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Article title

Economic valuation of ecosystem services in multifunctional agroforestry: implications of diversified systems for productive and resilient farming

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Summary of the characteristics of agroforestry systems under study

Table 1. Summary characteristics of agroforestry sites under study

Site	Inagro	CFE	Hof Lebensberg (Fruit/Nut)	Gibside	Wakelyns
Location	Flanders, Belgium	Taastrup, Denmark	Obermoschel, Germany	Newcastle upon Tyne, UK	Suffolk, England
Coordinates	50°54'19.4"N 3°08'00.2"E	55°40'20"N 12°17'40"E	49°42'48.0"N 7°46'04.3"E	54°54'36.7"N 1°42'58.5"W	52°21'41.1"N 1°21'09"E

Elevation (m)	22	20	325	180	52
Slope (°)	1	1	2	1	1
Mean rainfall (mm/yr)	962	717	706	994	626
Mean temperature (°C)	12.1	9.7	9.9	9.4	11
Establishment (year)	2023	1995	Nut: 2020/2021 Fruit: 2022/2023	2017	2001/2002
Agroforestry area (ha)	1.4	3	Nut: 10 Fruit: 7.5	1.7	2.5
Soil type	Sandy loam	Sandy loam	Sandy Loam (nuts) / Silt loam (fruits)	Loam	Sandy clay loam
Tree belts orientation (°)	339	352	Nut: ~15* Fruit: ~40*	358	17
Input management	Inorganic	No input**	Organic	Organic	Organic
Crop alley width (m)	24	200	Nut: 15 Fruit: 15	21	13
Tree belt width (m)	3	10.7	3	3	3
Tree density in tree belt (trees/ha of tree area)	306	1750 / 18670	Nut: 2700 Fruit: 8400	4267	127
Tree density in AF system (trees/ha of AF)	34	948	Nut: 450 Fruit: 1,400	533	24
Crop rotation and assessed species (bolt)	Winter wheat, maize, winter field beans, vegetables, clover-ryegrass ley	Winter wheat, spring barley , spring oat, clover-ryegrass ley	Nut: wheat, spelt, rye, vegetables, clover-ryegrass ley Fruit: clover-grass	Potatoes, brassicas, alliums, clover-ryegrass ley	Vegetables, cereals, pulses, clover-ryegrass-ley
Tree component and assessed species (bolt)	Walnut	Short rotation coppice (4-year cycle) with alder, willow spp., hazel	Nut: tree mix Fruit: tree mix	Hazel , willow, mix of fruit trees	Plum , walnut
Mean tree height at sampling (m)	2	7	1-2	2-3	5
System objective	Research	Research	Commercial	Commercial	Research and commercial

*Keyline design.

**Control monoculture field under inorganic fertilisation without pesticides.

Site descriptions and respective sampling designs

Inagro – Belgium

Located in Rumbeke, West-Flanders, the agroforestry plot at Inagro is a long-term research and demonstration site designed to explore the potential and feasibility of integrating trees with arable crops and vegetables. Established in 2023 on 1.4 hectares of sandy loam soil, this alley-cropping plot aims to promote sustainable agricultural practices while maintaining high productivity, addressing critical agricultural and environmental challenges.

Farm size and design

The plot features a layout with alternated rows of trees and food crops. The tree component consists of 41 walnut trees (*Juglans regia* ‘Broadview’), arranged in rows oriented NNW-SSE to minimise light competition and offer wind protection. The trees are spaced 8 meters apart within rows, and rows are set 24 meters apart, with 21 meters of clear cultivation area between them. This configuration is designed to provide ample space for conventional soil cultivation practices between the biomass belts, resulting in a total density of 34 trees per hectare.

The walnut trees are planted in strips 3 meters wide, which are undersown with a diverse mix of perennial grasses and flowering plants. This unmanaged perennial mix serves as a habitat for beneficial insects and birds, promoting natural pest control and supporting pollination. The intercropping system features a diverse rotation of arable crops, vegetables, and interspersed ryegrass, thereby ensuring long-term soil health. The 6-year crop rotation includes potatoes, winter wheat, maize, and winter field beans, alongside high-value vegetables such as leeks, cabbage, celeriac, and carrots. This rotation is designed to align with regional cropping patterns, with a focus on how species choice and management of crops and trees simultaneously can be optimised to increase crop yield. Additional design elements include mixed hedges planted along the plot’s borders to act as windbreaks and support biodiversity.

