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MASTER'S THESIS

Development of planning approaches for temperate silvoarable agroforestry systems for soil erosion and water management at the local and regional level

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Declaration of honour

"I declare that I have written this master thesis self-dependently and without additional devices except where indicated. I further declare that all citations and other authors' thoughts are quoted completely and correctly."

Freising	13.12.2023	Michaela Trimbs
Place	Date	Signature

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Abstract

Climate change intensifies the hydrological cycle and may cause an increase in extreme weather events like droughts or heavy precipitation associated with increases in potential soil erosion on arable fields. This study focuses on agroforestry systems – the integration of perennial woody structures into arable fields – for preventing soil erosion and enhancing water management in arable agriculture in temperate regions. It provides planning approaches for sustainable agroforestry on the regional and local levels based on a study area in Lower Bavaria, Germany. Objectives and the natural and socio-economic frameworks in the study area regarding the potential establishment of agroforestry are assessed using expert interviews. Planning and design factors for temperate agroforestry systems targeting the stated objectives (soil erosion, water balance and microclimate) are presented based on a literature review. It is investigated which arable fields in the study area show – potentially overlapping – priorities for the stated objectives and which agroforestry systems would be suitable to achieve these. An exemplary planning process for a silvoarable agroforestry system on one of the suitable and high-priority fields rounds off the study. In the study area, high priority for erosion control (52 %), water retention (30 %) and/or wind protection (4 %) was allocated to 66 % of the arable land. Establishing silvoarable agroforestry would be suitable and recommended on 94 % of the arable land. Field-scale studies reported reduced surface runoff (n=3), wind speed and erosion (n=7), water retention (n=7) and modification of microclimate variables (n=5) for short rotation systems. Reduced surface runoff and erosion (n=5) and wind speed (n=1), as well as water retention (n=12) and microclimate (n=7), were measured in timber and fruit systems, compared to arable cultivation. Planning factors derived from these studies, supplemented by practical recommendations, resulted in four basic design approaches for silvoarable agroforestry systems. These were assigned to the fields of the study area and serve as general planning approaches on the local scale for temperate regions. The developed planning approach on the regional level can provide a simplified method for municipalities and regions to get an overview of the suitability of fields for agroforestry regarding set objectives, thereby facilitating the establishment of such systems and enhancing climate change resilience of arable agriculture. Economic viability, legal security, and consultation are fundamental to removing barriers to its implementation. Future research should investigate the automation of simplified planning approaches on the regional scale and extend the scientific basis for field-scale effects depending on system designs and site specifics, as well as for landscape-scale effects.

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List of Abbreviations

AOI	Area of Interest
CAP	Common Agricultural Policy
GIS	Geographic Information System
QGIS	Open-source Geographic Information System
RCP	Representative Concentration Pathways
RQ	Research Question
SRA	Short Rotation Agroforestry

1 Introduction

The warming of the climate system causes widespread changes in the atmosphere, ocean, cryosphere and biosphere. Climate change is unequivocally caused by anthropogenic-induced increases in greenhouse gas concentrations, which contribute to tropospheric warming and continue to rise. The last decade 2011-2020 was the warmest since 1850 with a global mean land surface temperature 1.59 °C higher than in 1850-1900 (IPCC, 2021). Climate observations for Europe show seasonal and regional variabilities of changes in temperature, precipitation and extreme events, which have negative impacts on multiple sectors such as agriculture (Kovats et al., 2014). Climate change intensifies the hydrological cycle and may cause extreme weather events like heavy precipitation or droughts to increase in frequency and intensity. This is also associated with an increase in potential water erosion on arable fields (Borelli et al., 2020; IPCC, 2021). The impacts differ regionally, and are projected to increase with every degree of global warming (Caretta et al., 2022). Albeit precipitation-related projections are engrained with uncertainty, it seems wise for farmers to prepare for such events as in the past, single heavy rainfall events caused severe soil erosion and flash floods at individual locations, e.g. in the county of Rottal-Inn in June 2016 with up to 100 mm precipitation in 6 hours (StMUV, 2021). As a result, agricultural measures such as mulch sowing, cover crops or erosion control strips were recommended (LfL, 2017). In 2020, the neighboring municipality of Wittibreut again experienced severe soil erosion on arable fields during heavy rainfall events. The advisory institutions thereupon declared the municipality a project area for targeted soil erosion and water management measures. Here, agroforestry – a land-use system integrating perennial woody structures into arable fields – is to be considered as an additional agricultural adaptation measure (ABG Rottal-Inn, 2023). Agroforestry is associated, among other climate adaptation and mitigation effects, with soil erosion reduction and water retention (Schoeneberger et al., 2012).

The aim of this study is two-pronged, with a local and a general component. On the one hand, an initial overview of which fields and types of agroforestry would be suitable in the municipality of Wittibreut is provided. On the other hand, learning from the local example, this master thesis develops general, transferable planning approaches for agroforestry systems for preventing soil erosion and enhancing water management in arable agriculture in temperate regions, thereby facilitating the establishment of such systems by determining where they are reasonable. The thesis is divided into four research questions oriented towards local and regional scales, where the local scale refers to single (connected) fields and the regional scale to several field blocks of the study area, here the municipality of Wittibreut. The municipality is located in the county of Rottal-Inn, Lower Bavaria, Germany, and comprises 3,832 ha, of which 46 % is used as arable land (LfStat, 2023).

The first research question aims to assess the objectives of different stakeholders as well as the natural and socio-economic frameworks in the study area regarding the potential establishment of silvoarable agroforestry systems in arable agriculture (regional scale). The second research question considers the stated objectives of the first research question and investigates how temperate silvoarable agroforestry systems need to be designed to meet these goals (local scale). The third question integrates the results from before to match suitable fields with the stated objectives and derive agroforestry designs in the study area. It is investigated which arable fields in the municipality of Wittibreut show – potentially overlapping – priorities for the stated objectives (notably soil erosion, water balance and microclimate) and which agroforestry systems would be suitable to achieve these (regional scale). The last research question conducts an exemplary planning process for a silvoarable agroforestry system on one of the suitable and high-priority arable fields in the study area. Lessons learnt from this application of the rules identified above are reflected back into the planning process devised in the second and third research question. The next section expounds the background of climate change impacts on the water balance and soil erosion as well as of temperate silvoarable agroforestry and its planning factors. In the ensuing sections, the applied methodology and derived results for the four research questions are described and discussed.

2 Background

2.1 Climate change impact on the water balance and soil erosion

2.1.1 Water balance

The water balance describes the balance between precipitation and evapotranspiration, runoff and storage, including the following components of the hydrological cycle: evaporation from surfaces, transpiration from plants, interception as storage on plant surfaces, surface runoff, interflow and groundwater. In the last decades, the increase in atmospheric temperature went along with an increase in total atmospheric water vapour, global precipitation and evaporation. The rainfall intensity rises by 7 % with every degree of warming (Brutsaert, 2023). Climate change intensifies the hydrological cycle, and extreme weather events like heavy precipitation and droughts increase in frequency and intensity. The observed changes have numerous impacts on water security, society and ecosystems. The impacts differ regionally, and are projected to increase with every degree of global warming (Caretta et al., 2022). While increased water vapour leads to more intense precipitation events, regional annual precipitation distributions may decline due to higher air temperatures and increased evaporation (IPCC, 2021). In southern Germany, the average total precipitation of 903 mm decreased by 6 % since 2003 (reference period 1971-2000), and the precipitation in the winter half-year, contributing to groundwater recharge, decreased by 11 % (Fliß et al., 2021). Climate change is most likely also associated with an increased risk of heatwaves, such as those that occurred in continental Europe in 2003, 2015 and 2018 (Stott et al., 2004; Sippel et al., 2016; Aalbers et al., 2018). In these years, the average precipitation decrease in southern Germany accounted for one-third, causing significant deficits in groundwater recharge. Between 2003 and 2019, the groundwater recharge rate decreased from 175 mm/a (Bavaria 207 mm/a) by 19 % (Bavaria 15 %). Since the 1990s, dry days (< 30% usable field capacity) have increased with high variability over the years due to increased evaporation losses and reduced precipitation, especially in spring. Increased transpiration rates further dropped the soil available water due to favoured vegetation growth (higher temperatures and longer vegetation period) (Fließ et al., 2021). However, the changes are characterised by seasonal and regional differences, with the precipitation trend for the period 1951-2019 showing a -9 % to -23 % decrease in summer and 0-14 % increase in winter for Bavaria (StMUV, 2021). By mid-century, climate projections (Representative Concentration Pathways, RCP2.6 and 4.5) for Bavaria show an increase in air temperature of 0.5 to 2.6 °C and a range for annual precipitation from a decrease of -4.7 % to a rise of 11.4 % relative to the reference period 1971-2000. Days with precipitation of > 20 mm/day will likely increase, while dry days change by -8 to +15 days/yr and the climatic water balance changes by -0.14 to 0.23 mm/day (Pfeifer et al., 2020). The continuous rise in evaporation due to higher temperatures reducing plant available soil water threatens arable agriculture in Bavaria (StMUV, 2021). Due to heat and drought stress, crop yield and quality decline, especially in dry years (Beillouin et al., 2020).

2.1.2 Soil erosion

Soil erosion is the removal of soil particles by water or wind along the soil surface. The detachment of soil particles by wind starts with critical wind speeds above 6-8 m/s and above 3-5 m/s for soils most prone to erosion, such as dry and fine sandy soils at wind-exposed, uncovered fields (Blume et al., 2016). The push/pull forces of the airflow separate soil aggregates. Soil particles are lifted vertically into the air (saltation) and break or dislodge further soil particles when falling to the surface (abrasion). While soil particles > 500 µm are only pushed or rolled along the surface (surface creep), particles < 100 µm are transported with the airflow for larger distances (suspension) (Richter, 1998). Wind erosion is determined by the soil erodibility, the wind intensity and duration, climatic conditions of the location, surface roughness, the amount and type of soil cover and the field length along the prevailing wind direction (Chepil and Woodruff, 1963). In Germany, 25 % of the arable land is at risk for wind erosion, with a focus on mainly sandy north German soils, whereas clay-rich silt or loam soils with low risk for wind erosion prevail in large parts of southern Germany. One-third of the arable land is endangered by water erosion, showing four hotspots with highly erodible soils and hilly landscapes, including the Lower Bavarian Hills (BGR, 2014).

The detachment of soil particles by water begins with falling raindrops, filling soil pores (air burst), creating high shear stresses at the soil surface and detaching soil aggregates (splash erosion). Dissolved soil material is washed into soil pores (silting). When the infiltration capacity and soil water storage are exceeded, surface overflow forms. The overflow of the swale storage finally creates surface runoff. The rising velocity and volume of the runoff increase its transport capacity and enable the detachment of further soil material (wash erosion). With rougher surfaces, the runoff is not areal but follows the microrelief in concentrated flow sections, erosion grooves, and gullies develop (Richter, 1998). Soil erosion by water begins at a slope inclination of four per cent and a slope length of more than 50 m (Deumilch et al., 2006). The amount of soil loss by water for specific field or catchment areas is expressed in the Universal Soil Loss Equation (USLE), considering rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), the effect of crop management (C), and long-term soil protection measures (P) (Wischmeier et al., 2019). With the surface runoff, nutrients and pollutants are transported to lower areas, water bodies and ecosystems, causing damage to water bodies, ecosystems and crops (Kotremba et al., 2016). Soil erosion also shortens soil profiles, removes fine soil fractions, and reduces the soil's water storage capacity and ability to bind nutrients, resulting in a reduction in soil fertility and yields (Richter, 1998).

Climate change influences rainfall erosivity by altering precipitation amount, intensity and (seasonal) distribution (Auerswald & Menzel, 2021). Global climate projections indicate a trend towards intensified hydrological cycles, causing a potential increase in water erosion. Since the 1950s, the frequency and intensity of heavy rainfall events have increased over Europe (Borelli et al., 2020; IPCC, 2021). The rainfall erosivity depends on the raindrops' detachment power and both precipitation duration and intensity. At high rainfall intensities and in dry soils, the soil infiltration capacity quickly decreases, promoting surface runoff (Morgan, 1999). Soil erosion by water is expected to increase by 18 % in 2050 in 81 % of Europe, esp. in Northern and Central Europe (EC, 2015). In Germany, rain erosivity has doubled since the 1960s and shifted towards the winter season (October to May) as more precipitation fell as rain instead of snow and the rain intensity increased (Auerswald, 2019). Single heavy rainfall events caused severe soil erosion and flash floods at individual locations, e.g. in the county of Rottal-Inn in June 2016 with up to 100 mm precipitation in 6 hours (StMUV, 2021).

By changing biomass levels due to changes in temperature, soil moisture, and atmospheric carbon dioxide levels, climate change also affects soil erodibility (Li and Fang, 2016). The soil erodibility depends on the soil type and properties, where the grain size composition and humus content determine the structural stability and infiltration capacity. Soils with a high silt and fine sand content are susceptible to erosion, whereas soil organic matter (up to 12 %) increases aggregate stability (Deumilch et al., 2006). The combination of precipitation and temperature changes is likely accompanied by changes in crop management, such as planting and harvesting dates and type of cultivars (Borelli et al., 2020). The crop cover absorbs part of the runoff and wind energy, while the roots increase the mechanical soil strength (Morgan 1999). Increased land evapotranspiration regionally contributes to increases in dry periods and droughts (IPCC, 2021), leading to vegetation thinning and open soil, thereby increasing the susceptibility of soils to erosion (Kotremba et al., 2016). The changes in crop biomass and soil moisture and more frequent extreme wind speed events in central Europe will likely increase wind erosion (Bartkowski et al., 2023).

In the 1990s, the German Advisory Council on Global Change already warned of the consequences of soil degradation in the scope of climate change and called for soil protection measures that increasingly address soil functions (WBGU, 1994). Since 1999, the Federal Soil Protection Act (BBodSchG), implemented by the federal states, describes regulations for post- and precautionary soil protection, the long-term safeguarding of soil functions and the preservation of soil fertility. These include site-appropriate soil cultivation, avoidance of soil compaction, preservation and promotion of soil biological activity, structure and humus and elements such as hedges and trees (Blume et al., 2016).

2.2 Silvoarable agroforestry systems

2.2.1 Temperate silvoarable agroforestry systems

Agroforestry is a land-use system where perennial woody structures (trees or shrubs) are deliberately integrated with agricultural crops and/or livestock on the same land, and ecological and economic interactions occur between the different components (Nair, 1993; den Herder et al., 2017). Agroforestry systems are established at field, farm and landscape levels, widespread in tropical regions, and occur in the Mediterranean and temperate areas (FAO, 2013). The wide range of agroforestry systems results from differences in the arrangement of components, aimed functions, management level, and the agroecological and socio-economic situation (Nair, 1985). The prevailing historical agroforestry practices in Europe are silvopastoral systems (17.78 million ha, 4.1 % of EU territory) and silvoarable systems (360,000 ha, < 1 %) with focus on southern European countries (Mosquera-Losada et al., 2018). In temperate European countries, silvopastoral systems, including meadow orchards, have a total extent of 1.3 million ha. Hedgerows, shelterbelts and scattered trees in West and Central European countries account for 0.5 to 1.78 million ha. In France, silvoarable systems with poplar grow on 6,300 ha. Chestnut agroforestry is cultivated on 4,600 ha in Central and East European countries (den Herder et al., 2017; Mosquera-Losada et al., 2018). In silvoarable agroforestry, the spatial layout of trees and shrubs follows an alley cropping or includes scattered trees, tree lines and hedges combined with arable crops (Mosquera-Losada et al., 2018). The prevailing silvoarable agroforestry systems in Bavaria include short rotation systems, timber and fruit systems, combined systems and (riparian) buffer stripes (Winterling, 2023).

Timber and fruit systems pursue the (additional) production of timber or fruit products in long rotations. The historical predecessor of timber agroforestry systems is the so-called "Holzwiese". On alpine pastures and meadows, isolated trees were deliberately planted outside the forest in loose stands for producing fodder leaves and timber. The trees comprised beech, ash, rowan, spruce, hazel, sycamore maple, pine and birch (Reeg, 2009). In modern silvoarable agroforestry systems, high-value timber with specific dimensions and quality requirements is produced with deciduous tree species in 50-70-year rotations. The pruning of trees allows the growing of long knot-free trunk shafts (ca. 1/3 of final tree height), which are processed to veneer wood (Brix et al., 2009). The individual trees are planted at wide intervals in alley-cropping or contour farming systems (Schulz et al., 2020). The origin of fruit agroforestry systems goes back to the 15th century when fruit cultivation was extended from orchard gardens to fields and vineyards for additional income (Kornprobst, 1994). In 1900, the fruit tree census counted 168 million productive fruit trees in the German Empire (StMELF, 2021). By carefully arranging and managing the trees, competition between trees and agricultural crops was reduced (Reeg, 2009). Meadow orchards on grassland spread with the increase in dairy farming in the 20th century (Weller et al., 1986). Rows or irregular order of half and high-trunk fruit trees characterise meadow orchards. The trees vary in species, varieties, and age and produce fruits and wood. In the 20th century, many historical agroforestry systems were removed from agricultural land, and the remaining “Baumäcker” in the Steigerwald region were protected in 2018 as intangible cultural heritage (UNESCO, 2021). In modern silvoarable agroforestry systems, rows of suitable fruit and nut trees are arranged with arable crops, sometimes also combined with timber production (Jäger, 2017).

Short rotation agroforestry (SRA) includes fast-growing trees for energy and industrial wood (Nerlich et al., 2013; Tsonkova & Böhm, 2020). The integration of woody structures in the landscape, such as hedgerows used in short rotations, represents historical forms of short-rotation agroforestry systems. The trees and shrubs were used for fodder leaves, fence wood, wickerwork, firewood, etc., for demarcating property and to use microclimatic effects. Relevant planning aspects for today’s systems are the establishment of a mixture of woody species (by sowings or cuttings), site-specific species selection and management (e.g. headwoods in floodplains), vertical structural diversity due to flexible rotation periods, consideration of land cultural and aesthetic aspects, such as leaf emergence, flowering, or autumnal foliage colour (Konold, 2018). Modern short-rotation agroforestry systems (SRA) are oriented to short-rotation coppices and integrate strips of fast-growing tree species into arable fields. The regeneration of the stand through stock cuttings allows several rotation periods of 5 to 10 years for energy production in the form of wood chips and > 10 years (max. 20 years) for industrial wood. The experience from short rotation coppices is often used to plan and manage SRA, whereas SRA has significantly higher growth rates (Winterling, 2023).

In the last decades, many traditional agroforestry systems in Europe were removed from agricultural land with the intensification and mechanisation of agriculture. Today, the potential of agroforestry to foster biodiversity, climate adaptation and mitigation while sustaining agricultural productivity is increasing farmers' and public interest in agroforestry (Nerlich et al., 2013). Agroforestry sequesters carbon in the woody biomass and soil reduces GHG emissions on the field and substitutes fossil fuels and building materials. It reduces threats and increases resilience towards environmental risks, contributing to climate adaptation. The following effects are attributed to agroforestry: soil erosion reduction, microclimate modification, biodiversity enhancement, ground and surface water quality improvement, efficient use of resources and diversification of farmers´ incomes (Schoeneberger et al. 2012; Smith et al. 2014, FAO 2013). Newly established silvoarable agroforestry systems are adapted to modern agricultural production conditions, enabling an economically competitive agricultural production by keeping impediments for machinery at a minimum. Strips of woody structures are often arranged parallel, oriented to the width of agricultural machinery (alley cropping) (Winterling, 2023; cf. Figure 1).

Figure 1 Silvoarable agroforestry system comprising parallel arranged wood strips with timber and fruit trees (own photograph Hemmersheim, 2023)

2.2.2 Agroforestry water management systems

The “keyline design” is a landscape-related and relief-adapted water management system developed in the 1950s by farmer and engineer Parcival Alfred Yeomans as a holistic design approach for Australian agriculture. It aims at reducing erosion and (re)distribution, storage and infiltration of water from (heavy) precipitation events through a contour-oriented cultivation pattern. This pattern is based on topographical conditions and properties of the natural flow of water. It includes water management elements like swales, which collect and distribute rainwater from the valleys (primary valleys) to dry ridges (primary ridges) (Yeomans, 1958; cf. Figure 2 and 3).

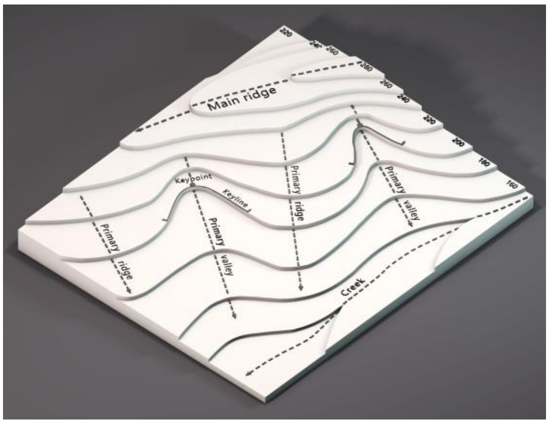


Figure 2 The keyline planning starts with the “key point” in the primary valleys just below the point (valley floor), where the slope changes from concave to convex. The contour line passing through the key point is the "keyline" (Pavlov, 2015).

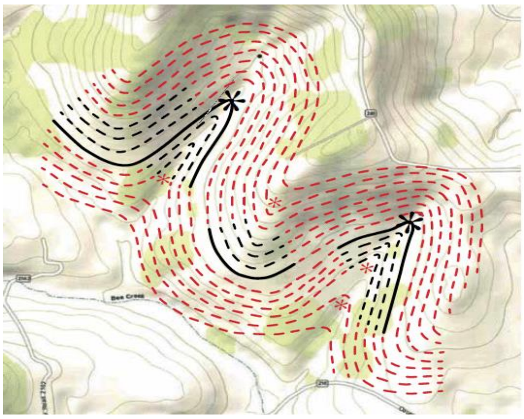


Figure 3 The parallel cultivation patterns in the primary valleys and ridges based on the keypoints causes water to spread to the ridges (Shepard, 2020).

The lines run downhill towards the ridge by a few per cent and are usually planted with trees. Along the lines, dams ("swales") or furrows are created by the “keyline plough”. The furrows and swales lead to a superficial and mostly laminar water flow downhill towards the ridges (Yeomans, 1958). The surface runoff reduces, and the infiltration rate and soil moisture increase. This is enhanced by the longer residence time, increased humus content, and improved soil structure due to the deep loosening of soil (Ryan et al., 2015; Duncan & Krawczyk 2017). The” keyline plan” further aims to achieve the buildup of fertile soil to ensure the infiltration and storage of distributed rainwater in the soil. It considers a gradual permanence of landscape-forming factors, where planning with soil, infrastrucutre and water is easier than with topography and climate. This “Scale of Permanence” is a planning tool to optimise the development and expansion of agricultural production systems (Yeomans, 1958). Accordingly, the keyline cultivation pattern is oriented to the geomorphology and climate, including heavy rain events, dry seasons and weather anomalies (Shepard, 2020). As the keyline design applies to Australian landscapes with regular terrain morphology and long and wide valley-slope ridges, Shepard (2020) developed the masterline approach to adapt the keyline design to irregular topography and small landscapes in Wisconsin (US) agriculture. The “masterline design” claims to apply to all geomorphological, topographical and limiting conditions and deals with irregularities, such as excessive slopes (>4%) or small areas of negative slope. In contrast to the keyline, the masterline already has a slight gradient in itself (0-1 %) or is oriented along property boundaries and possible water inlets (Shepard, 2020, cf. Figure 4).

The agroforestry planner Philipp Gerhardt developed a landscape-based water management system for temperate European conditions. It agrees in its basic considerations with the masterline design and is presented as “parallel systems of collecting and infiltration swales” in the master thesis of Fahrendorf (2022). The central elongated low point (minimal or no flow movements) draws in the water of the connected sub-catchments by minimal gradients at both ends of the swales and ensures infiltration in the low points. The swale profile should be vegetated, shallow and > 3 m wide, including > 0.5 m downhill with woody plants. The swales are established with minimal earthmoving (< 0.3 m fillings and < 0.6 m excavation) (cf. Figure 5). The management of swales includes regular mowing or mulching and, if required, the removal of sediments. Parallelism across all swales ensures minimised management restrictions. The geometry of swales is adapted to changing contours, which might lead to cut-off areas. To prevent runoff concentrations in swales during heavy rainfall events, overflow constructions should be installed, e.g. by levelled swales for wide-area overflow at the elongated low point, underground pipe system connecting swales to a retention basin, or cascading swale profile with minimal flow gradients towards vegetated headlands (Fahrendorf, 2022).

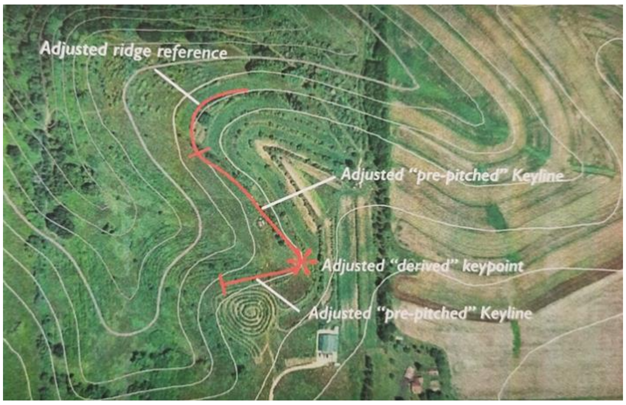


Figure 5 The keyline is adjusted so that the water flows downhill from the keypoint to the ridges (Shepard, 2020).

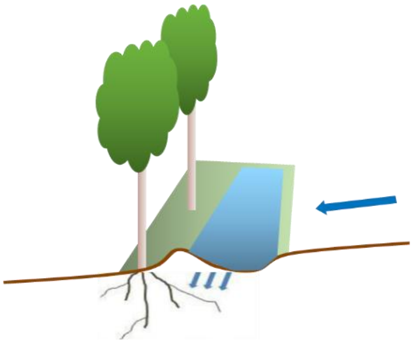


Figure 4 Masterline design according to Shepard and Gerhardt (own illustration based on Fahrendorf, 2022).

2.2.3 Basic planning factors for temperate silvoarable agroforestry systems

The successful establishment of agroforestry systems requires long-term integrated planning (Gold et al., 2013). The first step is the definition of targets and desired products, which determine the required tree species, arrangement and management of trees (Reeg et al., 2009; Böhm & Veste, 2018). Economic targets can be the production of energy, industrial or construction wood, fruits, nuts, honey, etc.; added by ecological targets like soil erosion reduction, biodiversity and other regulating ecosystem services; and/or cultural targets, e.g., landscape scenery or recreational value. To reduce economic risks and promote ecological benefits, it is essential to consider the local site specifics. Relevant planning factors comprise targets and priorities, site specifics, ownership and farm structures, available resources (labour, equipment, buildings, machinery, distance to farm, etc.) and legal framework (Gold et al., 2013; Böhm & Veste, 2018). To enable cultivation with large-scale agricultural technology, the establishment of temperate silvoarable agroforestry usually follows schematic guidelines for linear or strip-shaped systems (Böhm & Veste, 2018). To evaluate the suitability of fields for agroforestry systems, the following aspects need to be taken into account (Gold et al., 2013; Hofmann et al., 2019):

- *Abiotic:* risk of erosion, field geometry, climate, soil structure, depth and moisture
- *Biotic:* soil fertility, yield potential, natural conservation objectives, connectivity and biodiversity of the landscape, etc.
- *Social and economic*: interests and capacities of the farmers and landowners, financing options and profitability, market potentials, proximity to the farm centre, landscape aesthetics

The legal and federal framework in Germany includes conditions of eligibility for the Common Agricultural Policy (CAP) of the European Union, nature conservation law, and distance regulations in the neighbourhood law and road traffic regulations (Reeg et al., 2009). According to the CAP Strategic Plan, the German government aims to establish agroforestry systems on 200,000 ha until 2027 (BMEL, 2022). Therefore, the maintenance of agroforestry systems is rewarded as Eco-Scheme in the first pillar with 60 € (2023) and 200 €/ha (from 2024) if all given conditions are met (LfL, 2023a). In Bavaria, the establishment of agroforestry systems is promoted as a KULAP investment measure with 1,566 € for SRA, 4,138 € for shrubs and 5,271 € for timber systems per ha woody area, and 65 % of the eligible expenditure (StMELF, 2023). DeFAF (2022b) describe the requirements for funding via the CAP. At least two predominantly stocked wood strips covering 2-35 % of the field need to be established in a way that ensures a distance between wood strips and towards field borders of ≥ 20 m and ≤ 100 m. The wood strips require a minimum width of 3 m. Tree species on the negative list of the CAP Direct Payment Regulation must be avoided (DeFAF, 2022b). To clarify the respective legal situation, it is recommended to consult the agricultural and nature conservation authority, especially at sites of high nature conservation value and with protection status. Professional support in the planning process should be requested (Schulz et al., 2020).

3 Methodology

This chapter presents the applied methods for the four research questions. Within the first research question, expert interviews were used in addition to literature research to identify objectives and socio-economic frameworks in the study area. A literature review is conducted for the second research question to investigate how temperate silvoarable agroforestry systems need to be designed to meet the stated objectives. The third question integrates the results from before and includes the application of filter steps, decision trees, classification of map data, and QGIS to match suitable fields with the stated objectives and derive agroforestry designs in the study area. The fourth reseach question comprises an exemplary planning process on one of the suitable fields (cf. Figure 6).

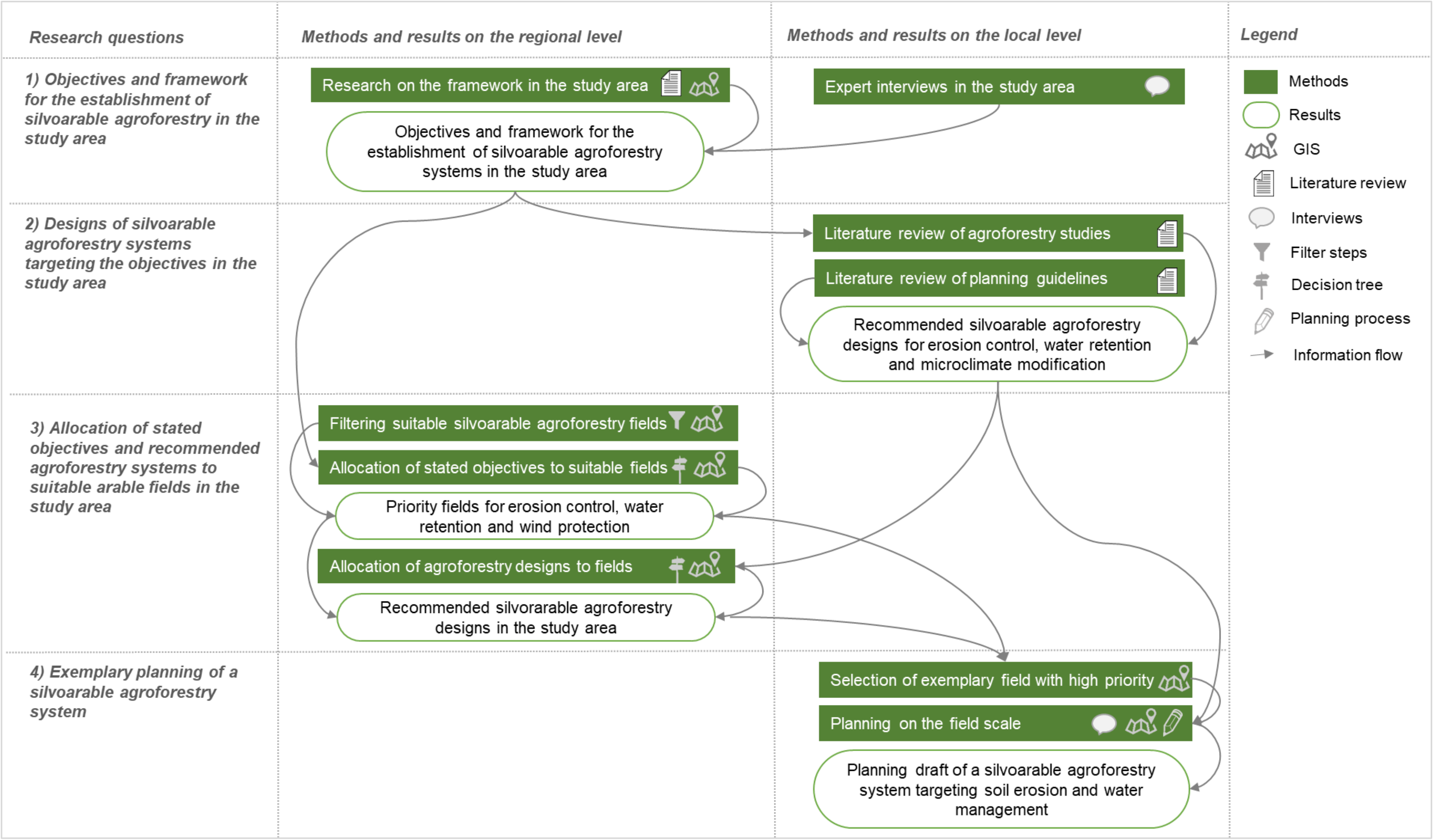


Figure 6 The methodology of this study has a regional and local component. Whereas the first research question (RQ) comprises both levels, the second and fourth refer to the local level and the third to the regional level only. Information flow (arrows) connects the four RQs. Results (ellipses) of the first RQ provide information for the methodology (green boxes) of the second and third RQs; the methodology of the third RQ uses information gained by the first and second RQs, and the fourth RQ refers to results of the second and third.

3.1 Methods presenting the framework and objectives for silvoarable agroforestry in the study area

The evaluation of the suitability of the fields for agroforestry presupposes the application of basic planning factors. The applied methods within the framework of the first research question were oriented to the basic planning factors for agroforestry systems, comprising the definition of economic, ecological and/or cultural targets and priorities (in this chapter, “objectives”) and the consideration of the natural-landscape, socio-economic and legal framework (cf. Chapter 2.2.3). Information on the natural and socio-economic framework was derived from different data sources (cf. Table 1). The soil, terrain, land use and crop rotation data was uploaded and processed in QGIS, an open-source geographic information system (GIS) where spatial information in vector, raster and other database formats can be created, edited, displayed and analysed (QGIS, 2023). The digital terrain model provided the slope gradient (tool “Hang“) and perspective (tool “Perspektive“). The frequency and dimension of maize cultivation were derived from the crop maps of the years 2017, 2018 and 2019 (cf. Table 1). In the respective years, all arable fields with silage and grain maize were marked with numbers showing the frequency of maize cultivation: once (1), twice (2) or each year (3) in 2017-2019.

Table 1 Indicators and data sources for the natural-landscape and socio-economic frameworks in the study area

Frame	***Factor***	**Indicators and Data**	**Data source**
Natural-landscape	*Soil*	Soil types *(Annex 5.2)*	*LfU, 2017*
		Potential soil erosion *(Figure 14)*	*LfL, 2023e*
	Climate	Climate parameters and projections for the county of Rottal-Inn	*Pfeifer et al.,, 2021; DWD, 2023*
	Terrain	DGM1 for slope gradient and perspective *(Annex 5.3)*	*Bayerische Vermessungsverwaltung, 2023a*
		Slope length factor *(Annex 5.4)*	*LfL, 2023e*
	Water	Degree of ground moisture, degree of congestion and adhesive wetness, water retention potential *(Annex 5.5)*	*LfU, 2020a; LfU, 2020b, LfU, 2020c*
	Wind	Wind speed at 10m height	*LfU, 2021*
	Protected areas	WMS for nature conservation area, flora-fauna-habitat area, water protection area, etc.	*LfU, 2023*
Socio-economic	*Landuse*	ALKIS actual use for arable fields *(Annex 5.1)*	*Bayerische Vermessungsverwaltung, 2023b*
	Structures	Ownership and farm structures	*LfStat, 2019*
	Agriculture	Crops and maize cultivation 2017-2019 *(Annex 5.6)*	*Schwieder et al., 2022*
		Crop rotation and cultivation methods	*LfStat, 2019*

Five expert interviews on the framework supplemented the relevant information from the listed data sources. The interviews aimed to obtain the objectives in the study area for the implementation of silvoarable agroforestry. As the present work focuses on the potential of agroforestry systems for erosion and water management, aspects regarding soil erosion and water balance have been included here in particular, but were not limited to these. According to Gläser & Laudel (2010), the experts should have special knowledge acquired either through high-ranking positions or experience (practical, scientific or consulting services). The research interest is not directed at the experts themselves but their experiences and knowledge. The method of guideline-supported individual interviews ensures the query of important aspects via a questionnaire. As non-standardised interviews, they aim to collect information on different topics relevant to the research question (Gläser & Laudel, 2010). The experts were selected within the working group soil and water protection in the county of Rottal-Inn, “Arbeitsgemeinschaft für Boden- und Gewässerschutz Rottal-Inn” (ABG Rottal-Inn). The interview partners were associated with the Office for Food, Agriculture and Forestry Pfarrkirchen (AELF), Office for Rural Development Lower Bavaria (ALE), Water Management Office Deggendorf (WWA) and Bavarian Farmers' Association Lower Bavaria (BBV). The working group also includes the following institutions and interest groups in the county Rottal-Inn: County Office, Nature Conservation Association, Landscape Conservation Association, Machinery Ring, fishing associations and advisory service (WWA, 2017). This group was initiated in 2012 in the scope of a 5-year project for the catchment area of the Rottauensee, Rott a. Inn, to prevent its increasing siltation. The subsequent 5-year project in the county was followed in 2022 by a consultation project in the municipality of Wittibreut due to pronounced erosion events in 2020 (ABG Rottal-Inn, 2023). Within the working group, six experts were requested for an interview, five expert partners participated. The interviews (in sum 240 minutes) were conducted in person or by telephone with the help of guideline questions (cf. Annex 1). The questions thematised observations on the change of site and framework conditions in the context of climate change for arable agriculture in the municipality of Wittibreut. The interview partners were asked to make a choice and prioritise objectives focusing on water and soil aspects for arable agriculture and with regard to climate change. Furthermore, the awareness of erosion control, the implementation of control measures after significant erosion events, e.g., in 2016, the present approaches of farmers and the status quo of crop rotations were discussed. The experts assessed the framework for the establishment of agroforestry systems, the interest of farmers and conditions for financial and consulting support in the study area. The statements relevant to the first research questions were noted by hand; a compilation of the responses is shown in Chapter 4.1.

