Initial report on studied innovations of agroforestry for arable farmers

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Contents

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1 Context

The AGFORWARD research project (January 2014-December 2017), funded by the European Commission, is promoting agroforestry practices in Europe that will advance sustainable rural development. The project has four objectives:

1. to understand the context and extent of agroforestry in Europe,
2. to identify, develop and field-test innovations (through participatory research) to improve the benefits and viability of agroforestry systems in Europe,
3. to evaluate innovative agroforestry designs and practices at a field-, farm- and landscape scale, and
4. to promote the wider adoption of appropriate agroforestry systems in Europe through policy development and dissemination.

This report (Milestone 17) contributes to the second objective. It describes the initial results of the studied innovations within 13 systems from the participative research and development network focused on the use of agroforestry in arable systems. Similar reports exist for agroforestry of high nature and cultural value, agroforestry with high value trees, and agroforestry for livestock systems. The data included in this report will also inform the modelling activities which help to address Objective 3. Further details of systems associated with the individual innovations can be found in the reference list.

2 Agroforestry for arable farmers

As part of work-package 4 of the AGFORWARD project, a participative research and development network (PRDN) was developed that focuses on agroforestry for arable farmers. Arable agriculture provides large quantities of food, but it can also result in reductions in soil and water quality and biodiversity and the release of greenhouse gasses. The integration of trees within arable systems can provide a variety of ecosystem services, product diversification and improved resource efficiency.

This PRDN has the following objectives:

i. to identify examples of the best practices, key challenges and innovations to address challenges identified by the stakeholder groups within the PRDN,

ii. to describe and explain the key inputs, outputs and ecosystem services flows for case studies (association with work-package 6),

iii. to agree within the PRDN, the key innovations or improvements in knowledge needed in order to promote adoption of high value tree systems,

iv. to agree and implement within the PRDN an experimental protocol to develop and test proposed innovations at existing experimental plots and through on-farm experiments, and;

v. to provide and promote guidelines for farmers on how to establish economically viable agroforestry practice in high value tree systems.

The area of silvoarable agroforestry in the EU, as estimated using the LUCAS land use and land cover dataset, is 358,000 hectares or about 0.1% of the territorial area (den Herder et al. 2017). The largest extent of silvoarable agroforestry can be found in Spain and Italy, followed by Portugal and Greece. Within work-package 4 of the AGFORWARD project stakeholder groups are present in Italy, Greece and Spain together with groups in France, Germany, Hungary, Switzerland, and the UK. The crops cultivated in arable agroforestry systems and studied by these stakeholder groups include cereals, potatoes, root crops, fodder crops (e.g. alfalfa) and pulses.

3 Initial results

This section describes the initial results of the innovations examined by each stakeholder group. For each system, the innovation is described, followed a description of the site and the initial results.

Table 1. Summary of innovations examined with the agroforestry for arable farmers participative research and development network

Institution and country	Stakeholder group	Innovation
USC, Spain	Silvoarable systems in Spain (Mosquera-Losada et al. 2016)	Growing maize within high density silvoarable systems with wild cherry trees Growing medicinal plants within high density silvoarable systems with wild cherry trees
UEX, Spain	Cereal production beneath walnut in Spain (Moreno et al. 2016)	Shade tolerant varieties of wheat and barley that are adapted to agroforestry systems
INRA, France	Mediterranean silvoarable systems in France (Gosme and Meziere 2016)	Breeding for shade tolerant varieties of wheat that are adapted to agroforestry systems
INRA, France	Weed study (Meziere and Gosme 2016)	Reduced weed competition and biodiversity potential of agroforestry systems
CNR/VEN, Italy	Trees for timber with arable crops in Italy (Paris et al. 2016)	Crop yield effects due to tree hedgerows
TEI, Greece	Silvoarable agroforestry in Greece (Mantzanas et al. 2016)	Combining the cultivation of dry beans and cereals with fast growing species (poplars) and walnuts inside or at the edges of small farms.
AFAF/IDF, France	Agroforestry for arable farmers in Western France (van Lerberghe et al. 2016)	Tree and crop yield potential within older agroforestry plantations
APCA, Picardy, France	Agroforestry for arable farmers in Northern France (Wartelle et al. 2016)	Effect of agroforestry age on weed abundance and biodiversity potential (number of species). Differences between conventional and organic systems
ORC, UK	Silvoarable agroforestry in the UK (Smith 2016)	Development of agroforestry adapted wheat populations (i.e. ‘alley-edge’ selected lines will perform better in the ‘alley-edge’ plots than ‘alley-centre’ lines)
ORC, UK	Silvoarable agroforestry in the UK (Smith and Venot 2016)	Managing the tree understorey for increased food production and biodiversity
BTU, Germany	Alley cropping systems in Germany (Mirck et al. 2016)	Effect of tree hedgerows on crop yield
EVD, Switzerland	Silvoarable agroforestry in Switzerland (Petrillo and Herzog 2016)	Monitor changes in farmers perception of agroforestry systems
NYME, Hungary	Alley cropping in Hungary (Vityi et al. 2016)	Effect of tree hedgerows on crop yield