Management practices

The Inagro agroforestry plot is managed conventionally with inorganic inputs, reflecting the prevailing agricultural practices in Flanders, where most farms are not organic. This approach allows Inagro to demonstrate agroforestry as a practical option for conventional farmers who may be reluctant to adopt new systems. The management responsibilities are divided between Inagro, which handles tree care, flower strips, and hedges, and a local farmer who is responsible for cultivating the intercropped crops. With this collaboration, Inagro ensures that the agroforestry system remains relevant to local farming contexts while gathering first-hand insights from practitioners in the field.

The plot's dimensions and layout have been carefully planned to accommodate conventional farming machinery, ensuring that local farmers can work efficiently within the agroforestry design. This aspect is critical to engaging farmers and contributing to the economic viability of agroforestry, as it minimises disruptions to their existing operations and allows Inagro to gather insights into the concerns and perspectives of farmers.

Impact and objectives

Inagro's primary objective with this agroforestry plot is to bring agroforestry into the mainstream by demonstrating its feasibility, benefits, and profitability within a local conventional farming context, which faces agricultural challenges such as extreme weather events, soil degradation, and declining biodiversity.

The trees serve as carbon sinks, helping to offset greenhouse gas emissions and mitigate the impact of climate change. The hedges and flower strips add to this by creating additional carbon storage and enhancing soil organic matter.

Economically, the plot serves as a model to evaluate the profitability of agroforestry for conventional farms. Many farmers remain hesitant to adopt agroforestry due to the long-term nature of tree crops and the uncertainty of financial returns. Inagro's research aims to address these concerns by providing science-based evidence of the financial viability of agroforestry systems. By showcasing agroforestry's potential to generate income through both crop yields and timber or nut production, the hope is to reduce financial barriers and encourage farmers to view agroforestry as a viable investment.

As co-founders of the Consortium Agroforestry Flanders, Inagro also prioritises demonstration and knowledge-sharing to foster a wider understanding of agroforestry's potential. Through field visits, workshops, and online communication, they share the findings with farmers, agricultural advisors, researchers, policymakers, and other stakeholders. Looking ahead, Inagro aims to continue refining the system, monitoring its long-term performance, and sharing lessons learned with the farming community. By demonstrating practical solutions and economic viability, the Living Lab aspires to accelerate the adoption of agroforestry in Flanders, contributing to a more sustainable and resilient agricultural landscape.

Further information can be found at <https://inagro.be/>.

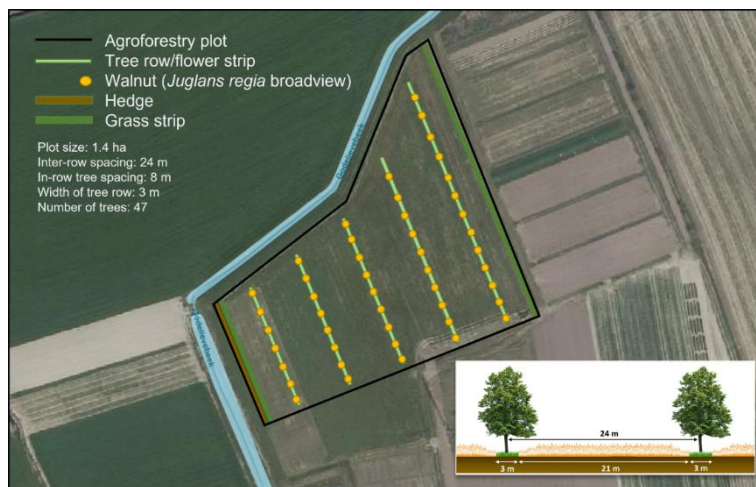


Figure 1. Layout of the agroforestry system at Inagro.



Figure 2. Sampling design followed at Inagro.



