MIXED

EFFICIENT AND RESILIENT MIXED FARMING & AGROFORESTRY

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## Table of changes made in revising the submitted deliverable (if applicable)

| Comment in review report | Response to comment | Page (paragraph) revised |
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# Recorded webinar

The hyperlink below loads the recorded webinar that presents the results of the modelling of the transitions of specialist farms to MiFAS scenarios. It uses four farm type case studies to show the potential impacts on the farming system, environmental and economic performance of the adoption of mixed, agroforestry or organic practices. The following executive summary then provides background material and an overview of the results, presented in the recorded webinar for Deliverable D5.4. The webinar is available at:

https://youtu.be/blIzb6Nw9YA?si=h4-Wxm_QNQtMB4AK

# Executive Summary

Globally, agriculture produces over 9 billion tonnes of CO2 equivalents annually (FAO, 2020), whilst increased farm specialization in Europe has led to greater separation between crop and livestock production, causing water contamination from excess nitrates and pesticides. Intensive livestock systems, particularly poultry, contribute significantly to environmental degradation through air, water, and soil pollution (Gržinić et al., 2023) and intensive farm systems are a major cause of climate change, pollution, biodiversity loss, and rural social issues (Garrett et al., 2020).

Mixed farming, integrating livestock and crops, has been proposed as a solution to reduce environmental impact by improving nutrient cycling and decreasing reliance on external inputs (Nesme et al., 2015). However, even mixed systems can be intensive, with nutrient flows often one-way, leading to excess nutrients and limited environmental improvement. Organic farming, which restricts external inputs and relies on a more circular system, offers a potential alternative. However, whilst reducing nutrient excesses, it may yield lower output and sometimes higher environmental impacts per product unit (Meier et al., 2015), although recent studies suggest similar impacts per product with lower land use (Hashemi et al., 2024). Agroforestry, incorporating trees alongside crops and/or livestock, is another promising innovation and can provide multiple environmental benefits, including carbon sequestration, nutrient cycling, biodiversity enhancement, and water retention (Sollen-Norrlin et al., 2020). However, the extent of carbon sequestration depends on biomass, and in short-cycle systems, it may only extend the carbon cycle rather than significantly reduce atmospheric CO2 (Quinkenstein et al., 2009).

Assessing these complex systems is challenging, as most studies focus on specialized systems and simplify farm dynamics. Integrated crop-livestock systems require a holistic approach, considering all interdependencies (Kronberg et al., 2021). The MIXED project aimed to evaluate the environmental performance of mixed and agroforestry-based systems compared to conventional agriculture. Due to the diverse nature of farms, the identification of causes for variations in performance can be challenging. We therefore adopted a modelling approach to study the environmental and economic impacts of the transitioning of four European conventional farm types (cropping with ruminants, intensive dairy, cropping with laying hens, and specialist pig farms) to mixed, agroforestry, or organic practices. Following LCA guidance within ISO14040 and ISO14044 guidelines, the study objectives were to evaluate the environmental and economic performance changes at the whole farm level and for key products (wheat, milk, pork, and beef) by applying cradle-to-farm-gate partial lifecycle assessments. Farm scale impacts were assessed for per hectare and per 100g protein functional units, whilst at product level per kg of product was used.

The baseline (**BASE**) systems were characterised from a combination of structural data from the 2020 FADN database, as well as relevant literature sources. The **MIXED** scenarios aimed to improve integration of cropping and livestock, reducing external inputs like fertilisers and feed. Nutrient and feed plausibility checks were performed using FarmLCA and Swiss GRUD recommendations. Two case studies incorporated agroforestry (**MiFAS**) by adding trees to pastures for nut production or bioenergy while providing carbon sequestration and livestock benefits. For two other case studies, organic (**ORG**) practices were adopted, including reduced stocking densities and legume-based rotations, with adjusted yields.

The baseline UKC system, a Scottish specialist cereal and oilseed rotation farm, included small beef and sheep enterprises with most crop outputs sold and nutrition based on mineral fertilisers and livestock diets using homegrown grain and imported feed. The MIXED system introduced legumes and grass-clover forage, reducing nitrogen fertiliser use and feed imports while maintaining productivity. The MiFAS system added walnut trees to pastures for nuts, carbon sequestration, and livestock shelter. Winter cereal grazing for lambs replaced concentrate feed, with surplus forage sold.