3.1 Silvoarable systems in Spain

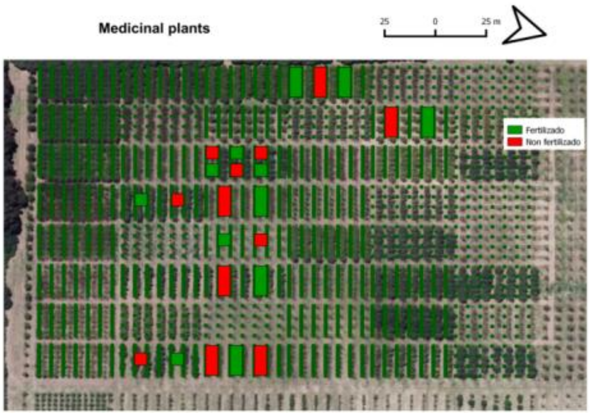
Summary of innovation

Growing maize and medicinal plants within high density silvoarable systems with wild cherry trees

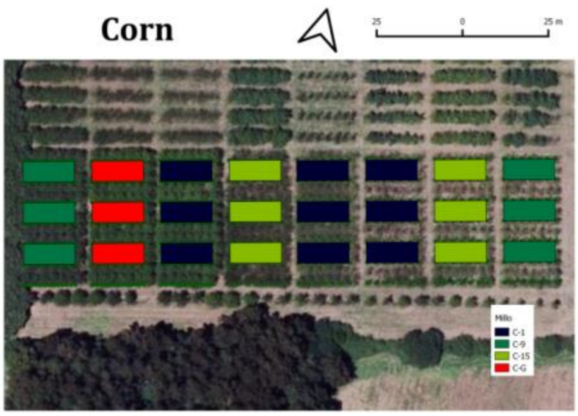
Experiments where medicinal plants are grown between wild cherry trees

Intercropping with maize between wild cherry trees

Map of system



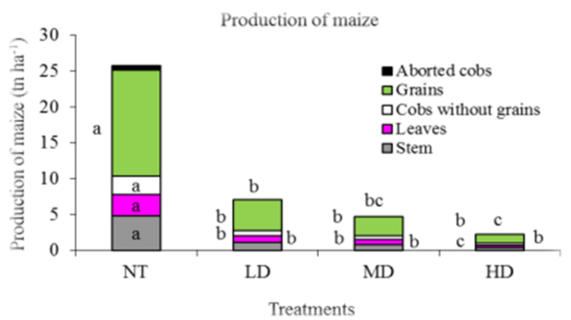
Location of the fertilised and non-fertilised plots. The areas shaded green were fertilised with 5 t ha^{-1} of sheep manure and mineral fertiliser. The red areas received no fertilisation.



Blue, dark green, light green, and red areas represent the C-1, C-9, C-15 and C-G wild cherry clones, respectively. The control treatment is a conventional agricultural field adjacent to the tree experiment (out of the range of this photo)

Tree component	Crop component
The tree species in the alley cropping system with medicinal plants consists is wild cherry (*Prunus avium* L.). The plantation densities are 6 m x 1.25 m and 6 m x 2.5 m, equivalent to 1333 and 667 trees per hectare, respectively. The trees were planted in 2008. The treatments consist of two tree densities where the medical plants (*Melissa officinalis* L. and *Mentha x piperita* L.) were established without fertilisation or with organic fertilisation (5 t ha^{-1} of sheep manure) combined with mineral fertiliser. The experiment with maize is at the same site as the medicinal plant experiment in Sendelle. The maize experiment includes three plantation densities (6 m x 5 m, 6 m x 2.5 m and 6 m x 1.25 m equivalent to 333, 667, and 1333 trees per hectare).	The medicinal plants are planted in the 6 m wide alleys in a randomized block design with three replicates. The plants have been planted in 4 m alleys, leaving a 1 m buffer between the base of the tree and the crop. Each experimental plot comprises the area between 7 trees (i.e. 6 x 7.5 m^2 = 45 m^2 and 6 x 15 m^2 = 90 m^2). The maize (variety: DKC 4608 Ponho) was planted using conventional machinery in 3 m alleys, leaving 1.5 m of distance between the alley at the base of the trees (1.5 m both sides of the tree row). The distance between plants rows was 0.75 m and the distance between plants within a row was 0.15 m. Each experimental plot had an area of 36 x 15 m^2 (7 trees separated by 6 m (6 m x 6 m) x 13, 7 or 4 rows of trees (12 m x 1.25 m, 6 m x 2.5 m or 3 m x 5 m)). Two control treatments were also established: maize grown in tree-less areas and trees grown without maize at the three plantation densities.