Figure 3. Overview of the agroforestry system at Inagro.

Combined Food and Energy system (CFE) - Denmark

The Combined Food and Energy (CFE) agroforestry system is located at the University of Copenhagen's experimental farm in Taastrup, Denmark, at an elevation of 20 meters above sea level. Established in May 1995, this site serves as a long-term research and educational platform under the Department of Plant and Environmental Sciences, Faculty of Science. Before the CFE system's implementation, the land was managed under a conventional annual crop rotation system.

Farm size and design

The CFE system spans 8 hectares, divided into 7 hectares in 4 alleys of arable land for food and fodder crops and approximately 1 hectare for biofuel production through 5 biomass belts. Designed as an alley-cropping system, the layout alternates between 10.7-meter-wide coppiced short-rotation crops (SRC) and four alleys of food and fodder crops, with each biomass belt spaced 50, 100, 150, or 200 meters apart. The varied distances allow for assessing the spatial influence of biomass belts on adjacent crop production.

The biomass belts include nitrogen-fixing alder (*Alnus glutinosa*), diverse willow clones (*Salix viminalis* "Jor," *Salix dasycladus*, and *Salix triandra* × *cinerea*), and common hazel (*Corylus avellana*). The trees are planted in five double-rows per belt with an intra-row spacing of 0.5 meters, an inter-row distance of 0.7 meters, and a distance of 1.3 meters between double rows. The inner three double-rows consist of willows, bordered by hazel to the east and alder to the west. Overall, the tree density reaches approximately 18670 trees per hectare inside the biomass belts and 1750 for the total agroforestry area.

The food and fodder crops grown in the alleys include winter wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), oats (*Avena sativa*), and a mixed grass-clover ley composed of ryegrass (*Lolium perenne*) and lucerne (*Medicago sativa*). The crop rotation is designed to maintain soil health and includes a pattern of barley undersown with clover/ryegrass, followed by two years of clover/ryegrass ley, and one year of wheat. This rotation provides a balance of food and fodder, with proportions of 45% fodder, 45% food crops, and 10% tree biomass.

Management practices

The CFE system is managed using no-input organic practices. No synthetic fertilisers, herbicides, or pesticides are applied, with soil fertility maintained through biological nitrogen fixation by the alder trees and the bi-annual grass-clover ley. This approach promotes soil biology and reduces the risk of nutrient runoff. Biomass belts are harvested on a four-year cycle, with the wood chips processed and sold to a nearby heat and power station, contributing to renewable energy production. Cereals are harvested annually, and fodder crops are cut 3-4 times per year during the grass ley.

Impact and objectives.

The primary goal of the CFE system is to develop a carbon-neutral model that integrates food, fodder, and bioenergy production, addressing Denmark's environmental and agricultural challenges. Traditional Danish agriculture often relies on intensive chemical inputs, leading to nutrient runoff and leaching that negatively impact downstream ecosystems through phenomena such as algal blooms and subsequent oxygen depletion. In contrast, the CFE system's organic approach mitigates these offsite effects and provides a sustainable alternative aimed at reducing pollution, soil erosion, and the environmental degradation associated with monoculture practices. By fostering biodiversity through a mix of trees, crops, and grasses, the system promotes soil health, provides habitats for beneficial pollinators and predatory insects, and reduces the buildup of pests and diseases, thereby promoting natural pest control.



Figure 4. Aerial view and layout of CFE agroforestry system.



Figure 5. Crop alley and tree belt at the CFE agroforestry system.