The baseline DED system was a specialist intensive dairy farm in Schleswig-Holstein/Hamburg, NW Germany. The BASE system relied on maize silage, grass silage, and permanent grass, with all dairy cattle housed continuously and manure stored as slurry. Feed included maize and grass silage with external concentrates at 0.31kg DM per kg of milk. For MIXED, external inputs were reduced by converting maize silage land to cropping land for livestock feed and human food supply (~50% of crop output). Smaller, more robust cows suitable for grazing replaced the larger BASE cattle, but cow numbers were reduced by 50% to balance forage and feed availability. Housing used more straw to reduce slurry and increase carbon return to soils. For ORG organic practices were adopted, enhancing nutrient circularity through legumes and manures. Cow numbers and type mirrored the MIXED system, with smaller cows, producing lower milk yields. Around 50% of crop produce by value was exported due to reduced concentrate needs. This system prioritized self-reliance and sustainability.

The selected specialist Polish cropping farm in Wielkopolska and Slask (FADN type: Specialist COP, 15). BASE farm operations included a simple rotation of cereals and grain legumes, with an added indoor laying hen enterprise (10,000 hens) for scenario comparability. Feed for hens was fully imported, while manure was distributed on arable and grassland, supplemented by mineral fertilisers. Crop yields were based on Polish agricultural statistics and feeding parameters were derived from literature. For MIXED external inputs were reduced and enhanced animal welfare system of hens on grassland (10% manure deposited outdoors) was adopted. Feed dependency on soybean imports was reduced by incorporating on-farm fava beans (+5 ha planted) and crops, covering 70% of feed needs while maintaining 50% of crops for sale and adjustments to hen productivity, mortality, and diet followed Leinonen et al. (2012). The MiFAS scenario introduced agroforestry with poplar energy crops for additional revenue and shade for laying hens. Laying hen numbers were reduced by 40% to improve welfare, while 62% of feed requirements were met on-farm (26% of total crop harvest). Productivity and mortality were adapted, with poplar modelled using MIXED project data.

The selected specialist pig farm in Bretagne, France (FADN type: Specialist Granivore, 50), with BASE system featuring a large indoor breeding and finishing pig enterprise and arable crops being sold. All pig feed was imported and slurry exported to a biogas plant, with digestate returned for crop fertilisation. Feed composition and productivity were based on Dorca-Preda et al. (2021). The MIXED scenario integrated crop and livestock enterprises, reducing external feed dependency by adding protein peas, but despite feeding all farm crops, only 28% of pig feed needs were met. Legume nitrogen reduced fertiliser and feed-imported nitrogen inputs. The ORG scenario transitioned to organic pig production, with sows housed outdoors in huts on temporary grass-clover leys and finishing pigs remained indoors at lower stocking densities in deep litter barns. Pig numbers were reduced to 20% of BASE levels to limit manure nitrogen load. Organic guidelines were followed, requiring at least 20% homegrown feed, with forage legumes partially replacing concentrates. Organic cropping inputs and outputs were adapted from Swiss ecoinvent data.

The study assessed whether mixed, agroforestry, or organic adaptations to conventional farming systems could improve environmental performance at both the farm and product levels, focusing on wheat, milk, pork, and beef. It also addressed methodological challenges and provided overall conclusions.

The UK system incorporating legumes into the rotation reduced external inputs and improved nitrogen use efficiency, leading to a decrease in environmental impacts. Adding agroforestry reduced the carbon footprint by 4%. The MIXED and MiFAS scenarios reduced feed impacts, leading to an 8% reduction in carbon footprint. Financial performance improved by 7% and 11% for MIXED and MiFAS, respectively. The German dairy farm reduced external inputs by switching to a MIXED dairy and cropping system, cutting carbon footprint by 60%. A transition to organic farming further reduced impacts by 70%. While the MIXED scenario increased costs, ORG maintained performance due to organic price premiums. In Poland, adapting to a MIXED system with homegrown feed reduced impacts per hectare, but impacts per 100g protein increased. The MiFAS system reduced impacts by 40% per hectare with similar protein outputs. Economic performance improved with MiFAS due to reduced costs and egg price premiums. In France, the MIXED system reduced nitrogen inputs by 21%, but the carbon footprint slightly increased. The ORG scenario, which eliminated mineral fertilizers and reduced feed imports, achieved significant reductions in carbon footprint and increased net margin by 183%, despite higher feed costs.

## System perspective

The results showed that through the adoption of alternative strategies, external nutrient inputs from mineral fertiliser and feeds could be reduced. In many situations this helped reduce excess nutrient balances, improved nutrient circularity and maintained or improved nutrient use efficiency. Analysing the overall impacts of system changes across the four case studies, Table 1 shows that for per hectare values, all system transitions resulted in reduced environmental impacts for carbon footprint, acidification and eutrophication. However, when assessed per 100g protein, we found that MIXED systems had variable results due to reduced output, especially for pig and poultry systems, whilst MiFAS and ORG were able to achieve reduced impacts for all case studies and indicators. However, it should be noted that the fundamental change in farm systems resulted in changes in the balance of outputs (crop vs livestock) and could have further impacts on land use in terms of quantity and type, however all scenarios showed reduced impacts per hectare, decreasing local impacts.