Initial results



The maize yield and production of the different components of maize (aborted cobs, cobs without grain, stems, grains and leaves) was measured in four treatments in 2015.

NT: 0 trees ha^{-1}, LD: 333 trees ha^{-1}, MD: 666 trees ha^{-1} and HD: 1333 trees ha^{-1}. Different letters indicate significant differences between treatments according the LSD test.

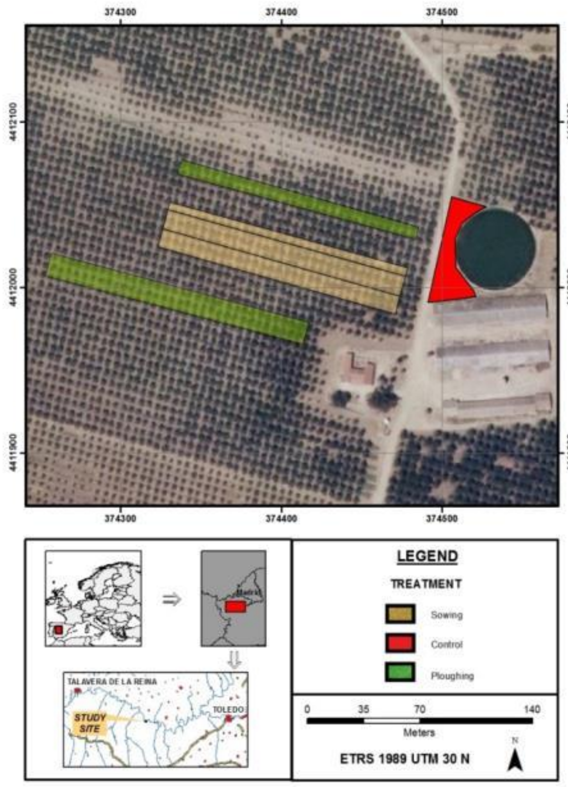
3.2 Cereal production beneath walnut in Spain

Innovation

Shade tolerant varieties of wheat and barley that are adapted to agroforestry systems

Cereals grown beneath walnut; the irrigation system for the trees can be seen in the tree row on the left hand side.

Cereals grown in an open field; colours show different varieties of wheat and barley



The layout of the experimental area during the 2014-2015 cropping season. The experiment to test the effect of shade included:

- Four varieties of wheat (*Triticum aestivum*):CCB Ingenio, Sublim, Nogal
- Four varieties of barley (*Hordeum vulgare*):Basic, Lukhas, Hispanic, Rgt Dulcinea
- One variety of triticale: Verato

(In 2013-2014 and 2015-2016 some varieties changed)

The trial includes three treatments:

1. Silvoarable, where the cereals are cultivated in alleys between walnut lines. This includes five replicated blocks (alleys) with the 9 varieties in each block; 4 x 20 m each plot. The cultivated area includes four lines of trees (perimeter lines excluded) with 36 trees each line
2. Agricultural control, where cereals are cultivated in an open area. This includes four replicated blocks with the 9 varieties in each block; 2 x2 m each plot.
3. Forest control, where trees growth without cereal in the alleys. Include four lines of trees, with 36 trees each line.

Tree component	Crop component
The walnut hybrid Mj209xRa *Juglans major* x *J. regia* is more tolerant of less well-drained sites. *J. major* is a walnut tree which grows to a height of 15-20 m that originates from the southwest of North America. *J. regia* is a walnut tree from Eurasia which grows to a height of 25-30 m. The	The crop alley had a width of 6 m. Different cereal species and cultivars have been cultivated in autumn (and harvested the spring of the following year) in the 4 m wide alleys in between tree rows (1 m uncultivated at both side of the tree rows). After ploughing, cereals were sown in autumn

resulting hybrid exhibits vigorous growth.

In the experiment, walnut trees were planted in 2007 at a regular spacing of 5 m x 6 m (333 trees per ha). In February 2016, the mean tree height was 10-11 m and the diameter at breast height was 16.3 cm.