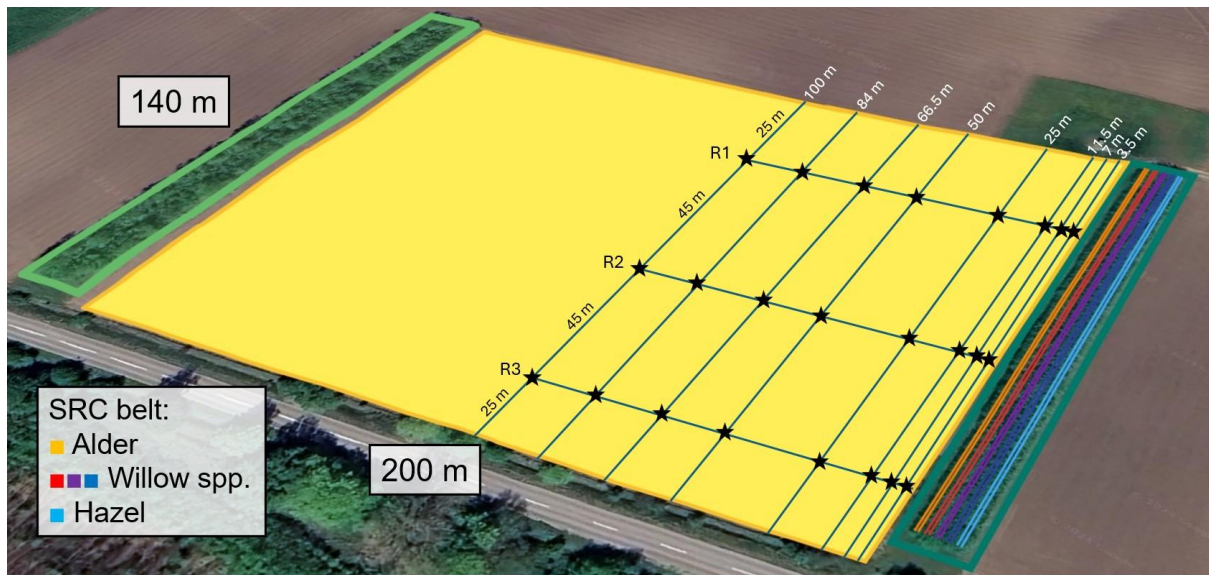


Figure 6. Sampling design followed in the CFE.

Hof Lebensberg – Germany

The Hof Lebensberg farm, located near the town of Obermoschel in the RhinelandPalatinate region of Germany, is a pioneering farm that embodies the principles of regenerative and sustainable agriculture. The farm is situated on a plateau surrounded by a mountainous area characterised by sandstone and volcanic soils from the nearby Donnersberg volcanic mountain. Spanning 40 hectares, of which 28 hectares are actively cultivated, Hof Lebensberg benefits from an annual average precipitation of 725 millimetres. These conditions create an ideal environment for a diverse range of crops and trees.

Farm design and management

Hof Lebensberg employs syntropic agricultural principles under certified organic standards, with a keyline design for efficient water management. The farm operates under a community-supported agriculture (CSA) model, engaging local communities in sustainable food production and distribution. The farm features two major agroforestry plots, each designed with specific objectives and crop combinations.

The Nuts System was established during the winter of 2020/2021 and covers 7.53 hectares. This plot features 30,000 trees and shrubs, comprising 674 main trees that include a mix of hazelnuts (*Corylus avellana*), walnuts (*Juglans spp.*), chestnuts (*Castanea sativa*), pecans (*Carya illinoensis*), cashews (*Anacardium occidentale*), almonds (*Prunus dulcis*), and hickory (*Carya spp.*). Fast-growing tree species, planted alongside the main trees, are utilised for biomass production and as mulch. Understory shrubs and flowering strips are also integrated into the design to support biodiversity and soil health. The plot's structure includes 15-meter spacing between tree rows and 3-meter spacing between main trees within rows, resulting in a total density of 450

trees/hectare. Crops such as wheat, spelt, einkorn wheat, and rye, as well as vegetables like potatoes, are cultivated between the rows.

The Fruits System was established in 2022/2023 and spans 10 hectares. With a similar layout to the Nuts System, this plot hosts 60,000 trees and shrubs at a density of 1400 trees per hectare, including fruit-bearing species such as apples (*Malus domestica*), pears (*Pyrus spp.*), or quinces (*Cydonia oblonga*). Cover crops, such as clover, are planted between tree rows to enhance soil fertility. Plans for this plot include cultivating pumpkins, further diversifying the farm's output and enhancing its ecosystem services.