Table 1 Comparison of changes in case study Carbon Footprint (CF), Terrestrial Acidification (TAC) and Freshwater Eutrophication (FEU).

| | | Per hectare[1] | | | | Per 100g protein[1] | | | |
|---|---|---|---|---|---|---|---|---|---|
| Impact | Case Study | BASE | MIXED | MiFAS | ORG | BASE | MIXED | MiFAS | ORG |
| CF | UKC | 8921 | -12% | -12% | | 1.38 | -15% | -19% | |
| kg CO2 eq | DED | 19426 | -60% | | -70% | 3.98 | -60% | | -59% |
| | PLC | 6783 | -21% | -36% | | 0.81 | 36% | -3% | |
| | FRP | 26141 | -14% | | -83% | 1.27 | 30% | | -59% |
| TAC | UKC | 0.10 | -9% | -10% | | 1.5E-05 | -13% | -17% | |
| kg SO2 eq | DED | 0.61 | -69% | | -71% | 1.2E-04 | -69% | | -60% |
| | PLC | 0.17 | -14% | -37% | | 2.0E-05 | 47% | -6% | |
| | FRP | 0.75 | -10% | | -69% | 3.6E-05 | 36% | | -25% |
| FEU | UKC | 0.41 | -6% | -7% | | 6.3E-05 | -10% | -14% | |
| kg PO4 eq | DED | 1.18 | -62% | | -63% | 2.4E-04 | -62% | | -49% |
| | PLC | 1.01 | -22% | -40% | | 1.2E-04 | 34% | -10% | |
| | FRP | 2.88 | -20% | | -76% | 1.4E-04 | 21% | | -42% |

[1] BASE values $ha^{-1}$ or 100g $protein^{-1}$, Change values as % change from BASE

UKC: UK Cropping, DED: German Dairy, PLC: Polich Cropping, FRP: French Pig farm

Assessing the impacts at crop level across the four case studies, Table 2 shows that for per kg of crop, the MIXED and MiFAS values for wheat were similar, whilst for ORG, results were more variable. For ORG, whilst forage values all improved, the wheat TAC and FEU values increased slightly to strongly, which is often seen within organic systems due to yield reductions and use of organic manures, compared to the conventional BASE system.

Table 2 Comparison of changes in case study crop product impacts for Carbon Footprint (CF), Terrestrial Acidification (TAC) and Freshwater Eutrophication (FEU).

| | | | Per kg crop (fresh) [1] | | | |
|---|---|---|---|---|---|---|
| Impact | Case Study | Crop | BASE | MIXED | MiFAS | ORG |
| CF | UKC | Wheat | 0.53 | -8% | -11% | |
| kg CO2 eq | DED | Temp. forage | 0.10 | 7% | | -50% |
| | PLC | Wheat | 0.42 | 0% | 2% | |
| | FRP | Wheat | 0.57 | -2% | | -48% |
| TAC | UKC | Wheat | 6.2E-06 | -10% | -12% | |
| kg SO2 eq | DED | Temp. forage | 8.4E-06 | -55% | | -63% |
| | PLC | Wheat | 1.3E-05 | 0% | -10% | |
| | FRP | Wheat | 1.8E-05 | -1% | | 4% |
| FEU | UKC | Wheat | 4.4E-05 | -3% | -7% | |
| kg PO4 eq | DED | Temp. forage | 1.7E-05 | -24% | | -29% |
| | PLC | Wheat | 5.3E-05 | 1% | 1% | |
| | FRP | Wheat | 4.8E-05 | -4% | | 42% |

[1] BASE values as kg product$^{-1}$. Change values as % change from BASE

UKC: UK Cropping, DED: German Dairy, PLC: Polich Cropping, FRP: French Pig farm

For livestock products, Table 3 summarises that for ruminant products, the environmental impacts were reduced, but for the eggs and pork, the situation was much more variable. In particular, the TAC was considerably worse for both eggs and pork, in part due to higher impacts from homegrown feeds that achieved lower yields than the typical sourcing regions as well as feed crops receiving manure, resulting in greater TAC impacts. However, a lower CF for the pig and poultry ORG cases is achieved through savings in mineral fertiliser.