2013, 2014 and 2015, at a rate of 200 kg grain ha^{-1} for wheat, and 180 kg ha^{-1} for barley and triticale. In all cases cereal was fertilized with 600 kg ha^{-1} of a 8:12:12 N:P_2O_5:K_2O compound fertilizer at the time of sowing and with 120 kg ha^{-1} of urea (46%) in spring.

Each June, the cereal was sampled at maturity in quadrats of 40 x 50 cm (n = 12-15). Above-ground biomass, grain biomass, number of grain per plant, and grain weight (weight of 100 grains) was measured. The phenological state of the cereal cultivars was assessed in 2016 at the time of walnut leaf-emergence.

Initial results

Cereal species	Cultivar	Mean total biomass ± SD (Mg ha^{-1})		Mean grain yield ±SD (Mg ha^{-1})	
		Control	Intercrop	Control	Intercrop
Barley	Doña Pepa	6.50 ± 1.60	7.83 ± 1.94 *	1.29 ± 0.85	1.94 ± 0.74 *
	Azara	6.13 ± 1.38	7.60 ± 1.76 *	1.09 ± 0.33	1.77 ± 0.85 **
	Mean	6.32 ± 1.50	7.72 ± 1.86 **	1.19 ± 0.65	1.85 ± 0.80 **
Wheat	Kilopondio	8.53 ± 0.82	8.43 ± 1.88	1.20 ± 0.53	1.33 ± 0.38
	Bologna	7.92 ± 1.21	8.14 ± 2.09	1.13 ± 0.34	1.46 ± 0.56
	Mean	8.23 ± 1.08	8.29 ± 1.99	1.16 ± 0.45	1.39 ± 1.99
Total		7.27 ± 1.62	8.00 ± 1.95	1.17 ± 0.56	1.62 ± 0.70

Cereal species	Cultivar	Mean total biomass ± SD (Mg ha^{-1})		Mean grain yield ±SD (Mg ha^{-1})	
		Control	Intercrop	Control	Intercrop
Barley	Basic	5.36 ± 0.97	6.12 ± 1.95	2.29 ± 0.90	3.23 ± 1.01 *
	Hispanic	4.79 ± 0.36	7.24 ± 2.06 **	3.24 ± 0.65	3.68 ± 0.95
	Lukhas	7.38 ± 1.41	7.57 ± 3.04	3.31 ± 0.96	3.91 ± 1.66
	Dulcinea	5.25 ± 0.80	5.96 ± 1.53	3.19 ± 0.84	3.08 ± 0.63
	Mean	5.52 ± 1.24	6.72 ± 2.27 **	3.03 ± 0.91	3.48 ± 1.18 *
Wheat	Ingenio	6.19 ± 0.51	6.97 ± 2.51	2.58 ± 0.77	2.15 ± 0.88
	Nogal	6.26 ± 0.89	6.90 ± 1.76	2.94 ± 0.93	1.89 ± 0.61 **
	Sublim	7.55 ± 1.23	7.70 ± 2.07	5.25 ± 0.99	2.38 ± 0.98 **
	Mean	6.84 ± 1.20	7.18 ± 2.11	3.92 ± 1.53	2.14 ± 0.86 **
Triticale	Verato	7.89 ± 0.70	8.41 ± 2.65	3.85 ± 1.28	2.86 ± 0.89 *
TOTAL		6.50 ± 1.39	7.10 ± 2.31	3.62 ± 1.39	2.94 ± 1.21

There were significant differences between the monoculture cereal and agroforestry cereal treatments in terms of total crop biomass both in 2014 ($F_{1,124}$ = 4.16, p < 0.001) and 2015 ($F_{1,200}$ = 7.00, p = 0.008).

In 2014, the crop biomass and the grain yield of two barley cultivars were greater in the intercrop area than the control; there was not a significant difference with the wheat cultivars (Uppermost table on the left).

In 2015, the mean grain yields for the wheat cultivars and the triticale was greater in the control than the intercrop area; by contrast the mean barley yield was greater in the intercrop than the control area (Lowermost table on the left).