3.2 Literature research on the designs of silvoarable agroforestry systems for soil erosion control, water retention, and microclimate modification

The second research question aims to investigate specific planning recommendations and relevant studies of agroforestry systems, which target erosion control, water retention and microclimate modification on arable fields. This part of the thesis aims to present specific agroforestry design drafts for timber and fruit systems and short rotation systems, respectively. The design drafts are based on synthesis of relevant studies, added by practical recommendations offered in agroforestry guidelines. The selection of relevant studies followed a literature research in Google Scholar of peer-reviewed and grey literature on temperate agroforestry systems. Therefore, combinations of keywords such as (agroforest* AND erosion AND temperate) were used. The keywords were replaced and added by similar terms like alley cropping, tree*, hedge* or windbreak; runoff, water*, microclimat*, evapotranspiration or wind; and Germany, Europe*, North America, USA, Canad* or China. The research separated field-scale studies on timber and fruit systems from those on short rotation systems. Relevant data from the studies were collected in Excel sheets containing basic information, planning factors and observed effects (cf. Annex 2). In the first step, the basic information on the location, soil description, mean annual precipitation and temperature was compared to the derived soil and climate properties of the study area (cf. Chapter 4.1). The studies were excluded if the deviations were (subjectively) too large, e.g. a mean annual precipitation < 500 mm led to an exclusion as the target region precipitation is ca. 860 mm/yr. From about 70 studies, 40 were considered suitable for field scale information, and another 18 were integrated for general statements in the results chapter. The planning factors comprised the relevant parameters as described in Chapter 4.2.1: orientation of wood strips [NS, NE-SW, EW], distance between tree rows [m], planting distance [m], width of wood strip [m], tree density [trees ha^{-1}], average tree height [m], vegetation in wood strip and tree species. Observed effects were subdivided into parameters on surface runoff and soil erosion by water, water retention (soil moisture, evapotranspiration), microclimate (air temperature, soil temperature, relative humidity, light intensity), wind speed, and erosion. For short rotation systems, studies on surface runoff *(amount: 3),* water retention on level fields *(7),* microclimate *(5)* and wind speed and erosion *(7)* were selected. Relevant studies on timber and fruit systems comprised surface runoff and erosion *(5),* water retention on slopes and level fields *(12),* microclimate *(7)* and wind speed *(1).* The planning factors of the investigated agroforestry systems were then compared to the observed effects, deriving recommendations for agroforestry designs and expected relevant effects. The field-scale studies were taken in agroforestry systems, either measuring surface runoff, soil erosion or water retention on slopes or investigating microclimatic parameters, water retention and wind erosion on level fields. This subdivision was adopted for the evaluation structure, now divided into timber and fruit agroforestry and systems implemented on slopes or level fields. In the next step, this scientific evidence was complemented by practical recommendations in agroforestry guidelines *(12)* and literature reviews (cf. Chapter 4.2). Practical guidelines and handbooks for temperate agroforestry were accessed on the website of the German Association for Agroforestry (DeFAF, 2023a). Based on the derived planning recommendations, the final step comprised of producing draft drawings for silvoarable agroforestry systems targeting soil erosion control, water retention and microclimate modification. Having identified possible systems at the local level, the next research question investigated the potential allocation of these systems at the regional level.

3.3 Methods allocating the suitability of agroforestry systems on arable fields in the study area

The target of the third research question was developing a regional-scale approach that, by using a hierarchical cascade of filter steps, identifies the potential suitability of agroforestry systems on arable land in the study area. The applied method for the identification of suitable fields was inspired by the decision support tool META-AfS (Multicriteria Evaluation Tool for the Allocation of Agroforestry Systems), which was developed in the scope of the five-year research project “AUFWERTEN” (Böhm et al., 2020b; cf. Annex 3). Therein, the suitability of agricultural fields is evaluated by environmental and economic criteria, which the user can prioritise. The selection of several parameters enables a multi-criteria evaluation of fields; the output is depicted in cartographic form. The tool was exemplarily developed for a region of 37,750 ha in South Brandenburg. In this work, the study area is the municipality of Wittibreut in Lower Bavaria comprising 3,832 ha and 1,981 inhabitants (LfStat, 2023; Gemeinde Wittibreut, 2023; cf. Figure 7 and 8).

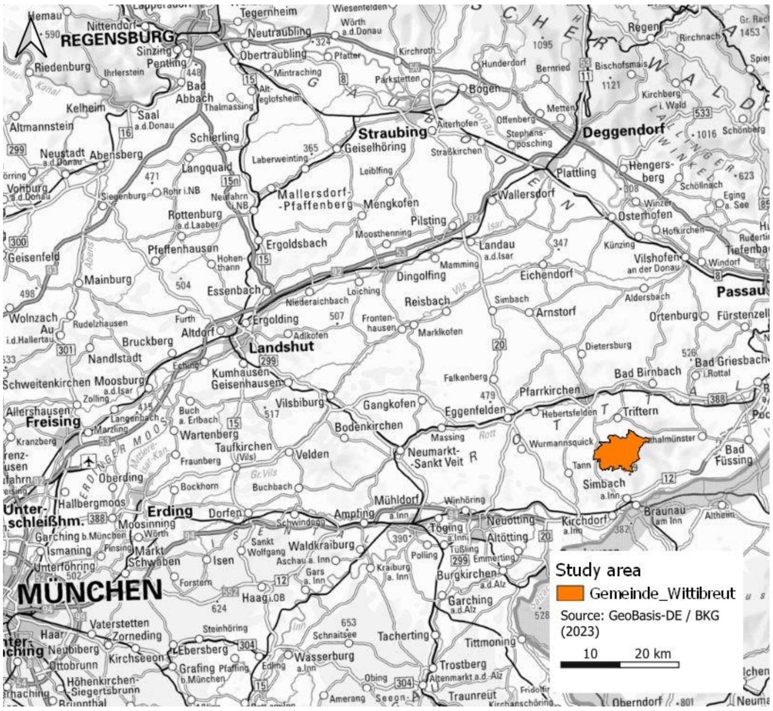


Figure 8 The county of Rottall-Inn in Lower Bavaria, Germany (Pfeifer et al., 2021)

Figure 7 The municipality of Wittibreut is located at 460 m.a.s.l. in the county of Rottal-Inn (48°19’44” N, 12°59‘23“ E).

According to the authors, the transfer of the tool to other regions is possible if the required map data is provided and a uniform spatial reference level (“base layer”) is created. The base layer for Wittibreut was derived from ALKIS data of agricultural parcels. The allocation of data to the base layer requires time, as case-by-case decisions might be necessary due to mismatching geometries and map levels (Böhm et al., 2020b). An exchange with one of the developers of

META-AfS revealed barriers of too great an extent for the transfer and application of the tool in the study area. Thus, the author decided to forego the direct use of META-AfS for this thesis, but rather adapt and augment the fundamental planning steps incorporated into this tool to the target region and stipulated research questions. This included, foremost, the creation of a base layer and the application of filter steps.

Three consecutive steps were applied to answer RQ3. First, suitable fields for establishing silvoarable agroforestry systems were selected using filter steps, which are detailed below. Second, the stated objectives in the study area, derived from the expert interviews for RQ1, were allocated to these fields. Third, and finally, bespoke agroforestry designs were allocated to these fields, drawing upon the planning recommendations derived in RQ2 (cf. Figure 9).

These approaches were carried out in QGIS. The required data, as listed in Table 1, was gathered and harmonized in QGIS and, where needed, cut to the municipality of Wittibreut. The *base layer* for implementing the above-described approaches was derived from the *ALKIS actual use* layer and is identical to blocks of arable fields, which are separated by recognisable external boundaries. While an even more precise plot level would have been possible when using InVeKoS data - which were unavailable for this study due to data protection regulations – the presented approach is spatially explicit and could easily be transferred to actual field boundaries, likely with only marginal changes in results.

3.3.1 Filter steps selecting suitable fields for agroforestry

Five filter steps were applied to derive suitable fields for silvoarable agroforestry systems, drawing upon ideas included in the META-AfS tool e.g., excluding fields with specific land use or protection status like nature reserves, flora-fauna-habitat areas, or water protection areas (Böhm et al., 2020b). Accordingly, in the first step, the arable fields were separated from the *ALKIS actual use* layer, as this work focuses on silvoarable agroforestry. Secondly, protected areas were allocated using *WMS* data for protected areas. The excluded arable fields were marked as non-suitable areas in the *base layer*. In the study area, this only applied to a flora-fauna habitat area in the northwestern part of the municipality (cf. LfU, 2023). The tool further uses distance buffers for several parameters, e.g. distance from wind turbines, surface waters and streets (Böhm et al., 2020b). Instead of distance buffers from streets and field boundaries, the filters minimum field size, width, and length were applied in QGIS. Establishing agroforestry systems on arable fields according to the federal framework (cf. Chapter 2.2.3) and planning recommendations derived from the second research question (cf. Chapter 4.2) requires a minimum field size of 0.5 ha and length/width of 66 m. Therefore, the area, length and width of the fields were added to the attribute table of the *base layer*. Fields not meeting the criteria were marked as non-suitable.

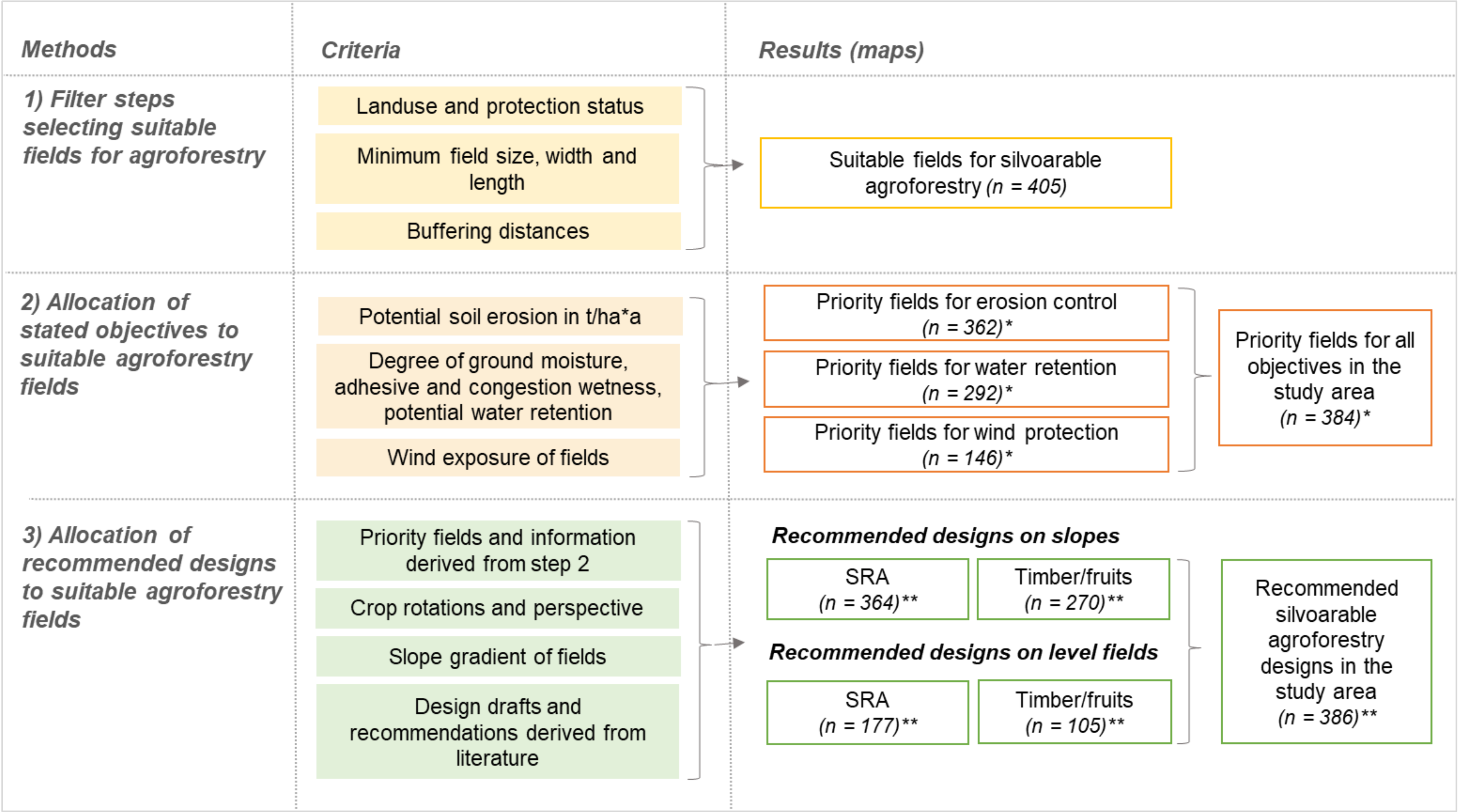


Figure 9 Methodology to identify suitable fields and allocate idiosyncratic design suggestions for agroforestry to each suitable field. The relevant number of fields (n) is part of the results but added here for clarity (fields with medium and (very) high priority, ** fields with suitable and (highly) recommended agroforestry). Recommendations for agroforestry were not limited to medium and high priority fields, as the establishment of agroforestry is also possible on low priority fields; therefore, the number of total fields differs.*

The last filter step comprised the buffer distance from flowing waters as depicted in *ALKIS actual use* and *LfU WMS Gewässerrandstreifen* of 50 m. As single-field geometries may have changed, the affected fields were re-evaluated whether they still fulfilled the antecedent criteria for the minimum field size, width and length. Even if they did no longer fulfill them, such fields could still be suitable for the targeted establishment of a different form of agroforestry: riparian buffer stripes (cf. Chapter 2.2.1). All fields excluded by the filter steps were marked as unsuitable in the attribute table of the base layer. The resulting map shows the suitable arable fields for silvoarable agroforestry systems.

3.3.2 Allocation of stated objectives in the study area

The applied approach was oriented to processes of the META-AfS tool but is subdivided into two steps; the allocation of agroforestry designs follows the allocation of relevant objectives in the study area. The criteria are identical to the stated objectives in the scope of the first research question and comprise the priority for soil erosion control, water retention and wind protection. Following the recommendation for reprocessed maps for the suitability allocation of agroforestry systems (cf. Böhm et al., 2020b), the present work included the creation of classified maps. These maps depict the objectives with regard to the priority for the implementation of relevant measures. The priority was derived from the expression of the respective indicators and comprises three classes of priority: low, medium and high. Notably, a high/low priority should not directly be equated with a high/low suitability of agroforestry, as suitability may still be present for a given field even when other fields are considered to have higher priority.

All arable fields considered suitable for establishing agroforestry were associated with priorities. A field was marked with the relevant class if the majority of the area (> 66.7 %) showed the respective expression. If this was not the case, it was classified one level lower. Only for potential soil erosion by water of > 20 t ha^{-1} a^{-1}, the field was allocated to a very high priority class, with more than half of the area showing the expression. The subdivision of erosion classes was oriented to DIN 19708 (2005), where a potential soil erosion of < 5 t/ha*a corresponds to a low risk and > 5 t/ha*a to a medium risk. The following classes started at > 12 t/ha*a and > 20 t/ha*a for the differentiated classification of sites with high and very high erosion risk. The categories for water retention resulted from the composition of three indicators (degree of ground moisture, degree of congestion and adhesive wetness, potential water retention at heavy rainfall events) representing the priority for measures aiming at improved water retention in agricultural-used soils (cf. Figure 10).

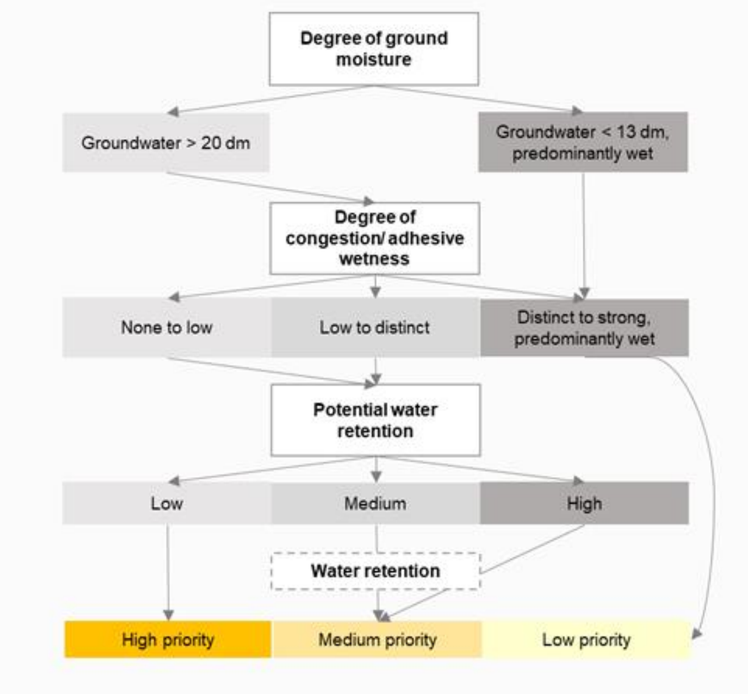


Figure 10 The priority for water retention was classified by means of three indicators. Starting from the degree of ground moisture (LfU, 2020a), the degree of congestion and adhesive wetness (LfU, 2020b) was selected and added by the potential water retention at heavy rainfall events (LfU, 2020c) to determine the priority class.

The third objective targets the reduction of wind erosion and wind protection by sheltering the effects of the wood strips. As the potential wind erosion map showed non-significant expressions in the study area (cf. BGR, 2014), the wind exposure of fields served as an indicator. It was expressed as the proximity of sheltering woody structures, following DIN 19706 (2013), which considers wind obstacles next to soil texture and wind conditions to calculate the potential wind erosion risk. The proximity to woody structures (hedge, tree row, forest), derived from the ALKIS map, was classified in directly adjacent in the prevailing wind direction (western field border), adjacent (20 m > x ≤ 100 m), and low proximity.

To present the results, map layouts were created in QGIS, showing the allocated priority levels on arable fields of the objectives separately and combined. The latter was created by assigning the combination in the attribute table to each field. Potential combinations are visualised by the matrices (cf. Figure 11).

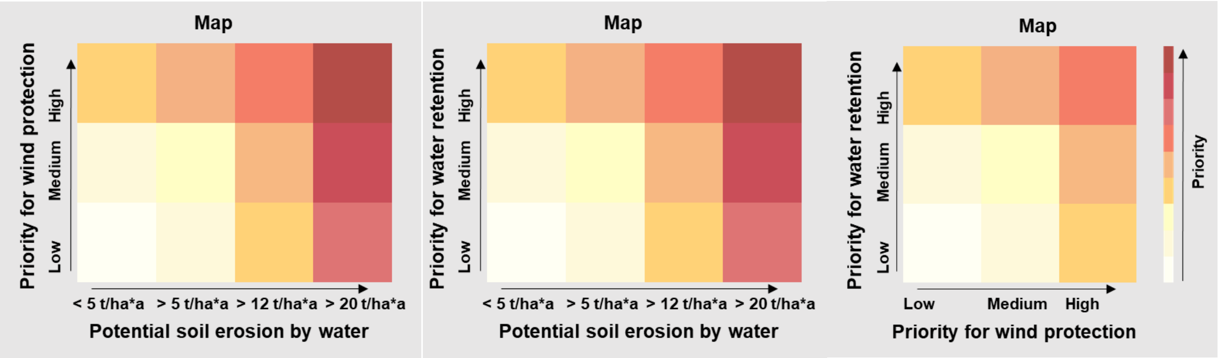


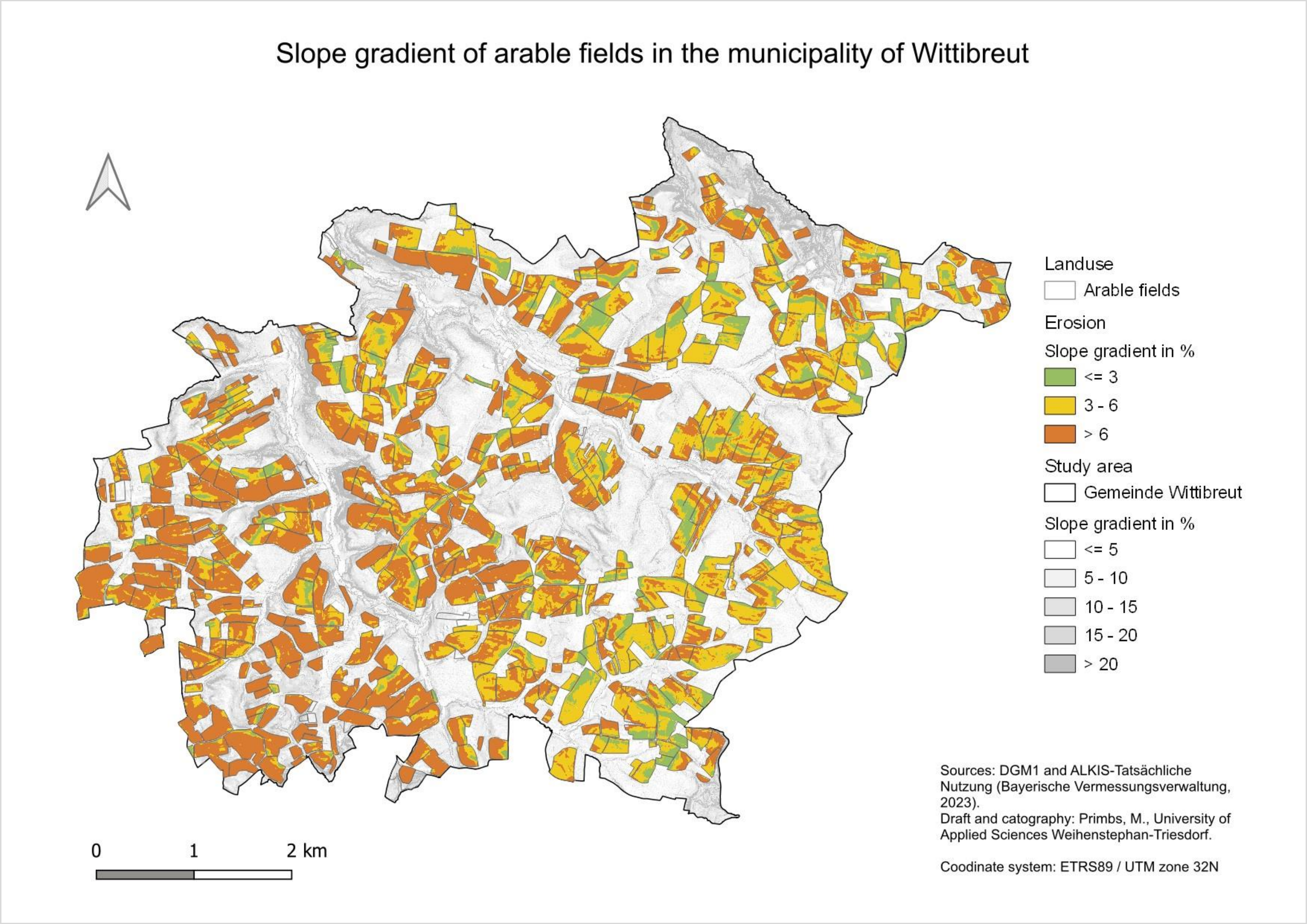
Figure 11 The tree objectives erosion control, based on the potential soil erosion by water, water retention and wind protection were classified into priority classes and combined to derive priority fields in the study area. The matrices visualise potential combinations, the colours represent the map symbology for priority classes.

The combinations were categorised into ten levels with increasing preference: only low priorities *(level: 1)*, medium priority *(2)*, two medium *(3)*, three medium *(4)*, high *(5)*, high and medium *(6)*, high and two medium *(7)*, two high and medium *(8)*, very high *(9)*, three high to very high priorities *(10)*. The resulting map showed the hotspot areas of the study area, where the implementation of agroforestry could have the highest effects on soil erosion reduction, water retention and/or wind protection. Calculations of the results, receiving the share of arable area and share of arable fields with the respective expression, were conducted in Excel.

3.3.3 Allocation of recommended agroforestry designs in the study area

The allocation of agroforestry systems is based on the slope gradient of fields (cf. Figure 12), refering to the recommendation for agroforestry systems targeting erosion control by water on > 3 % slopes (cf. Chapter 4.2). Agroforestry designs for level fields were assigned to fields with slope gradients of < 6 %. For fields with slope gradients > 3 % and < 6 %, the degree of potential water erosion was selected as the determining factor for the type of agroforestry design.

The protective effect and suitability for agroforestry systems increase when the potential water erosion risk increases, particularly in loess-dominated soils on slopes and high precipitation. The authors of META-AfS consider agroforestry systems suitable on fields with a potential soil erosion of > 2.5 t/ha*a (Böhm et al., 2020b). In a European modelling study, Kay et al. (2019) allocated agroforestry systems to arable areas with a critical soil loss threshold of more than 5 t soil ha^{-1} a^{-1} derived by Panagos et al. (2015). In the present study, a recommendation for agroforestry designed for slopes started at > 5 t/ha*a (medium erosion risk according to DIN 19708), whereas at < 5 t/ha*a (low risk) and slope gradients < 6 %, both designs were suitable. Similar to the second research question, agroforestry systems were subdivided into timber/fruit systems and short rotation systems. On arable fields with slope gradients > 3 %, with a medium to high priority for water retention and (very) high erosion class, the implementation of both systems was (highly) recommended based on literature findings (cf. Chapter 4.2.2). Whereas timber and fruit systems are not recommended on predominantly wet sites, in short rotation systems, selecting adapted tree species and manual harvesting methods enables the cultivation on wet sites (cf. Chapter 4.2.1). Conflicts on slope agroforestry systems might occur at a high wind exposure and simultaneously EW-oriented cultivation (resulting from an across-slope implementation). Not orienting the wood strips perpendicular to the prevailing wind direction could decrease wind speed reductions (cf. Chapter 4.2.3). In the study area, this conflict only occurred in fields with recommended timber and fruit systems. For short rotation systems, an EW orientation might lead to a potential conflict in maize-dominated crop rotations. In contrast to high-set pruned tree crowns, the more pronounced shading effect of SRA might lead to light competition with annual crops (cf. Chapter 4.2.3).


Slope gradient of arable fields in the municipality of Wittibreut

Sources: DGM1 and ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023).
Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure 12 The slope gradient of arable fields in the study area was divided into three classes based on recommendations for agroforestry systems targeting erosion control on slopes > 3 %. This illustration is presented here to support the methodology.

Agroforestry designs for level fields were allocated to arable fields with slope gradients < 6 % and a low priority for erosion control. Similar to the steps above, timber and fruit systems were not recommended on predominantly wet sites. To target water retention and microclimatic effects on the fields, wind protection (decrease of wind velocity) is important (cf. Chapter 4.2.3). Relevant agroforestry designs were therefore (highly) recommended on fields with high and medium priority for wind protection but were also considered suitable on fields with low priority. The allocation of silvoarable agroforestry systems to the suitable fields was finally used to create a map presenting recommended and/or suitable agroforestry design(s) on each arable field.

3.4 Planning of a silvoarable agroforestry system for soil erosion and water management for one exemplary field in the study area

The fourth research question aimed at transferring the agroforestry design drafts to an exemplary suitable agroforestry field in the study area. The selected field had to show the highest priority class for achieving the derived objectives for the study area as derived from the third research question. The recommended agroforestry design on this field was used as a suggestion for the planning process on the local level (cf. Chapter 4.3). The planning method was oriented to the standard planning process recommended by Wack et al. (2023), which comprises ten steps: initial interview, on-site appointment, first draft, consultation, detailed planning, plant material order, measurement, planting, and supervision. The applied method for the fourth research question covered the first three steps. The initial interview was conducted at the on-site appointment with the landowner of the selected field. The visit comprised an inspection of the field and the initial interview based on a questionnaire oriented to basic planning requirements provided by Triebwerk (2023). It included data on the natural-landscape and socio-economic framework, the definition of targets and priorities, the site description and planning factors for the field (cf. Annex 4). Specific information on the site conditions, e.g., terrain, climate, soil, and erosion risk, was derived from additional data sources (cf. Table 1; Chapter 4.1). The information was considered in the planning process to determine the relevant planning factors of the agroforestry system: selection of tree species, planting distance, wood strip width and orientation, crop alley spacing, and management measures (cf. Chapter 4.2.1). Thereby, the recommended system design derived from the second research question was adapted to the specific site conditions, objectives, machine width and further planning factors. Additionally, the legal framework conditions were included for the design layout on the field (cf. Chapter 2.2.3).

Considering the relevant planning factors, the agroforestry system was laid out on the selected field with standard vector digitisation tools in QGIS. The system design was based on the target to reduce the described threats and fulfil desired objectives derived from the third research question: high priority for soil erosion reduction, water retention and wind protection (cf. Chapter 4.3.1). The wood strips were laid out across the field considering the desired crop alley spacing, wood strip width and required distances from the field boundaries. These are defined by conditions of eligibility for the CAP, neighbourhood law and road traffic regulations (cf. Chapter 2.2.3) and were added by the desired headland width. In contrast to the regional level, here, the actual land parcel boundaries were used to determine the field boundary.

In the initial interview, a deviation from the linear design following a water management system was discussed based on the site characteristics with strong surface runoff and soil erosion in sinks. The adapted masterline design with a parallel system of collecting and infiltration swales (cf. Chapter 2.2.2) was considered the eligible system for the study site. For the layout of the masterline system, the contour lines from the DGM1 were combined with the standard vector digitisation tools and the QGIS extension “Piste Creator”. This method is oriented to considerations of Mitzel (2022).The determined keyline was adapted to get the masterline with a slight flow gradient of 0-1 % (cf. Shepard, 2020). The parallel transfer of the defined masterline with desired distances of wood strips was carried out with the tool "array of offset parallel lines". This step provided the allocation of parallel swales on the field (cf. Mitzel, 2022). To ensure the slight slope gradient of swales, the geometry of swales was adapted to the changing contours (cf. Shepard, 2020). The maintenance of the desired crop alley spacing resulted in cut-off areas. These were added and subtracted from the wood strip, maintaining the required minimum strip width. In accordance with the recommended design, the tree lines were positioned downhill of the swales (cf. Fahrendorf, 2022). The trees were added with the tool "points along geometry" using recommended planting distances for suitable tree species. The layout of the agroforestry system was likewise oriented to the required distances from field boundaries and the desired headland width. The wood strips were adapted where necessary to the management width to minimize inefficient cut-off areas in the crop alleys and headlands. The resulting area covered by wood strips and the number of trees were calculated with QGIS statistics and compared for the two system layouts.

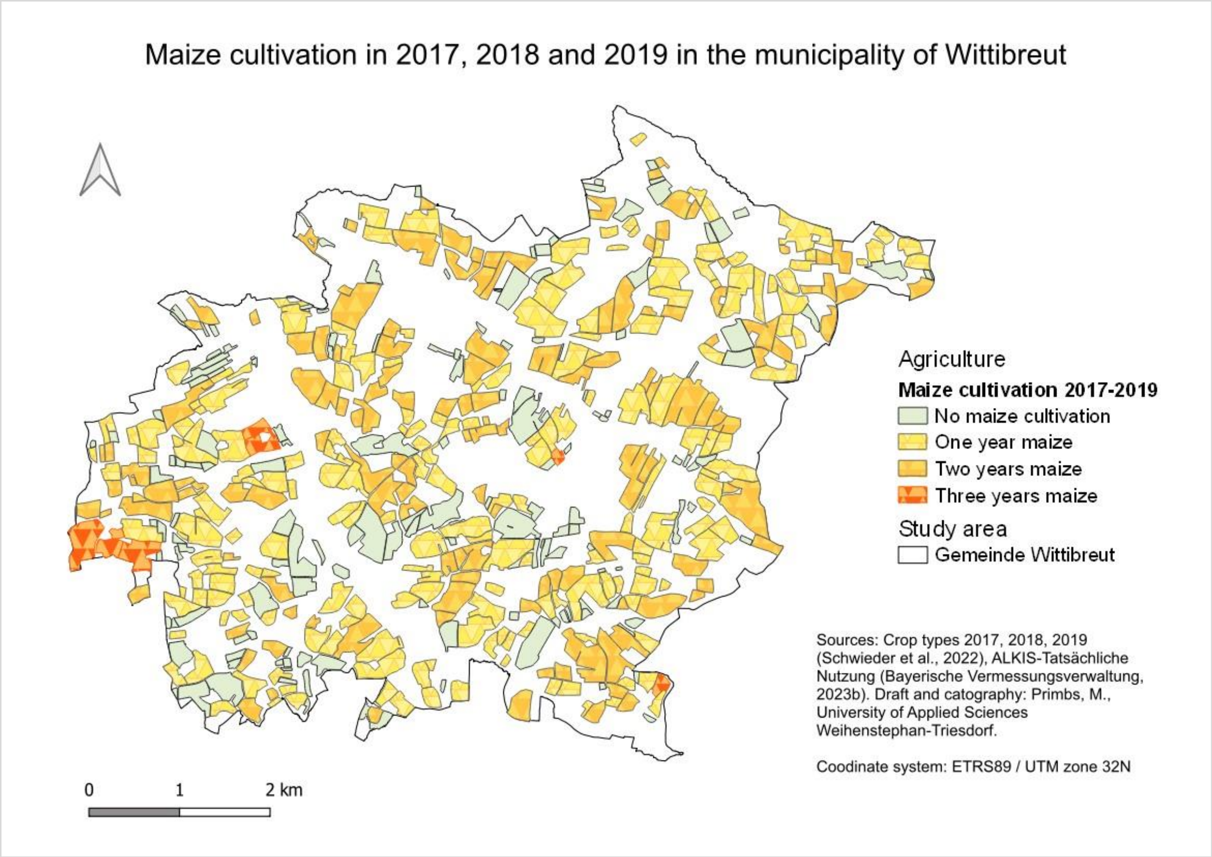
4 Results

4.1 Framework and objectives for the establishment of silvoarable agroforestry systems in the municipality of Wittibreut

4.1.1 Natural framework, landuse and soil erosion in the study area

The municipality of Wittibreut comprises 3,832.46 ha, of which 46 % is arable land, 27 % forest and 19 % grassland (LfStat, 2023; cf. Annex 5.1). The municipality has many sideline farms (ABG Rottal-Inn, 2023). Over 50 % of farms manage less than 20 ha each, and one-third of farms manage 20 to < 50 ha (LfStat, 2019). Organic farming (EU-Öko-Vo) comprises 6 % of the agricultural area and is dominated by livestock farms (ABG Rottal-Inn, 2023). The composition of terrain, soils and land use characteristics explains why 95 % of the arable land is endangered by potential soil erosion of > 5 t ha^{-1} a^{-1} (cf. Figure 14). In the municipality of Wittibreut, the estimated mean erosivity factor by precipitation in 2020-2030 accounts for 149 N ha^{-1} a^{-1}, 16 % above the average R-factor of Bavaria (LfL, 2023d) and increases with climate change (cf. Chapter 2.1.2). Within the arable land, the soils are dominated by pseudogley and brown earth pseudogley (loam to silty clay) (35 %) and brown earth (sandy loam to silty clay) (25 %). Brown earth and pseudogley brown earth with (slightly) different soil textures amount to a further 19 % and 12 %, respectively. These soil types have formed over molasse and/or loess loam. Podsolic brown earth under forests (gravel-bearing molasse) accounts for 4 %, and gleye and other groundwater-influenced soils for 5 % (LfU, 2017; cf. Annex 5.2). Consequently, the majority of soils consist of easily erodible grain sizes (sandy loam, silt, loam, silty clay) and tend to silt up quickly (ABG Rottal-Inn, 2023). The region is described as very hilly (ABG Rottal-Inn, 2023). Slope gradients above 6 % characterise the majority of arable fields; few fields have slope gradients below 3 % (cf. Figure 12). There is a trend to increasing sizes of field plots; at individual farms, erosion protection stripes reducing the slope length were established (ABG Rottal-Inn, 2023). In 2017-2019, half of the arable land was covered with cereals (50 % wheat), and one-third of arable fields were cultivated with a silage maize-dominated crop rotation (LfStat, 2019). Silage maize is grown for biogas production and livestock fodder (dairy cattle, bull fattening) (ABG Rottal-Inn, 2023). From 2017 to 2019, maize was cultivated once, twice or each year on 44 %, 34 % and 3 % of the arable land, respectively (cf. Figure 13).

For several years, many farmers in the municipality have implemented five-member crop rotations (including silage maize and soybean), and the cultivation of cover crops has become more common. According to the interview partners, the effectiveness of crop rotations regarding soil erosion reduction, however, varies with the soil cultivation and management of seedbeds. For example, soybeans require the preparation of fine seedbeds, thus increasing the risk of siltation of the soil surface. Cultivating silage maize and soybeans increased the susceptibility of soils to erosion. Although many farmers implemented mulch seed, the soils have become more prone to erosion because of intensified soil cultivation. The interview partners estimate that cover crops and mulch seed alone are insufficient measures for soil erosion control in the municipality. Despite heavy erosion events in the last years, many farmers did not change slope-parallel management to across-slope cultivation (ABG Rottal-Inn, 2023).

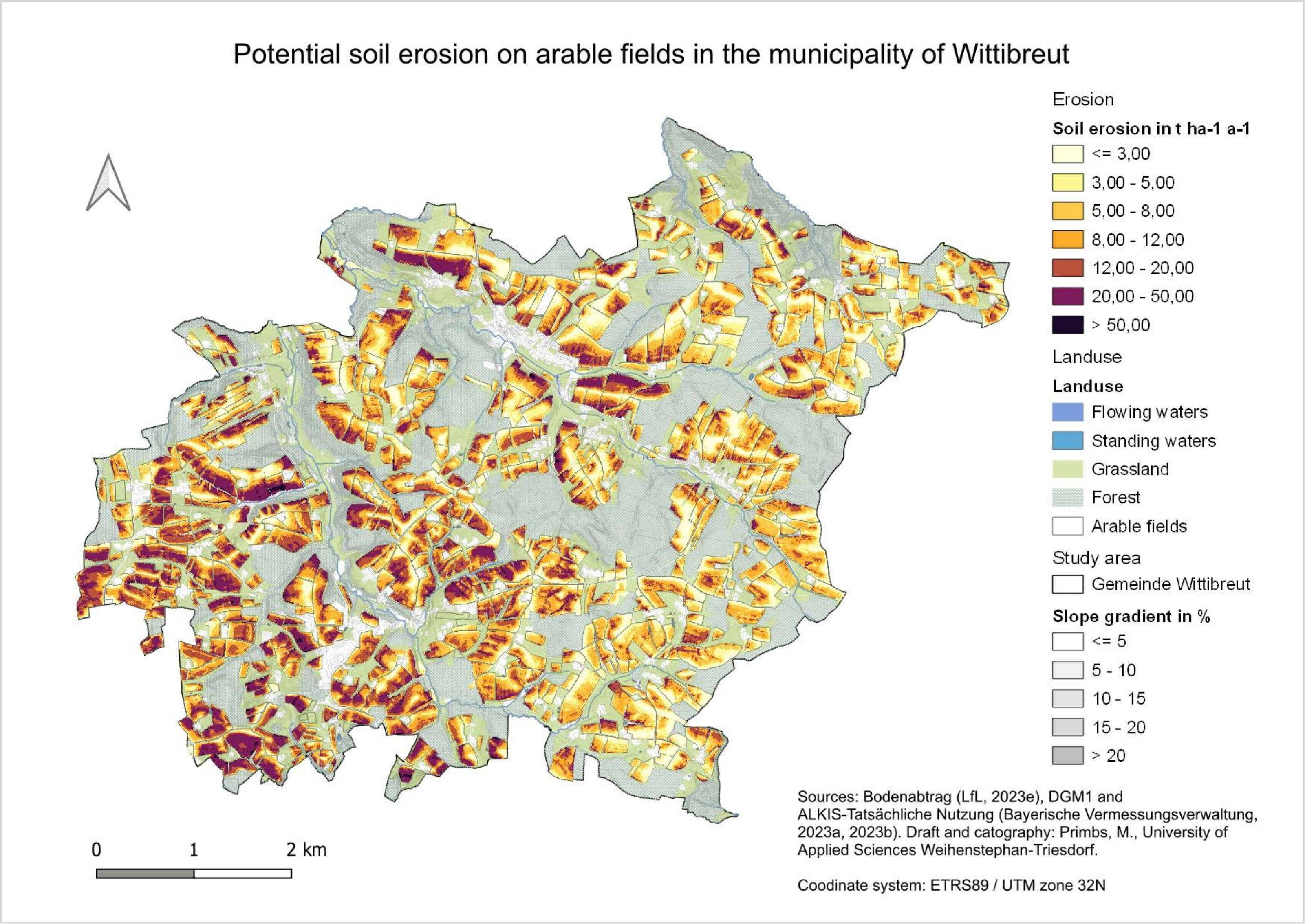

Maize cultivation in 2017, 2018 and 2019 in the municipality of Wittibreut

Sources: Crop types 2017, 2018, 2019 (Schwieder et al., 2022), ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023b). Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure 13 Number of years with maize cultivation on arable fields in 2017, 2018 and 2019 in the municipality of Wittibreut

Soil erosion was observed in single events such as erosion of soil material, outwash of roads, and regularly occurring loss of soil material. The observed erosion hotspots were uncovered fields in winter, furrows acting as channels, soil erosion in maize fields, and missing riparian strips leading to sedimentation of surface waters. This sediment input was also observed at weir systems in the catchment area. Wittibreut is part of the catchment area “Altbach” draining into the river “Rott” in Lower Bavaria. At heavy rainfall events, an accelerated, unabated surface runoff and sediment deposition at the Altbach were observed (ABG Rottal-Inn, 2023).



