.04.059