3.3 Mediterranean silvoarable systems, France

Innovation

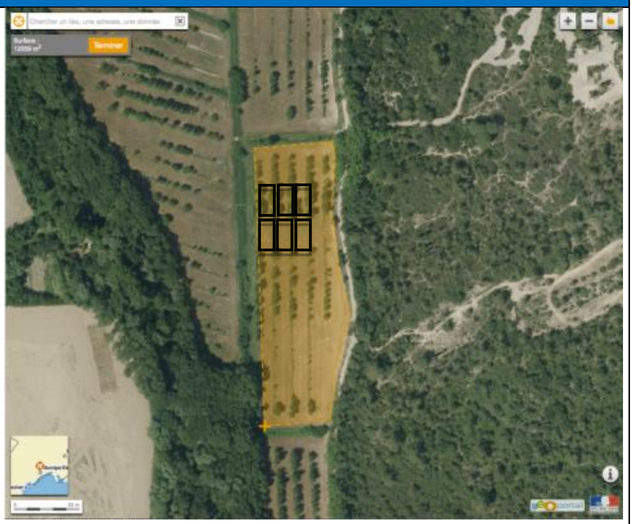
Breeding for shade tolerant varieties of wheat that are adapted to agroforestry systems

Plot B17: Wheat under poplars in the foreground with wheat in full sun in the background (17 June 2015)

Plot A6: soil preparation (23 October 2015) before sowing, the tractor is below ash trees. The two trees in the foreground (right- hand side) are wild cherry trees, and the "full sun" plots will be located in the gap between the last wild cherry and the first ash tree.

Map of system

Aerial photograph of the B17 plot, the black squares indicate the location of the experimental plots (under poplars/in full sun).

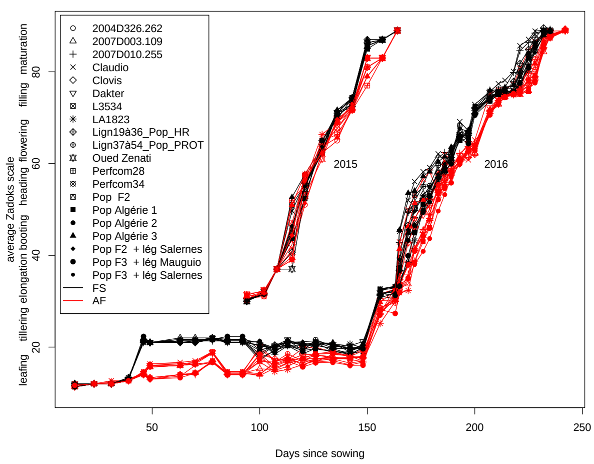


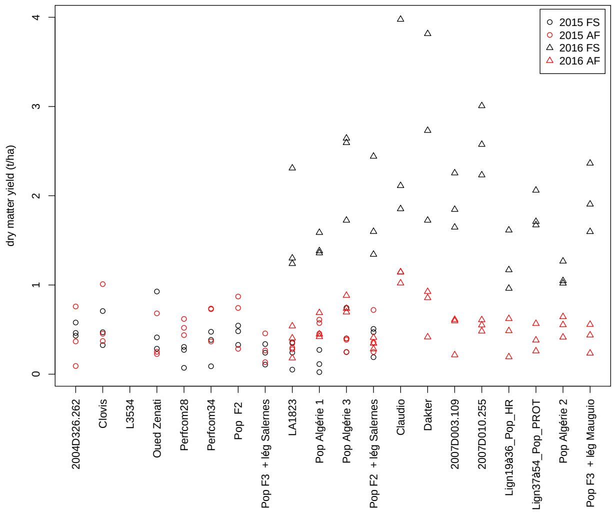
Aerial photograph of the A6 plot, the black squares indicate the location of the experimental plots (under ash trees/full sun).

Tree component	Crop component
In plot B17, the poplars were planted in 1999 (to replace *Paulownia tomentosa*, which had died because of the cold). In plot A6, the ash trees were planted in 1995. Tree rows are 13 m apart and trees spacing within the row is 6 m.	Twelve durum wheat varieties (old varieties taken out of the genebank maintained by INRA + 1 or 2 "control varieties") were tested in a 13 m wide crop alley each year. In 2015, the control variety was LA1823, a variety recently created for organic farming; in 2016, the control varieties were LA1823 and Claudio (the variety usually used by

the farmer). Sowing density was 350 seeds m^{-2}. Sowing was completed on 12 January 2015 (because of floods that prevented sowing in autumn) and 2 November 2015. Harvest was completed on 30 June 2015 and 6 July 2016. No fertilizers or pesticides were applied in 2015 and the growing season was shorter than normal, because the sowing was later compared with other wheat plots of the farmer. For the 2016 growing season, herbicide Athlet (bifénox + chlortoluron; 3.6 l ha^{-1}) was applied manually on 13 November 2015. Fertilizer (ammonium nitrate 60 kg ha^{-1}) was applied on 12 January 2016.

Initial results





The figure to the left shows the seasonal change in the growth stage (Zadok's scale) as a function of days since sowing for the 12 varieties of wheat grown each year under the trees (red) and in the sun (black).