Beyond the agroforestry plots, Hof Lebensberg incorporates three greenhouses, a vegetable garden, and a rye field. A mobile chicken coop is used in the rye field, providing natural fertilisation and enhancing nutrient cycling. Cattle rearing will be added in the future to further integrate livestock into the system.

Products and outputs

Hof Lebensberg produces a wide range of high-quality agricultural products. These include cereals and vegetables, and the farm's tree crops yield a variety of fruits and nuts. Additional products include herbs, berries, and perennial specialities, which cater to local markets and CSA members. The farm also serves as a hub for knowledge exchange, hosting workshops, excursions, and ecotourism activities to promote sustainable agriculture. This diversified production ensures a steady food supply while supporting the farm's economic viability.

Impact and objectives

The farm's vision is rooted in restoring soil balance and creating a resilient, multifunctional ecosystem. The soils at Hof Lebensberg had been significantly degraded due to years of monocropping and erosion. Recognising the urgent need for soil restoration, the farm adopted a regenerative approach using green manure crops and the terra preta method.

Flowering strips and diverse woody species support pollinators and wildlife, increasing on-farm biodiversity. Fast-growing trees similarly play a key role in the agroforestry system. Planted at high densities within the plots, these trees generate large quantities of biomass, which is periodically chipped and incorporated into the soil. This practice not only enriches the soil with organic matter but also helps to stabilise the soil structure and improve water infiltration. By restoring soil fertility, Hof Lebensberg aims to address the challenges of soil degradation, biodiversity loss, climate resilience, and food security, while ensuring the long-term sustainability of its agricultural systems. Socially, the farm fosters community engagement, educational activities, and collaboration with researchers, positioning itself as a regional model for sustainable farming.

Further information can be found at:

<https://www.hoflebensberg.de/landwirtschaft#agroforst>

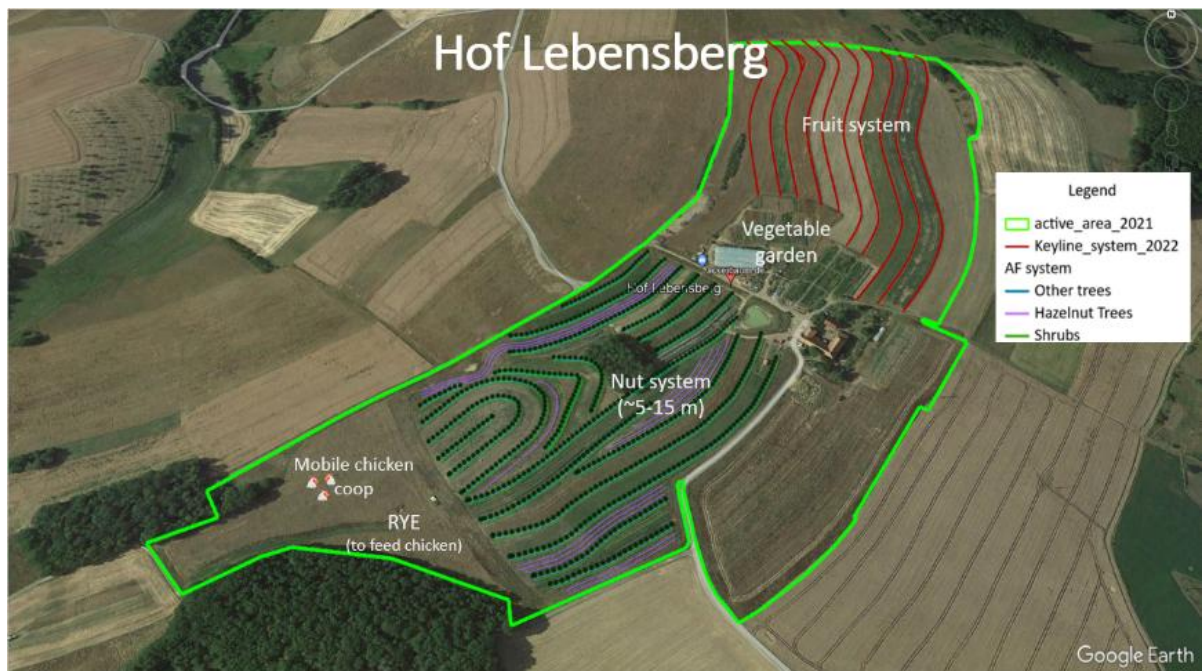


Figure 7. Aerial view and layout of Hof Lebensberg agroforestry system.