Potential soil erosion on arable fields in the municipality of Wittibreut

Sources: Bodenabtrag (LfL, 2023e), DGM1 and ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023a, 2023b). Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure 14 Potential soil erosion by water in tonnes per ha and year on arable fields in the study area. The map also visualises grassland and forest areas and flowing and standing waters. The remaining grey spots comprise residential and recreational areas, infrastructure and areas of mixed use in the municipality.

4.1.2 Climate change parameters and projections for the study area

The municipality of Wittibreut is part of the county of Rottal-Inn, for which GERICS provides climate parameters and projections for different climate scenarios. As part of the temperate climate zone, the average annual mean temperature accounts for 8.4 °C in the period 1971-2000 (Pfeifer et al., 2021). In the county of Rottal-Inn, an increasing trend of the annual mean temperature of 1.1 °C was observed in the period of 1991-2020 in reference to 1961-1990 (DWD, 2023). By mid of the 21st century, climate models show an increase in annual mean temperature of 1.2, 1.8 and 2.0 °C for low (RCP2.6), medium (RCP4.5) and high (RCP8.5) emission scenarios, relative to the reference period 1971-2000 (cf. Table 2). This includes an increase in summer and hot days, tropical nights and a decrease in frost and ice days. The maximum duration of hot spells is predicted to increase by a range from 0.3 to 10.1 days/year, depending on the emission scenario, by the middle of the 21st century. The average annual precipitation sum in the period 1971-2000 is 863.9 mm in the county of Rottal-Inn (Pfeifer et al., 2021) but 980 mm in the municipality of Wittibreut. The lowest precipitation occurs in February, with an average monthly precipitation of 54 mm, and the highest values in July, with an average of 122 mm. In Wittibreut, the average annual precipitation increased by 13.8 mm in the period of 1991-2020 in reference to 1961-1990 (DWD, 2023). In the county of Rottal-Inn, a mean increase of 37.0 mm is observed for the period of 1986-2015 in reference to 1951-1980. However, the change shows natural fluctuations from year to year and is not statistically significant (cf. Figure 15). By mid-century, a range from a decrease of -5.8 % to an increase of 19.6 % is projected for the annual precipitation. The increasing tendency is only robust for the high and medium emission scenarios (Pfeifer et al., 2021; Table 2).

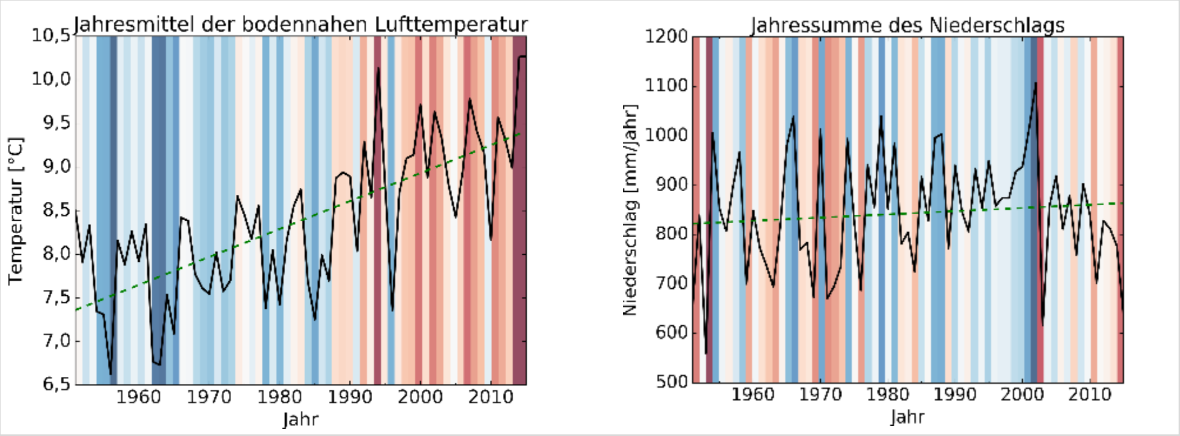


Figure 15 Mean annual temperature and average annual precipitation, county of Rottal-Inn (Pfeifer et al., 2021)

For dry days, no significant change is predicted; the values range from -14.3 to 11.9 days/year for all emission scenarios by mid-century. In contrast, days with precipitation ≥ 20 mm/day will increase by 0.3, 0.7 and 1.3 days/year by mid-century for low, medium and high emission scenarios, respectively. The trend is predicted to be more pronounced for medium and high emission scenarios by the end of the 21st century. This applies also to the 95th and 99th percentile of precipitation. The climatic water balance will change in a range from -0.14 to 0.36 mm/day by mid-century, with an increasing trend for medium and high emission scenarios. A decreasing tendency is projected for the mean wind speed (Pfeifer et al., 2021).

Table 2 Climate parameters and projections for the county of Rottal-Inn

Climate parameters	**1971-2000**	**Climate change in the 21st century (median)**		
		RCP2.6	**RCP4.5**	**RCP8.5**
Temperature	8,4 °C	*Increase + 1.2*	*Increase + 1.8*	*Increase + 2.0*
Summer days > 25 °C	35,6 days/year	*Increase*	*Increase*	*Increase*
Hot days > 30 °C	4,6 days/year	*Increase*	*Increase*	*Increase*
Tropical nights > 20 °C	0,0 days/year	*Increase*	*Increase*	*Increase*
Maximum duration of hot spells	2,3 days	*Increase*	*Increase*	*Increase*
Days > 5°C	229,3 days/year	*Increase*	*Increase*	*Increase*
Frost days	104,8 days/year	*Decrease*	*Decrease*	*Decrease*
Late frost days	5,1 days/year	*Decrease*	*Decrease*	*Decrease*
Ice days	29,7 days/year	*Decrease*	*Decrease*	*Decrease*
Dry days < 1 mm	234,4 days/year	*No change*	*No change*	*No change*
Precipitation	863,9 mm/year	*Tendency to increase*	*Increase*	*Increase*
Precipitation ≥ 20 mm/day	5,9 days/year	*Tendency to increase*	*Tendency to increase*	*Increase*
95th percentile of precipitation	12,0 mm/day	*Tendency to increase*	*Tendency to increase*	*Increase*
99th percentile of precipitation	24,2 mm/day	*Tendency to increase*	*Tendency to increase*	*Tendency to increase*
Sultry days > 18.8 hPa	3,2 days/year	*Increase*	*Increase*	*Increase*
Climatic water balance	-	*No change*	*Tendency to increase*	*Tendency to increase*
Wind speed	-	*Tendency to decrease*	*Tendency to decrease*	*Tendency to decrease*

In the last years, the interview partners observed an increase in extreme weather conditions. On the one hand, hot and dry periods in springs and summers have become more frequent. On the other hand, heavy rainfalls have become more frequent during the year and have increasingly become the focus of attention. Precipitation often falls highly localized from a few hours to days and cannot infiltrate into (dry) soils. In the last decade, the amount of available water in arable agriculture was observed to decrease. Although the amount of precipitation in the winter period increased considerably, the upper 40 cm soil has become less soaked with water. The groundwater formation decreased, which was observed in deep wells (ABG Rottal-Inn, 2023).

4.1.3 Objectives and barriers for the establishment of agroforestry systems in the study area

According to the interview partners, the economic viability of implemented measures is the priority of farmers in the municipality of Wittibreut. However, many farmers - according to the interviewers' perception - are aware that in the face of climate change, implementing measures towards environmental objectives is fundamental for achieving economic objectives. Water erosion control was estimated to be necessary on 90 % of arable fields in the municipality

(ABG Rottal-Inn, 2023), which corresponds to the potential soil erosion > 5 t ha^{-1} a^{-1} on 95 % of arable fields (cf. Chapter 4.1.1). All interview partners agreed that establishing silvoarable agroforestry systems could be an effective additional measure for water erosion control in the municipality. Furthermore, agroforestry systems could contribute to the objective of water retention, especially in the form of rainwater infiltration in the soil, next to cultivation measures like mulch sowing. The microclimate modification was also mentioned, focusing on the cooling effects of soil and air temperature in hot periods. Wind erosion control might be significant in dry periods when soil dust occurs during soil cultivation (ABG Rotal-Inn, 2023).

According to the interview partner, on the farmer´s side, economic security is the greatest barrier to establishing agroforestry systems. Due to high lease prices, the price pressure in the region is pronounced. In the past, the willingness for structural interventions and investments was very low; farmers preferred to implement required measures with the least financial impact. Newly implemented measures need to be profitable (via yields or funding) and labour-economical (regular incomes). On the other hand, an economic benefit can be a strong motivation for farmers. Further challenges for the establishment of agroforestry systems were seen in the diverse expositions of fields influencing, e.g. shadowing or wind protection effects. Most farmers are also concerned about the federal and legal framework for agroforestry and fear that nature conservation authorities define agroforestry stripes or single trees as biotopes, landscape features or natural monuments. These barriers could be reduced if legal security is given and the federal framework becomes more profitable. Further, facilitating legal requirements, e.g. erosion protection requirements covered by agroforestry systems, could motivate farmers to implement measures. Therefore, the consultation was considered an important key to inform farmers about the feasibility of legal, federal and economic framework measures.

The official consultation for farmers in the county of Rottal-Inn is provided by the AELF, ALE, Boden:ständig, BBV and information events of the ABG Rottal-Inn. In response to heavy erosion events in 2020, the municipality of Wittibreut was selected in 2021 for the "Leuchtturmprojekt Gewässerschutzberatung. Further, three "Boden:ständig" project areas are designated in the county of Rottal-Inn, including the municipality of Wittibreut. The responsible persons approach these projects jointly. The consultation of farmers for erosion protection measures so far comprised stripe measures in the form of grass stripes, hedge plantings across the slope or riparian buffer stripes, and areal measures like mulch sowing, reduced soil cultivation, and the usage of cultivators instead of ploughs in spring. Stripe measures were implemented to reduce the erosive slope length. Areal measures shall increase the infiltration (e.g. by rainworm pores) and water-holding capacity of the soil, thereby reducing surface runoff, which was observed on fields after a 3-5-year transformation period. Establishing a demonstration field for agroforestry was promised to be very helpful for the consultation in the county (ABG Rottal-Inn, 2023).

Across the county, including the municipality of Wittibreut, several farms grow short rotation coppices producing wood chips. Many farmers run wood chip heating plants or sell wood chips, which are often dried with the waste heat of biogas plants. In the municipality, some meadow orchards can be found. Many hedges are located on communal land, usually planted voluntarily or as compensatory planting and were mostly not integrated into agricultural production. One farm in the county cultivates an agroforestry system with walnut trees. In 2023 (state of May, 12), no application for the investment funding of agroforestry systems was submitted. However, according to the interlocutors, there is a high potential for the implementation of agroforestry systems in the municipality, especially for erosion protection. The following potentials and advice were given in the interviews: SRA could be interesting due to existing structures for wood chip production. As prices at harvest time for timber systems are uncertain, a combination of nut and fruit production could be targeted for earlier yields. To effectively reduce surface runoff, a ditch along the strip could be added to 3 m wide wood strips with herbaceous undergrowth. For the establishment of wood strips, including herbaceous, shrub and tree layers, a width of ≥ 6 m was recommended. Fruit systems could be interesting for sideline farms on meadows for additional income (ABG Rotall-Inn, 2023). In order to enable a site-adapted and target-oriented implementation of silvoarable agroforestry systems in the study area, the following chapter describes observed effects and recommended planning factors of relevant agroforestry designs.

4.2 Designs of silvoarable agroforestry systems for soil erosion control, water retention and microclimate modification

4.2.1 Planning factors and recommendations from practice for temperate silvoarable timber and fruit and short rotation agroforestry systems

4.2.1.1 Suitable sites and tree species

The determining site characteristics for the tree species selection are the following: soil type, temperature, rainfall (total amount and distribution within the year), frequency of early or late frosts, water availability (groundwater connection, water holding capacity, waterlogging), soil aeration and nutrient availability of the soil (Bender et al., 2009; Morhart et al., 2015). Bender et al. (2009) list as possible sites for timber agroforestry systems: low to high-yield arable land, areas susceptible to erosion, grassland and neglected meadow orchards, compensation and eco-account areas. However, shallow and dry soils and predominantly wet and drained sites are not recommended. SRA is suitable for a wide range of site conditions, but the yield potential and costs vary, and adaptation to site conditions is highly recommended. Sites with ≥ 500 mm annual precipitation, loamy and sandy well-aerated soils with groundwater connection (0.6-1.5 m) are preferred. At the following sites, the establishment of SRA is not recommended: stony, shallow sites < 50 cm depth; steep slopes; sites with pH value < 5.5; heavy clay soils and gleys; drained fields; waterlogged and poorly load-bearing sites during winter (Becker et al., 2014; Lignovis, 2018). Manual harvesting methods could contribute to a decision favouring SRA on partially waterlogged and steep sites (Böhm & Veste, 2018; Smith et al., 2012). Production-oriented AFS should not be established on marginal sites (Chalmin, 2009).

To reduce water, nutrients and light competition between crops and trees, the tree species should fulfil the following characteristics: Late leaf emergence, light-permeable crown, tap or heart root system, site-adapted water consumption, no germ-inhibiting effects or intermediate hosts and fodder plants for agricultural pests. A mixture of tree species is favoured, as it is less vulnerable to disease and pest infestation, weather extremes, and fluctuating market prices (Bender et al., 2009). Recommended tree species for windbreaks should have good growth rates, a tall, narrow crown, a deep root system, stress tolerance, and insect and disease resistance (Brandle et al., 2009). To foster biodiversity, tree species which have habitat functions and provide food sources for birds and insects can be included, e.g. Sorbus species (Reeg et al., 2009). Further, the tree crown architecture influences the throughfall of raindrops. Stacked crown layers slow down raindrops, but a cascading effect builds larger raindrops with higher erosive effects (Nair, 1993; Young, 1989). The interception varies temporally, with higher rates in the vegetation period due to mostly deciduous trees, and spatially, depending on the canopy structure. In dense tree crowns, more precipitation is retained, reducing throughfall and stem flow to the soil. Therefore, the tree crown architecture and species composition influence the water balance (Jacobs et al., 2022).

Recommended tree species with straight growth form of the stem for high-quality timber agroforestry systems are listed in Table 3. The combination of timber and fruit systems is possible with tree species, which produce high-value timber and simultaneously fruit and/or nut yields (Bender et al., 2009; Brix et al., 2009). For the combined use, special walnut varieties, sweet chestnuts, European aspen, and special apple and pear varieties can be considered (Jäger, 2017). The combined system focuses on timber production, as high-set crowns complicate the fruit harvest. Fruit species used for shaking or falling fruit are suitable (Schulz et al., 2020). To avoid harvest conflicts, the tree species selection and the crop rotation have to be adapted, e.g. early to medium-early fruit trees with a harvest window between harvest of the main crop and sowing of the following crop would be suitable (Jäger, 2017).

Table 3 Recommended tree and shrub speies for agroforestry systems

Tree and shrub species		***Shrubs***	***Timber***	***TxF***	***Fruit***	***SRA***
Alder	*Alnus* spp.		🟧			🟨
Apple	*Malus domestica*		🟧	🟨	🟧	
Appleberry	*Aronia* spp.	🟨			🟧	
Birch	*Betula* spp.					🟨
Blackberry	*Rubus fructicosus agg.*	🟨			🟧	
Blacknut	*Juglans nigra*		🟧	🟨	🟧	
Cherry	*Prunus cerasus, P. avium subsp. duration*				🟧	
Chestnut	*Castanea sativa*			🟨	🟧	🟨
Chestnut	*Castanea mollissima, Castanea crenata*				🟧	
Currant	*Ribes nigrum*	🟨			🟧	
Elder	*Sambucus nigra*	🟨			🟧	
Elsberry	*Sorbus torminalis*		🟧	🟨		
Field maple	*Acer campestre*		🟧			🟨
Flourberry	*Sorbus aria*		🟧			
Fluttering elm	*Ulmus laevis* Pall.					🟨
Hazel	*Corylus avellana*	🟨			🟧	🟨
Hornbeam	*Carpinus betulus*					🟨
Hybridnut	*Juglans intermedia*		🟧			
Lime	*Tilia platphyllos, Tilia cordata*		🟧			
Mirabelle	*Prunus dom. subsp. Syriaca*				🟧	
Mulberry	*Morus alba, Morus nigra, Morus rubra*			🟨		
Norway maple	*Acer platanoides*		🟧			
Oak	*Quercus* spp.					🟨
Pear	*Pyrus communis*		🟧	🟨	🟧	
Plum	*Prunus domestica, P.dom.subsp. domestica*			🟨	🟧	
Poplar	*Populus* spp.					🟨
Raspberry	*Rubus idaeus*	🟨			🟧	
Rosehip	*Rosa* spp.	🟨			🟧	
Rowan berry	*Sorbus aucuparia*			🟨		
Seaberry	*Hippophae rhamnoides*	🟨			🟧	
Shadbush	*Amelanchier* sp.	🟨			🟧	
Silverberry	*Eleagnus angustifolia*	🟨			🟧	
Speierling	*Sorbus domestica*		🟧	🟨		
Sycamore maple	*Acer pseudoplatanus*		🟧			🟨
Tree hazel	*Corylus colurna*		🟧			
Walnut	*Juglans regia*		🟧	🟨	🟧	
Wild cherry	*Prunus avium*		🟧			
Wildapple	*Malus sylvestris*		🟧		🟧	
Wildpear	*Pyrus pyraster*		🟧		🟧	
Willow	*Salix* spp.					🟨
Wych elm	*Ulmus glabra*					🟨
(DeFAF, 2022a; Hofmann et al., 2019; Jäger, 2017; Morhart et al., 2015; Schulz et al., 2020; Winterling et al., 2019)						

For SRA, it is highly recommended to use only certified (according to FoVG) seedlings and cuttings from forest nurseries (LWF, 2020). Suitable tree species show rapid juvenile growth and resprouting ability, including poplar, willow and alder, and additional native tree species (cf. Table 3). While black poplar hybrids are suitable for medium-term rotations on warm sites with good groundwater connections, balsam poplar hybrids are less demanding and suitable for short rotations (Würdig, 2020). In Bavaria, crosses of the balsam and the black poplar "Max 1" and "Max 3" were commonly used. These poplar varieties showed strong growth performance on test sites, especially in the first four vegetation periods (Winterling et al., 2019). It is recommended to diversify the system, thereby reducing risks and increasing structural diversity, biodiversity, and the natural-like appearance, with various species planted in blocks within the strips (Böhm & Veste, 2018; Winterling et al., 2019). Among native tree species, grey alder, silver willow and fluttering elm showed good growth performances and resprouting but significantly lower yields. For example, grey alder is recommended in addition to poplar clones in blocks of up to 30 % and rotation periods of > 8 years, as they reach their maximum growth rates in later stand years. Black alder may be interesting for areas with high groundwater levels (Winterling et al., 2019).

4.2.1.2 Planting distances and wood strip design

The planting distance in timber systems is oriented at the expected final crown diameters and derived from the targeted breast height diameter (BHD, 1.30 m) by BHD x 25. If the BHD accounts for 60 cm, the minimum planting distance is 60 cm x 25 = 1500 cm. Thus, a minimum distance of 15 m between the individual trees is applied. While for nut trees and wild cherry, BHDs of up to 60 cm can be targeted, a BHD of 45-60 cm should be assumed for slower-growing trees like Elsbeere or Wild pear. Here, planting distances of 12 m are sufficient (Morhart et al., 2015). The group planting of tree seedlings (1-2 m distance) with the following selection of the best-developed tree is recommended, whereby the planting distance between group centres should be maintained (Brix et al., 2009; Morhart et al., 2016). The minimum planting distance in fruit systems depends on the fruit species and their final crown diameters; 10-12 m for apples and pears, 12-15 m for cherries and walnuts and 8 m for plums are recommended (Sicona, 2014; Jäger, 2017). A minimum wood strip width of 2 meters is recommended for timber systems. Increasing strip width minimises the negative edge influences on the crop alley (Bender et al., 2009; Brix et al., 2009; Chalmin, 2009). The sowing of site-adapted, annual to perennial flowering mixtures reduces weed growth and promotes biodiversity in the wood stripes (Sharaf, 2018). Planting distances of > 10 m can promote well-developed undergrowth providing a dense soil cover (Spiecker, 2009). From a nature conservation perspective, 3 m wide wood strips are suitable as a habitat for grass and herb fringe species. If shrubs are integrated, at least 5-8 m are required (Schulz et al., 2020). Further biodiversity-enhancing elements can include nesting aids, branches or stone piles (Reeg et al., 2009). The strips can be optionally augmented with berry bushes, ornamental plants and shrubs, and shade-loving herbs (Bender et al., 2009).

For windbreaks, larger planting distances or pruned trees should be prevented as they decrease porosity of the wood strip, potentially causing higher wind turbulences on the leeward side (Nuberg, 1988; Quinkenstein et al., 2009). To ensure a mean porosity of 40-60 % during the entire growing season, the tree strip consisting of deciduous trees (mostly leafless at planting time) can be added by a dense shrub understory (Brandle et al., 2009; Jacobs et al., 2022). Further, the alternating arrangement of at least two tree rows is recommended (Brandle et al., 2009; Quinkenstein et al., 2009; Bitog et al., 2012). Strips of at least 5 m width and four to eight rows within one wood strip have proved successful for SRA on Bavarian sites. Here, the successive harvest of rows ensures the maintenance of the windbreak effect and the negative edge effects (crop yield reduction on edges, branches windthrow, browsing) decrease compared to one to three rows (Winterling et al., 2019; Winterling, 2023). Pecenka et al. (2020) also recommend six tree rows and the successional harvest of three rows for the continuous windbreak effect. The appropriate planting distance for SRA depends on the rotation time, tree species, available harvesting and weed control techniques (Winterling et al., 2019). The distance between two rows or double rows should account for ca. 2-2.4 m to enable harvest with harvesting machines (LWF, 2020; Pecenka et al., 2020). Poplars and willows can be cultivated in 3-5 year rotations, in single rows of 0.5 m x 2 m (in row x between rows) or double rows of 0.75 m x 0.75 m and 2.2 m distance between double rows, resulting in tree densities of ca. 10,000 trees ha^{-1} woody area (w.a.) (Lignovis, 2018; LWF, 2020). On Bavarian test trials, poplar cultivation in 5-6 year rotations planted in 1-1.25 m x 1.5-2 m (5,000 trees ha^{-1} w.a.) proved practicable (LWF, 2020; Winterling, 2023). In medium rotations of 6-8 years, single rows of 1-1.5 x 2.4 m (2,500 – 4,000 trees ha^{-1} w.a.) are recommended, and in long rotations of 8-12 years, tree rows of 1.5-2.5 m x 3 m (1,300-2,200 trees ha^{-1} w.a.) (Lignovis, 2020). White clover, camelina, winter rye, or autochthonous forest and forest fringe species can be sown in the wood strips. The cultivation of shade-tolerating plants like wild garlic is possible. Flowering mixtures can be established in the fringes along the wood strips (Böhm & Veste, 2018; Winterling et al., 2019).

4.2.1.3 Crop alley spacing and orientation of wood strips

The distance between tree strips should be adapted to available machine technology and the light requirements of arable crops (Morhart et al., 2015). Jäger (2017) recommends 18-26 m wide crop alleys for fruit systems. The spacing depends on site characteristics and multiples of the existing machine widths, e.g. 24 m or 48 m (Brix et al., 2009). Recommended designs for timber systems have a tree density of 26 to a maximum of 50 trees per ha (Brix et al., 2009; Bender et al., 2009). Wider spacing is especially advised on high-yield sites, humid sites to ensure aeration and dry sites to minimise water competition (Chalmin, 2009). Smaller distances between tree strips result in more effective slope length reduction (Heindorf, 2007) and should be preferred at higher slope gradients (Nair, 1993; Young, 1997), but reduce solar radiation more profoundly. In terms of soil erosion by water, the distance between wood strips might be more important than the planting distance, as an increase in tree density did not lead to a linear decrease in erosion (Palma et al., 2007).

For SRA in temperate agricultural conditions, an area share of wood strips between 10 and 20 % is practicable (Böhm & Veste, 2018). The working width of the available technique limits the spacing. Additional distance for lateral tree growth is recommended (ca. ½ of the planting distance between tree rows). The distance between tree strips should be between 26 to 60 m (Pecenka et al., 2020). With increasing distances between wood strips, microclimatic processes decrease in intensity and wind erosion increases (Quinkenstein et al., 2009). For silvoarable agroforestry systems, Brandle et al. (2009) recommend a distance of 10-20 H between wood strips, depending on the machines, soil properties, crop residue management and climatic conditions. To increase the protected area, the wood strips can be located at a distance of 2-5 H from the field edge. Headlands should be established on both sides of tree strips ≥ 12-20 m, corresponding to the working width of the available technique (Böhm & Veste, 2018; Pecenka et al., 2020). A recommended design for a windbreak agroforestry system in Germany comprises, for example, 72 m crop alleys and 8 m wide tree strips with timber trees and additional substructures of shrubs and trees in every third strip (Brix et al., 2009).

The orientation of windbreaks determines the extent of wind speed reduction and the degree of shading (Quinkenstein et al., 2009). The orientation perpendicular to the prevailing wind direction is recommended because different angles reduce the extent of the protected zone leeward. Additional windbreaks with different orientations are recommended if major winds come from several directions. To reduce the extent of turbulences around the ends of the tree strips, a length of at least ten times the height of the wood strip is recommended (Brandle et al., 2009). The degree of shading is determined by the position of the sun relative to wood strips (orientation of wood strips), tree shape and height (tree species, planting distances, pruning), foliage period and the weather. North-south orientations, wide distances and high-set tree crowns reduce the shading on the crop alleys (Rosskopf et al., 2017; Schulz et al., 2020; Swieter et al., 2021). A north-south orientation is often recommended for economic reasons, as the noon shadow falls in the wood strips, which is significant > 20 m tree height (Chalmin, 2009). An east-west orientation is favoured from a nature conservation perspective, as the warm and light south side benefits many insect species (Reeg et al., 2009). For choosing the direction of wood strips, slope-parallel cultivation, prevailing wind directions, and landscape aesthetics should be considered (Brix et al., 2009).

4.2.1.4 Planting, pruning and management of trees

Fruit and timber trees are planted on frost-free days in October to November or February to March, but not in dry periods. The autumn planting is favoured for root development, except on waterlogged fields. The planting holes are prepared by a spade, earth driller or small excavator, have a loosened sole, and the soil can be enriched with compost. Grafting points of trees need to remain above the ground, and the seedlings have to be watered and mudded in (Morhart et al., 2015; Sicona, 2014; LPV MFR, n.d.). To obtain well-growing timber trees, the seedlings should meet the following requirements: suitable provenance, best genetic quality with straight growing characteristics, good vitality, well-developed roots, and > 1.5 m height at planting (Morhart et al., 2015). One meter around the base of the seedlings should be kept free of weeds by hoeing or mulching, for example, with a thick layer of wood chips (Schulz et al., 2020). Sweep and gnaw protection in the form of growth protectors and root wire baskets against mice is recommended. Wooden piles support the trees in the first years and are placed in line with the prevailing wind direction to reduce bark damage (Morhart et al., 2015). If wild boars regularly visit the area, it is advisable to plant trees with fruits and nuts only at the edges of the fields (Bender et al., 2009).

Poplars and willows can be planted from March to May in prepared soil by a planting machine or manually. For short rotations, 20 cm cuttings are used, longer cuttings (30-40 cm) or planting rods (90-175 cm) are recommended for medium and long rotations and at difficult sites (Lignovis, 2018; Lignovis, 2020). The soil preparation is best carried out by ploughing to a depth of 25-30 cm in autumn, followed by a seedbed preparation in spring. To reduce weed growth, the cultivation of clover grass for at least one year before planting is recommended (Winterling et al., 2019; Würdig, 2020). Other tree species are planted as rooted seedlings; here, the planting bed preparation is less necessary (Winterling et al., 2019; LWF, 2020). To control the accompanying flora after planting, undersowings of white clover, camelina, or winter rye are established, or mechanical weed control is carried out three to four times in the first year (Winterling et al., 2019; LWF, 2020). Installing perches for buzzards is recommended against field mice, whereas fencing is considered not economical. The trees will sprout again from the rootstocks after harvest (motor manual or with harvester); in this way, the system can be used for at least 30 years until reinstallation or removal by grubbing up the rootstocks (Winterling, 2023).

The pruning of fruit trees starts with planting and determining the long-term crown structure. The trunk extension and 3-4 leading branches at 45° angles are defined at high-trunk fruit trees. The pruning of fruit trees is continued regularly in winter (January to March) for apples and pears and in summer for cherries and walnuts (Sicona, 2014; LPV MFR, n.d.). The pruning of timber trees allows the production of knot-free, high, valuable wood. It reduces the obstruction of mechanical fieldwork and shadowing effect on crops and improves the growing shape of trees and aesthetic appearance. It is, therefore, an important measure and planning factor in timber systems (Bender et al., 2009; Morhart et al., 2015; Rosskopf et al., 2017). Timber trees need to be pruned in late winter or early summer (wild cherry, walnut) to reach the targeted knot-free shaft length. The minimum knot-free shaft length can be 5 m, e.g., for *Prunus avium, Juglans* spp., whereas wild fruit species like *Pyrus pyraster* reach 2.5 m. Depending on the tree species and target, the pruning is carried out every 1-3 years in the first 15-20 years. In addition, water tears should be removed regularly (Morhart et al., 2015; Schulz et al., 2020). The following rules should be respected: Pruning with ladder technique, sharp (telescope) saws and shears; maximum branch thickness 4 cm; cut on branch ring; avoid bark tears by relief cuts; < 1/3 of the total crown volume is removed (Ehring & Keller, 2005; Sheppard et al., 2016).

Management measures should already be considered in the planning process. Regular soil cultivation at > 20 cm depth close to the trunk forces the tree roots to grow deeper and minimises root concurrence with annual crops (Ong et al., 1991). To avoid damage to the trunks, the machines should not drive closer than 0.5-1 m to the trees (Schulz et al., 2020; Bender et al., 2009). Irrigation might be necessary for dry periods for the first 1-3 years (Morhart et al., 2015; LPV MFR, n.d.). The understory in the tree strips should be mown regularly, e.g. two to three times per year, to minimise possible weed and pest pressure, e.g. mice or snails. Additionally, predators are encouraged by setting up perches for birds of prey or creating branch piles with nesting chambers for weasels (Schulz et al., 2020).

4.2.2 Soil erosion and surface runoff reduction and water retention in temperate silvoarable agroforestry

Previous reviews on agroforestry systems found a reduction of surface runoff and soil erosion by water and higher soil moisture contents due to increased snow accumulation and reduction of evaporation by shading, rain trapping on the windward side and more even redistribution in the soil (Nuberg, 1998; Quinckenstein et al., 2009). The findings agree with the literature review on temperate agroforestry systems of Smith et al. (2012): Higher soil water levels compared to open land appear due to the windbreak and shading effect, but water competition between trees and crops might appear. By reducing surface runoff and increasing infiltration and soil water-holding capacity, agroforestry systems reduce the risk of flash flooding after heavy rainfall events. According to the meta-analysis of Zhu et al. (2020), in silvoarable agroforestry systems, the surface runoff reduces by 6-92 % and soil erosion by 14-99 %. Woody strips form a physical barrier of continuous vegetation cover with trunks, low branches, superficial roots and foliage layer, dense trees and shrubs (Young, 1989; Smith et al., 2012). This barrier shortens the slope length, diverts surface runoff and reduces the flow velocity. Thereby, it decreases the erosive force of surface runoff and leads to higher infiltration rates. As a semi-permeable barrier, the tree strip sorts grain size compositions and accumulates sediments, reducing sediment and debris loading into rivers (Spiecker et al., 2009; Smith et al., 2012).

The preservation of organic matter and perennial roots below wood strips improves the soil structure. The deep and extensive root systems of woody and herbaceous plants open compacted soil layers and provide fast-draining pores (Young, 1989; Spiecker, 2009). The fine root turnover and litter layer provide a reliable carbon source for microorganisms, favouring the humus build-up and formation of stable aggregates. The improved soil structure reduces the silting of the soil surface and increases infiltration rates of precipitation. It reduces soil erosion as long as the negative impacts of climate, slope and land cover do not exceed (Young, 1989; Sinclair, 1999). The soil type and amount of macropores further determine the effectiveness of agroforestry stripes in reducing surface runoff (Akdemir et al., 2016; Anderson et al., 2009). The increased porosity below wood strips is mentioned as a reason for higher soil moisture contents compared to crop alleys, in addition to increased water absorption capacities and infiltration rates (Seobi et al., 2005; Spiecker et al., 2009). The the enhanced water infiltration and interception of raindrops proved to significantly reduce soil erosion in agroforestry systems (Pavlidis and Tsihrintzis, 2018; Torralba et al., 2016). The soil improvement, infiltration rates and nutrient uptake increase with the root system growth and age of trees (Spiecker, 2009).

The review of Jacobs et al. (2022) aggregates the modification effects of temperate silvoarable agroforestry systems on the microclimate and water balance. Changes in the water balance include the reduction of surface runoff and increased infiltration rates. The water loss in agroforestry systems by evapotranspiration (transpiration, interception and evaporation) potentially reduces in the crop alleys by modified factors such as wind speed and air temperature. While the transpiration and raindrop interception from trees rise, evaporation and crop transpiration rates were found to decrease. For example, Kanzler et al. (2019) measured 25 % lower evapotranspiration rates in silvoarable short-rotation agroforestry systems compared to arable fields. Furthermore, the saturated hydraulic conductivity and redistribution in the soil increases, but trees and crops might compete for water resources. Competition for water between trees and agricultural crops might occur in the crop alleys up to a distance of 2 to 15 m from the tree strips, depending on tree species and the age of the trees. Hydraulic redistribution of water from deeper soil layers by the trees in the growing season could balance the water competition. Root barriers and pruning potentially reduce the root extension in the crop alley and water competition (Jacobs et al., 2022).

The soil moisture content shows spatial and temporal variations. In the vegetation period, especially in summer, lower soil moisture contents were observed in and close to tree strips of short rotation systems due to the water consumption of trees (Jacobs et al., 2022). Kay et al. (2018) modelled the water balance for temperate agroforestry systems and found an average groundwater recharge rate of 36.9 %, which was 6.7 % lower compared to comparable arable or grassland. However, no significant changes in soil moisture were measured in the centre of crop alleys, and several studies found higher soil moisture contents on the leeward side. The spatial variations might decrease in wet periods, and during precipitation periods, as soil moisture rises faster in the wood strips than in the crop alleys. In general, changes in soil moisture occur more frequently in the topsoil than in deeper soil layers (Jacobs et al., 2022).

Water balance dynamics in silvoarable agroforestry systems are determined by the infiltration rate, water use of tree and crop species, interception, throughfall, and microclimate. Influencing factors of the agroforestry system comprise the spatial layout of tree rows, rooting and tree physical properties, soil management and macropores, and the microclimate (Jacobs et al., 2022; cf. Figure 16). Zhu et al. (2020) list the multi-layered canopy, ground surface cover, extensive root system and improved soil quality as influencing factors modifiying the water balance in agroforestry systems. According to Heindorf and Reeg (2008), the following parameters of silvoarable agroforestry systems are important for minimising water erosion: distance between the wood strips, width of the wood strips, planting distance of trees, the orientation of the wood strips, trees and other vegetation layers, structure of the woody layer.

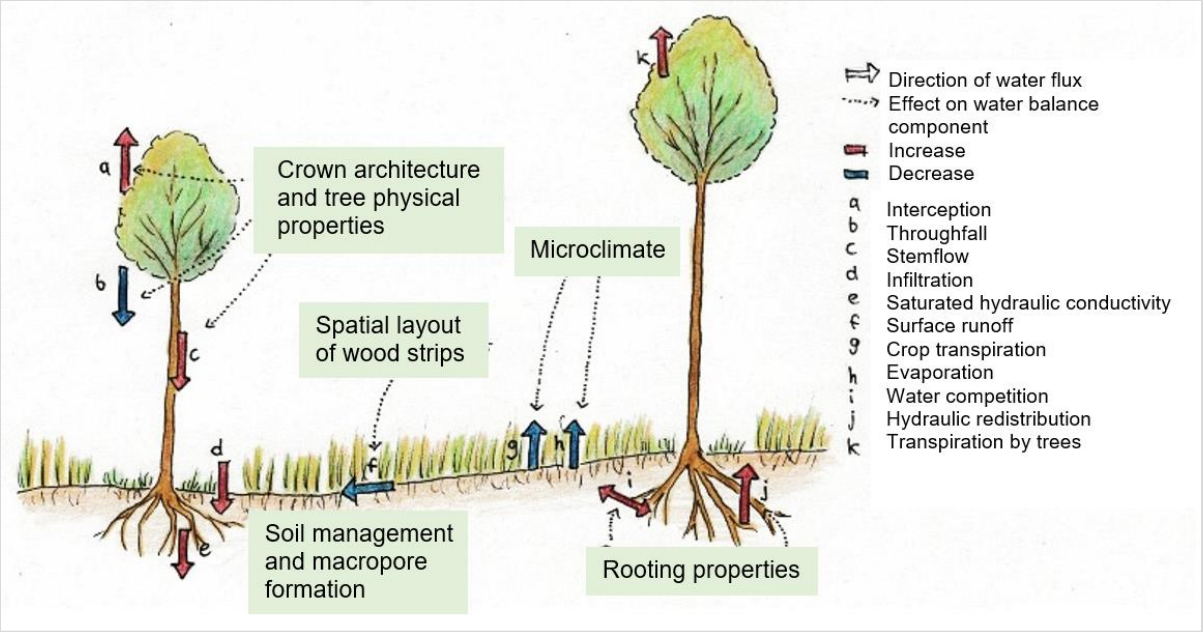


Figure 16 Influencing factors on the water balance, surface runoff and soil erosion in silvoarable agroforestry systems (Jacobs et al., 2022)

4.2.2.1 Timber and fruit agroforestry designs targeting surface runoff reduction, soil erosion control and water retention on slopes

Across-slope design: European modelling studies with tree densities of 50, 80 and 113 trees ha^{-1} showed significant reductions in soil erosion on slopes (Kay et al., 2018; Palma et al., 2007). Nerlich et al. (2013) measured surface runoff at single heavy rainfall events and after periods of continuous rain and snowmelt periods. They could determine a 90 % reduction in surface runoff compared to arable land below 2 m wide wood strips in 15 and 30 m distances across the slope (7 % slope gradient). In the wood strips, sown with a flower mixture, sycamore (*Acer pseudoplatanus*), wild cherry (*Prunus avium*), hybrid walnut trees (*Juglans spp.*) and poplar trees (*Populus deltoides x nigra*) were planted every 15 m (26 trees ha^{-1}). A regional case study in Saxony showed that introducing one to two hedgerows (shrubs and trees) on steep slopes reduced the slope length and the potential soil loss by 33 % (Frank et al., 2014).