In 2015, the wheat under the poplar reached Zadok's GS30 (1 cm head) quicker than the wheat in the full sun. However after 28 May 2015, the development of wheat under full sun was more advanced, and maturity was reached 10 days earlier in full sun than under the poplars.

In 2016, development was always quicker in full sun than under the ash trees, and maturity was 7 days earlier in full sun than under the ash trees.

Yields were **very low** in 2015, both in full sun and in agroforestry, due to the very late sowing and the lack of fertilizer and herbicide (both problems being caused by the flooding in autumn that prevented sowing at the same time as the farmer). Yields were slightly higher in agroforestry than in full sun in 2015 (0.46 t/ha of dry matter in agroforestry vs 0.36 t/ha in full sunlight. In 2016, yield was strongly reduced in agroforestry (0.55 t/ha) compared to that (1.94 t/ha) in full sun conditions. The registered variety Claudio performed best, both in full sun and under agroforestry conditions, among all 12 varieties tested in 2016.

3.4 Mediterranean silvoarable systems, France (Weed survey)

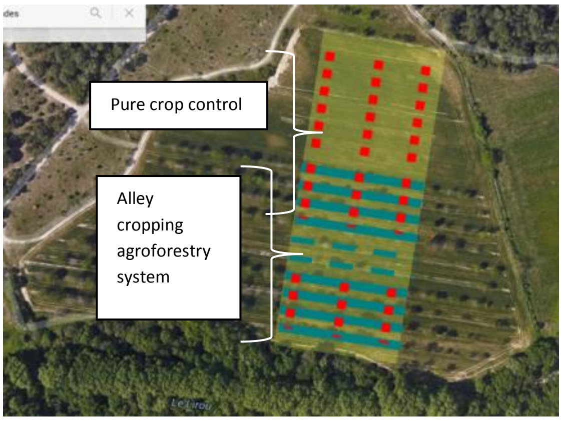
Innovation

Determining the effect of agroforestry on weed competition and biodiversity

Harvesting of the alley crop in July 2015 © C. Dupraz

Growth of the alley crop in May 2015 © D. Meziere

Map of system



Schematic map of the alley cropping system (Source: Google map, 2015).

In red, the three transects along for weed survey. In blue, the tree lines (in the middle of the agroforestry part. The two pollard-tree lines (blue dash lines) were not studied for the weed survey.

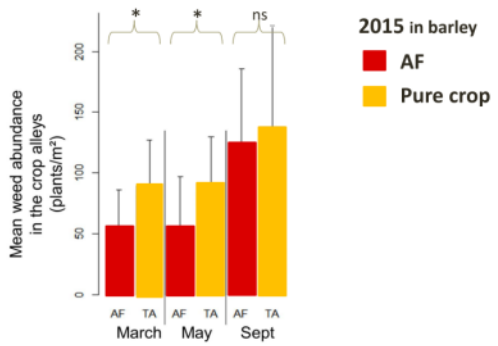
Tree component	Crop component
The Restinclières estate site comprises 40 ha under agroforestry, divided in about 15 fields. About 30 species of trees were planted in 1995, and new planting occurred in 2000 on some fields to replace non-adapted tree species (*Paulownia tomentosa*) composed of two agricultural plots. The field used for the weed survey was planted in 1995 with hybrid walnut at 200 trees per hectare. In 2003, a thinning was performed to remove half of the trees, resulting in a density of 100 trees per hectare. Because thinning was made by selecting	The crop alley is 13 m wide. The crop rotation involves durum wheat as the main cash crop. The first crop in the rotation is typically a legume (*Pisum sativum*), although oilseed rape (*Brassica napus*) was sometimes used in the past. This is followed by two cereal crops such as durum wheat (*Triticum turgidum* subsp. *durum*), but in 2015 the second cereal was barley (*Hordeum sativum*).

the best quality trees, some trees are still separated by 4 m on the tree line, whereas some others are at 12 m. The trees were pruned at 4 or 6 m.

Initial results

Comparison of agroforestry alley cropping system vs. pure crop system:

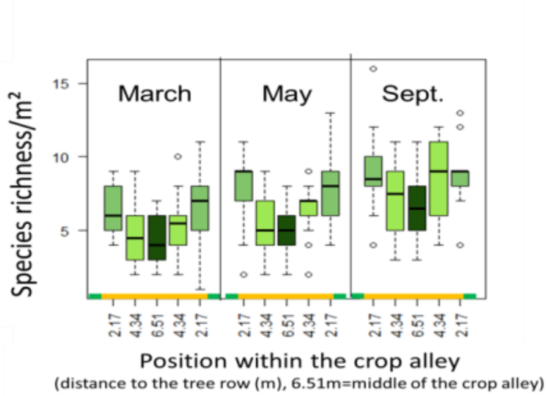
(a)