Figure 8. Crop alleys and tree belts in Hof Lebensberg agroforestry system.



Figure 9. Sampling design followed in Hof Lebensberg.

Gibside Community Farm – UK-North

Situated in the cooler climate of northern England, Gibside Community Farm operates in a region characterised by moderate precipitation and exposure to challenging growing conditions, particularly at higher elevations. At relatively marginal conditions for vegetable farming, the farm utilises agroforestry practices that combine a silvo-horticultural system with organic vegetable production to address challenges such as exposure to wind and other environmental pressures. Operating as a community-supported agriculture (CSA) initiative, the farm integrates local community involvement into its organic food production, creating a sustainable model that addresses both social and ecological needs.

Farm size and design

Gibside Community Farm encompasses a 1.4-hectare silvo-horticultural system that forms part of a larger 5.7-hectare field. The farm is designed to integrate vegetable production with trees in a way that optimises both ecological and agricultural outcomes.

Seven vegetable plots, each measuring 21 meters wide by 100 meters long, are separated by 3-meterwide belts of trees. This design yields a tree density of 430 trees per hectare, allowing sufficient space for agricultural machinery to operate efficiently and minimise tree-crop competition. The alleys are also oriented north-south to ensure minimal competition for sunlight and maximise wind protection, crucial for the farm's exposed location.

The vegetable plots follow a 7-year crop rotation system designed to sustain soil fertility and control pest buildup. The rotation includes 3 years of vegetable crops—potatoes, brassicas, and alliums—followed by 4 years of green manure to restore the soil. To further enrich the soil, horse manure sourced from a nearby stable is applied to the beds. In addition, the farm features a large greenhouse to supplement vegetable production and a hay area used for producing approximately 10 silage bales annually, which are processed by a contractor.

The farm's silvo-horticultural design incorporates a diverse array of tree species chosen for their multifunctional benefits, including wind protection, fruit production, and potential future uses such as energy biomass. These include basket willow (*Salix* spp.), hazel (*Corylus avellana*), and a combination of delicate and hardy fruit trees. Beyond these three rows, a dedicated fruit orchard is positioned in the northwest corner of the farm. This orchard comprises 44 apple trees, representing a carefully selected mix of varieties that provide staggered harvests over an extended period.

Surrounding the farm are strategically placed shelterbelts. These include several rows of semi-mature native species, such as walnut, sweet chestnut, and medlar, which contribute not only to substantial wind protection but also to biodiversity and carbon sequestration.

Production and outputs

Gibside Community Farm produces a range of organic crops, including wheat, barley, beans, potatoes, brassicas, and alliums. The fruit orchard contributes apples, while the tree alleys provide additional fruit and wood biomass, which contribute to the economic viability of the agroforestry project.

Environmental and social impact

The incorporation of trees into the farm's design delivers multiple environmental benefits. The trees act as a carbon sink, contributing to climate change mitigation by sequestering carbon dioxide. The shelterbelts and tree alleys enhance biodiversity by creating habitats for a variety of wildlife, while also forming a microclimate that improves conditions for crop growth, stabilises the soil, and increases organic matter. The reduction of wind exposure across the farm is particularly critical, given its high elevation location.

The farm's CSA model distributes the organic products directly to local members, reinforcing its connection to the community. Volunteers and workshares actively participate in the farm's operations, creating opportunities for residents to engage with sustainable agriculture whilst improving the economic viability of the farm and strengthening local social cohesion. Surplus produce is donated to a local soup kitchen or shared through gleaning initiatives, ensuring that no food goes to waste.

Challenges and objectives

The farm has also faced some challenges, including the failure of certain tree rows in its windbreak system. Plans are underway to replace these rows and expand tree cover by incorporating additional species, potentially including medicinal trees. The farmers also hope to explore the integration of livestock into their systems, recognising the potential for trees to provide shelter, particularly in the winter months, and additional resources for grazing animals in upland areas. The farm recognizes the potential for private financial incentives in the future tied to tree planting, which could provide additional income.