On-contour design: When combined with contouring practices at medium (> 0.5 and < 3 t ha^{-1} a^{-1}) and high (> 3 t ha^{-1} a^{-1}) erosion sites, silvoarable agroforestry systems, including hybrid walnut (*Juglans spp.*), wild cherry (*Prunus avium L.*) and poplar trees (*Populus spp.*), could reduce soil erosion by up to 65 % (Palma et al., 2007). 7-year measurements in a watershed, including on-contour 4.5 m wide agroforestry stripes in 36.5 m (22.8 m) distance, demonstrated in total 24 % less produced surface runoff. The wood strips were established in 1991 with grass-legume undersowing and oaks (*Quercus* spp.). The highest reduction effects on the 2-9 % slopes were observed during large runoff events. However, in the first two years, the sediment losses exceeded the amounts of watersheds without disturbance (Udawatta et al., 2002). Three to 14 times higher saturated hydraulic conductivities were measured below the agroforestry stripes in the same setup. Despite similar infiltration rates, the soil water retention was higher in the agroforestry treatment than in the crop alleys (corn and soybean). Only during the growing seasons lower soil water contents were measured below tree rows (Akdemir et al., 2016; Anderson et al., 2009; Sahin et al., 2016; Seobi et al., 2005). Below the wood strips, soil porosities in 0-20 cm depth were 3 to 33 % higher, and the potential water storage increased by 0.9 to 1.1 cm per 30 cm depth compared to the crop alleys (Seobi et al., 2005).

Parallel-swale design: Based on GIS models, Fahrendorf (2022) found a significant reduction of surface runoff pathways and subdivision of sub-catchment areas with a parallel-swale system on a 9-12 % slope. The 3 m wide strips included 2.5 m wide vegetated swales and timber trees in 15 m distance (13 trees ha^{-1}). The parallel wood strips alternated with 30 m wide crop alleys. The agroforestry design basics for masterline-oriented agroforestry systems are described in Chapter 2.2.2. One design draft, including fruit and timber trees, is presented in Chapter 4.4.

Silvoarable agroforestry systems with timber or fruit trees on slopes, which have shown significant reductions in surface runoff and increased water retention, are designed with wood strips of 15 to 36.5 m distance and 2 to 4.5 m width. The trees are planted in 3 to 15 m distance in one row; the tree density accounts for 13 to 113 trees per ha. Sown grass-legume or flowering mixtures provide additional soil cover within the wood strips (cf. Chapter 4.2.1). To reduce soil erosion by surface runoff, previous studies recommended layouts along the contour lines at slopes > 3 % and smaller distances between wood strips at higher slope gradients (up to 14 %). The crop alleys should account for 10-25 m and the wood strip width for 1-5 m with trees planted in distances of > 10 m depending on the final crown diameter (cf. Chapter 4.2.1). According to practical recommendations, the tree density should not exceed 50 trees per ha. The planting distance is derived from the expected final crown diameters of timber and fruit tree species. While wild cherries and nuts require 15 m, 12 m is sufficient for wild pears or elsberry and 10 m for apples. Planting groups of two to three seedlings is recommended for timber trees. On high-yield, dry and humid sites, the minimum distance between wood strips of 18-26 m should be widened, using multiples of machine widths (cf. Chapter 4.2.1). To reduce weed growth, promote biodiversity, and reduce negative edge influences, the recommended wood strip width of 2 m can be extended to 3 m with the flowering mixture and grass sowing or to 5-8 m, including shrubs (cf. Chapter 4.2.1). The tree species in the available studies correspond in principle to the recommended list presented in Table 3, but can be optimised, e.g. by drought-resilient trees and should be chosen site-specific and based on ecological and socio-economic targets. The combination of the results and recommendations results in the following composition of timber and fruit agroforestry systems targeting the reduction of soil erosion, surface runoff and water retention on slopes (cf. Figure 17).

a) Wood strips across the slope or on contour, on > 3 ≤ 14 % slopes
b) 30 ± 12 m distance between wood strips; the steeper the slope, the closer the distance; determined by machines width and site-characteristics
c) ≥ 2 m wide wood strips covered with vegetation, e.g. flowering mixture
d) 10-15 m planting distance, depending on the final crown diameter (≤ 50 trees ha^{-1})
e) Tree species as listed in Table 3

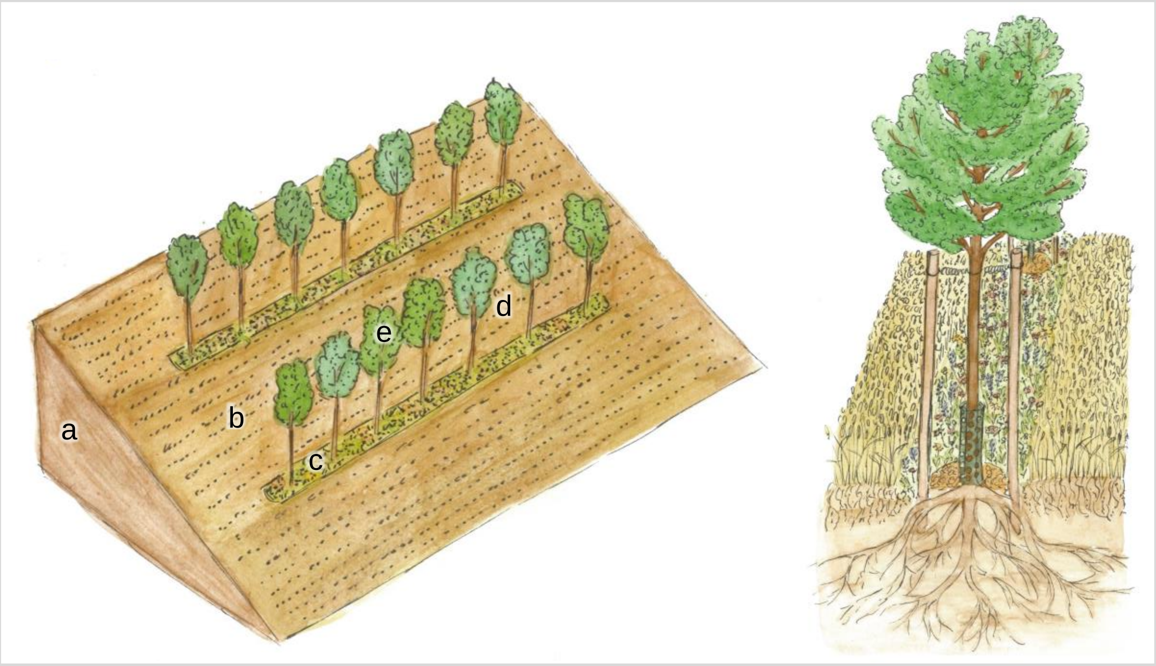


Figure 17 Examplary design of a timber and fruit agroforstry system across the slope (a), with 30 ± 12 m crop alleys (b), ≥ 2 m wide wood strips (c) and 10-15 m planting distance (d) with timber and fruit tree species (e) (own illustrations).

4.2.2.2 Short rotation agroforestry systems on slopes targeting surface runoff reduction and water retention on slopes

Wood strips with fast-growing trees and shrubs across 3-14 % slopes with 5 to 10 m width have shown reductions in surface runoff during relevant rainfall events of 35 % to 49 %. A 35 % reduction of surface runoff across the slope (3 % slope gradient) was measured during relevant rainfall events in buffer strips below grain corn. The 5 m wide buffer strip included poplar trees planted in 1.25 m x 1.5 m distance (5,000 trees ha^{-1} w.a.) and an undersown grass layer (Duchemin & Hogue, 2009). Dunn et al. (2022) set up 10 m wide buffer strips across the slope (14 %) below silage grass and maize. The wood strips included willows in 0.75 m x 1.5 m distance (3,200 trees ha^{-1} w.a.) and a mixture of deciduous trees in 0.85 m x 1.75 m distance (3,200 trees ha^{-1} w.a.). These comprised hornbeam (*Carpinus betulus L.*), sweet chestnut (*Castanea sativa Mill*.), hazel (*Corylus avellana L*.), pedunculate oak (*Quercus robur L*.), small-leaved lime (*Tilia cordata Mill*.) and wych elm (*Ulmus glabra Huds*.). During fifteen events, surface runoff was reduced by 49 % in the willow strips and 46 % in the mixed strips. A field trial by Schmitt et al. (1999) demonstrated that most sediments during runoff events are trapped within the first 4 to 7.5 m of a buffer strip. The wood strip was established across the slope (6-7 %) with mixed grasses, deciduous trees, and shrubs in a 1.25 m x 1.25 m distance.

The presented studies were conducted with fast-growing trees and shrubs in 5 to 10 m wide strips and distances of 0.75-1.25 m x 1.25-1.75 m (in row x between rows) (cf. Chapter 4.2.1). The planting distance is similar to the recommended distances of 0.5-1.25 m x 1.5-2 m for fast-growing trees grown in rotations of 3-6 years. When harvesting machines are to be used, the distance between rows should account for ca. 2 m (cf. Chapter 4.2.1). If the recommendation of 10-20 % proportion of wood strips per ha (cf. Chapter 4.2.1) is applied, the tree density of the studies mentioned above of 5,000-10,000 trees ha^{-1} w.a accounts for 500-2000 trees ha^{-1}. The tree species agree with the suitable species lists presented in Table 3. Native tree species, as used in the study of Dunn et al. (2022), however, showed better growth performances in longer rotations of > 8 years with planting distances of 1.5-2.5 m x 3 m (130-440 trees ha^{-1}). In addition to the rotation time and tree species, the planting distance needs to be adapted to the harvesting technique. On steep, unstable slopes, the need could arise to change the harvesting method to a motor manual. Therefore, the majority of guidelines consider steep, unstable slopes not suitable for the establishment of SRA (cf. Chapter 4.2.1). The limitation to slopes of 3 to 14 %, as presented in the studies above, therefore appears advisable. The 5- to 10-meter strip widths correspond to recommendations for Bavarian sites of at least 5 meters in width with four to eight rows. Undersowings, as used in the study of Schmitt et al. (1999) with mixed grasses, are recommended as white clover, camelia, winter rye, or autochthonous forest and forest fringe species. Additionally, flowering mixtures along the wood strip fringes can be established (cf. Chapter 4.2.1). Since the wood strips in the studies consisted of individual buffer strips, no data for crop alley spacing could be extracted. SRA guidelines refer to the effect as a windbreak and recommend distances of ≥ 50 m to minimise yield reductions of annual crops close to the tree lines. The focus on surface runoff reduction requires a different layout, as seen for timber agroforestry with a 30 ± 12 m distance between wood strips (cf. Chapter 4.2.1). The combination of the results and recommendations results in the following composition of SRA targeting the reduction of soil erosion, surface runoff and water retention (cf. Figure 18):

a) Wood strips across slope or on contour, on > 3 ≤ 14 % slopes
b) 30 ± 12 m distance between wood strips; the steeper the slope, the closer the distance; determined by machines width and site-characteristics
c) ≥ 5 m wide wood strips, undersowings possible, e.g. white clover
d) Planting distance of 0.75-1.25 m x 1.25-2 m (in row x between rows), depending on rotation period, tree species and available techniques (≤ 2,000 trees ha^{-1})

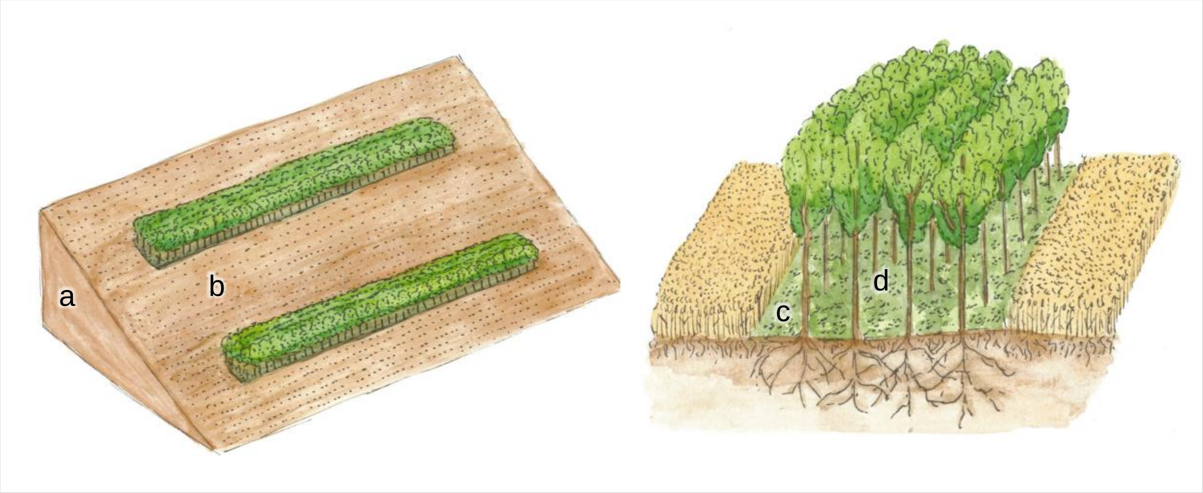


Figure 18 Examplary design of a short rotation agroforestry system across the slope (a) with 30 ± 12 m crop alleys (b), ≥ 5 m wide wood strips (c) and planting distances of 0.75-1.25 m x 1.25-2 m (in row x between rows) (d) (own illustrations).

4.2.3 Microclimate modification and wind erosion reduction in temperate silvoarable agroforestry

Woody structures can modify microclimatic parameters by creating structural diversity in a landscape (Kort, 1988). Established as a windbreak, tree strips reduce wind speed (Kort, 1988; Nuberg, 1998; Jose et al., 2004; Quinkenstein et al., 2009) and reduce wind erosion and mechanical damage to crops (Brandle et al., 2009; Smith et al., 2012; Kucera et al., 2020). Wind erosion is reduced in the sheltered zone by decreased wind speeds below the threshold for soil movement. The division of fields into smaller units reduces the field width and stops soil avalanching (Brandle et al., 2009). The wind speed significantly decreases in the first meters windward and leeward of the windbreak and up to a certain distance on the leeward side, depending on the tree height (H). Whereas the wind speed is reduced up to 20-25 * H leeward, the zone of reduced wind turbulence only extends to 6-10 H leeward (Brandle et al., 2009). The extent of wind reduction strongly depends on the tree height. The maximum wind reduction leeward extends from four to 12 times the height of the wood strip if the orientation is perpendicular to the prevailing wind direction (Nuberg, 1998). The extent and effectiveness of wind speed reduction is a function of the porosity of the windbreak, which is recommended to account for 40-60%, depending on the windbreak design, wind direction and wind speed (Nuberg et al., 1998; Brandle et al., 2009; Quinkenstein et al., 2009; Weninger et al., 2021; Jacobs et al., 2022). In systematic research on windbreaks consisting of at least one tree row, Weninger et al. (2021) reported wind speed reductions between 9.7% and 78%. The reduction of wind speed below the threshold value for soil movement and the reduction of field width prevent and interrupt wind erosion (Brandle et al., 2009; van Ramshorst et al., 2022). On the leeward side, the reduced wind turbulence favours the accumulation of water vapour (Young, 1989). Higher relative humidity (Brandle et al., 2009; Jacobs et al., 2022) and increased frequency of dew development were reported (Vetter et al., 2012).

In silvoarable agroforestry systems, lower air temperatures were observed in and close to the tree strips during the daytime due to reduced solar radiation (Jose et al., 2004; Brandle et al., 2009; Smith et al., 2012; Jacobs et al., 2022). The trees reflect and absorb solar radiation, thereby reducing daily temperature fluctuations in agroforestry systems (Martin-Chaveet al., 2019). This depends on the time of day, season of the year and reflectivity of the tree surface (Brandle et al., 2009). Due to reduced wind turbulence, higher air temperatures were reported in the sheltered zone leeward (Kort, 1988; Nuberg, 1998; Brandle et al., 2009). By reducing the sensible heat flux, evapotranspiration might further influence air temperatures (Brandle et al., 2009; Jacobs et al., 2022). The evapotranspiration rate varies with vegetation type and soil cover, wind speed and air temperature (Jacobs et al., 2022) and was found to decrease in agroforestry systems (Nuberg et al., 1998; Jose et al., 2004). Decreased evaporation rates and lower soil temperatures were reported in the shaded area of agroforestry systems (Brandle et al., 2009; Kanzler et al., 2019). Windbreaks provide sheltered zones for annual crops, e.g. by reducing physical damage and drought stress. However, increased relative humidity could be accompanied by negative effects, e.g., uneven ripening of crop diseases (e.g., Brandle et al., 2004; Brandle et al., 2009). Water competition reduces the yields of arable crops close to the tree strips (e.g., Winterling et al., 2019). However, the yield effects vary significantly between the arable crops (Brandle et al., 2009). Furthermore, below windbreaks, soil aggregates were found to be more stable (Weninger et al., 2021).

Microclimate modification strongly depends on the type and design of the agroforestry system (e.g., Kort, 1988; Böhm et al., 2014; Jacobs et al., 2022), as well as on the geographical location, atmospheric conditions, time of the day, soil type and the annual crop species (Brandle et al., 2009). For successful planning, further research on the design and its influencing factors on the microclimate effects is required (Jacobs et al., 2022). These are height, density/porosity, orientation and location of the wood strips (e.g., Nuberg, 1998; Quinkenstein et al., 2009); the length, width and continuity of the wood strip and its cross-sectional shape (e.g., Brandle et al., 2009; van Ramshorst et al., 2022) influenced by tree species, crown architecture, season and management (Jacobs et al., 2022).

4.2.3.1 Timber and fruit agroforestry systems targeting wind (erosion) reduction and microclimate modification

Wind speed: Böhm et al. (2020a) investigated a 40-year-old poplar tree row of 25 m height, including wide gaps and a fragmentary shrub layer in a 10 m wide stripe windward (N-S) of a 100 m wide crop alley. The wind speed was reduced leeward of the tree strip, showing higher effects with increasing wind speeds and wind directions of perpendicular direction. Because parts without a shrub layer only had a minor reduction effect, adding a shrub layer in systems with wide planting distances is recommended. The wind speed reduction decreased with increasing distance to the tree row, especially after 48 m leeward. Here, the reduction of > 2 ms^{-1} and > 4 ms^{-1} wind speed accounted for 42 % and 49 %, respectively.

Temperatures and relative humidity: In a study site in France with apple trees (*Malus domestica*) of 2.5 m height, N-S oriented tree strips were established in a 1.6 x 12 m design (planting distance x distance between tree strips). The relative humidity close to the trees (at a 1.5 m distance) was 5 % higher than at a 5 m distance from the tree strip. The daytime temperatures close to the apple trees were, on average, reduced by 1.5°C (Ramananjatovo et al., 2021). Reduced daytime temperatures were also measured in an N-S silvoarable agroforestry system in France with mature hybrid walnut trees (*Juglans nigra* L. *x Juglans regia* L.) of 17 m height, grown in one meter wide strips with a 10 x 10 m design. From July to September, the daytime temperatures close to the trees were 1.5°C lower during the daytime and 1.5°C higher during the nighttime (Martin-Chave et al., 2019). The same trend of temperature changes was measured in a mature timber agroforestry system in France with poplar and ash trees of 15-30 m height, grown in NW-SE lines with a 6 x 13 m design (Inurreta-Aguirre et al., 2018). No significant daytime temperature changes were found in an N-S agroforestry system with Paulownia trees of 12.8 m in height planted at 5 x 60-70 m distance (Chirko et al., 1996).

Water retention: In agroforestry timber and fruit systems, Carrier et al. (2019), Peng et al. (2009), and Chirko et al. (1996) observed no significant changes in soil moisture with distance to the tree rows. Carrier et al. (2019) conducted measurements in a Canadian agroforestry system with NW-SE and N-S tree rows with a mixture of timber trees: American ash (*Fraxinus* *americana* L.), red oak (*Quercus rubra* L.), bur oak (*Quercus macrocarpa* Michx.) and poplar hybrids. The trees were planted in 5-6 m distance in 1.5 m wide strips, established with 25 to 40 m distance (ca. 60 trees ha^{-1}). In a second trial, timber trees with 12 m height grew on 1.5 m wide strips with 90 m crop alleys (28 trees ha^{-1}). Chirko et al. (1996) carried out measurements in a mature timber system with 60 m crop alleys. In contrast, Peng et al. (2009) observed young walnut (*Juglans regia* L.) and plum trees (*Prunus salicina*) with a 5 m distance between tree rows. Both systems had N-S layouts. In the studies of Jose et al. (2000), Caubel et al. (2003), Reynolds et al. (2007), and Coussement et al. (2018), reduced soil moisture contents in and close to the tree strips were measured compared to the crop alley, especially in summer. These agroforestry systems had N-S and NW-SE layouts. They consisted of black walnut (*Juglans nigra* L.) and red oak (*Quercus rubra* L.) planted in a 3 m distance with 9 m crop alleys (Jose et al., 2000), a mature poplar row planted along the field (Coussement et al., 2018), and a single row with oak trees (*Quercus rubra* L.) (Caubel et al., 2003). In a system with maple and poplar trees in 3-6 m distance and 12-15 m crop alleys, Reynolds et al. (2007) reported lower soil moisture contents in 2 and 6 m distance to tree strips. However, the reduction effect in 5 and 15 cm depth was significantly higher with poplars than maple trees. Close to the maple trees, lower contents were measured in maize, whereas higher contents were found in combination with soybeans. Jose et al. (2000) also reported stronger soil moisture effects in upper soil layers. Furthermore, they observed that barriers or ditches along tree strips, which obstruct tree root growth in the crop alleys, resulted in significantly lower soil moisture contents in the tree strips and higher contents in the crop alley. Blanchet et al. (2021) investigated soil moisture contents in a timber system in an E-W layout. Here, hybrid walnuts (*Juglans regia x nigra, cv.* NG23) were planted in 8 m distance with 13 m crop alleys (80 trees ha^{-1}). During the vegetation period, changes were more pronounced in the upper soil layers. From early March to mid-May, they found lower soil moisture contents in the tree row than in the crop alleys. After mid-May, the differences decreased and were no longer perceptible at harvest. Furthermore, the water balance modelling of Kay et al. (2018) in a cherry orchard with a tree density of 50-80 trees ha^{-1} showed groundwater recharge rates of 34 %, which were 5 % lower than non-agroforestry fields.

Light intensity and yield impact: Several studies in silvoarable fruit and timber agroforestry systems reported reduced solar radiation close to the tree strips and its impact on the crop yield in young (< 5 years) and mature systems. Peng et al. (2009) and Carrier et al. (2019) conducted studies in young N-S-oriented systems. With walnut (*Juglans regia* L.) and plum (*Prunus salicina*) trees (3 x 5 m distance, 3 m height), reduced solar radiation was measured up to 2.5 m near the tree strip, resulting in 38 % yield reduction at corn and 29 % decrease at soybean (Peng et al., 2009). Reduced solar radiation in a Canadian timber system with oak and poplar trees of 3.5-7.7 m height (6 x 25-39 m distance, 1.5 m strip width) led to yield reductions at maize, soybean and black bean in ½H distance to the tree strips. The same effect was seen with NW-SE strips of mature oak and ash trees of 12.7 m height (4 x 90 m distance, 1.5 m strip width). Whereas at the centre of the crop alleys, no significant reduction in light intensity was observed (Carrier et al., 2019). In a Canadian agroforestry system with mature maple and poplar trees (3-6 x 12.5-15 m distance, 12 m height), a significant reduction of photosynthetically active radiation was measured in a 2 m distance from the tree row. Here, the shading effect of poplars was higher than that of maple trees, and corn yield was more affected than the one of soybeans (Reynolds et al., 2007). In an agroforestry system with black walnut trees (*Juglans nigra* L.) and red oak (*Quercus rubra* L.) of 7.5 m height (2.4 x 8.5 m distance), Gillespie et al. (2000) found up to 42 % decreased photosynthetically active radiation close to the tree row. Chirko et al. (1996), Inurreta-Aguirre et al. (2018), Martin-Chave et al. (2019), and Ramananjatovo et al. (2021) also reported reductions in light intensity close to the tree strips in mature timber and fruit systems with N-S-orientation. Measurements on the light reduction were also conducted in a W-E-oriented silvoarable agroforestry system in France with hybrid walnut trees growing in an 8 x 13 m design. Close to the tree rows, Dufour et al. (2013) (7.8 m tree height) measured light reductions of 31 % and cereal yield reductions of up to 50 %. In total, the protein yield per hectare was less reduced than the dry matter grain yield. Dufour et al. (2020) (10.7 m tree height) measured an average light reduction of 20 % relative to full sun conditions at the northern side of the tree strips at 6.5 and 11 m distances. Here, wheat yield was reduced by 32 % and pea yield by 31 %, whereas barley mean yields were unaffected. The pollarding of trees resulted in decreased light and yield reductions in the first two years. At a 3.5 m distance from the tree rows, Blanchet et al. (2021) (10.9 m tree height) found average light reductions of 19 % on the southern side and 35 % reductions at the northern site in the vegetation period. Whereas in normal rainfall conditions, pea yield decreased by 25-77 % in the tree shade, in spring drought conditions, it was reduced by 22 % in full sun and 1-47 % in the shade.

The presented studies unambiguously showed the reduced photosynthetically active radiation close to the tree strips. In N-S layouts, the significant light reduction occurred in a 2-4 m distance; in E-W layouts, it was also measurable in an 11 m distance at the northern side. These results explain the economic-based recommendation for N-S layouts (cf. Chapter 4.2.1). However, to enhance further microclimatic effects through wind protection, the wood strips should be oriented perpendicular (or diagonal) to the prevailing wind direction (cf. Chapter 4.2.1). The presented studies, on the one hand, showed negative soil moisture effects in the vegetation period in and close to wood strips in timber and fruit systems in N-S, NW-SE and E-W layouts with 5-15 m crop alleys. On the other hand, in studies with mature timber trees with 25-90 m crop alleys and 28-60 trees ha$^{-1,}$ no significant changes in soil moisture were observed. This corresponds with the recommended tree density of < 50 trees per ha and the minimum distance between wood strips of 18-26 m, which can be widened on high-yield, dry and humid sites (cf. Chapter 4.2.1). However, the study of Böhm et al. (2020a) indicated that the wind speed reduction decreases significantly after 48 m leeward. The planting distance is derived from the expected final crown diameters of timber and fruit tree species. The derived distances of 10-15 m differ from the above-presented designs, rather reflecting the recommended group planting for timber trees of two to three seedlings each (cf. Chapter 4.2.1). The tree species in the available studies correspond to the recommended list presented in Table 3 and can be optimised, e.g., by drought-resilient trees and should be chosen site-specific and based on ecological and socio-economic targets. The tree species selection and the pruning management have been shown to influence, among other factors, such as the orientation of wood strips, the magnitude of wind speed reduction (tree height, porosity of wood strip) and light reduction (shade). The recommended pruning management of timber trees favours a smaller shading impact on crops but reduces the porosity of the wood strip (cf. Chapter 4.2.1). To increase the wind speed reduction, Böhm et al. (2020a) advised the additional implementation of shrubs, which helps to achieve the recommended porosity of 40-60 % for windbreaks. Adding a dense shrub understory might require an extension of the wood strip width from 2-3 m to 5-8 m (cf. Chapter 4.2.1). The observation of Jose et al. (2000) that barriers or ditches along tree strips reduce tree root growth in the crop alleys and, therefore, decrease the negative soil moisture impact close to the tree strips corresponds to practical recommendations. Regular soil cultivation, e.g., by deep ploughing 0.5-1 m close to the trunk, forces the tree roots to grow deeper and minimises the root concurrence to annual crops (cf. Chapter 4.2.1). The combination of the above results and recommendations results in the following composition of timber and fruit agroforestry systems (cf. Figure 19):

a) Wood strips perpendicular (diagonal) to the main wind direction; N-S layout rather than E-W layout (light reduction)
b) ≥ 18 m to < 50 m crop alleys; determined by machines width and site-characteristics
c) ≥ 2 m wide wood strips, added by shrubs to reach 40-60 % porosity
d) 10-15 m planting distance, depending on the final crown diameter (≤ 50 trees ha^{-1})
e) Tree species as listed in Table 3

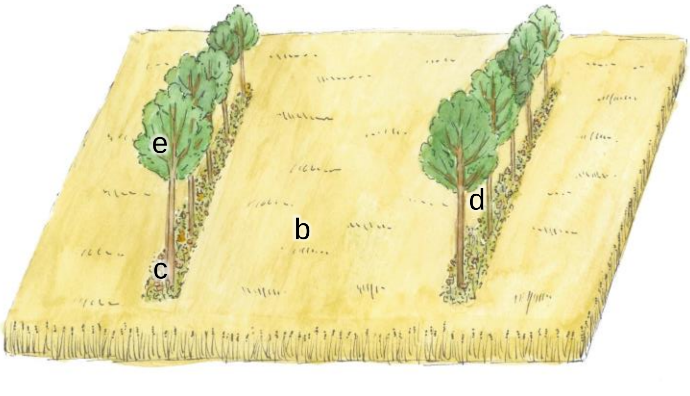


Figure 19 Examplary design of a timber and fruit agroforestry system on level fields with ≥ 18 m to < 50 m crop alleys (b), ≥ 2 m wide wood strips (c) and 10-15 m planting distances of timber and fruit trees (e) (own illustration).

4.2.3.2 Short rotation agroforestry systems targeting wind (erosion) reduction and microclimate modification

Wind speed and wind erosion: Böhm et al. (2014, 2020a), Kanzler et al. (2019), and van Ramshorst et al. (2022) investigated wind speeds in an SRA site in Northern Germany with black locust (*Robinia pseudoacacia*) and poplars (*Populus maximowiczii x Populus nigra* Max) in 5-year rotations. In 2010, N-S-oriented tree strips were established in 24, 48 and 96 m distances across a flat field of 40 ha. The 10 m wide wood strips of 640 m length include four double rows of 1.8 m distance with trees planted in 0.75-0.9 m distance (8,700 trees ha^{-1}) (Böhm et al., 2014). The highest windbreak effect was measured in the summer months and on the leeward side of the tree strips and increased with tree height. At 3 m tree height, significant wind speed reductions were seen up to 9 m leward (up to 70 %) and 3 m windward (30 %) (Böhm et al., 2014; Kanzler et al., 2019). Compared to an open field, the average wind speed reduction over one year accounted for 49, 29 and 4 %, and the reduction of winds above 5 ms^{-1} for 99, 94 and 61 % at the centre of 24, 48 and 96 m wide crop alleys, respectively. Accordingly, Böhm et al. (2014) recommend crop alleys of ≤ 50 m width. At 7 m tree height and 48 m crop alleys, Böhm et al. (2020a) measured average reductions of > 5 ms^{-1} winds by 55 % to > 70 %, depending on the season. Model simulations of van Ramshorst et al. (2022) showed average reductions for wind speed of 17 % and 67 % and potential wind erosion of 24 % and 97 % with 2 m and 8 m tree height, respectively. When oriented perpendicular to the prevailing wind direction, tree strips of ≤ 48 m and 2 m height could reach average wind erosion reductions of > 80 % (van Ramshorst et al., 2022). The amount of reduction is strongly dependent on the orientation of tree strips to wind directions (perpendicular > diagonal > parallel), where the latter could cause tunnel effects with increased wind speeds (Böhm et al., 2014; Böhm et al., 2020a; van Ramshorst et al., 2022). The average reduction of potential wind erosion accounts for 92, 86 and 35 % for perpendicular, diagonal and parallel orientation of tree strips, respectively (van Ramshorst et al., 2022). Winterling et al. (2019) measured wind speed in two SRA sites with poplar (*Populus nigra* L. x *P. maximowiczii*) in Southern Germany, consisting of N-S oriented, 7.5 m wide strips (1.25 x 1.25 m planting distance) and 80 m crop alleys. Significant wind speed reductions reached up to 40 m leeward, with the highest reductions of 50-60 % at west winds in 5-20 m leeward, esp. in 5 and 10 m leeward and 5 m windward. Similar observations were made by Rivest et al. (2022) in a Canadian SRA with N-S oriented strips of 2.5 m width, 100 m length, 40 m crop alleys, and 2 m high willows (*Salix viminalis* L. and *Salix miyabeana* Seemen) (13,000 trees ha^{-1}). The greatest wind speed reductions of 50% and 22 % were measured in 5 m and 20 m leward, respectively. Foreid et al. (2002) observed wind reductions up to 12H leeward of a 10 m wide willow strip of 5 m height planted along the field.

Temperatures and relative humidity: Swieter et al. (2021) investigated microclimatic parameters in June and July in a German SRA. The system consisted of 24, 48 and 96 m wide crop alleys and N-S tree strips of 13 m width, including poplars (10,000 trees ha-1) of 5.8-9.4 m height. Next to the tree strips, lower solar radiation was observed. In the morning, they measured higher relative humidity in the shaded zone and lower air temperatures compared to the control field. The temperatures went up in the afternoon, except in the wood strips. The highest relative humidity occurred in the wood strips at noon and evening. The differences were particularly pronounced on hot and sunny days (Swieter et al., 2021). From May to August, Kanzler et al. (2019) reported a smaller temperature amplitude with lower daytime (>3.4°C in July) and higher nighttime air temperatures (>1.6°C in May) within the poplar wood strips and in the shaded zones (6-7 % less solar radiation). A lower vapour pressure deficit was also measured compared to an open field. Higher temperatures (up to 1.7°C) and vapour pressure deficits in the crop alleys varied with months and time of day. In contrast, in August, ~1°C lower temperatures were observed in the evening and night. The effect on vapour pressure deficit resulted in 36 % less water stress and 29 % more suitable growing conditions for crops in the SRA than in open fields. In the above-presented SRA, Winterling et al. (2019) also reported a smaller air temperature amplitude with lower daytime values in the shaded zone and higher temperatures in wind-protected zones and during the night. The relative humidity was higher during night and morning hours; at noon, the highest humidity was measured next to the tree strips. Below the wood strip, the soil temperature was lower, esp. in the summer months, with a smaller amplitude than in the crop alley. Ehret et al. (2018) also measured lower soil temperatures and less solar radiation close to the 7.5 m wide tree strips with willows (12,000 trees ha-1) than in the centre of the 9 m wide crop alley. Rivest et al. (2022) also found a significant increase in daytime air temperature of up to 1 °C in the wind-protected zone close to the willow strips compared to open field.

Water retention: Measurements in several studies in SRA in Germany show the spatial and temporal variability of soil moisture contents. During the vegetation period, Winterling et al. (2019) measured lower volumetric water contents in the tree row and higher contents at 5 and 10 m distances on the leeward side of the wood stripes, and no changes in the centre of the crop alley (50 m). At a 1 m distance leeward, Ehret et al. (2018) also measured higher volumetric soil moisture contents at 35 cm depth (4-6 %), while at 15 cm depth, it varied temporarily. At a 1 m distance in luv, the soil moisture content was, on average, lower than the control. In the centre of the crop alley, no significant changes were measured. In spring, Beule et al. (2020) found higher water-filled pore spaces in the topsoil in the tree row (14-20 %) and at 1 m distance (3-9 %). Beyond the 7 m distance, the soil moisture content was similar to the monoculture cropland. From June to July, the soil water tension in the tree row and in 1.5 m distance in lee in 30-60 cm soil depth was higher than in 1.5 m in the topsoil and in 24 m distance (Swieter et al., 2022). Medinski et al. (2015) made similar observations in July to August with significantly lower soil moisture contents below poplar stripes. However, the potential evaporation was found to be up to 58 % lower close to the tree strips (3 m leeward) and 24-32 % lower in the crop alley compared to open fields (Kanzler et al., 2014, 2019). The evapotranspiration rates close to tree stripes and in the crop alleys are contrary, esp. in dry years, but compensate for each other over the year (Markwitz et al., 2020). Leeward of an Austrian 6 m wide hedgerow of 8 m height, including a dense shrub layer, reduced windspeeds resulted in overall reduced evapotranspiration rates and less water stress for annual crops (Gerersdorfer et al., 2009).

Yield impact: Winterling et al. (2019) reported that the SRA did not affect the overall yields and quality of oats, winter wheat, and clover grass. Lower yields in 5-10 m leeward and windward were compensated by higher yields in up to 50-60 m distance from the tree strips. Accordingly, crop alleys of ≥ 50 m are recommended. Swieter et al. (2021) observed a delay in the phenological development of winter wheat in the shaded zone. Kanzler et al. (2019) found that winter wheat grain yield in the crop alleys was, on average, 16 % higher due to increased temperatures and water supply. For clover grass, no significant impact on the quality was observed (Ehret et al., 2018), and impacts on the forage yield varied with climatic conditions. They were compensated over the vegetation period (Rivest et al., 2022).

The presented studies were conducted in SRA systems with 9, 24, 48, 80 and 96 meters crop alleys. Significant wind speed reductions were observed up to 24 m leeward, continuing in lower magnitude up to 48 m leeward. To take advantage of the windbreak effect and minimise negative yield effects on the annual crops, a distance of ≥ 50 m and < 80 m is recommended between tree lines (cf. Chapter 4.2.1). Wind erosion could decrease significantly with wood strips in perpendicular (or diagonal) orientation towards prevailing winds, explaining the N-S (NW-SE) layouts. This orientation is further recommended for the reason of shade reduction on the crop alley (cf. Chapter 4.2.1). The 7.5 to 13 m strip widths correspond to recommendations for Bavarian sites of at least 5 m. A minimum of four to eight rows allow successional harvest and ensure the maintenance of the windbreak effect (cf. Chapter 4.2.1). The presented studies showed significant wind erosion reductions with fast-growing trees, which was more pronounced for 8 m than 2 m tree height, but already high with 2 m high trees in perpendicular orientation. The tree species, mainly poplar clones, black locusts and willow, agree with the suitable species lists presented in Table 3. However, it is recommended to diversify the system with additional native species grown in blocks of up to 30 %, such as alders, elms or maples. The tree strips could be further enriched by undersowings and added by flowering mixtures along the tree strip fringes (cf. Chapter 4.2.1).