(b)

Distribution along the crop alley within the agroforestry system:

(c)



The mean weed abundance was high in both the agroforestry and non-agroforestry plots (Figure a) However the abundance of weeds (number of weed plants per m²) was lower in agroforestry than in pure crop control during the crop growing season (Figure a). Conversely the number of species per m² (alpha diversity) was almost twice as much in agroforestry as in the control (results not shown here). The total number of spontaneous species over all samples of a given field (gamma diversity) was higher in the crop of agroforestry, and even more when considering the additional species of the under-tree strip than in the pure crop field (Figure b). There was no observable increase in weed density close to the tree row (not shown here), however there were significantly more species ($p < 0.01$) close to the tree row compared with the centre of the alleys

At a quadrat scale (alpha-diversity), the distribution of the species richness varied with the position in the crop alley in the agroforestry part of Field A (Figure c). Each boxplot is the distribution of the richness for the 6 alleys x 3 transects = 18 quadrats.

3.5 Trees for timber with arable crops in Italy

Innovation

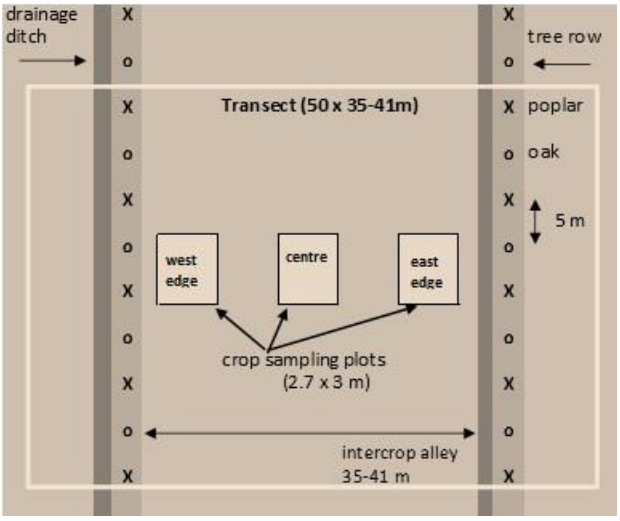
Determining the effect of tree hedgerows on crop yield

Winter view (December 2015) of the experimental site, with durum wheat as intercrop, in succession to sugar beet. The farm is currently under conversion to organic farming.

Winter view (March 2017) of Casaria farm (credit: P. Burgess)

Map of system

Aerial photograph of Casaria Farm. The yellow line is the border of the agroforestry area. The red lines represent the tree rows alternated with arable areas.



Schematic lay-out of transect along the crop alleys and poplar rows.

Tree component	Crop component
Tree establishment took place in winter 2013, using unrooted two year old rods for poplar and two years old seedlings for oak. Trees were planted by hand, in rows parallel to the existing ditches. Tree shelters were used to protect against wild animal browsing. Support posts were also used for the oaks. Poplar trees are pruned annually by hand. The tree intra-row is weeded annually, with mechanical mowing, along with the vegetation growing in the ditches. The tree spacing is 5 m within row alternating poplar and oak and about 35 m between the tree rows.	The crop alley is about 35 m wide. The crop alleys in between the tree rows are planted with conventional crops common in Italy such as maize (*Zea mays*), wheat (*Triticum* spp.), barley (*Hordeum vulgare*), soybean (*Glycine max*), sunflower (*Helianthus annuus*), alfalfa (*Medicago sativa*), clovers (*Trifolium* spp.), and sugar beet (*Beta vulgaris*). Since the year 2015-16, the farm is in conversion to organic farming. All farm operations use conventional machinery and seek to minimise hand labour. The farm has an irrigation system which is used during dry conditions.
Initial results	
The initial results are still to be reported.	

3.6 Silvoarable agroforestry in Greece

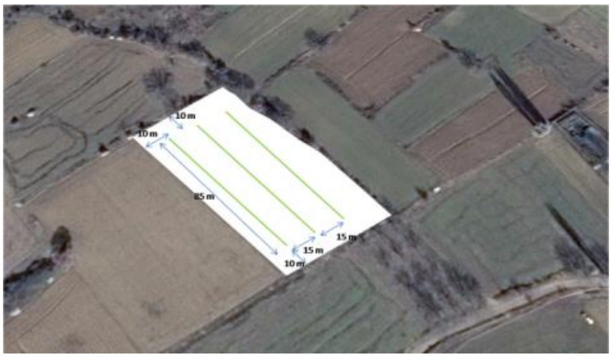
Summary of innovation

1. Integrating the cultivation of dry beans and cereals with fast growing poplars and walnuts inside or at the edges of small farms.
2. Combining the cultivation of medicinal plants and cherry trees.