Table 3 Comparison of changes in case study livestock product impacts for Carbon Footprint (CF), Terrestrial Acidification (TAC) and Freshwater Eutrophication (FEU).

| | | | Per kg product[1] | | | |
|---|---|---|---|---|---|---|
| Impact | Case Study | Product | BASE | MIXED | MiFAS | ORG |
| CF | UKC | Beef (LW) | 15.91 | -8% | -8% | |
| kg CO2 eq | DED | Milk (ECM) | 1.29 | -4% | | -18% |
| | PLC | Eggs | 2.75 | -1% | 7% | |
| | FRP | Pork (LW) | 2.64 | 2% | | -24% |
| TAC | UKC | Beef (LW) | 2.2E-04 | -6% | -7% | |
| kg SO2 eq | DED | Milk (ECM) | 4.0E-05 | -28% | | -22% |
| | PLC | Eggs | 6.3E-05 | 17% | 13% | |
| | FRP | Pork (LW) | 7.5E-05 | 7% | | 41% |
| FEU | UKC | Beef (LW) | 4.6E-04 | -10% | -10% | |
| kg PO4 eq | DED | Milk (ECM) | 7.8E-05 | -21% | | -19% |
| | PLC | Eggs | 4.8E-04 | -6% | 0% | |
| | FRP | Pork (LW) | 3.1E-04 | -10% | | -1% |

[1] BASE values ha$^{-1}$ or 100g protein$^{-1}$, Change values as % change from BASE

UKC: UK Cropping, DED: German Dairy, PLC: Polich Cropping, FRP: French Pig farm

Overall, the results showed that the adoption of MIXED practices has the effect of integrating nutrient flows within the farm system, but this can often only provide minor, or sometimes even negative changes in environmental impacts or economic performance. We found that greater system change, such as MiFAS or ORG practices adoption provided a better level of performance improvement. However, studies such as Smith et al. (2019), Mueller et al. (2017) and Kremmydas et al. (2024)

showed that widescale adoption of organic production could have impacts on food provision, nutrient supply and economic performance. Therefore, more drastic farm system adaptations need to be linked to consumption and whole food system changes (Moschitz et al., 2021), related to reduced livestock product consumption and greater diversity of products (Gliessman, 2016; Simon et al., 2024). Furthermore, whilst price premia may support more extensive production methods that reduce environmental impacts, transition periods from existing specialised systems could take years before production stabilises or reaches similar levels to before (Schrama et al., 2018), therefore policy support through and payments and advice to farmers would likely be required (Ruggeri Laderchi, C. et al., 2024).

**Methodologically**, the FarmLCA tool allowed this study to model a wide range of baseline farm systems and then flexibly adapt those systems to include greater integration, organic and agroforestry elements. Whilst methodological constraints remain, tools such as this respond to the call from e.g. Martin et al. (2020) to develop and utilise farm assessment tools that can include diverse systems and species. Novel advancements within this study included the ability to include grazed winter cereals as a wheat crop co-product within a lamb finishing system as well as co-use of land for e.g. bioenergy trees within free-range chicken outdoor runs. Within the laying hen rangeland, deposited manure emissions were assigned through biophysical allocation to either trees or grazing land, resulting in allocation to either eggs via the intake of grass, or bioenergy timber when utilised as a manure. Whilst the impacts of each are small, improved modelling of complex and novel systems is essential to further our understanding of the likely impacts of these alternative systems. Furthermore, whilst this work was deliberately focussed on the farm level, when modelling significant system changes, impacts beyond the on-farm situation could provide a wider perspective through a consequential basis or through system expansion. This type of analysis would aim to understand the wider impacts of systemic changes, such as significant reductions in livestock production or wide-scale adoption of organic practices, such as attempted by Smith et al., (2019) or Berton et al., (2023).

In **conclusion**, we found that specialised intensive systems can be efficient in their use of nutrients, but their high inputs overburden local environments through excessive nutrient balances and expose farms to price volatility of global commodities. Re-integration of cropping and livestock systems showed some potential to improve environmental indicators when underutilised resources are utilised as inputs to reduce external inputs. However, the straight substitution of externally sourced concentrate feeds for on-farm produced feeds is unlikely to improve environmental performance, and potentially, there may even be a negative effect if on-farm crop yields for feed production are lower than regions producing imported feed. Furthermore, due to inefficiencies in protein use, farm productivity may decline if crop production is utilised on-farm instead of being sold. However, we found that organic production created more balanced systems with high nutrient use efficiency, reduced external reliance on inputs, similar or lower product environmental footprints, as well as potentially improved economic performance due to price premia. We found that agroforestry can provide additional benefits to mixed systems, but these may be time-limited and depend on the scale of implementation and should be applied where their use will enhance rather than reduce productivity. Whilst we found that mixed, organic and agroforestry systems may support more environmentally sound agricultural practices, fundamental change is also required within the whole food system as more diverse farm systems rely on consumers adapting their behaviour. Methodologically, the use of an integrated farm system and LCA tool allowed a diverse range of systems to be assessed, and results compared on an equal basis, but further work is required to improve our understanding of more integrated systems, their impacts on soil carbon changes, nutrient cycles and wider ecosystem service provision.

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