The planting distances of 0.5-1.25 m x 1.25-2.5 m (in row x between rows) correspond to recommended distances for fast-growing trees grown in rotations of 3-6 years. When harvesting machines are used, the distance between rows should account for ca. 2 m (cf. Chapter 4.2.1). Consequently, with the recommended wood strip proportion of 10-20 % per ha, the tree density accounts for 800-2400 trees ha^{-1}. Here, the recommended porosity of 40-60 % for windbreaks should be adhered to (cf. Chapter 4.2.1). The combination of the above results and recommendations results in the following composition of timber and fruit agroforestry systems targeting the reduction of soil erosion by water (cf. Figure 20).

a) Wood strips perpendicular (diagonal) to the main wind direction
b) ≥ 48 m and ≤ 80 m crop alleys; determined by machines width and site-characteristics
c) ≥ 5 m wide wood strips with a minimum of two alternating tree rows and 40-60 % porosity of wood strips
d) Planting distance of 0.5-1.25 m x 1.5-2.5 m (in row x between rows) depending on rotation period, tree species and available techniques (800 - 2,400 trees ha^{-1})
e) Tree species as listed in Table 3

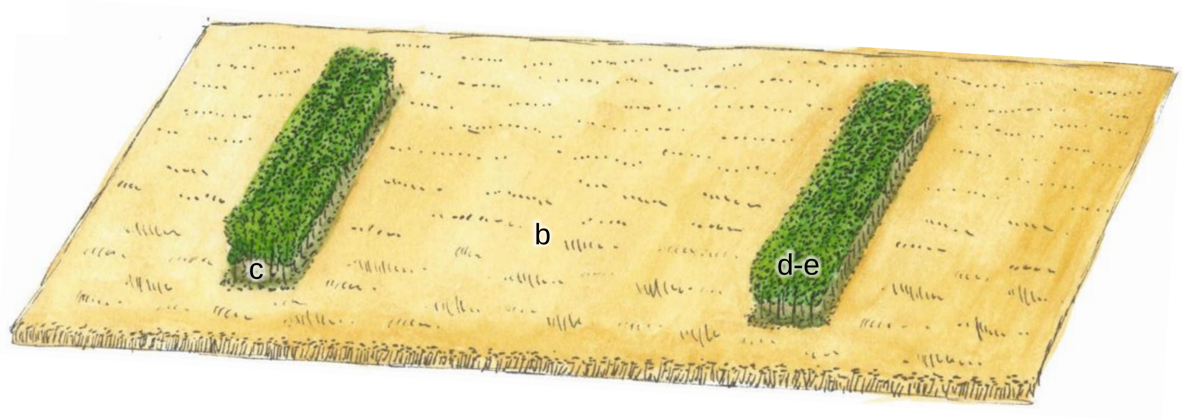


Figure 20 Examplary design of a short rotation system on level fields with wood strips perpendicular (diagonal) to the main wind direction, ≥ 48 m and ≤ 80 m crop alleys (b), ≥ 5 m wide wood strips of 40-60 % porosity (c) and planting distances of 0.5-1.25 m x 1.5-2.5 m (in row x between rows) (d) of fast-growing tree species (e) (own illustration).

4.3 Suitability of silvorarable agroforestry systems in the municipality

4.3.1 Allocation of stated objectives on arable fields

The defined objectives of water erosion control, water retention, microclimate modification and wind erosion protection in arable agriculture (cf. Chapter 4.1.3) were allocated to arable fields in the study area on the regional scale. Of all arable fields in the municipality, 78 % (comprising 96% of the arable land) were suitable for establishing silvoarable agroforestry systems. They fulfilled the minimum field size and width criteria, excluded protected areas and were sufficiently distant from surface waters (cf. Figure 21).

Starting with the soil erosion objective, 95 % of the arable land showed a medium or high priority for erosion control measures. On 10 % of the arable land (6 % of arable fields), more than half of the respective field was threatened by potential soil erosion of ≥ 20 t ha^{-1} a^{-1}. It was classified as a very high priority for erosion control. Where the majority of the field showed a potential soil erosion of ≥ 12 and < 20 t ha$^{-1,}$ a^{-1} erosion reduction had a high priority. This applied to 42 % of the arable land or 30 % of arable fields. Medium priority for erosion control with a potential soil erosion of ≥ 5 and < 12 t ha^{-1} a^{-1} was valid for 39 % of the arable land (34 % of fields). Only on 5 % of the arable land (8 % of fields) the potential soil erosion was < 5 t ha^{-1} a^{-1} and classified with a low priority (cf. Figure 22).

The objective for water retention comprised the degree of groundwater, congestion and adhesive wetness, and potential water retention at heavy rainfall events. Thirty per cent of the arable land was classified with a high priority for water retention measures. At these 22 % of arable fields, the groundwater depth was > 20 dm, and the potential water retention was low. Additionally, they showed no or a low degree of congestion and adhesive wetness. Medium priority for water retention measures applied to 23 % of the arable land (19 % of fields). Here, the low to significant congestion and adhesive wetness met a medium to high water retention potential at heavy rainfalls. Where the groundwater was pending at < 13 dm depth, the fields were predominantly wet and were characterised by waterlogging; there was a low priority for water retention. This was allocated to 43 % of the arable land (37 % of arable fields) (cf. Annex 6.1).

The requirement for wind protection considered the presence of woody structures (small woody features and forests). Two per cent of arable fields or four per cent of arable land was wind-exposed without woody structures adjacent to the west, thereby classified with high priority for wind protection measures. 34 % of the arable land (27 % of fields) showed a medium priority as they were less wind-exposed and had woody structures adjacent to the west. A low priority for wind protection was allocated on 58 % of the arable land or half of the arable fields.

Here, woody structures grew directly at the western corner of arable fields, or the fields were predominantly wet (cf. Annex 6.2).

Merging the results, priority fields for the implementation of silvoarable agroforestry systems presented themselves based on the allocation of objectives, categorised into ten levels with increasing preference. Level one represented only low priorities and accounted for 3 % of the arable land. On 17 % of the arable land, erosion control or water retention had a medium priority (level 2). Medium priorities for water retention and erosion or wind protection were allocated to 5 % of the area (level 3). The same area share applied to level four, where all objectives are medium-priorised. Levels five and six accounted for 11 % of the area, respectively. Here, water retention or erosion had high priority, added by one medium-prioritised objective in level six. On 10 % of the arable land, there were one high- and two medium-prioritised objectives (level 7), whereas the highest share of area (23 %) had two high- and one medium-prioritised objectives (level 8). The two highest levels comprised 10 % of the arable land, where erosion control was very highly, and erosion control, water retention and wind protection were highly recommended (cf. Figure 23).

4.3.2 Suitable designs of agroforestry systems on arable fields

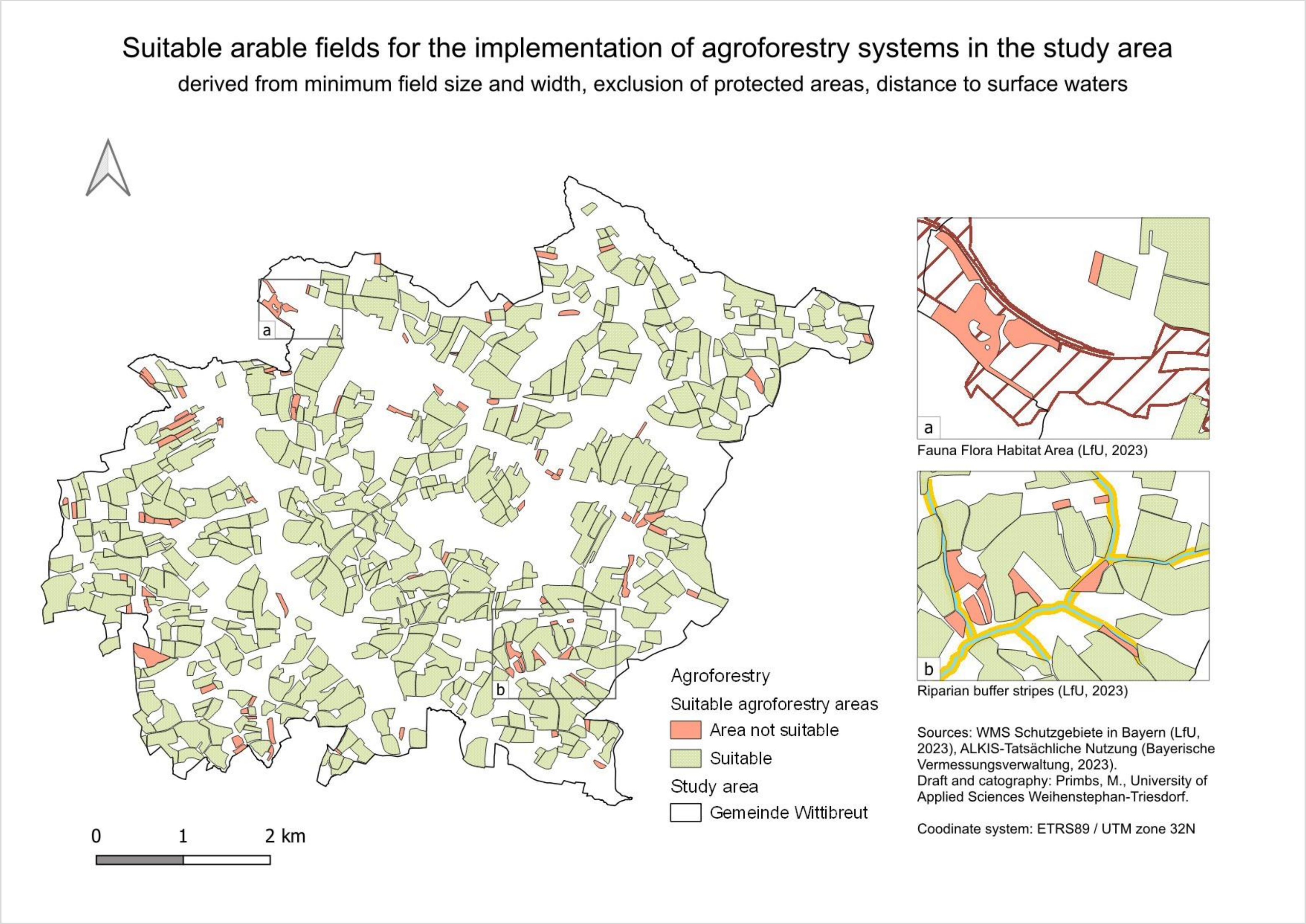
The designs of silvoarable agroforestry timber and fruit systems and short rotations systems for slopes and level fields were derived in Chapter 4.2. The four resulting design drafts were assigned to the arable fields of the study area. The degree of recommendations, suitability or potential conflict on the fields was derived from the allocated targets, including site characteristics (cf. Chapter 4.3.1) and crop rotation (cf. Chapter 4.1.1). The allocation of suitable agroforestry systems to arable fields was conducted by means of a decisions tree (cf. Figure 24).

Agroforestry design drafts for slopes were allocated to arable fields of the study area with > 3 % slope gradient. This applied to 92 % of the arable land and 70 % of the fields (cf. Figure 26). The design of timber and fruit agroforestry systems on slopes (cf. Chapter 4.2.2.1) was highly recommended on 10 % of the arable land (6 % of arable fields), where the priority for erosion protection was very high, and water retention was important. Therefore, on 1 % of the fields, a potential planning conflict could arise with the high priority for wind protection. Here, the recommended across-slope design would result in an east-west orientation of the wood strips, which is parallel to the prevailing wind direction. On 55 % of the arable land (46 % of fields), timber and fruit systems on slopes were recommended, where the targets of erosion protection and water retention had high to medium priorities, respectively. Establishing timber and fruit trees was not recommended on predominantly wet fields with heavy waterlogging and groundwater tables < 13 dm. This applied to 30 % of the arable land and 22 % of fields (cf. Annex 6.3).

Short rotation agroforestry systems on slopes were highly recommended on 4 % of the arable land (3 % of fields) where erosion protection was of very high importance. Short rotation systems on slopes are recommended on 45 % of the land and 38 % of arable fields. Here, the priority for erosion protection was medium to high. On 43 % of the arable land (29 % of fields), establishing short-rotation agroforestry could cause a potential conflict with the annual crops, especially the cultivation of maize. The recommended across-slope design would result in an east-west orientation of wood strips, thereby increasing the light reduction on the northern side of the strips (cf. Figure 25).

Agroforestry design drafts for level fields were allocated to fields in the study area with < 6 % slope gradient and with low to medium priority for water erosion protection, which applied to 43 % of the arable land and arable fields, respectively (cf. Figure 26). Timber and fruit agroforestry systems for level fields were highly recommended on 2 % of the arable land (1 % of fields), where the wind protection requirement was high, water retention was important, and establishing an additional shrub layer was advised. A recommendation for timber and fruit systems can be pronounced for 10 % of the arable land and fields, where wind protection requirement was medium and water retention of importance. Timber and fruit agroforestry was suitable on a further 8 % of the land (10 % of fields). The establishment was not recommended on predominantly wet fields and heavy waterlogging, which applied to 18 % of the land (14 % of fields) (cf. Annex 6.4). Short rotation agroforestry was highly recommended on 2 % of the arable land with high wind protection and water retention requirements. Short rotation systems were recommended and suitable on 11 % and 25 % of the arable land (10 % and 23 % of fields), respectively. However, 16 % of the arable land (10 % of fields) held a potential conflict with maize cultivation resulting from the increased light reduction of an east-west orientation (cf. Annex 6.5).

In sum, agroforestry systems were recommended and suitable on 94 % of the arable land and 74 % of arable fields in the study area. Consequently, of the filtered 96 % suitable arable land, on 2 % agroforestry was not recommended e.g., on predominatnly wet sites. The design drafts for agroforestry systems on slopes could be applied on one-quarter of the arable land. Only timber and fruit systems on slopes were recommended for nearly another quarter. On the other hand, on 15 % of the arable land, each of the presented systems would be suitable. Four per cent of the land was rather suitable for agroforestry design drafts for level fields, and 28 % of the arable land should be planned with short rotation systems only (cf. Figure 26).



Suitable arable fields for the implementation of agroforestry systems in the study area

derived from minimum field size and width, exclusion of protected areas, distance to surface waters

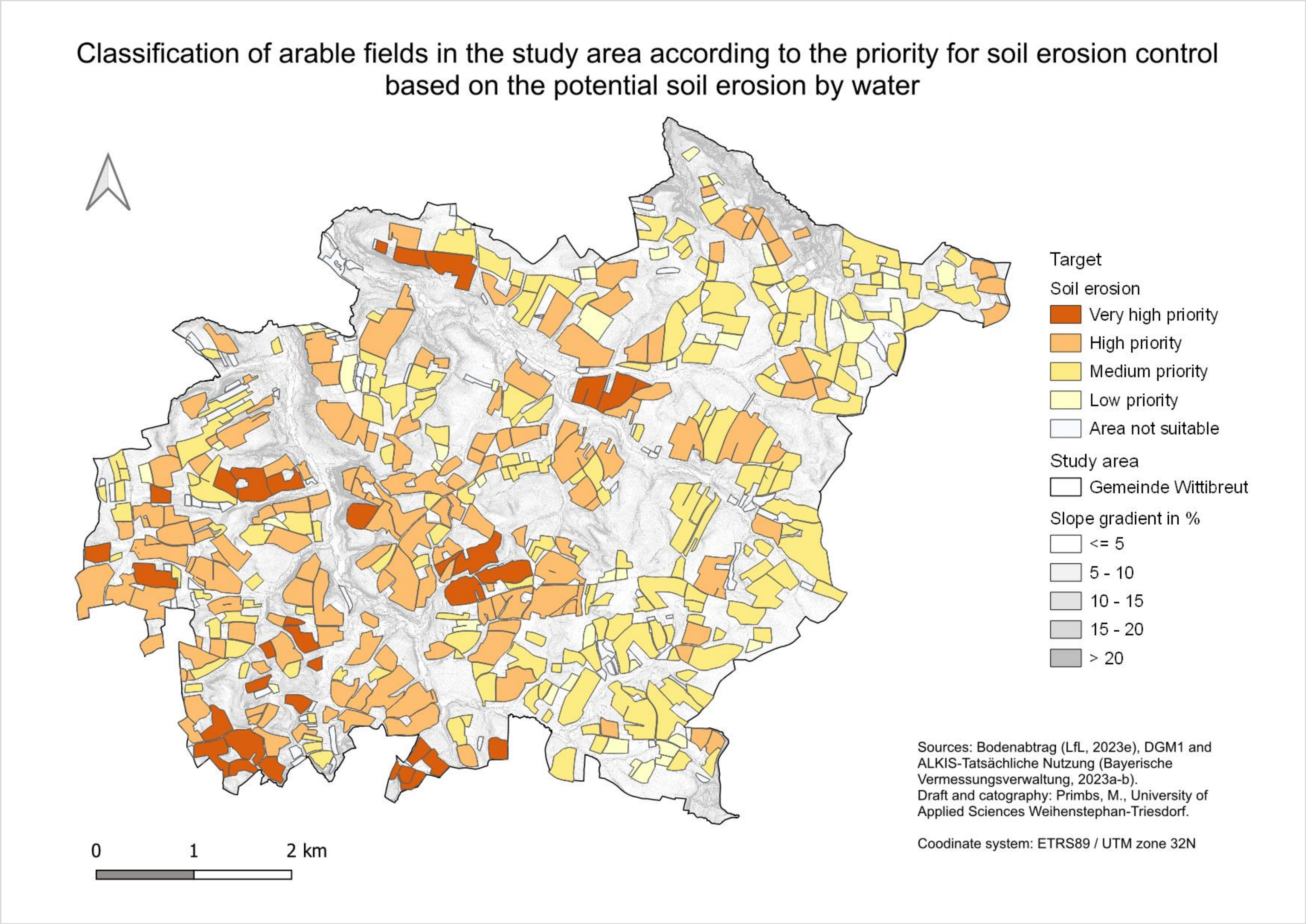
a Fauna Flora Habitat Area (LfU, 2023)

b Riparian buffer stripes (LfU, 2023)

Sources: WMS Schutzgebiete in Bayern (LfU, 2023), ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023).
Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure 21 Suitable arable fields for the implementation of silvoarable agroforestry systems in the study area (light green) derived from minimum field size and width, exclusion of protected areas and distance to surface waters.

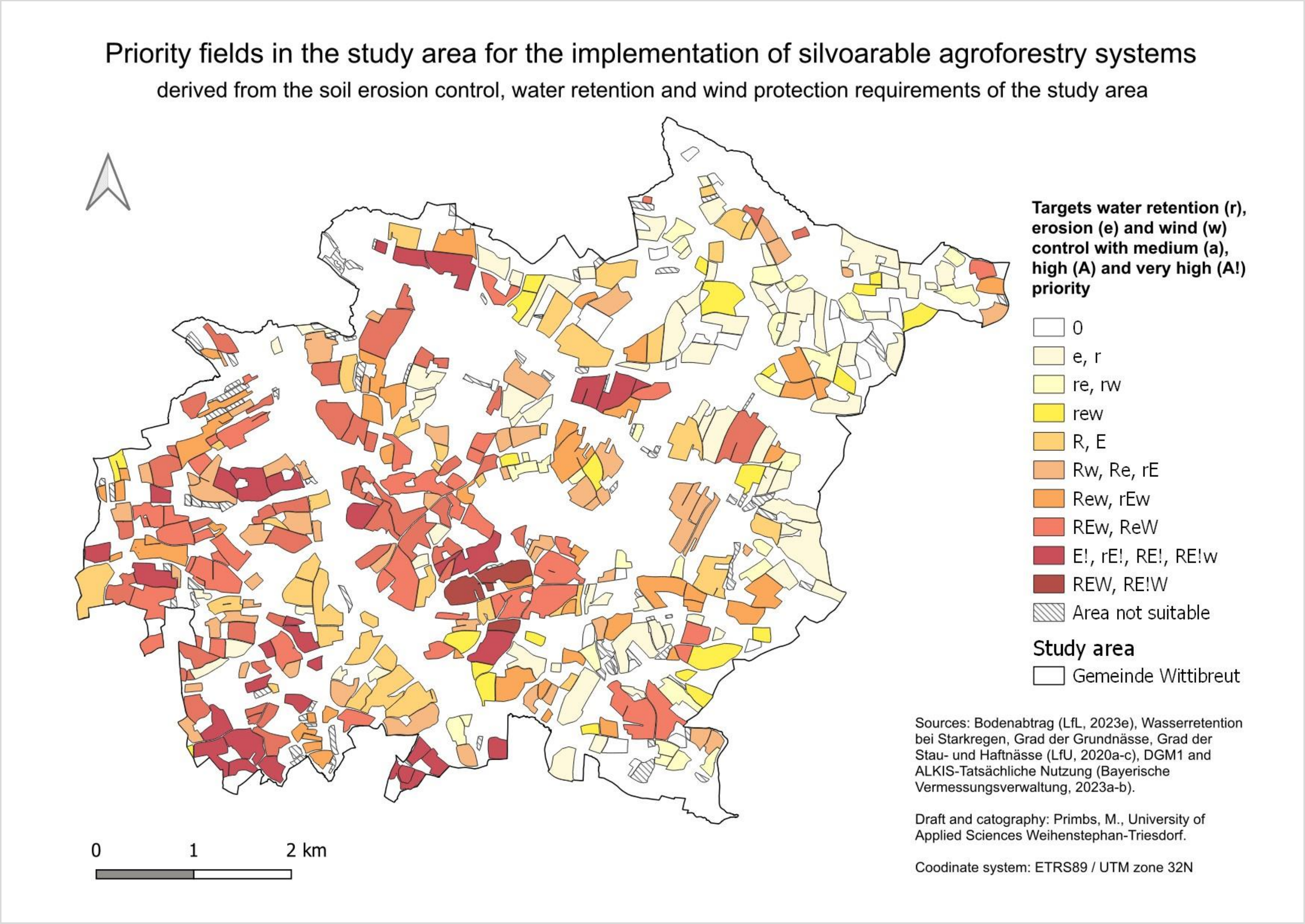


Classification of arable fields in the study area according to the priority for soil erosion control based on the potential soil erosion by water

Sources: Bodenabtrag (LfL, 2023e), DGM1 and ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023a-b).
Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure 22 Classification of arable fields in the study area accordint to the priority for soil erosion control based on the potential soil erosion by water on arable fields.



Priority fields in the study area for the implementation of silvoarable agroforestry systems

derived from the soil erosion control, water retention and wind protection requirements of the study area

Sources: Bodenabtrag (LfL, 2023e), Wasserretention bei Starkregen, Grad der Grundnässe, Grad der Stau- und Haftnässe (LfU, 2020a-c), DGM1 and ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023a-b).

Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure 23 Priority fields in the study area for the implementation of silvoarable agroforestry systems derived from the priority classes of the objectives soil erosion control, water retention and wind protection. The map visualises ten levels of priority combinations focusing on objectives with medium, high and very high priorities, assigned to arable fields.

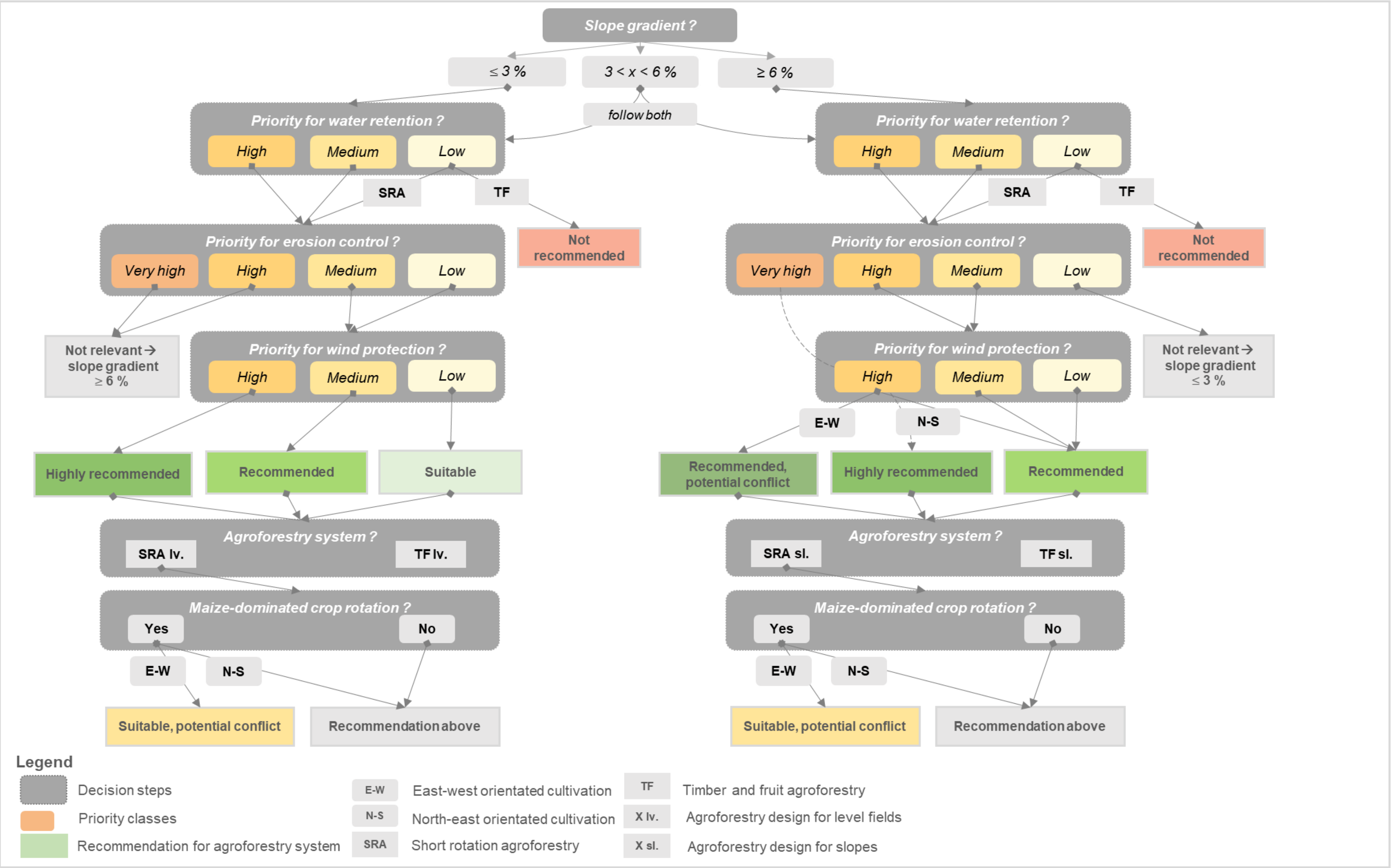
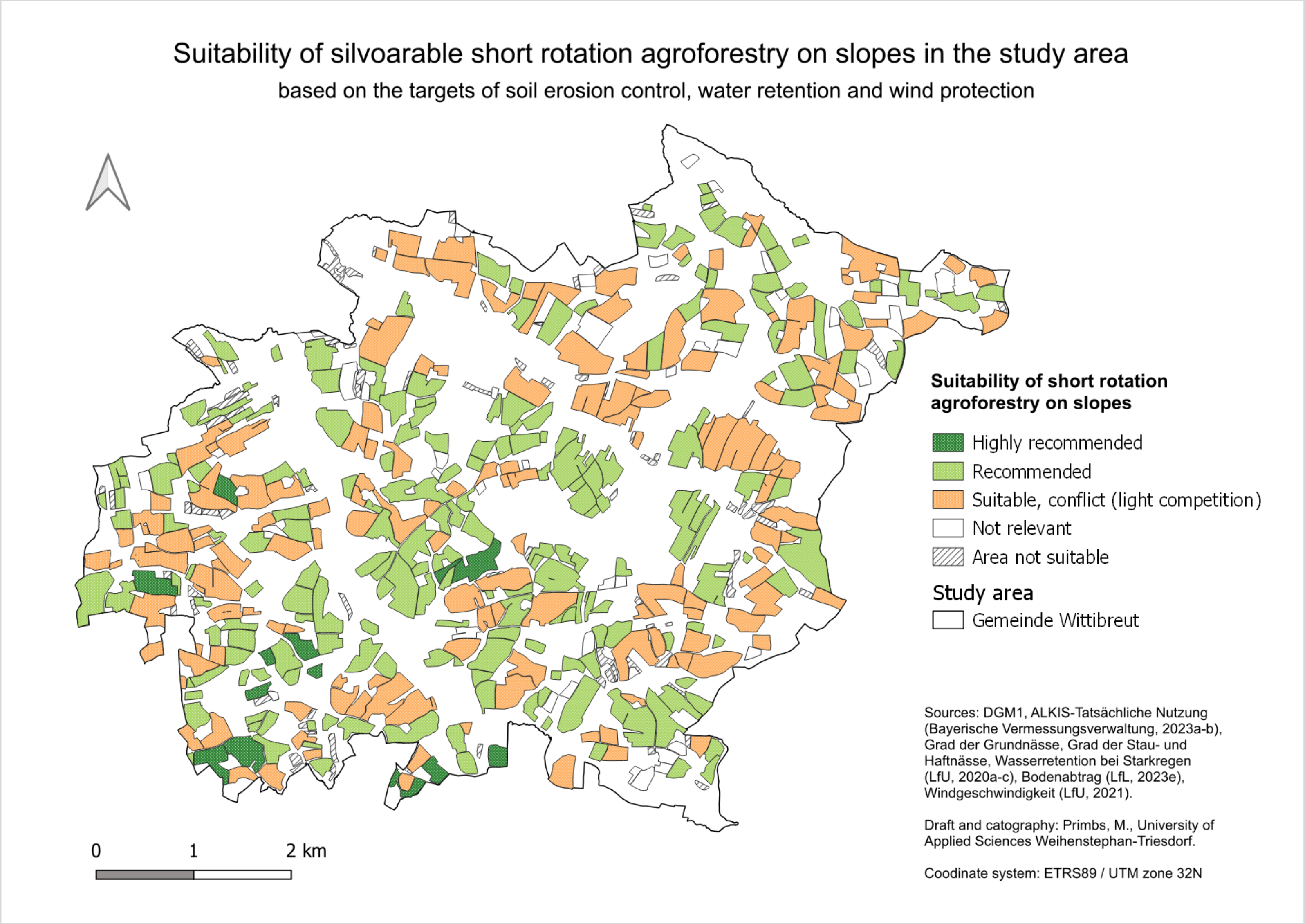


Figure 24 Decision tree for the allocation of agroforestry systems to arable fields based on the priority classes of the objectives water retention, soil erosion control, wind protection and crop rotation.



Suitability of silvoarable short rotation agroforestry on slopes in the study area

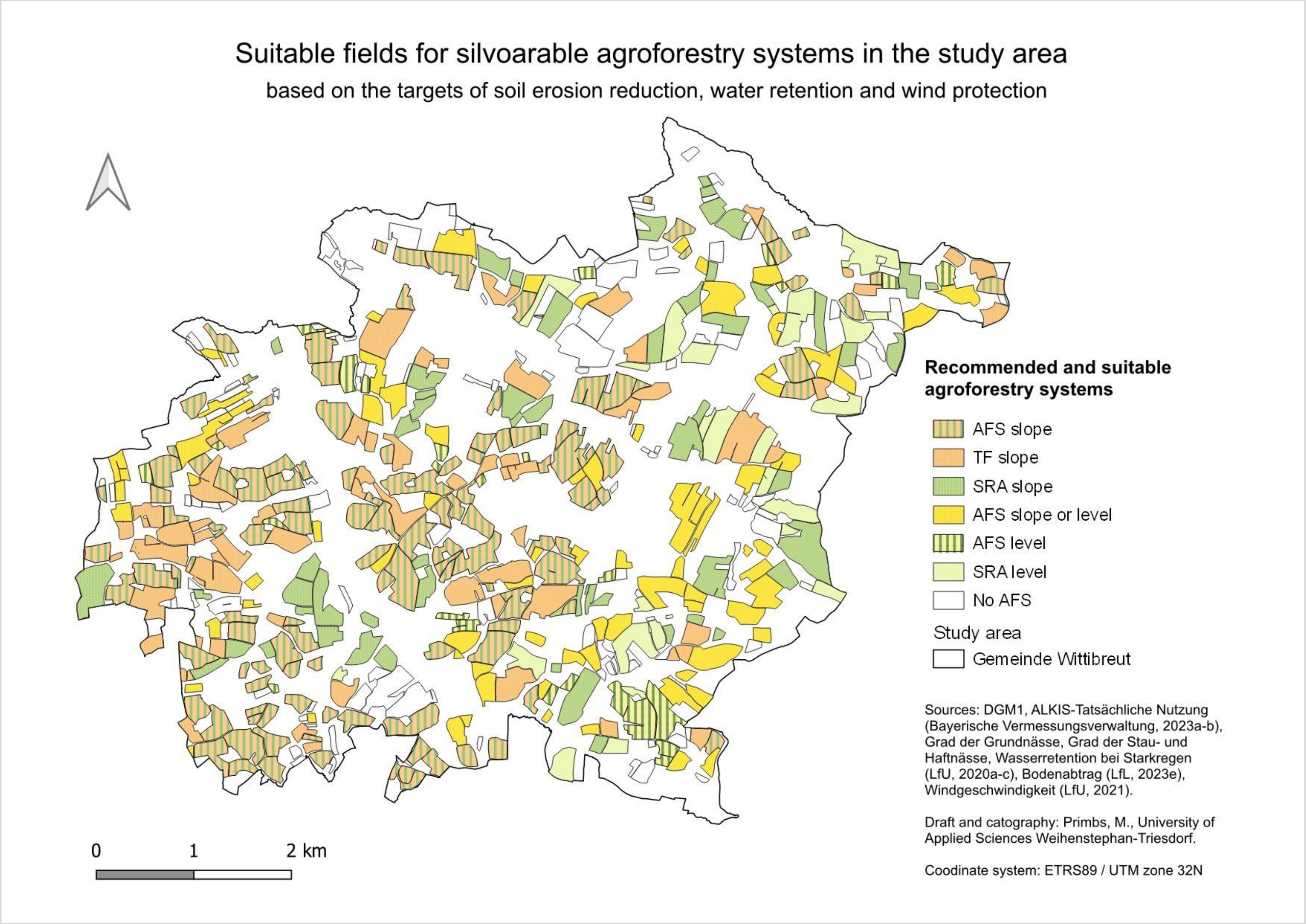
based on the targets of soil erosion control, water retention and wind protection

Sources: DGM1, ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023a-b), Grad der Grundnässe, Grad der Stau- und Haftnässe, Wasserretention bei Starkregen (LfU, 2020a-c), Bodenabtrag (LfL, 2023e), Windgeschwindigkeit (LfU, 2021).

Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure 25 Suitability of short rotation agroforestry systems on arable fields in the study area based on the targets of soil erosion control, water retention and wind protection.


Suitable fields for silvoarable agroforestry systems in the study area

based on the targets of soil erosion reduction, water retention and wind protection

Sources: DGM1, ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023a-b), Grad der Grundnässe, Grad der Stau- und Haftnässe, Wasserretention bei Starkregen (LfU, 2020a-c), Bodenabtrag (LfL, 2023e), Windgeschwindigkeit (LfU, 2021).

Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

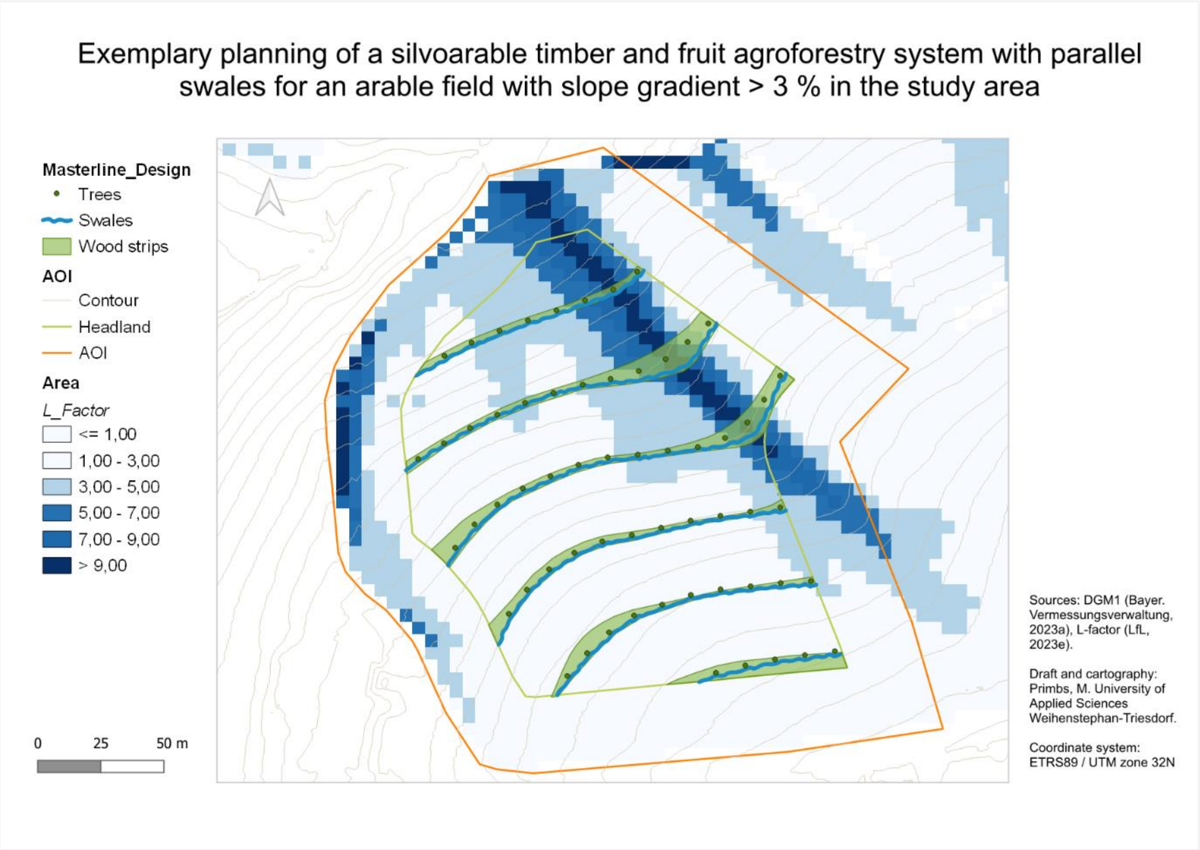
Figure 26 Suitable fields for silvoarable agroforestry systems in the study area based on the targets of soil erosion control, water retention and wind protection. Four agroforestry systems are recommended and suitable: timber and fruit systems on slopes (orange) and level fields (light yellow), short rotation systems on slopes (green) and level fields (light green), and selectable one of those (yellow and stripes).

4.4 Planning example for a silvoarable agroforestry system for soil erosion and water management on the field level

High-priority levels were allocated to the selected exemplary field for the planning process for the objectives of soil erosion control, water retention and wind protection (cf. Chapter 4.3.1). The arable field (4.4 ha) is located at 48°33' N, 13°00' E in the municipality of Wittibreut. The soil is characterised by sandy loam and a pH value of 5.9 (cf. Annex 4), and the prevailing soil type is pseudeovergleyed brown earth (cf. Annex 5.2). The field shows a risk for waterlogging, and the groundwater level is > 20 dm deep except at the northern field border close to a stream (cf. Annex 5.5.1). The field is accessible from two sides and directly adjacent to the farmyard (cf. Annex 7.1). It is exposed to the north (cf. Annex 5.3) and has an average slope gradient above 6 % (cf. Figure 12). The significant sink along the slope results in high L-factors and potential surface runoff (cf. Figure 27; Annex 7.2). The potential soil erosion at the majority of the selected field accounts for > 12 t ha^{-1} a^{-1}, whereby almost half of the area is threatened by potential soil erosion of > 20 t ha^{-1} a^{-1} (cf. Figure 14). The current crop rotation includes maize, wheat, triticale, rape and barley. The establishment of an agroforestry system agrees with the farm's long-term vision of research and seminar offers about agroforestry and the adaptation of farming methods towards climate adaptation. The agroforestry system is expected to support yield security of annual crops, species promotion, and the modification of the landscape water balance and landscape scenery. Public relations and research were also marked as important objectives by the landowner. Long-term capital investment, development of new branches, breaking of work peaks, biotope networking and carbon storage could further be considered in the planning. The desired agroforestry products and system components comprise valuable timber and bee pasture (high priority), logs, dessert and commercial fruits with long storage time, and possibly shrubs (medium priority) (cf. Annex 4).