Further information can be found at <http://gibsidecommunityfarm.co.uk/>



Figure 10. Sampling design following at Gibside.



Figure 11. Crop alleys and tree belts at Gibside Community Farm.

Wakelyns – UK-South

Established in 1992 in Suffolk, England, by plant pathologist Professor Martin Wolfe and his wife Ann Wolfe, their vision sought to transform a landscape previously subjected to intensive, chemically aided farming into a thriving ecosystem where biodiversity, productivity, and resilience coexist harmoniously.

The transformation of Wakelyns began as an experiment to demonstrate that alternative, sustainable food production systems could be not only scientifically viable but also practically advantageous. Over the years, the farm has evolved into a living laboratory, integrating a diverse array of trees and crops within an organic framework. Today, Wakelyns serves as a hub for research, education, and outreach, hosting workshops, courses, and public events to promote agroforestry adoption. This approach showcases how polyculture systems can replace industrial monocultures to achieve long-term agricultural sustainability.

Farm size and design

Wakelyns is characterised by its four silvoarable systems: short rotation coppiced willow and hazel, mixed top fruit and nut trees, and mixed hardwood trees. These are arranged in rows interspersed with 10-12 meter wide crop alleys. This layout was designed to increase spatial and species diversity, providing benefits such as pest and disease control, biodiversity enhancement, and climate resilience.

The North Field, covering approximately three hectares, represents a key example of this integrated design. In February 2001, 20 walnut trees were planted in this field in rows separated 13 to 16 m, followed by the addition of various plum varieties in January 2002.

Over time, supplementary planting of walnut and plum trees, as well as interspersed vines, has occurred. The 3 m-wide tree rows are managed to maintain form, with lower limbs pruned to facilitate crop cultivation in adjacent alleys. A grassy sward has naturally regenerated within the tree rows, maintained through regular mowing to prevent scrub growth and support the ecosystem.

Management practices

Wakelyns operates under organic principles, avoiding external chemical inputs and emphasizing natural ecosystem processes. The diverse range of outputs includes timber, fruit and nuts, vegetables, cereals, pulses, and hay. Specialty products such as juice and cider are produced from farmgrown fruits, while hazel and willow coppices provide raw materials for bioenergy. The woodchip generated from these species is used to fuel a boiler that meets the farmhouse's year-round heating needs, exemplifying the feasibility of decentralised energy production. Wakelyns also incorporates on-farm processing and value-added activities, such as milling grains and producing bakery goods, which strengthen its economic sustainability.

Through collaborations with local businesses, the farm has facilitated the development of British-grown pulses like multiple varieties of lentils. Wakelyns also supports the local community by producing food for nearby markets and hosting events where visitors enjoy meals made from the farm's produce.

Environmental and social impact

The primary aim of Wakelyns centres is to increase diversity at every level of the agricultural system, inspired by the belief that adaptation to environmental conditions through diversity leads to greater productivity and resilience. Wakelyns applies this philosophy by integrating a wide array of crops, from annual cereals and vegetables to perennial herbs and trees, as well as livestock, moving away from industrialised monocultures. Its diversified systems contribute to pest and disease control, pollinator habitats, and soil health, while reducing the risks associated with farming single commodities. The farm also highlights how smallscale agriculture can mitigate climate change by fostering carbon sequestration and reducing reliance on fossil fuels.

Another central aim is to decentralise agriculture, enabling local production to support local consumption and challenging globalised food systems dominated by multinational corporations. By working closely with local communities, Wakelyns has inspired similar initiatives across the region and provided practical evidence that sustainable, localised agriculture is not only feasible but also highly productive.

As a pioneering example of innovative agroforestry practices in the UK, this farm has been extensively studied throughout its development. Further information can be found at

<https://wakelyns.co.uk/>.



Figure 12. Aerial view and layout of the north field at Wakelyns agroforestry system.



Figure 13. Agroforestry system at Wakelyns farm. Source: Smith and Westaway (2020).