The integration of timber and fruit trees agrees with the recommendation given in the regional scale approach for the selected field (cf. Chapter 4.3.2). According to the recommended system design, the planting distance of timber and fruit trees accounts for 10-15 m (≤ 50 trees ha^{-1}), depending on the final crown diameter (cf. Chapter 4.2.2.1). Suitable tree species are to be selected according to the intended use (e.g. species for high-valuable timber or varieties of *Malus domestica* with long storage time) and objectives (e.g. *Sorbus* species for biodiversity promotion) (cf. Chapter 4.2.1). In order to fulfil the conditions of eligibility for the CAP, the wood strips require a minimum width of 3 m. At least two predominantly stocked wood strips covering 2-35 % of the field need to be established in a way that ensures a distance between wood strips and towards field borders of ≥ 20 m and ≤ 100 m (cf. Chapter 2.2.3). The recommended distance for timber and fruit systems on slopes targeting soil erosion and water management accounts for 30 ± 12 m (cf. Chapter 4.2.1). The machines in operation on the selected field required a minimum distance between wood strips of 27 m (cf. Annex 4).

The crop alley spacing of 27 m and minimum wood strip width of 3 m enabled the implementation of six wood strips across the slope on the exemplary field. The desired headland of 30 m and an average planting distance of 12 m resulted in 60-64 timber and/or fruit trees on the field, equal to 14-15 trees ha^{-1}. In a linear design, the wood strips would cover 5.43 % of the field (2,350 m^2) (cf. Annex 7.4). In a masterline design, the area covered by wood strips accounted for 7.67 % of the field (3,317 m^2) due to adapted strip widths (cf. Figure 27; Annex 7.3). For both systems, the sowing of grass- or flowering mixtures is recommended in the wood strips. Practices like root and tree pruning, undergrowth management and tree protection are fundamental in the agroforestry system (cf. Chapter 4.2.1).



Sources: DGM1 (Bayer. Vermessungsverwaltung, 2023a), L-factor (LfL, 2023e).

Draft and cartography: Primbs, M. University of Applied Sciences Weihenstephan-Triesdorf.

Coordinate system: ETRS89 / UTM zone 32N

Figure 27 Example for a masterline agroforestry design with parallel swales on an arable field with a slope gradient > 3 % and high L-factors in the study area. The wood strips include 64 timber and fruit trees in 12 m planting distance, the crop alleys account for 27 m.

5 Discussion

5.1 Discussing the results

This study started by identifying objectives (soil erosion, water balance and microclimate) and the natural and socio-economic frameworks in the municipality of Wittibreut regarding the potential establishment of silvoarable agroforestry (cf. Chapter 4.1). Planning factors for temperate silvoarable agroforestry systems targeting the stated objectives, derived from the literature review, resulted in four basic design approaches (cf. Chapter 4.2). These systems were assigned to the fields of the study area, which would be suitable and recommended on 94 % of the arable land. In the municipality, 66 % of the arable land showed – potentially overlapping – high priorities for erosion control (52 %), water retention (30 %) and/or wind protection (4 %) (cf. Chapter 4.3). Exemplary planning for a silvoarable agroforestry system on one of the suitable and high-priority fields comprised six wood strips with timber and fruit trees across the slope and in the masterline design (cf. Chapter 4.4).

Regarding the stated objectives in the study area – as defined in the first research question, the implementation of adaptation measures seems highly recommendable in the face of climate change, including future increases in the frequency and intensity of heavy rainfall events and hot and dry spells (cf. Chapter 2.1; 4.1.2). Whereas this study focused on implementing agroforestry strips as an adaptation measure, arable cultivation should also be considered as part of a holistic agroforestry system. The adaptation of crop rotations, crop types, management systems, and soil cultivation should be mentioned here. Mulch sowing, for example, reduced the surface runoff at maize fields in Lower Bavaria by 44 % and 13 % at daily precipitations of 20 mm and 80 mm, respectively (LfL, 2017). Frank et al. (2014) found that the combined implementation of wood strips, cover crops, and no-till cultivation reduced water erosion by 92 % most efficiently.

The first research question also identified possible barriers to implementing agroforestry systems in the municipality. Economic viability, legal security and consultation were seen as fundamental to removing barriers to its implementation (cf. Chapter 4.1). Material and labour costs are high, especially for implementation and the establishment phase (Morhart et al., 2015; DeFAF, 2023b). Depending on the system, the profit phase only starts after 5-10 years (fruit and SRA) or 60 years (timber) (cf. Chapter 2.2.1). Although high average prices of 400 € per solid meter can currently be expected for value timber (AELF Traunstein, 2023), the future revenues at harvest are uncertain. Whereas the planting can be funded as a KULAP investment measure, funding in Eco-Scheme 3 for the maintenance of agroforestry systems can only cover the high costs in the establishment phase to a limited extent. In 2023, only 60 € (from 2024, 200 €) per hectare of wooded area per year was available (cf. Chapter 2.2.3).

Additionally, several regulations must be complied with, some of which have been criticised as too limiting for agricultural practice (DeFAF, 2023b). Consequently, in 2023, the actual funded area of 51 ha by Eco-Scheme 3 in Germany was by far falling short of the German government´s target of 200,000 ha of agroforestry until 2027 (DeFAF, 2023b). Advisory services can indeed be regarded as fundamental for the widespread implementation of agroforestry, as they inform about the legal and federal regulations and provide the required specific knowledge and experience for site-specific planning, establishment and management. Consultations, information events and establishing demonstration areas can be helpful here.

In the context of the second research question, field-scale studies reported reduced surface runoff, wind speed and soil erosion, water retention and modification of microclimate variables, compared to arable cultivation (cf. Chapter 4.2). These results justify the recommendation of agroforestry systems as a climate adaptation measure on arable fields. For soil moisture, air temperature, relative humidity, and evapotranspiration, variations among studies were found with temporal and spatial differences within agroforestry systems (cf. Chapter 4.2). The findings confirm the assumption of Jacobs et al. (2022) that microclimatic and water balance effects vary between short rotation and fruit and timber agroforestry systems and depend on design factors. Agroforestry systems targeting soil erosion reduction and water retention on fields with slope gradients > 3 % were characterised by smaller crop alleys and wood strips covered with vegetation. In contrast, the orientation, height and porosity of the wood strips were crucial for agroforestry systems targeting wind (erosion) protection and microclimate enhancement on the field (cf. Chapter 4.2). In contrast to this subdivision, in practice, combined systems with fast-growing, fruit and/or timber trees and shrubs can also occur, as well as agrisilvopastoral systems, where animal husbandry further influences the system. In addition, agroforestry systems planted on slopes to reduce erosion and retain water can also contribute to wind protection and modify the microclimate. Therefore, agroforestry planning practice should consider all objectives, as well as further effects associated with agroforestry, for example, biodiversity, nutrient dynamics, landscape scenery, and socio-economic aspects. Further, the role of further site-specific factors like topography, landscape diversity and climate remains to be investigated (Jacobs et al., 2022). The studies were conducted in young and mature agroforestry systems, but no statement can be made as to when (year after planting) the observed effects begin and to which extent.

For the transfer into agricultural practice, the impacts of annual crops and arable cultivation are of particular interest. On the one hand, yield reduction in the area close to the wood strips was reported depending on the crop type, site and weather, eventually compensated by improved growing conditions in the crop alleys (cf. Chapter 4.2). On the other hand, reduced soil erosion holds fertile topsoil on the field, which is vital for yield amount and quality. In addition, soil fertility is improved by the input of organic material and nutrients and the creation of coarse and medium pores (cf. Chapter 4.2.2). Increased relative humidity in night and morning hours below the tree canopy (cf. Chapter 4.2) and enhanced long-wave radiation downward from the trees could also buffer late frosts to a certain extent (Synder & Melo-Abreu, 2005). However, higher relative humidity close to the wood strips might increase the grain moisture content at the harvest date, complicating harvesting by requiring additional drying time. Fieldwork could further be hampered if wood strips of different orientations are integrated on one field, optimising the windbreak effect, or if the machine width does not comply with the crop alley design. Low-set tree crowns might grow into the crop alley, hampering fieldwork close to the wood strips. The necessary management of wood strips could tie up the working time needed for the cultivation of annual crops. However, the management of the wood strips is necessary to ensure well-established trees generating and maintaining desired targets. For the implementation, if possible, the design of the agroforestry should comply with the federal law of the CAP (cf. Chapter 2.2.2). In many points, the design drafts derived from literature findings agree with the given regulations. Some planning factors need to be adapted, though. A comparative overview of design factors and regulations is provided in Annex 8. For the final planning process of agroforestry systems on slopes, the slope length can be further considered for the suitable crop alley spacing, as it determines the slope-shortening effect of wood strips and, thereby, the surface runoff reduction (Seibert & Auerswald, 2020).

The findings in the scope of the third research question may support the stakeholders in evaluating potential agroforestry areas in the municipality. Based on the potential area and expected effects at the field scale (findings of the second research question), initial assessments can be made of the extent to which the implementation of such systems can contribute to achieving stated objectives and thus mitigating potential challenges in the municipality. The potential agroforestry areas can be used as a starting point for further investigations, integrating, for example, the effects on flood protection or water quality at the regional level. The derived results for regional and local planning approaches of this study can also provide assistance for the consulting process at the field level. In this context, an information event organised by the AELF in the municipality of Wittibreut in October 2023 also proved fruitful. Around 40 participants, including many farmers, were introduced to agroforestry and had a lively discussion about the presentation of the results of this study and possible implementation options on their land (PNP, 2023). This underlines the importance of consultation, to which this thesis, with its readily applicable, scientifically founded framework, can contribute.

Within the fourth research question, the first comparative planning of a linear and masterline design provides assistance for the landowner's decision in favour of one system. It enabled comparing the wood strip width and area share of the field (cf. Chapter 4.4), and economic calculations could provide further comparison. The results give an overview of the number of trees, plant spacing and arrangement of wood strips in the field and allow an initial estimate of the extent to which surface runoff and soil erosion could be reduced by the implementation. However, to ensure long-term effectiveness, the final design should be adapted to the potential amount of surface runoff and sediment deposition. In this regard, the planning drafts provide a basis for a detailed planning process, including the selection and allocation of tree species, economic calculations, preparation of the planting, and detailed management recommendations.

5.2 Discussing the methodology

This study comprised several methods; expert interviews were used for the first research question to identify objectives and frameworks in the study area. A literature review on agroforestry studies, supplemented by practical guidelines, provided findings for the second research question. The third question referred to the regional approach and included the application of filter steps, decision trees, classification of map data, and allocation of priority classes and agroforestry systems to fields in the study area in QGIS. An exemplary planning process on the field scale was conducted within the fourth research question (cf. Chapter 3).

The method applied for the first research question proved to be helpful in identifying relevant objectives for the study area, as the expert interviews supplemented the literature findings. The interviews also proved helpful in identifying possible barriers to implementing agroforestry systems in the municipality. Additional interviews with farmers could have widened the insight into farming methods and experience with already established adaptation measures.

The literature research provided reliable and detailed information for planning factors of silvoarable agroforestry systems for erosion and water management. Integrating practical planning guidelines complemented the information derived from relevant studies. The gained insights into planning approaches were subsequently reflected in the method of the third research question. Information on site and species selection was integrated into the recommendation of suitable agroforestry systems. The limitation for timber and fruit systems growing at predominantly wet sites and the shadow impact of SRA on annual crops was derived from here. The subdivision of agroforestry designs based on the reported effects, site condition (slope gradient), and purpose of the system (short rotation, fruit and timber) was adopted for the methodology of the third research question. The findings were consequently used for the allocation of agroforestry systems to the fields based on the allocated priority classes of the objectives. As the selection of the studies within the second research question was already based on the natural and climatic conditions in Wittibreut, the tendencies of measured effects could be transferred to the study area. However, deviations could occur due to the diversity and complexity of the systems and site characteristics. For some effects, the state of research was insufficient to provide conclusive trends, e.g. only one study on wind protection in timber and fruit systems was available (cf. Chapter 3.2), and results on soil moisture varied between several studies (cf. Chapter 4.2). Further, the methodological approach of the studies was not assessed and could already contain limitations for transferability. Furthermore, measured effects could change in future due to changing climatic conditions (cf. Chapter 2.1).

The planning recommendations derived from the second research question supported the general approach of initially classifying the fields according to their site conditions (simplified by the objectives) as a starting point for the planning with agroforestry on the regional level. The design drafts were also used as a starting point for exemplary planning at the field level. By taking up the defined objectives of the first research question and integrating the results into the third and fourth research questions, the literature research thus played a central role as a connecting component in the master thesis.

The applied method for the third research question can be recognised as a suitable method in the scope of this thesis, as it has produced reliable results for the study area, as argued below. It also proved to be a relatively simple method that did not require the handling of large data sets. However, the applied method comes with several limitations, as discussed in the following lines.

First, it includes a relatively high capacity for generalisation as it used average values for field blocks and four averaged agroforestry systems. This, however, limits its direct transferability into practical planning processes. The results can thus be used as an initial decision-making aid. Decisions favouring one system can be made by including further farm-specific planning factors such as socio-economic aspects. The final planning process would be site- and farm-specific, considering all relevant planning factors, including additional site-specific factors, preferred management methods, available infrastructure and marketing, etc. (cf. Chapter 2.2.2). Further limitations suggest detaching the given recommendations from the final planning process. If the applied site-specific factors change or differ from the used data basis, the given recommendation for agroforestry systems eventually needs to be adapted. If, for example, the slope gradient changes within the field, the system must be adjusted so that the direction of cultivation does not favour erosion.

Second, the applied data comes with limitations. Whereas the applied ALKIS data with field blocks enhanced the generalisation, using InVeKoS data with a more precise plot level would have allowed a more differentiated allocation of priority classes. Some uncertainties are also seen in the applied method for allocating priority classes. The method was chosen as the classification of fields according to the precedence of defined objectives simplified the subsequent allocation of agroforestry systems tailored to the respective objectives. The associated generalisation of field values simplified the process but led to the above-discussed limitations. Further limitations are seen here in the used data basis for the respective objectives. Whereas the prioritisation for water retention comprised three data sets, only one was used for soil erosion. The data for potential soil erosion on arable land included cultivation aspects, namely the cover management factor (C-factor). Therefore, a change in crop rotation, such as fewer maize crops, would reduce the C-factor and the potential soil erosion (LfL, 2017). This would, in turn, change the classification of the priority fields. For wind protection, the proximity to sheltering woody structures was used as a factor to determine the priority classes. However, the wind sheltering effect differs with the height, orientation and porosity of the obstacle (Schäfer et al., 2010; cf. Chapter 4.2.3). Therefore, the planning process on a field scale might include the objectives even if deviations from the priority classes are observed. For more reliable statements, the classification of priority classes could be covered with additional datasets. However, the generalisation of field blocks may still lead to biases, e.g. fields with allocated average low erosion risk might show high surface runoff and soil erosion in parts of the field at heavy rainfall events. Here, the implementation of wood strips would be highly recommended even though the field was only allocated as suitable for agroforestry without specific recommendation. In conclusion, it can be noted that the results can only be used for an initial assessment of potential agroforestry areas.

Third, some aspects of the recommendation of agroforestry systems need to be differentiated. Although timber systems were not recommended on predominantly wet sites, Pedunculate oak tolerates waterlogging for up to one month and could be added on heterogeneous fields with partly wet areas (LfL, 2023c). Maize-dominated crop rotations were considered potentially unsuitable for SRA, whereas timber and fruit systems were not considered here due to lower planting densities and tree crown pruning. However, at denser planting distances and if the pruning is neglected or reduced, shading could also apply to a greater extent in timber and fruit systems (cf. Chapter 4.2). In SRA, the negative shading effect can be influenced by the orientation, height and porosity of the wood strip (Iwasaki et al., 2021). An economic evaluation with regard to the design and expected yield effects could complement the planning process of the agroforestry system, although this could entail a high degree of uncertainty.

Fourth and finally, the applied planning approach for regional levels could also be transferred beyond the current scale and location. The application of filter steps and priority classes for objectives, allowing a first recommendation of suitable agroforestry systems, could be a decision-support tool for evaluating potential agroforestry areas. For a transfer to other regions and/or relevant objectives, the data basis can be exchanged by relevant local data sources. Automating the steps applied in QGIS would enable the transfer to regional scales to a greater extent. The transfer of the method could be accompanied by the inclusion of further target groups to identify and prioritise relevant objectives. In the following cases, the presented method should be preferred over the existing software META-AfS for multi-criteria planning on the regional scale. If here not included specific objectives are to be assessed for the study area; if several potential agroforestry systems are to be included in the planning; if there is no training time available for a new program in comparison to QGIS as a familiar program.

Within the fourth research question, the exemplary planning of one high-priority field considered several of the discussed aspects necessary for the transfer into practice, e.g. the specific site characteristics, regulations of the federal law and additional objectives like biodiversity and socio-economic aspects. The initial interview with the landowner proved to be vital for the planning process as it provided the objectives and framework conditions for the field. The applied method can be transferred to other planning processes on the field scale and needs to be followed up with a detailed planning process.

6 Conclusion

This study was characterized by the own development of planning approaches for agroforestry systems, in particular the application of filter criteria and QGIS planning at the regional level. The regional scale approach can provide a simplified method for municipalities and regions to get an overview of the suitability of fields for agroforestry regarding set objectives, thereby facilitating the establishment of such systems and enhancing climate change resilience of arable agriculture. The planning approaches merge scientific and practical planning factors for aided decision-making for agroforestry planning that is inspired by practitioners’ needs but founded in science, therby building a bridge between theory and practice. This study illustrated recommended agroforestry designs for soil erosion and water management on arable fields. Future research should extend the scientific basis for field-scale effects depending on system designs and site specifics, as well as for landscape-scale effects, and investigate the automation of simplified planning approaches on the regional scale.

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8 Annex

Annex 1 Guideline and timeframe of the expert interviews

Interview guideline questions:

1) *Which objectives are (most) important in arable agriculture in the municipality of Wittibreut within water and soil aspects and with regard to climate change?*
2) *(How) have site and framework conditions already change with climate change, especially for agricultural production on arable land?*
3) *(How) has the management of arable land (e.g. maize cultivation) changed after the 2016 floods?*
4) *Which measures are already being implemented on arable fields facing these challenges?*
5) *(Where) do you see implementation options for agroforestry in the municipality?*
6) *Which barriers do you see for agroforestry implementation in the municipality? Are there conflicts of interest with widespread arable farming methods?*

Table Annex 1 Experts and timeframe of expert interviews in the study area

Expert	Institution	Timeframe
Maximilian Gerl	AELF Pfarrkirchen-Landau	30 min
Ruth Brummer		90 min
Maximilian Frank	ALE Niederbayern	60 min
Fabian Pex		
Christian Fuchsgruber	BBV Niederbayern	30 min
Marijana Schmidt	WWA Deggendorf	30 min

Annex 2 Tables with literature findings of agroforestry studies

Table Annex 2.1 Generic literature findings on the design and effects of agroforestry systems on the water balance and microclimate, measured decreases in blue, increases in yellow, both tendencies in green

Study	Location	Type	Surface runoff	Soil moist.	ET	Light intensity	Wind speed	Air temp. day	Air temp. night	Soil temp.	Relative humidity
Brandle et al. 2004, Brandle et al. 2009	USA	Generic				🟦	🟦			🟦	🟨
Jose et al. 2004	USA	Generic			🟦	🟦	🟦	🟦			
Kay et al. 2018	Switzerland, UK	Generic	🟦	🟦							
Kort 1988	Worldwide	Generic					🟦	🟨			
Nuberg 1998	Worldwide	Generic		🟨	🟦	🟦	🟦	🟨	🟦		🟨
Quinckenstein et al. 2009	Worldwide	Silvoarable	🟦	🟩			🟦	🟩			
Smith et al. 2012	USA	Generic	🟦	🟩		🟦	🟦	🟦	🟨		
Weninger et al. 2021	Worldwide	Generic			🟦		🟦			🟩	
Zhu et al. 2020	Worldwide (Europe and North America)	Silvoarable	🟦								

Table Annex 2.2 Literature findings on the design and effects of timber and fruit agroforestry systems on the water balance and microclimate, measured decreases in blue, increases in yellow, both tendencies in green, non-significant changes in dark grey – Part 1

Study	Location	Type	Coordinates	Soil	MAP [mm]	MAT [°C]	Orientation	Crop alley [m]	PD [m]	WSW [m]	TD [trees ha^{-1}]	TH [m]	Veg.	Tree species	Surface runoff	Soil moist.	ET	Light intensity	Wind speed	Air temp. day	Air temp. night	Soil temp.	Relative humidity
Akdemir et al. 2016	USA	FT mature	40°01'N, 92°11'W	Putnam silt loam, Kilwinning silt loam	920	11,7	across the slope	22.8, 36.5	3	4.5	–	–	grass-legume	Pin oak (Quercus palustris Muenchh), swamp white oak (Quercus bicolar Willd.), bur oak (Quercus macrocarpa Michx.)		🟨							
Anderson et al. 2009	USA	FT mature	40°01'N, 92°11'W	Putnam silt loam, Kilwinning silt loam	920	11,7	across the slope	22.8, 36.5	3	4.5	–	–	grass-legume	Pin oak (Quercus palustris Muenchh), swamp white oak (Quercus bicolar Willd.), bur oak (Quercus macrocarpa Michx.)		🟦	🟨						
Blanchet et al. 2021	France	FT mature	43°42'N, 3°51'E	Alluvial fluvisol	853	14,1	E-W	13	8		192 thinned to 81	10,9		Hybrid walnuts (Juglans regia x nigra, cv. NG23)		🟩		🟦					
Carrier et al. 2019	Canada	FT < 5 years	45°17'-27°37'N, 69°44'-74°26'W	Humic Gleysol, Humo-Ferric Podzol, Melanic Brunisol	924–1,077	3.4–6.0	NW-SE, N-S	25, 30, 38, 39	5, 6	1.5	51–67	3.5–7.7		Red oak, bur oak, hybrid poplar (Populus deltoides W. Bartram ex Marshall x P. nigra L. (DN), DN x P. maximowiczii A. Henry)		🟨		🟦					
Carrier et al. 2019	Canada	FT mature	45°22'N, 73°02'W	Humic Gleysol	1,103	6,5	NW-SE	90	4	1.5	28	12,7		American ash (Fraxinus americana L.), red oak (Quercus rubra L.), bur oak (Quercus macrocarpa Michx.)		🟨							
Caubel et al. 2003	France	FT mature	–	Luvisol, Reductisol	710	–	NW-SE	Single tree row	2	–	–	–		Quercus robur		🟦							
Chirko et al. 1996	China	FT mature	35°N, 113°E	Silt loam to silty clay loam	–	–	N-S	60, 70	5	–	–	12,8		Paulownia		⬛		🟦		⬛			
Coussement et al. 2018	Belgium	FT mature	50°52'N, 2°48'E	Luvisol	–	–	NW-SE	Along field	5	–	–	19		Populus spp.		🟦	🟦						
Dufour et al. 2013	France	FT mature	43°42'N, 3°51'E	Alluvial fluvisol	951	14.5–15	E-W	13	8	–	200 thinned to 100	7.2–7.8		Hybrid walnuts (Juglans regia x nigra, cv. NG23)				🟦					
Dufour et al. 2020	France	FT mature	43°42'N, 3°51'E	Alluvial fluvisol	762	15	E-W	13	8	–	200 thinned to 100	10,7		Hybrid walnuts (Juglans regia x nigra, cv. NG23)				🟦					
Everson et al. 2009	South Africa	FT < 5 years	–	–	743	–	N-S	5.25	0.5–1	–	–	–		Acacia karroo, Leucaena leucocephala, Morus alba, Gleditsia triacanthos		🟩							
Fahrendorf 2022	Germany	FT < 5 years	51°29' N, 9°58' E	loam to sandy loam	–	–	across slope 9-12 %	30	15	3	13				🟦								

Table Annex 2.2 Literature findings on the design and effects of timber and fruit agroforestry systems on the water balance and microclimate, measured decreases in blue, increases in yellow, both tendencies in green, non-significant changes in dark grey – Part 2

Study	Location	Type	Coordinates	Soil	MAP [mm]	MAT [°C]	Orientation	Crop alley [m]	PD [m]	WSW [m]	TD [trees ha^{-1}]	TH [m]	Veg.	Tree species	Surface runoff	Soil moist.	ET	Light intensity	Wind speed	Air temp. day	Air temp. night	Soil temp.	Relative humidity
Gillespie et al. 2000	USA	FT mature	39°03'N, 85°30'W	Ultic Hapludalf	2,120	10,8	N-S	8,5	2,4	–	–	7,42		Black walnut trees (Juglans nigra L.), red oak (Quercus rubra L.)				🟦					
Inurreta-Aguirre et al. 2018	France	FT mature	43°42'N, 3°51'E	Calcareous silty clay	–	–	NW-SE, N-S	13	6	–	–	15–30		Poplar (Populus canadensis CV I214), ash (Fraxinums angustifolia Vahl)				🟦		🟦	🟨		
Jose et al. 2000	USA	FT mature	39°03'N, 85°30'W	Ultic Hapludalf	–	–	N-S	8,5	2,4	–	–	8.2–8.4		Black walnut trees (Juglans nigra L.), red oak (Quercus rubra L.)		🟦	🟨						
Martin-Chave et al. 2019	France	FT mature	44°03'N, 4°08'E	Sandy loam	740	–	N-S	10	10	1	–	17		Hybrid walnut trees (Juglans nigra L. x Juglans regia L.)						🟦	🟨		
Peng et al. 2009	China	FT < 5 years	34°19'N, 107°38'E	Sandy loam	679	11.6	N-S	5	3	–	–	2.9–3.4		Walnut (Juglans regia L.), plum (Prunus salicina)		⬛		🟦					
Ramananjatovo et al. 2021	France	FT mature	47°28'N, 0°36'W	Luvisol Redoxisol	690	11,5	N-S	12	1,6			2,5		Malus x domestica Borkh, var. “Elstar”, “Gala”, “Fuji”, “Granny Smith”, “Red winter”, “Golden Delicious”, “Reine des Reinettes”		🟩		🟦		🟦			🟨
Reynolds et al. 2007	Canada	FT mature	43°32'N, 80°12'W	Alfisol, Typic Hapludalf	833	–	N-S	12.5–15	3–6			7.6–12.1		Acer, Populus		🟩		🟦					
Sahin et al. 2016	USA	FT mature	40°01'N, 92°11'W	Putnam silt loam, Kilwinning silt loam	–	–	across slope	22.8, 36.5	3	4.5	–	–		Pin oak (Quercus palustris Muenchh), swamp white oak (Quercus bicolar Willd.), bur oak (Quercus macrocarpa Michx.)		🟩							
Seobi et al. 2005	USA	FT mature	40°01'N, 92°11'W	Putnam silt loam, Kilwinning silt loam	–	–	across slope	22.8, 36.5	3	4.5	–	–		Pin oak (Quercus palustris Muenchh), swamp white oak (Quercus bicolar Willd.), bur oak (Quercus macrocarpa Michx.)		🟨							
Spiecker, 2010; Nehrlich et al. 2013	Germany	FT < 5 years	48°94'N, 8°50'E	Clayey loam	720	–	N-S, across slope 7 %	15, 30	15	2	26	–	flowering mixture	Sycamore (*Acer pseudoplatanus*), wild cherry (*Prunus avium*), hybrid walnut trees (*Juglans* spp.), poplar (*Populus deltoides* x *nigra*)	🟦								
Udawatta et al. 2002	USA	FT mature	40°01' N, 92°11' W	Putnam silt loam, Kilwinning silt loam; clay in B	920	11.7	on contour (2-5/9 % slope)	22.8, 36.5	3	4.5	80	–	grass-legume	Pin oak (*Quercus palustris* Muenchh), swamp white oak (*Quercus bicolar* Willd.), bur oak (*Quercus macrocarpa* Michx.)	🟦								

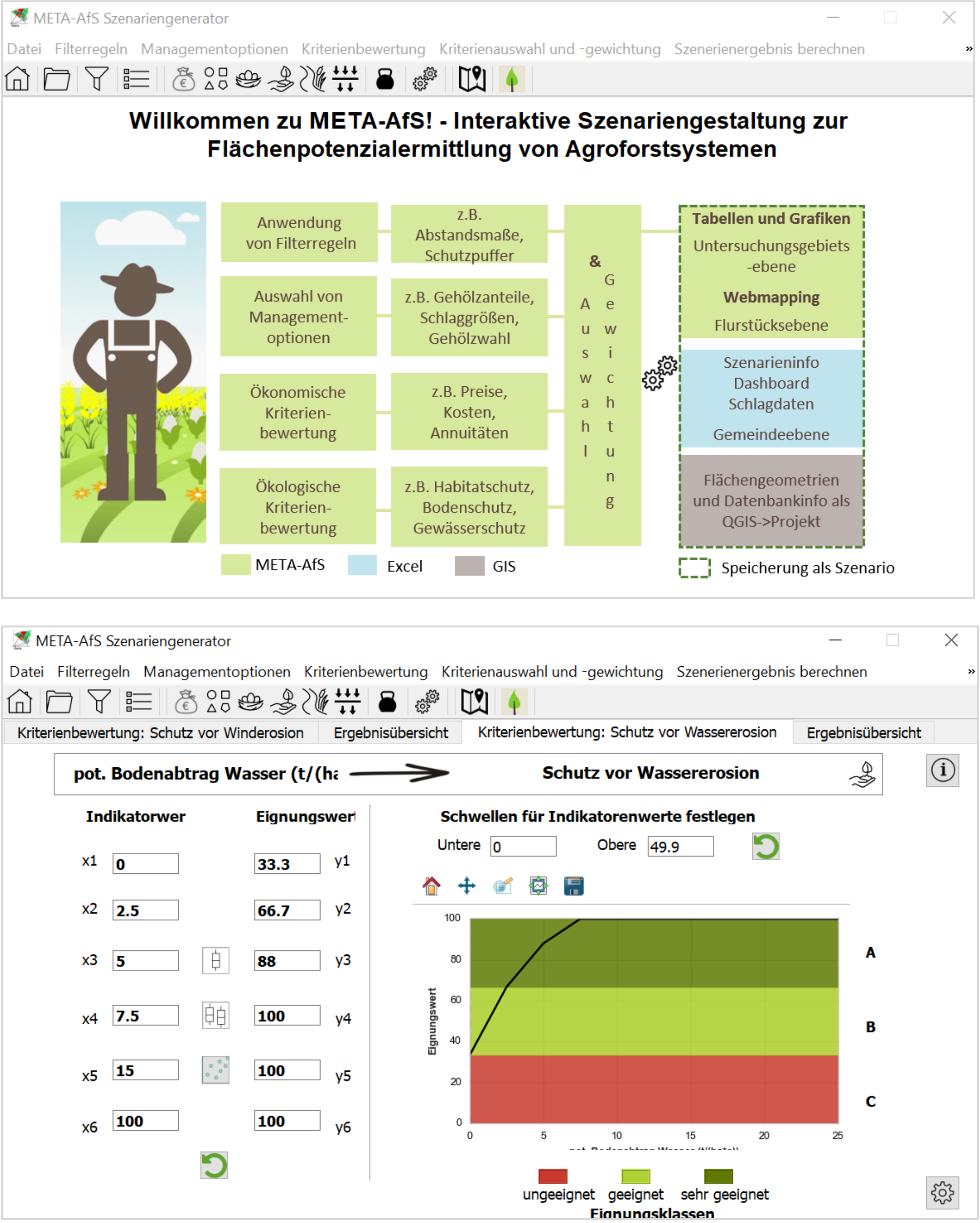
Table Annex 2.3 Literature findings on the design and effects of short rotation agroforestry systems on the water balance and microclimate, measured decreases in blue, increases in yellow, both tendencies in green – Part 1

Study	**Location**	**Type**	**Coordinates**	**Soil**	**MAP [mm]**	**MAT [°C]**	**Orientation**	**Crop alley [m]**	**PD [m]**	**WSW [m]**	**TD [trees ha^{-1}]**	**TH [m]**	**Veg.**	**Tree species**	**Surface runoff**	**Soil moist.**	**ET**	**Light intensity**	**Wind speed**	**Air temp. day**	**Air temp. night**	**Soil temp.**	**Relative humidity**
Beule et al. 2020	Germany	SRA	51°00'-52°20'N, 10°37'-14°38'E	Calcaric Phaeozem, Gleyic Cambisol, Certic Cambisol	568–637	9.6–9.9	N-S	48	–	12	–	–	herbaceous layer	Poplar clone Max1 (Populus nigra x P. maximowiczii)		🟨							
Böhm et al. 2014	Germany	SRA	51°37'-51°47'N, 14°19'-14°38'E	Sandy loam (Regosol, Gleyic Fluvisol)	560	9,3	N-S	24, 48, 96	0.75–1.8	10	8,715–9,227	0.74–4.51		Black locust (Robinia pseudoacacia), poplar clone Max (Populus maximowiczii x Populus nigra)					🟦				
Böhm et al. 2020		SRA	51°47'N, 14°37'E	Sandy loam (Gleyic Fluvisol)	568	9,6	N-S	24, 48, 96	0.8–1.8	10	8,715	7		Black locust (Robinia pseudoacacia L.), poplar clone 'Max' (Populus nigra L. x P. maximowiczii Henry)					🟦				
Duchemin et al. 2009	Canada	SRA	46°36'32 N, 71°10'34 W	Silty loam			across the slope (3 %)	_	1,25-1,5	5	3,200	1.36	grass	Populus trichocarpa x Populus deltoides cultivar 'Boelare'	🟦								
Dunn et al. 2022	UK	SRA	50°46'N, 3°55'W	Clayey loam	1032	10,1	across the slope (14 %)		0,75-1,5	10	20,000		none	Willow	🟦								
Dunn et al. 2022	UK	SRA	50°46'N, 3°55'W	Clayey loam	1032	10,1	across the slope (14 %)	0.85	1.75	10	3,000		none	Hornbeam (Carpinus betulus L.), sweet chestnut (Castanea sativa Mill.), hazel (Corylus avellana L.), pedunculate oak (Quercus robur L.), small-leaved lime (Tilia cordata Mill.) and wych elm	🟦								
Ehret et al. 2018	Germany	SRA	51°39'N, 9°98'E	Stagnosol	642	9,2	NW-SE	9	0.75–1.5	7.5	12,000	0.82–3.97		Willow clone 'Tordis' (Salix schwerinii x S. viminalis x S. vim.)		🟩		🟦				🟦	
Everson et al. 2009	South Africa	SRA	–	–	743	–	N-S	5.25	0.5–1	–	–	–		Acacia karroo, Leucaena leucocephala, Morus alba, Gleditsia triacanthos		🟩							
Foereid et al. 2002	Denmark	SRA	55°40'N, 12°18'E	–	–	–	–	Along field	–	10	–	5		Willow				🟦	🟦	🟨			🟨
Kanzler et al. 2014	Germany	SRA						48				3.5-4		Poplar			🟦						
Kanzler et al. 2015	Germany	SRA	51°37'-51°47'N, 14°19'-14°38'E	Sandy loam (Regosol, Gleyic Fluvisol)	560	9,3	N-S	24, 48, 96	0.75–1.8	10	8,715–9,227	3.5-4		Black locust (Robinia pseudoacacia), poplar clone Max (Populus maximowiczii x Populus nigra)			🟦		🟦				🟨
Kanzler et al. 2019	Germany	SRA	51°47'N, 14°37'E	Sandy loam (Gleyic Fluvisol)	568	9,6	N-S	24, 48, 96	0.8–1.8	10	8,715	3–5		Black locust (Robinia pseudoacacia L.), poplar clone 'Max' (Populus nigra L. x P. maximowiczii Henry)			🟦		🟦	🟦	🟨		🟩

Table Annex 2.3 Literature findings on the design and effects of short rotation agroforestry systems on the water balance and microclimate, measured decreases in blue, increases in yellow, both tendencies in green – Part 2

Study	Location	Type	Coordinates	Soil	MAP [mm]	MAT [°C]	Orientation	Crop alley [m]	PD [m]	WSW [m]	TD [trees ha^{-1}]	TH [m]	Veg.	Tree species	Surface runoff	Soil moist.	ET	Light intensity	Wind speed	Air temp. day	Air temp. night	Soil temp.	Relative humidity
Markwitz et al. 2020	Germany	SRA	51°00'-52°34'N, 9°28'-14°38'E	–			N-S, NW-SE	24, 48, 96, 125				6.2–6.5		Poplar			🟩						
Medinski et al. 2015	Germany	SRA	51°47'N, 14°37'E	Gleysol	590	8.3	N-S	24, 48, 96	0.4–2.5	10	8,715–9,804			Black locust (Robinia pseudoacacia L.), poplar clone Max 1 (Populus nigra x P. maximowiczii)		🟩							
Rivest et al. 2022	Canada	SRA	45'69' N, 75'97'W	Humic-Gleysol	981	5.9	N-S	40	0.75-1	2.5 (3 rows)	13,333	1.9-2.6	wood chips	Willow (Salix viminalis L. and Salix miyabeana Seemen)					🟦	🟨			
Schmitt et al. 1999	USA	SRA	41° 29' N, 96° 30' W	Silty clay loam to sandy loam	690		across the slope (6-7%)		1,25	7.5, 15		0,5-2	mixed grasses	Honeysuckle (Lonicera maackii) ,golden currant (Ribes aureum), eastern cottonwood(Populus deltoides Bartr.), silver maple (Acer saccharinum L.)	🟦								
Swieter et al. 2021	Germany	SRA	52°19'N, 10°37'E	Silty clay	616	9.8	N-S	24, 48, 96	–	13	10,000	5.8–9.4		Poplar (Populus nigra L. x P. maximowiczii, P. maximowiczii x P. trichocarpa, P. koreana x P. trichocarpa)		🟩		🟦		🟨	🟦		🟩
van Ramshorst et al. 2022	Germany	SRA	51'47' N, 14'37' E	Sandy loam (Gleyic Fluvisol)	568	9.6	N-S	24, 48, 96	0.75–1.8	10	8,715–9,227	2-8		Black locust (Robinia pseudoacacia L.) and Poplar (Populus nigra L. × P. maximowiczii Henry)					🟦				
Winterling et al. 2019	Germany	SRA	48°21' N, 11°42' E; 48°46' N, 10°48' E	Silty loam (Cambisol, Stagnosol, Regosol, Gleysol)	820	8,2 - 8,5	N-S	80	1.25	7.5				Poplar (Populus nigra L. x P. maximowiczii)		🟩			🟦	🟩		🟦	🟩

Annex 3 META-AfS



Willkommen zu META-AfS! - Interaktive Szenariengestaltung zur Flächenpotenzialermittlung von Agroforstsystemen

Anwendung von Filterregeln	z.B. Abstandsmaße, Schutzpuffer
Auswahl von Management-optionen	z.B. Gehölzanteile, Schlaggrößen, Gehölzwahl
Ökonomische Kriterien-bewertung	z.B. Preise, Kosten, Annuitäten
Ökologische Kriterien-bewertung	z.B. Habitatschutz, Bodenschutz, Gewässerschutz

Auswahl & Gewichtung

Tabellen und Grafiken
Untersuchungsgebiets-ebene
Webmapping
Flurstücksebene

Szenarieninfo
Dashboard
Schlagdaten
Gemeindeebene

Flächengeometrien und Datenbankinfo als QGIS->Projekt

🟩 META-AfS
🟦 Excel
⬜ GIS
⬚ Speicherung als Szenario

pot. Bodenabtrag Wasser (t/(ha → **Schutz vor Wassererosion**

	Indikatorwer	Eignungswert	
x1	0	33.3	y1
x2	2.5	66.7	y2
x3	5	88	y3
x4	7.5	100	y4
x5	15	100	y5
x6	100	100	y6

Schwellen für Indikatorenwerte festlegen

Untere 0 Obere 49.9

🟥 ungeeignet 🟩 geeignet 🟩 sehr geeignet
Eignungsklassen

*Figure Annex 3 For each objective, the tool uses two criteria and indicators; e.g. the indicator of “potential soil erosion” is used for the criteria of reducing soil erosion by water and wind. In the next step, the tool user chooses the priority criteria for establishing agroforestry. The tool produces a suitability value for each parcel of the base layer, subdivided into three classes: very suitable, suitable and not suitable area for agroforestry. The classes express if the chosen criteria will likely, only conditionally, or not improve by establishing agroforestry. The tool allocates suitability using the expressions of the indicators, e.g. soil erosion of 10 t/ha*a will lead to “very suitable”. For each indicator, the user can set threshold values (Böhm et al., 2020b).*

Annex 4 Questionnaire for agroforestry planning on the field-scale

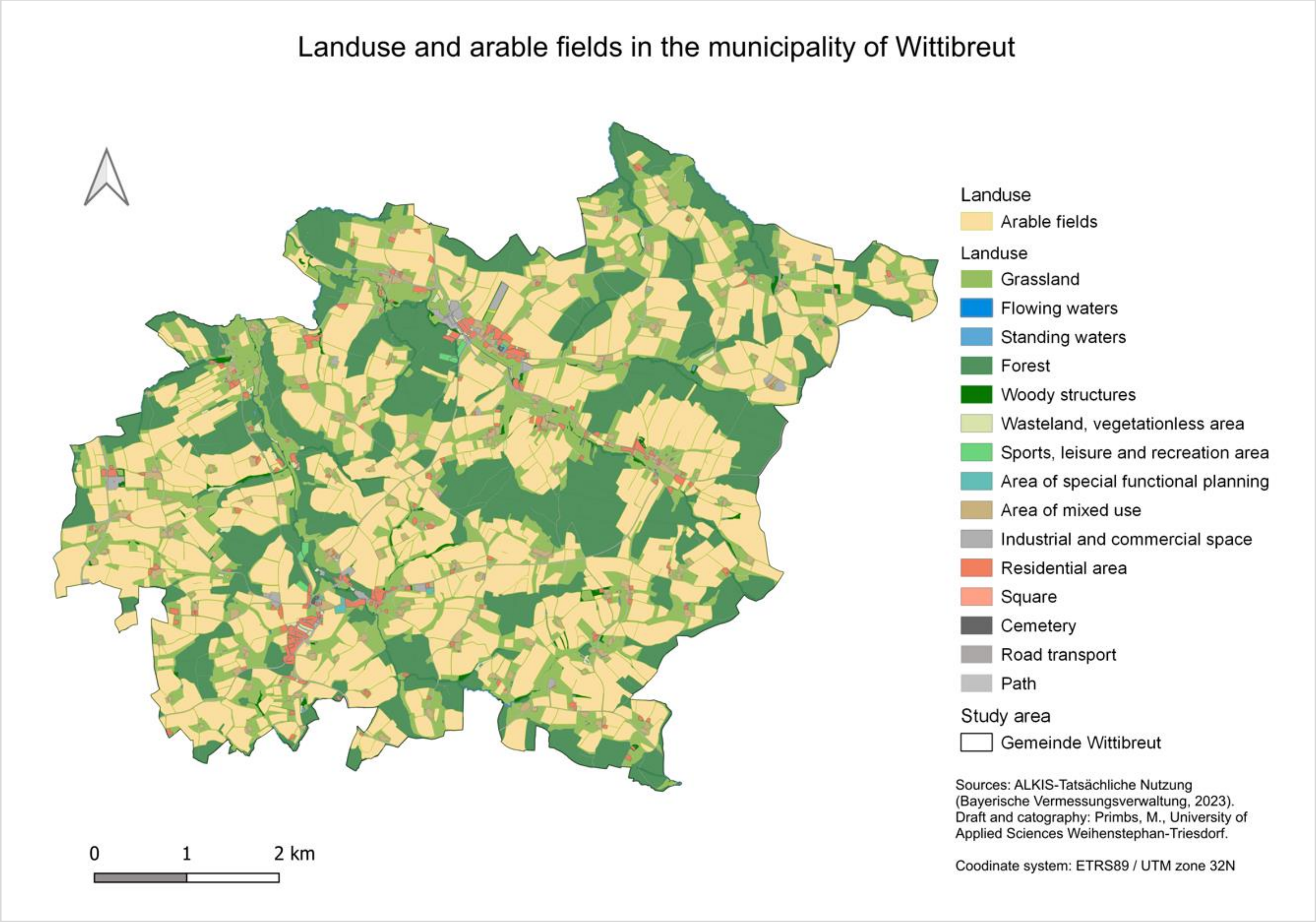
Farm data	
Farm name	Friedl
Adress	Friedlöd 5, 84384 Wittibreut, Bayern
Total area	10,6 ha
Farm type	Leased, arable farming, fruit growing
Farm branches	Fruit growing, research
Number of employees	2 x 50 %
Certifications	EU-Organic certificate for grassland and fruit growing
Natural framework	
Region	Lower Bavarian hill country
Altitude (m NN)	490-500 m
Sunshine (h/a)	1700-1800 h/a
Precipitation (mm)	963,8 mm (DWD, Wittibreut 1991-2020)
Temperature (°C)	9,2 (DWD, Falkenberg 1991-2020)
Late frost days	88,6 (DWD, Falkenberg 1991-2020)
Personal assessment of future climatic trends	Redistribution of precipitation (heavy rain, winter, slight decline), longer weather phases (including droughts), higher temperature
Geographical characteristics	Windy (3.5-4 m/s at a height of 10 m, Windatlas Bayern), cooler climate, vegetation (tree blossom, grain harvest) up to 2 weeks later than in the Inn Valley
Farm areas	
Arable land	4.4 ha (in ownership); one field; rape, triticale, maize (105 dt/ha), wheat (67 dt/ha)
Grassland	3.5 ha (in ownership); one field
Fruit growing	0.5 ha of grassland
Forestry	2.7 ha (in ownership)
External and inner traffic situation	15 km to the next city; rounded
Objectives	
Farm vision	- Long-term vision: research and seminars, research area (agroforestry) - Areas still leased, change in farming methods (ploughless arable farming) - Forest under own management
Development stages for the farm vision	- Establishment of the agroforestry system - Conversion of the arable farming system to ploughless cultivation - Extension of barns

Economic objectives	*Important*	*Nice to have*	*Not important*
Yield security	x		
Fast return on investment			x
Long-term capital investment		x	
Development of new branches		x	
Further economic objectives	Breaking work peaks, increased yield through longer crop rotation, good adaptation to support programmes		
Ecological objectives	*Important*	*Nice to have*	*Not important*
Species promotion	x		
Biotope networking		x	
Landscape water balance	x		
Carbon storage		x	
Further objectives	*Important*	*Nice to have*	*Not important*
Landscape scenery	x		
Promotion of animal welfare (shade providers)			x
Public relations	x		
Other: Research	x		
Products	*Important*	*Medium important*	*Not important*
Dessert fruits	(x)	x	
Commercial fruit		x	
Stinging fruit			x
Valuable timber	x		
Industrial timber			x
Posts			x
Logs		x	
Wood chips			x
Bee pasture	x		
Living fence posts			x
Deciduous hay			x
Shrubs		x	
Notes	Fruit: long storage time, shrubs: keep minimum shading, possibly selectively to slow down runoff		
Site description and planning factors of the area to be planned			
Coordinates of the area	48°33' N,13°00' E		
Current utilisation	Arable land		
Field size	4.4 ha		
Distance to the farm	Rounded		
Accessibility	From 2 sides		
Rock source	Upper freshwater molasse		

Soil type	Brown earth/para-brown earth/pseudo gley
Soil texture	sL
Soil pH value	5.9 (2 samples with 5.8 at the foot of the slope and 6.1 on the mountainside, 2018)
Ackerzahl	45 (estimated)
Results of soil analyses	P_2O_5 6mg, K_2O 12mg
Area structure	Square
Landscape elements	No
Hollows/dumps	Yes see DGM
Depth of soil & risk of waterlogging	Deep, prone to waterlogging
Topography (slope)	~ 4%
Wind (direction & exposure)	Wind from the west, exposure to the north
Game population	Yes
Drainage (present/not present)	Probably none
Distance to groundwater	>20 dm, only at the lower border <13 dm (stream) (LfU, 2023)
Reasons for selecting this area	The only possible
Infrastructural restrictions	(radio mast if necessary)
Existing machines and their widths	4-coulter plough, 4.50 m disc harrow, 3.00 m seed drill-circular harrow-drill combination, 27.00 m sprayer and fertiliser spreader, 9.00 m slurry tank with trailing shoe
Desired wood strip width	According to the system
Desired crop alley width	According to the machine width
Headland width	(30 m)
Planned animal husbandry	None
Possible arable crops	Maize, wheat, triticale, rape, barley
Labour for low- and high demand activities	Low-demand: Yes; high-demand (planting, pruning): Yes, via the Landscape Conservation Association
Expertise in AFS management	No
Nature conservation areas, FFH, neighbourhood law	Biotope (stream) at the lower border; neighbourhood law Bavaria
Current support programmes	None
CC-relevant categorisations	CC2
Equity capital	Yes
Debt capital	Yes, Landscape Conservation Association and AELF

Annex 5 Maps of the study area

Annex 5.1 Land use in the study area



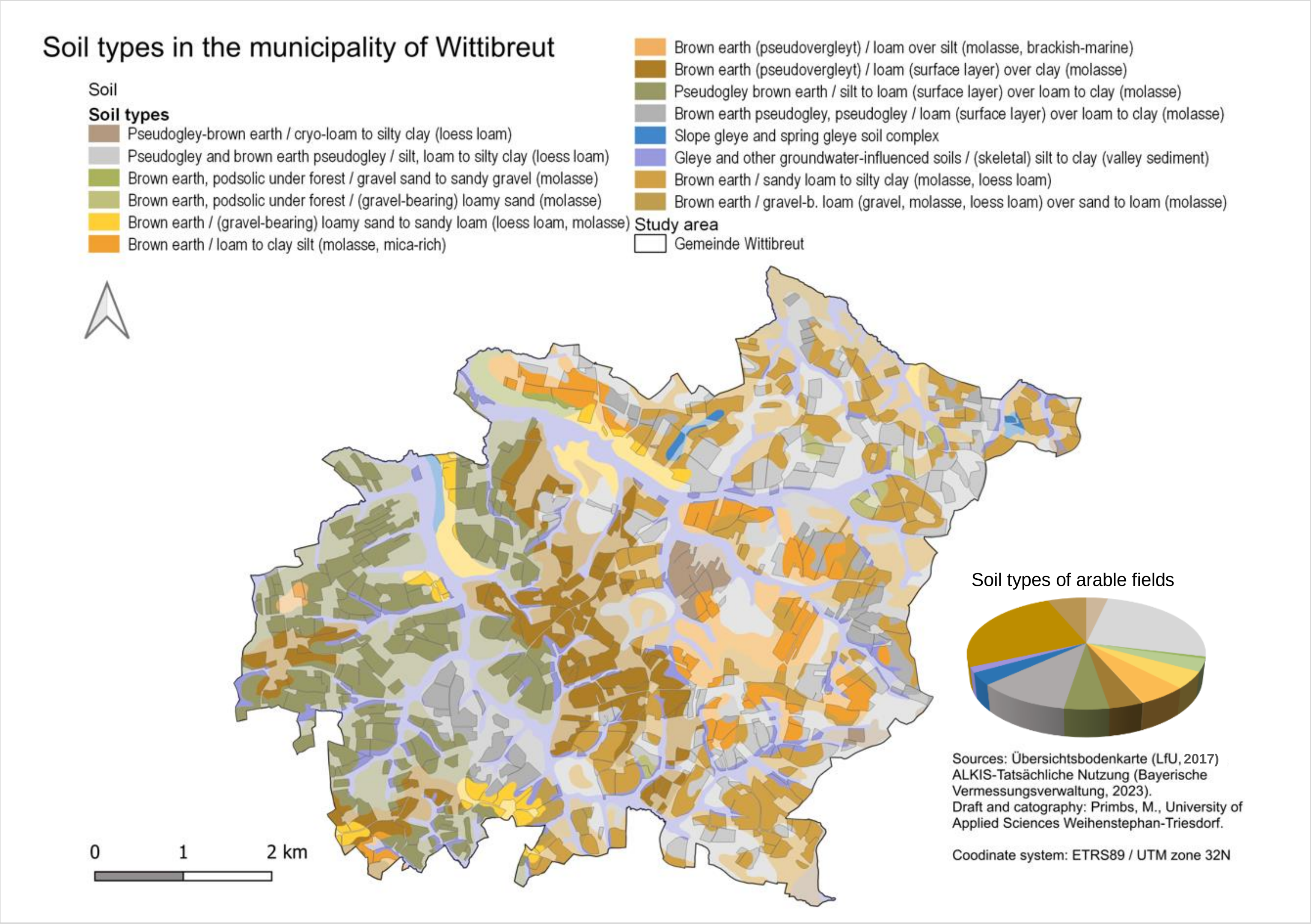
Landuse and arable fields in the municipality of Wittibreut

Sources: ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023). Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 5.1 Landuse and arable fields in the municipality of Wittibreut

Annex 5.2 Soil types in the study area

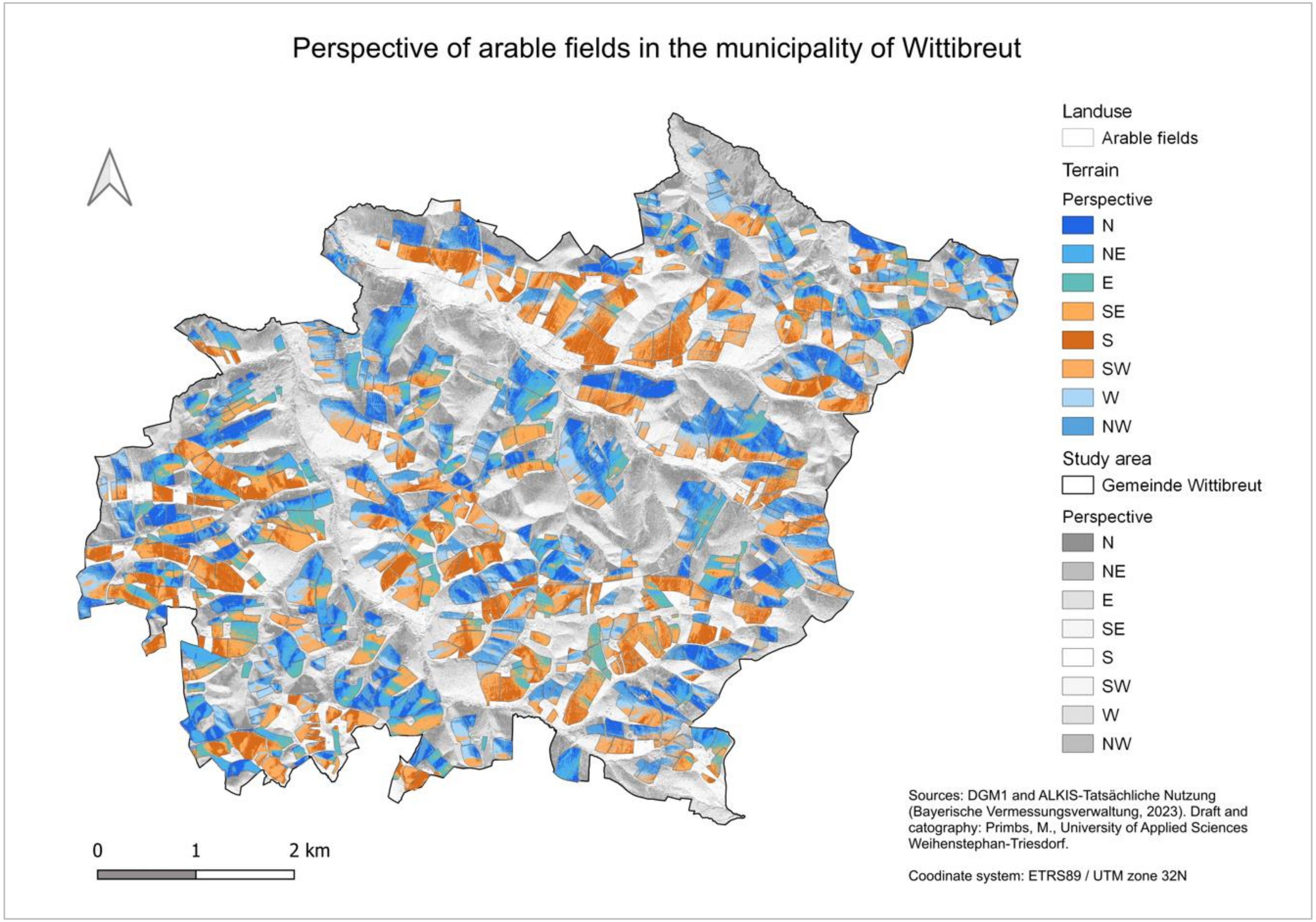


Sources: Übersichtsbodenkarte (LfU, 2017)
ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023).
Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 5.2 Soil types in the municipality of Wittibreut

Annex 5.3 Perspective of arable fields

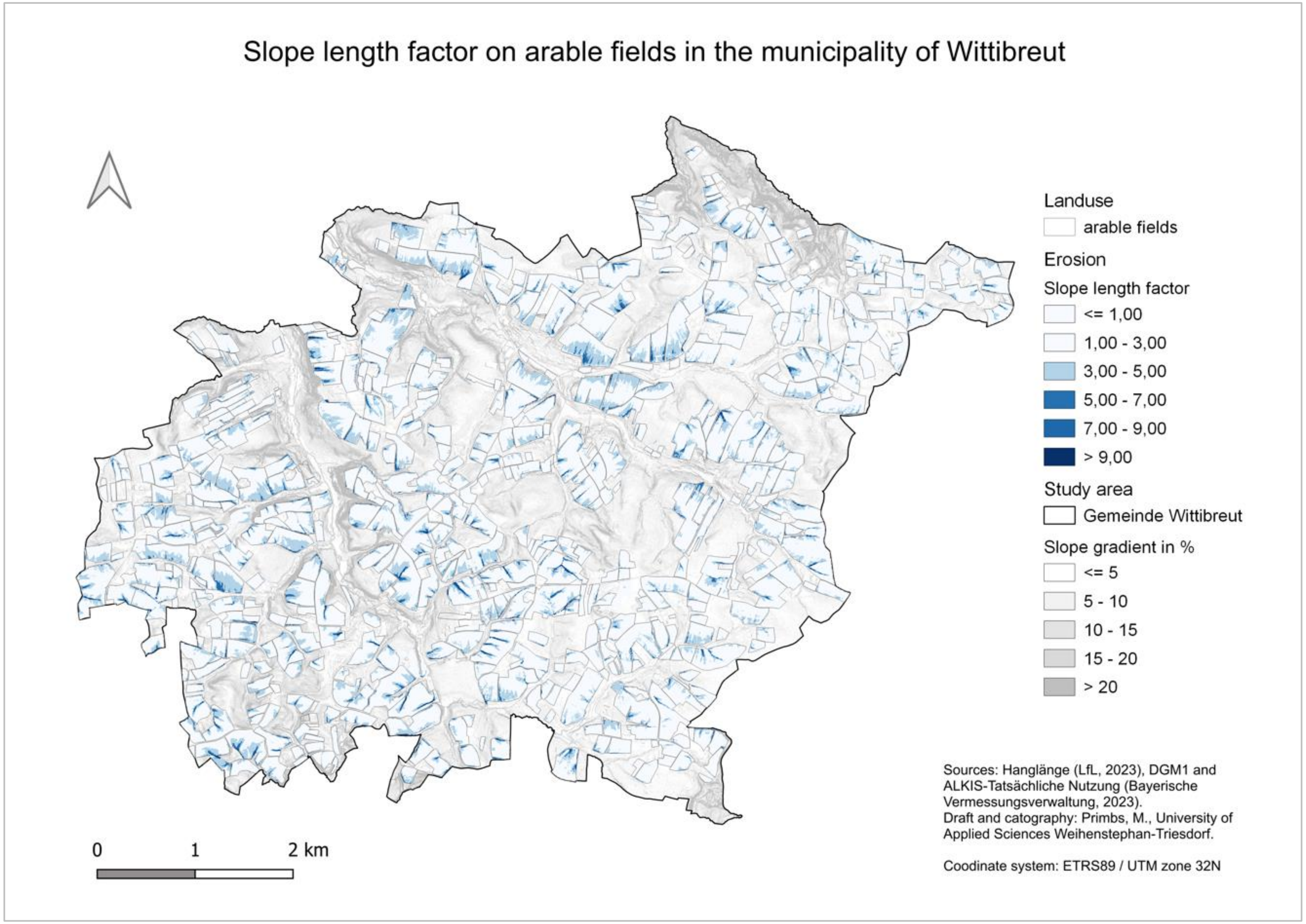


Sources: DGM1 and ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023). Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 5.3 Perspective of arable fields in the municipality of Wittibreut

Annex 5.4 Slope length factor in the study area



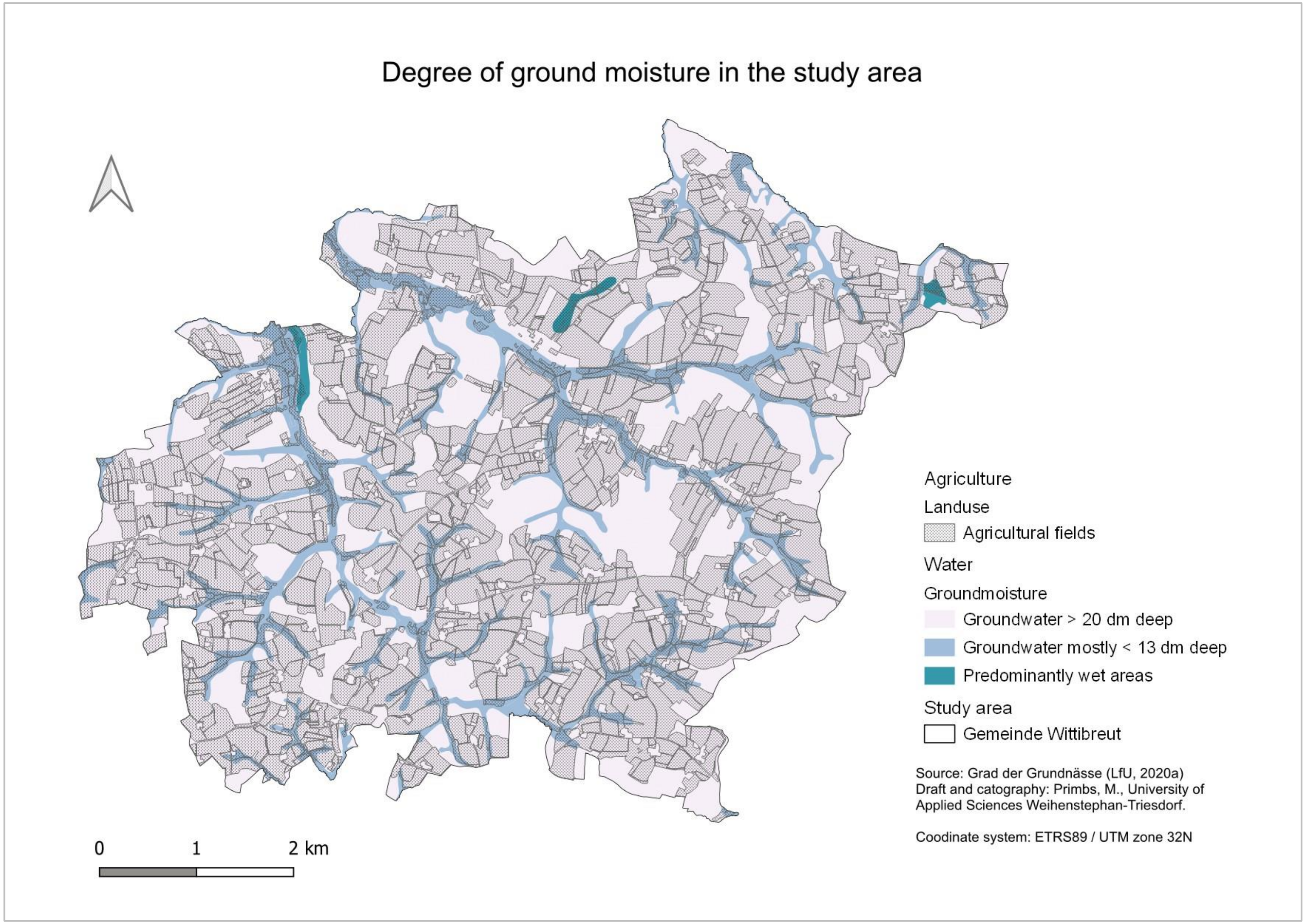
Slope length factor on arable fields in the municipality of Wittibreut

Sources: Hanglänge (LfL, 2023), DGM1 and ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023).
Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 5.4 Slope length factor on arable fields in the municipality of Wittibreut

Annex 5.5 Degree of ground moisture, adhesive and congestive wetness and water retention potential in the study area

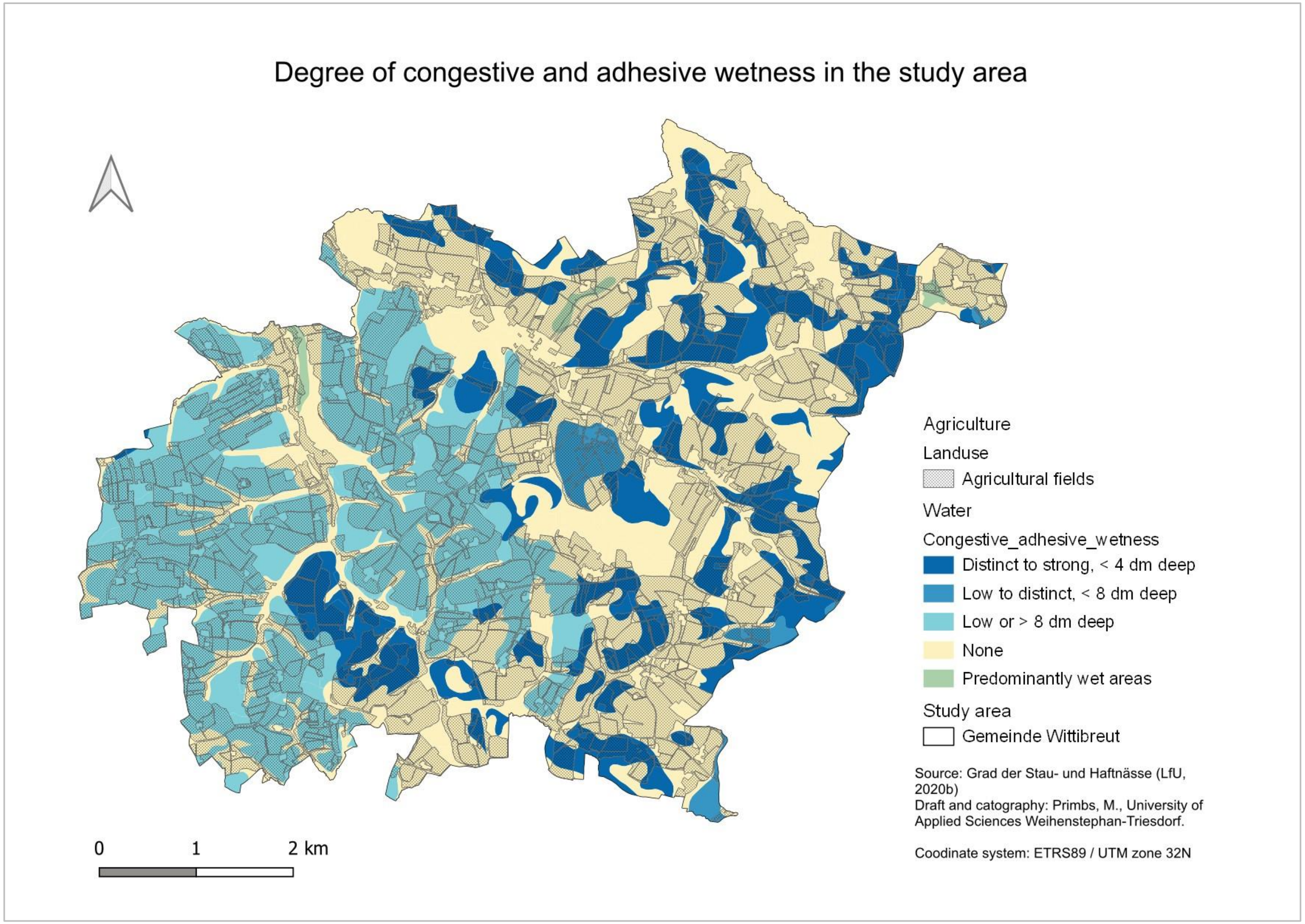


Degree of ground moisture in the study area

Source: Grad der Grundnässe (LfU, 2020a)
Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

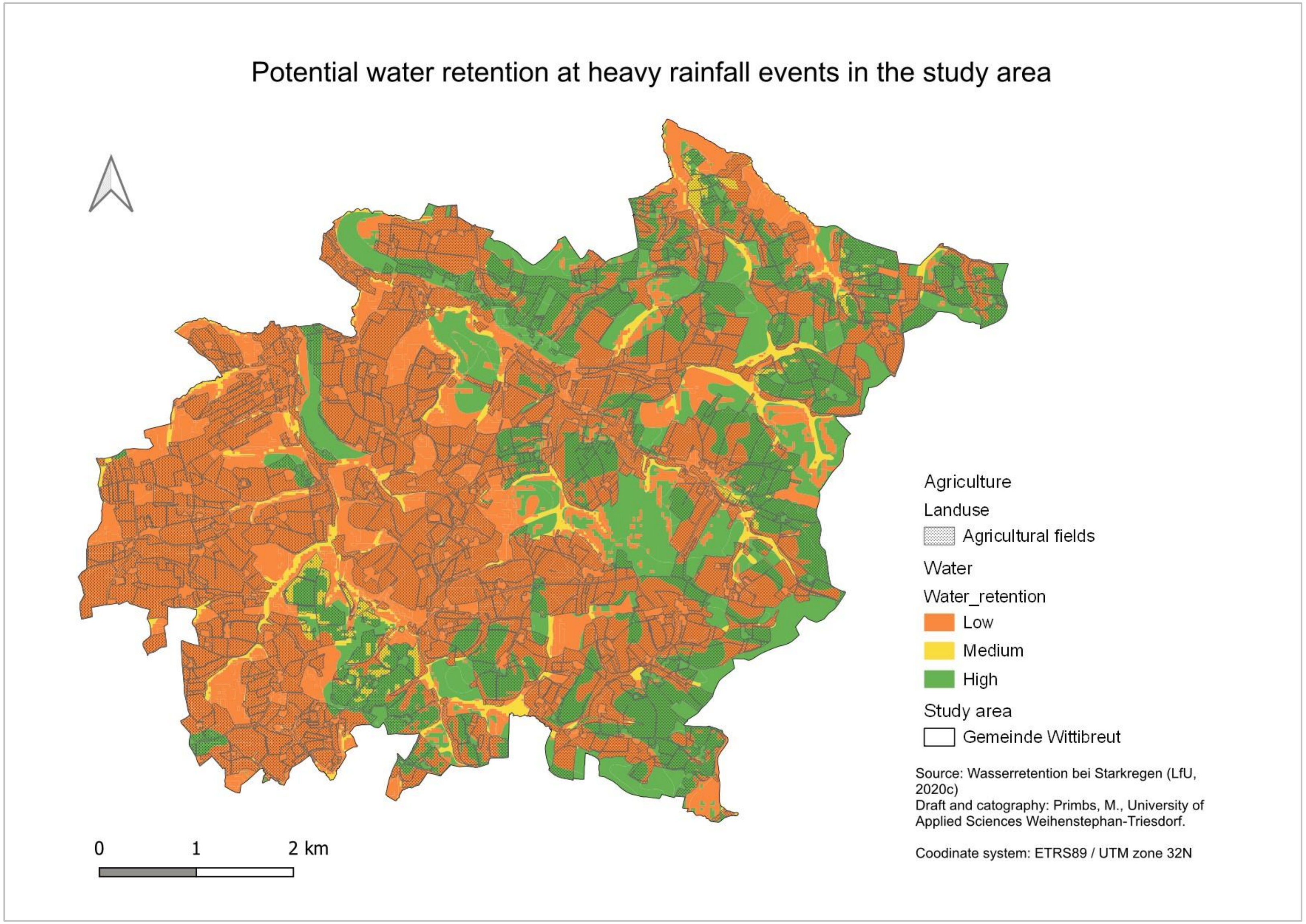
Figure Annex 5.5.1 Degree of ground moisture and overlap with arable fields in the study area



Source: Grad der Stau- und Haftnässe (LfU, 2020b)
Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 5.5.2 Degree of congestive and adhesive wetness and overlap with arable fields in the study area

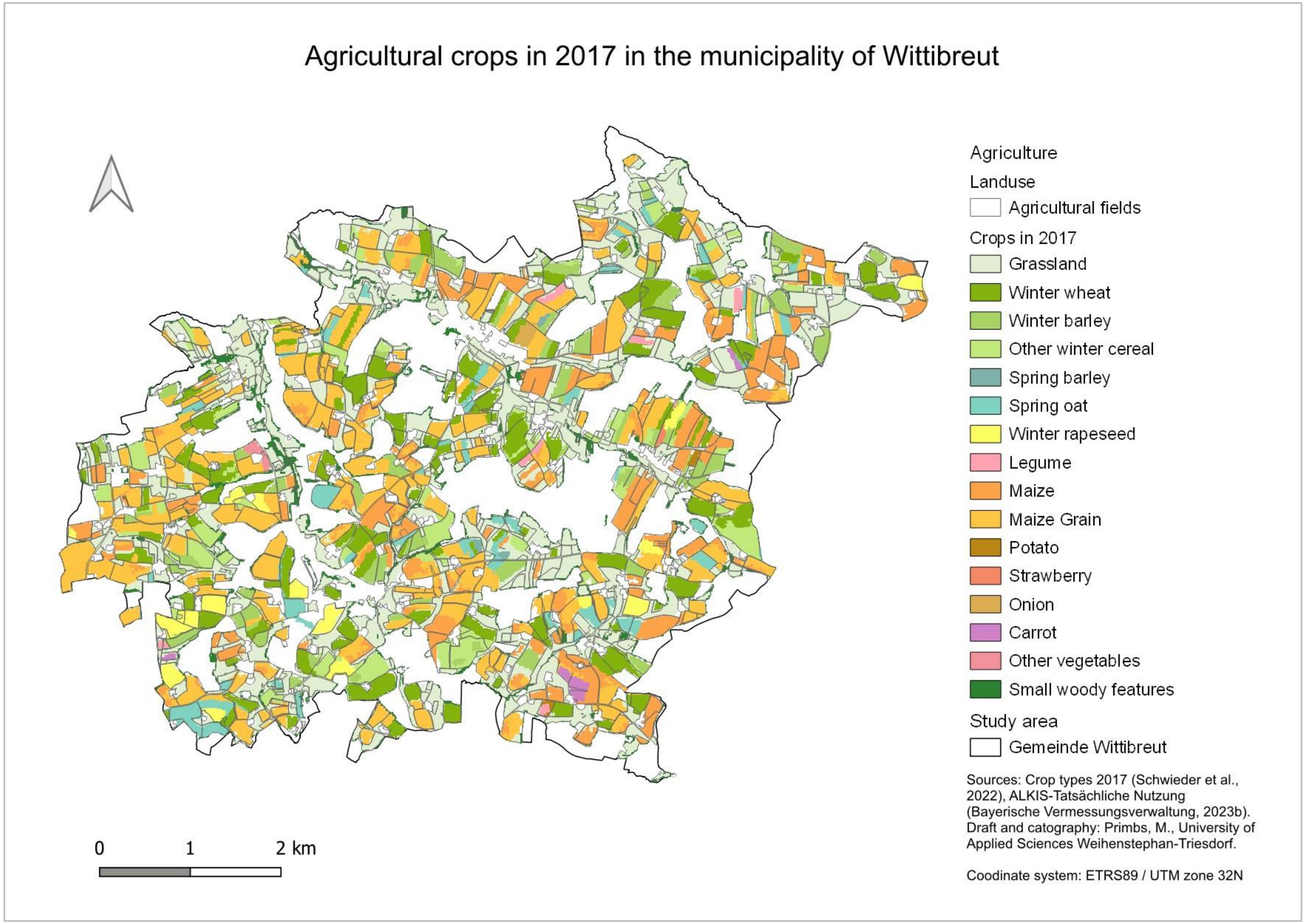


Source: Wasserretention bei Starkregen (LfU, 2020c)
Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 5.5.3 Potential water retention at heavy rainfall events and overlap with arable fields in the study area

Annex 5.6 Crop maps of the study area


Agricultural crops in 2017 in the municipality of Wittibreut

Sources: Crop types 2017 (Schwieder et al., 2022), ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023b). Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 5.6.1 Agricultural crops in 2017 in the municipality of Wittibreut

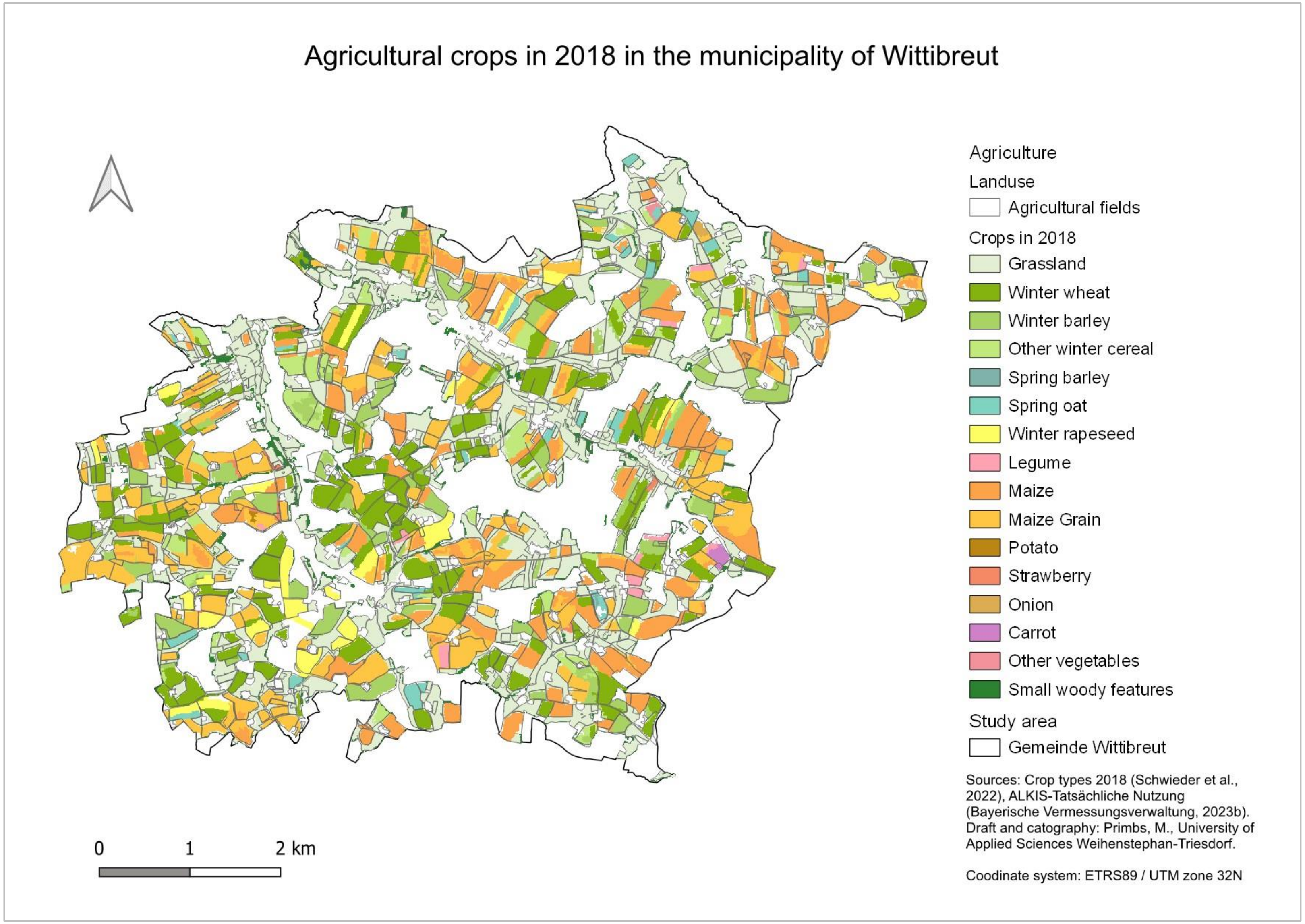
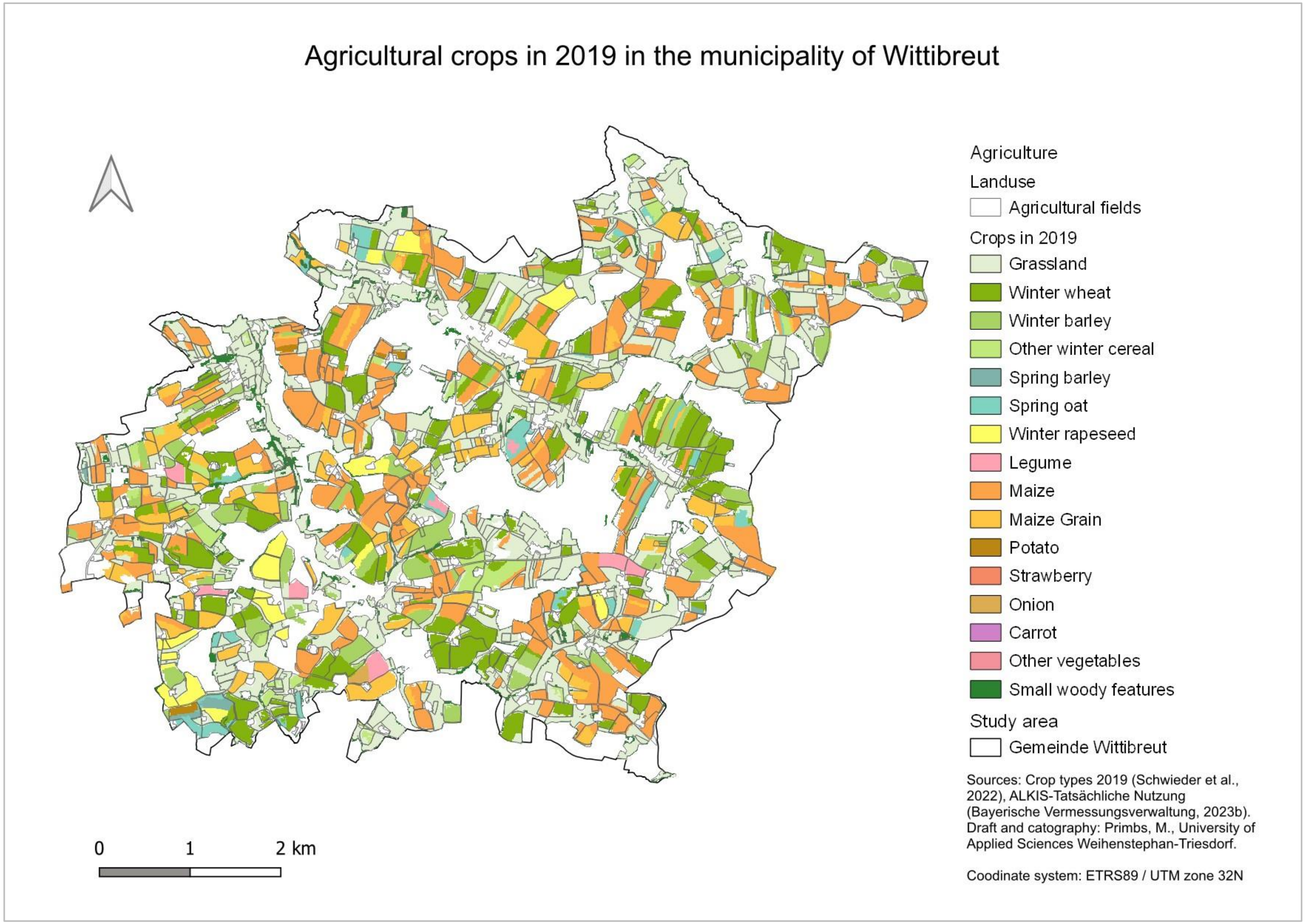


Figure Annex 5.6.2 Agricultural crops in 2018 in the municipality of Wittibreut



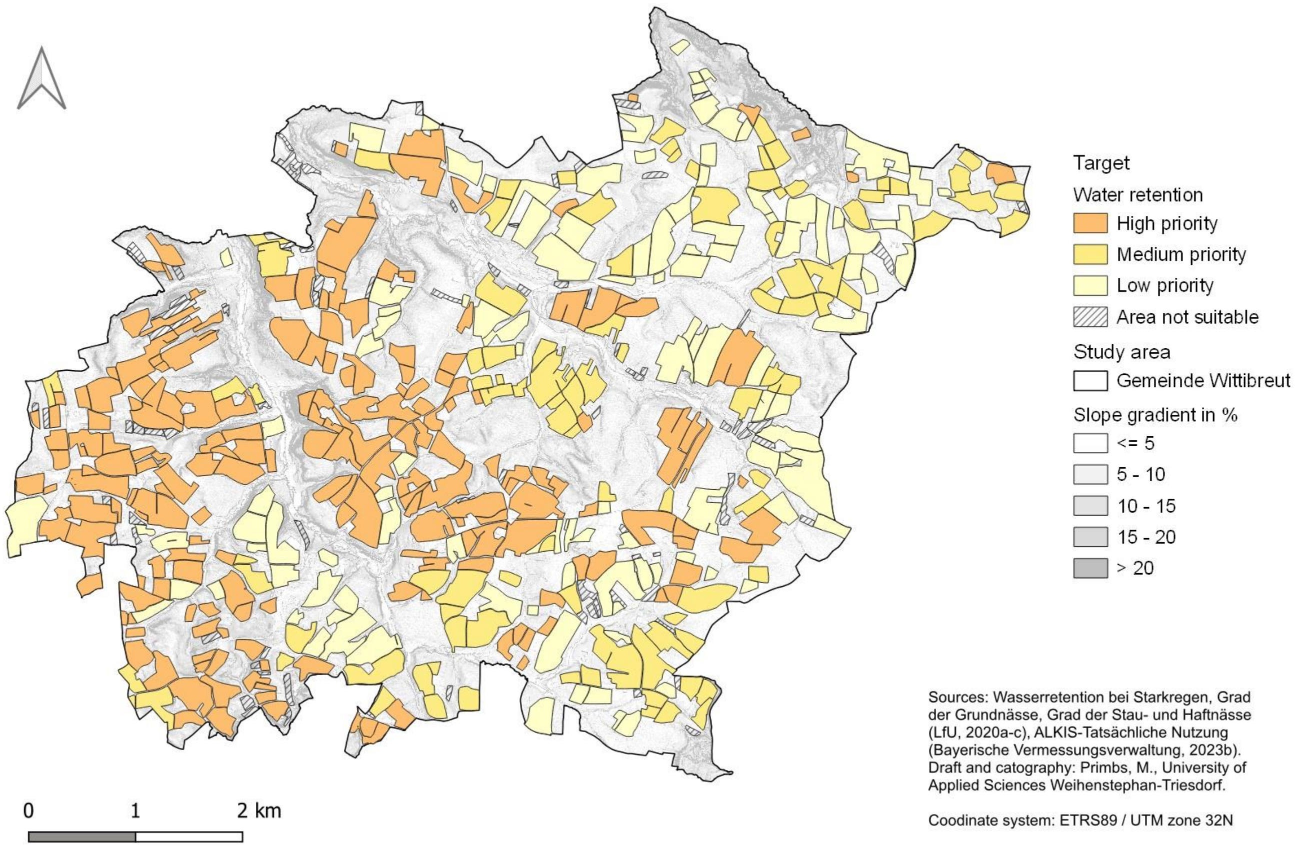
Sources: Crop types 2019 (Schwieder et al., 2022), ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023b). Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 5.6.3 Agricultural crops in 2019 in the municipality of Wittibreut

Annex 6 Output maps for RQ3

Annex 6.1 Priority fields for water retention in the study area



Classification of arable fields in the study area according to the water retention requirement

derived from the level of groundwater, waterlogging, adhesive wetness and water retention at heavy rainfall events

Sources: Wasserretention bei Starkregen, Grad der Grundnässe, Grad der Stau- und Haftnässe (LfU, 2020a-c), ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023b). Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 6.1 Classification of arable fields in the study area according to the water retention requirement derived from the level of groundwater, waterlogging, adhesive wetness and water retention at heavy rainfall events

Annex 6.2 Priority fields for wind protection in the study area

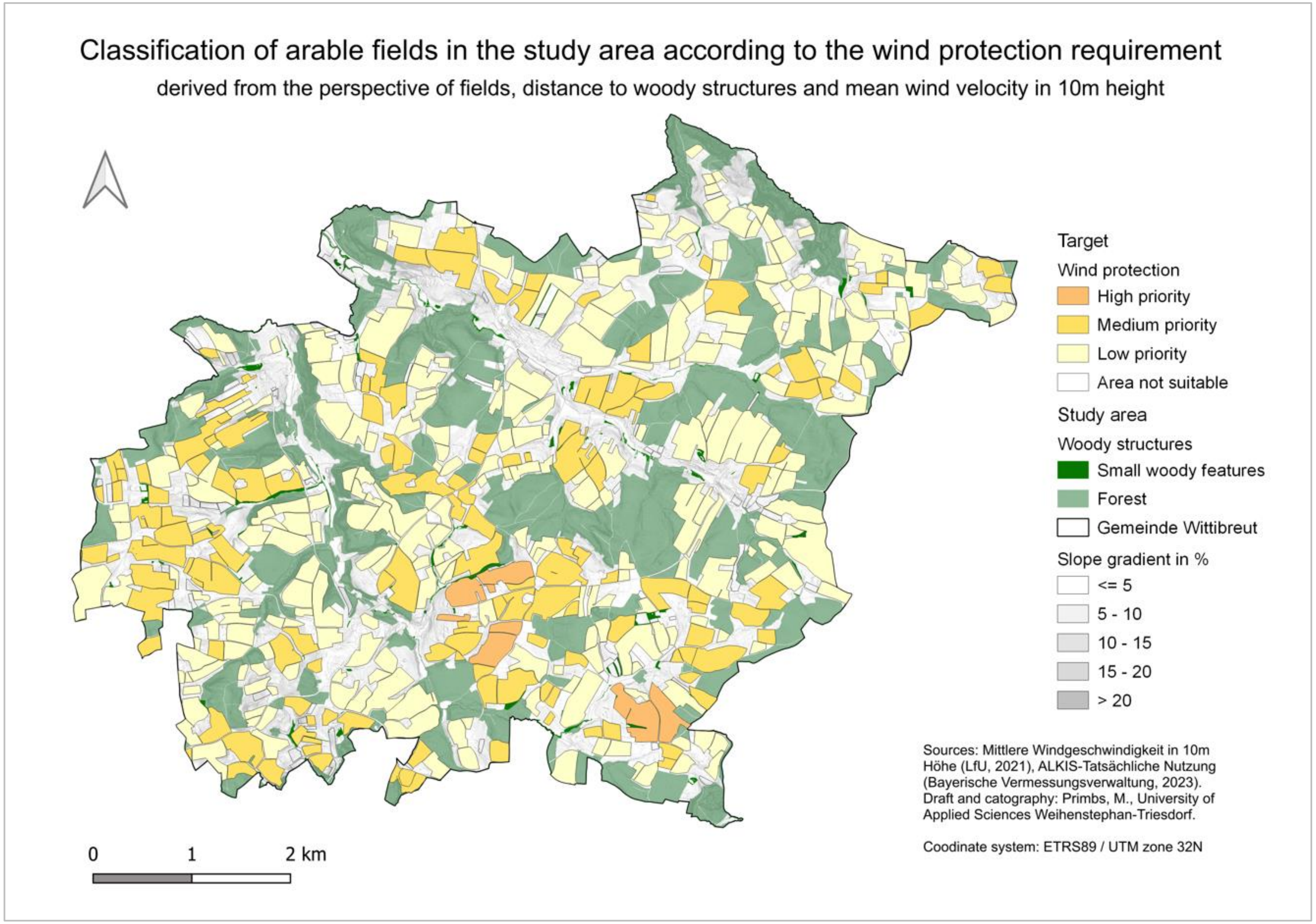
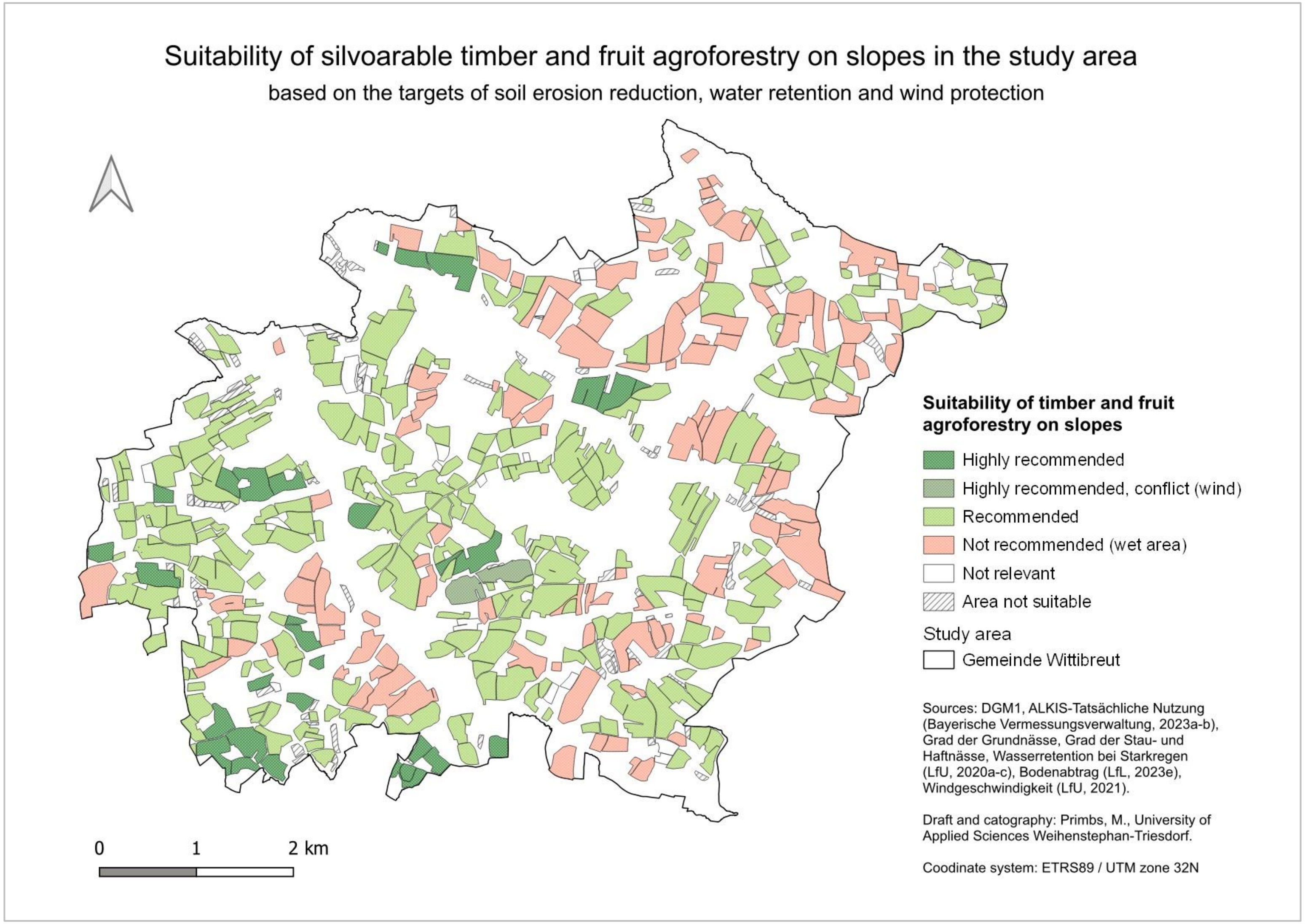


Figure Annex 6.2 Classification of arable fields in the study area according to the wind protection requirement derived from the perspective of fields, distance to wood structures and mean wind velocity in 10m height

Annex 6.3 Timber and fruit agroforstry systems on slopes in the study area



Suitability of silvoarable timber and fruit agroforestry on slopes in the study area

based on the targets of soil erosion reduction, water retention and wind protection

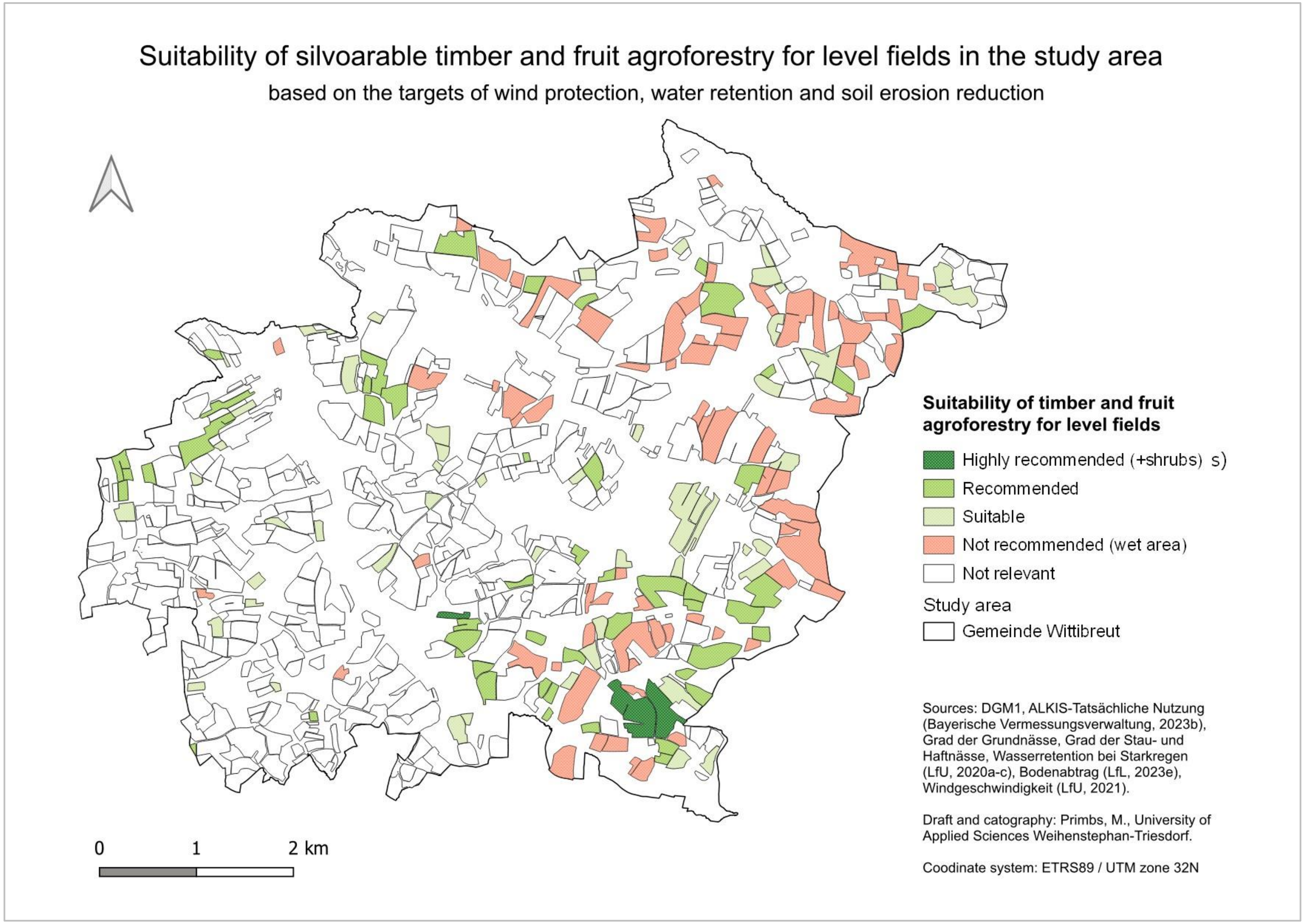
Sources: DGM1, ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023a-b), Grad der Grundnässe, Grad der Stau- und Haftnässe, Wasserretention bei Starkregen (LfU, 2020a-c), Bodenabtrag (LfL, 2023e), Windgeschwindigkeit (LfU, 2021).

Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 6.3 Suitability of silvorarable timber and fruit agroforestry systems on slopes in the study area based on the targets of soil erosion reduction, water retention and wind protection

Annex 6.4 Timber and fruit agroforstry systems on level fields in the study area



Suitability of silvoarable timber and fruit agroforestry for level fields in the study area

based on the targets of wind protection, water retention and soil erosion reduction

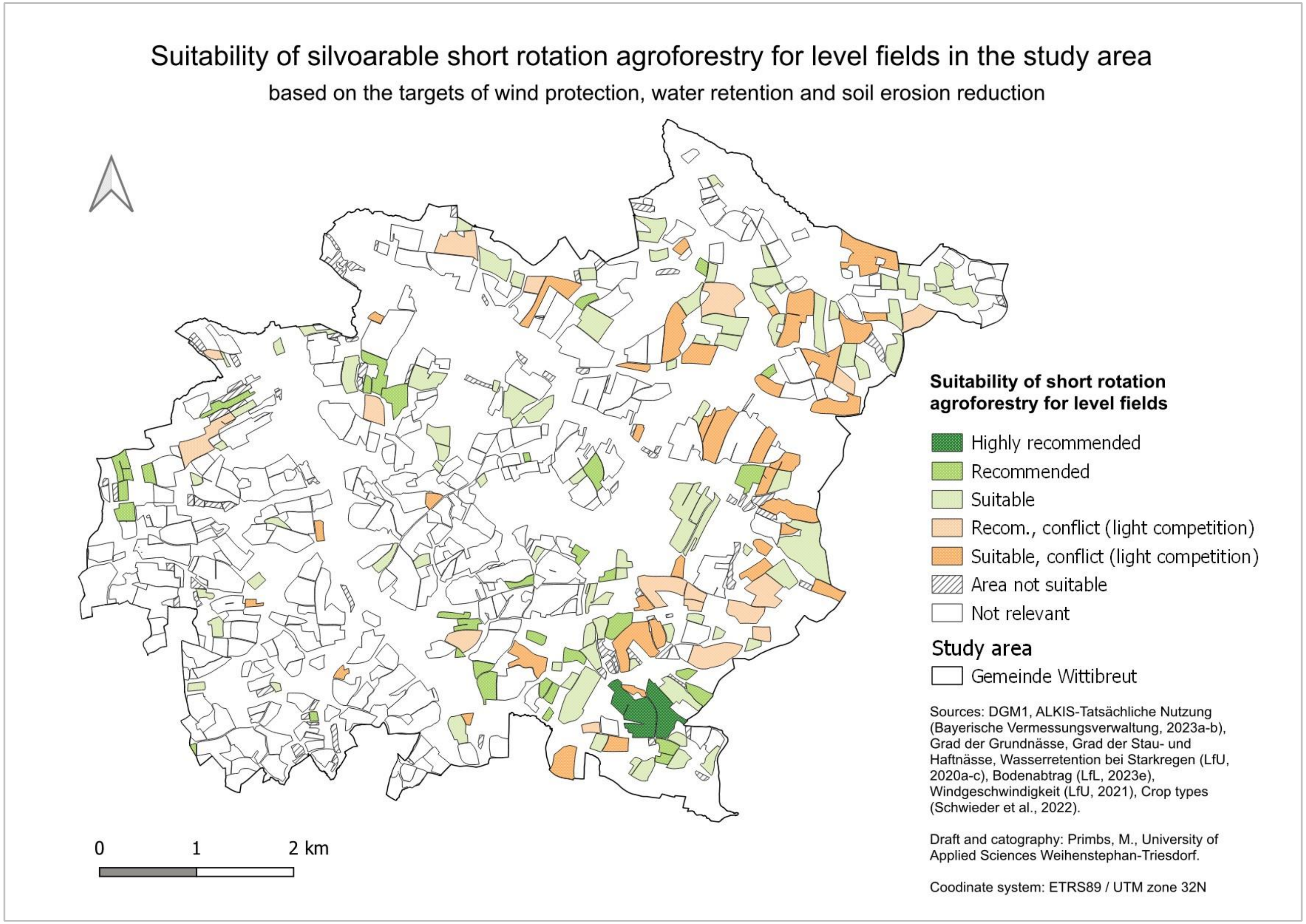
Sources: DGM1, ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023b), Grad der Grundnässe, Grad der Stau- und Haftnässe, Wasserretention bei Starkregen (LfU, 2020a-c), Bodenabtrag (LfL, 2023e), Windgeschwindigkeit (LfU, 2021).

Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 6.4 Suitability of silvorarable timber and fruit agroforestry systems on level fields in the study area based on the targets of soil erosion reduction, water retention and wind protection

Annex 6.5 Short rotation agroforestry on level fields in the study area



Sources: DGM1, ALKIS-Tatsächliche Nutzung (Bayerische Vermessungsverwaltung, 2023a-b), Grad der Grundnässe, Grad der Stau- und Haftnässe, Wasserretention bei Starkregen (LfU, 2020a-c), Bodenabtrag (LfL, 2023e), Windgeschwindigkeit (LfU, 2021), Crop types (Schwieder et al., 2022).

Draft and catography: Primbs, M., University of Applied Sciences Weihenstephan-Triesdorf.

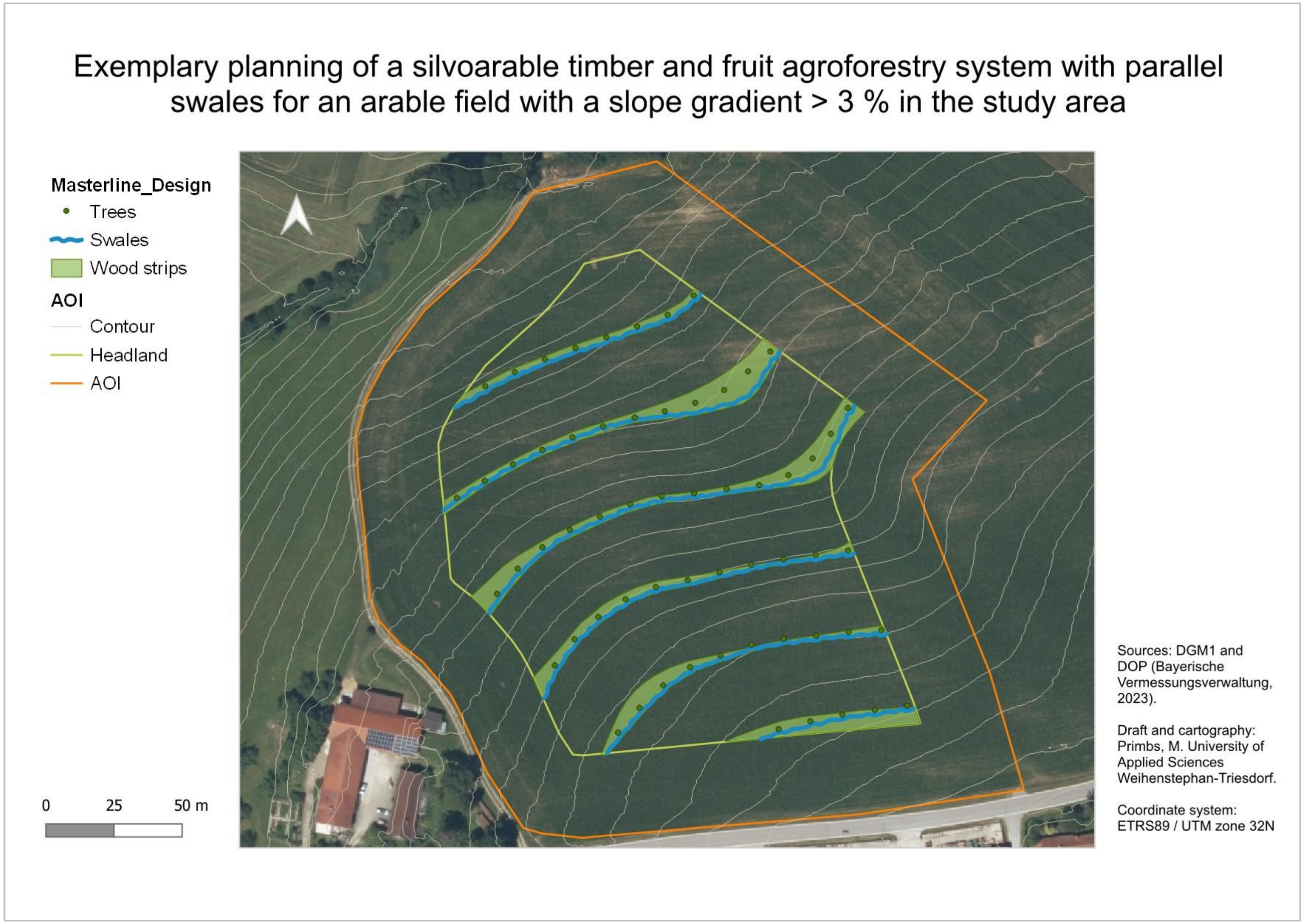
Coodinate system: ETRS89 / UTM zone 32N

Figure Annex 6.5 Suitability of silvorarable short rotation agroforestry systems on level fields in the study area based on the targets of soil erosion reduction, water retention and wind protection

Annex 7 Planning example for a silvoarable agroforestry system

Figure Annex 7.1 Arable field in the municipality of Wittibreut to be planned with an agroforestry system, framed by the street (southern border), field path in front of the farm (W, house left corner), creek (N) and arable field (E) (own photograph, Friedlöd 06/2023)

Figure Annex 7.2 The arable field to be planned is characterised by a sink with high potential surface runoff, the cultivation is carried out across the slope (own photograph, Friedlöd 06/2023)

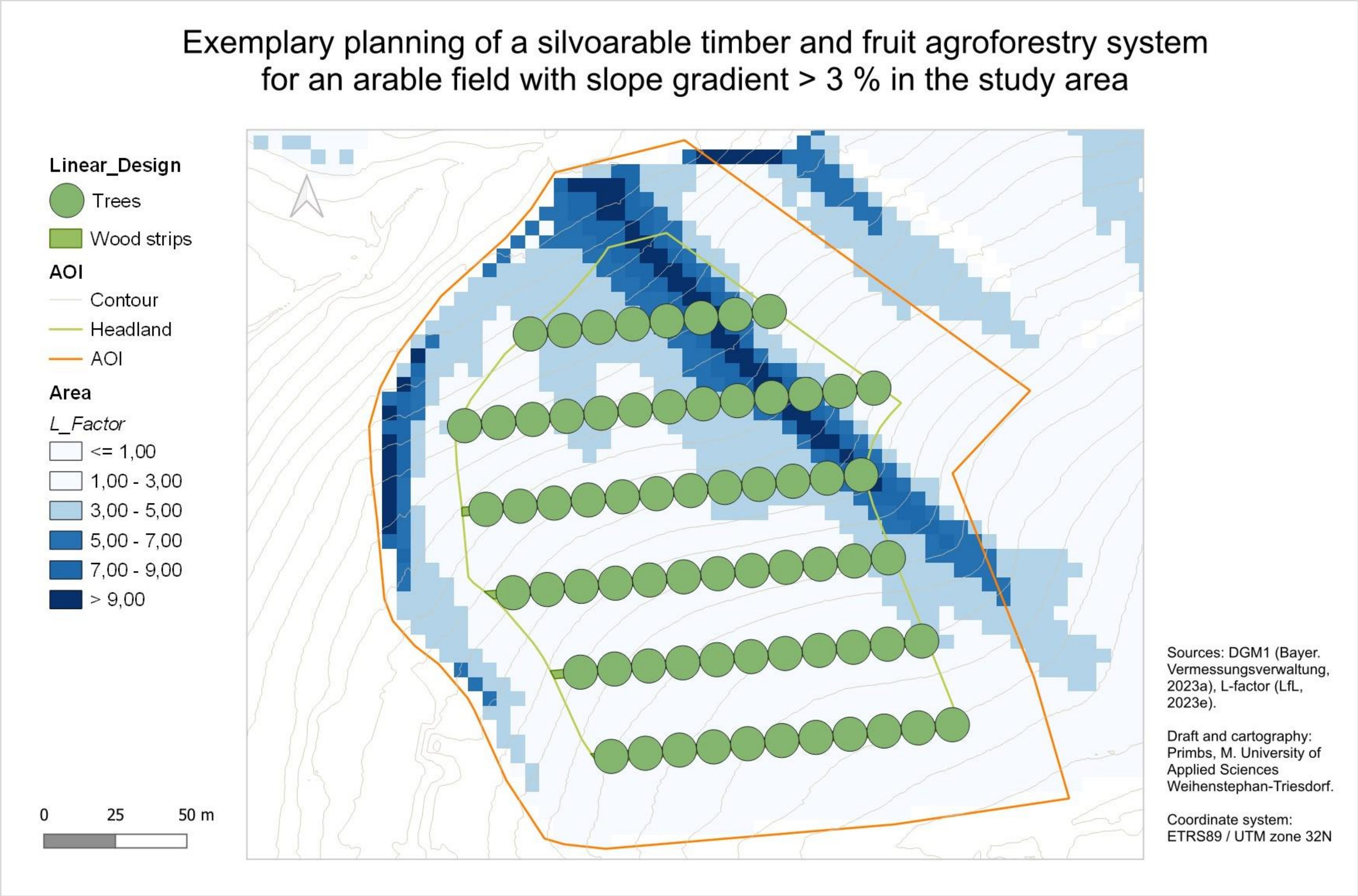

Exemplary planning of a silvoarable timber and fruit agroforestry system with parallel swales for an arable field with a slope gradient > 3 % in the study area

Sources: DGM1 and DOP (Bayerische Vermessungsverwaltung, 2023).

Draft and cartography: Primbs, M. University of Applied Sciences Weihenstephan-Triesdorf.

Coordinate system: ETRS89 / UTM zone 32N

Figure Annex 7.3 Exemplary planning of a silvoarable timber and fruit agroforestry system with parallel swales for an arable field with a slope gradient > 3 % in the study area


Exemplary planning of a silvoarable timber and fruit agroforestry system for an arable field with slope gradient > 3 % in the study area

Sources: DGM1 (Bayer. Vermessungsverwaltung, 2023a), L-factor (LfL, 2023e).

Draft and cartography: Primbs, M. University of Applied Sciences Weihenstephan-Triesdorf.

Coordinate system: ETRS89 / UTM zone 32N

Figure Annex 7.4 Exemplary planning of a silvoarable timber and fruit agroforestry system for an arable field with slope gradient > 3 % in the study area. The parallel wood strips are oriented to the field borders and machine working with of 27 m.

Annex 8 Comparing agroforestry planning factors and regulations of the CAP

Table Annex 8 Comparison of planning factors for silvoarable agroforestry systems as derived in Chapter 4.2 with regulations of the legal definition and Eco-Scheme 3 of the CAP

Planning factor	***Recommendations** (Chapter 4.2)*				***Legal definition and Eco-Scheme 3*** *(DeFAF, 2022b)*	
System components	***Timber and fruit systems***		***Short rotation systems***		***Agroforestry systems***	
	Slope Design	***Level Design***	***Slope Design***	***Level Design***		
Minimum field size					≥ 0,3 ha	*§ 3 Abs. 3 GAPInVeKoSV*
Number of wood strips	≥ 1	≥ 1	≥ 1	≥ 1	≥ 2	*Definition (§ 4 Abs. 2 GAPDZV)*
Area share of wood strips			10-20 %		< 40% (stripes) 2-35 %	
Orientation of wood strips	Across the slope or on contour, on > 3 ≤ 14 % slopes	Perpendicular (diagonal) to the main wind direction, if possible N-S layout	Across slope or on contour, on > 3 ≤ 14 % slopes	Perpendicular (diagonal) to the main wind direction, if possible N-S layout	20-100 m distance to field borders (exept riparian buffers)	
Distance between wood strips	30 ± 12 m; the steeper the slope, the closer the distance	≥ 18 m and < 50 m	30 ± 12 m; the steeper the slope, the closer the distance	≥ 48 m and ≤ 80 m (< 100 m)	≥ 20 m and < 100 m	*Eco Scheme (Anlage 5 Nr. 3 GAPDZV)*
	Determined by machines width and site-characteristics		Determined by machines width and site-characteristics			
Strip width	≥ 2 m wide wood strips covered with vegetation	≥ 2 m wide wood strips, added by shrubs	≥ 5 m wide wood strips covered with vegetation	≥ 5 m wide tree strips with a minimum of two alternating tree rows	3-25 m	
Strip design	Undersowings e.g. grass or flowering mixture	40-60 % porosity of wood strips	Undersowings e.g. white clover	40-60 % porosity of wood strips	Predominantly stocked with woody plants	
Management	Root and tree pruning recommended		Root pruning recommended		Wood harvest only Dec.-Febr.	
Planting distance	10-15 m		0.75-1.25 m x 1.25-2 m (in row x between rows)	0.5-1.25 m x 1.5-2.5 m (in row x between rows)		
	Depending on the final crown diameter		Depending on rotation period, tree species and available techniques			
Tree density	≤ 50 trees ha^{-1}		≤ 2,000 trees ha^{-1}	800 - 2,400 trees ha^{-1}	50 - 200 trees ha-1 (non-stripes)	*Definition (§ 4 Abs. 2 GAPDZV)*
Tree species	Tree species as listed in Table 3		Tree species as listed inTable 3		c.f. "Negativliste"	*Eco Scheme (Anhang 1 GAPDZV)*