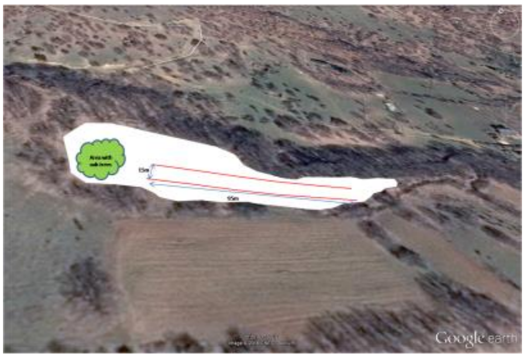
Planting of beans in between walnut trees

Planting of cherry trees

Map of system



Aerial photograph showing the layout of the walnut-bean system.



Aerial photograph showing the layout of the cherry trees plantation

Tree component

The research site comprises two arable plots. An 0.6 ha site was planted with walnut trees (*Juglans regia*) at the end of March 2015 which is intercropped with common beans. There is also a 0.4 ha site planted with cherry trees (*Prunus avium*) and it will be intercropped with aromatic plants (spring 2016).

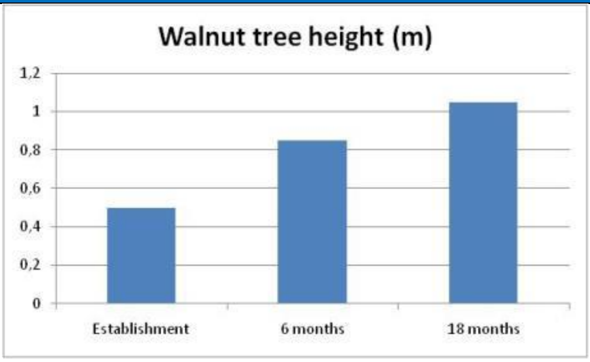
In the 0.6 ha plot, three tree rows were established with an inter-row distance of 15 m (Figure above). The tree distance within the row is 5 m. In total, 54 walnut trees were planted .The mean height of trees was 0.50 m and the mean diameter (at a height of 20 cm) was 15 mm at time of planting.

In the 0.4 ha plot, two rows of cherry trees were established at the same inter-row (15 m) and intra-

Crop component

The crop alley width is 15 m. The 0.60 ha plot was intercropped with common beans (*Phaseolus vulgaris*), which were sown on 15 May 2015 and they were harvested on 10 November 2015 (Figure above left).

The 0.4 ha site was intercropped with aromatic plants in spring 2016 within a 15 m crop alley.

row (5 m) distance as the first plot (above right). In total 40 trees were planted. The mean height was 2 m and the mean diameter (in a high of 20 cm) was 20 mm at time of planting.	
Initial results	
	Walnut trees (Figure to the left) did not grow successfully and suffered from the cold in the winter period of 2015-2016 and a storm during the flowering phase in 2016. The result was lower tree growth from the average in the area. Crop yield for the 2015 growing period was 1000 kg ha^{-1}, lower than the average for the area which is about 1500 kg ha^{-1}. The lower yield was probably due to a lack of fertilizers and pesticides application. It was the farmer's decision to not use any fertilizer and pesticides.

3.7 Agroforestry for arable farmers in Western France

Innovation

Tree and crop yields within an old agroforestry plantations

View along an alley of black walnuts: trees harvesting for biomass and volume estimation

View along an alley of black walnuts: harvesting of barley with combine harvester

Map of System

Aerial photograph of the walnut agroforestry (to the south) and forest system (to the north). The red dots represent the sampled trees. These trees are harvested and cut (December 2015) for biomass and volume estimations.

Tree component

Biomass and tree volume is being measured in two contiguous parcels of 40 years old black walnut:

- Agroforestry planting (to the south): on a 6.86 ha plot, black walnut were planted in seven rows. The rows are 700 m long with 14 m spacing between rows and 7 m between trees on the row; the crop alleys were cultivated every year, most often with cereals.
- Forest plantation (to the north): on a 1.96 ha plot, the trees have been planted in 4 rows (n°8 to n°11). The rows are 700 m long, with 7 m between rows and 7 m between trees within the rows. The inter-rows have included cover crops and have been weeded using disks.

Crop component

The crop alley width is 14 m with a cultivation area of 9 m. Following soil preparation with a disc harrow in October 2015, the crop alleys have been planted with the winter barley variety "Etincel". Crop yield will be measured at four sites:

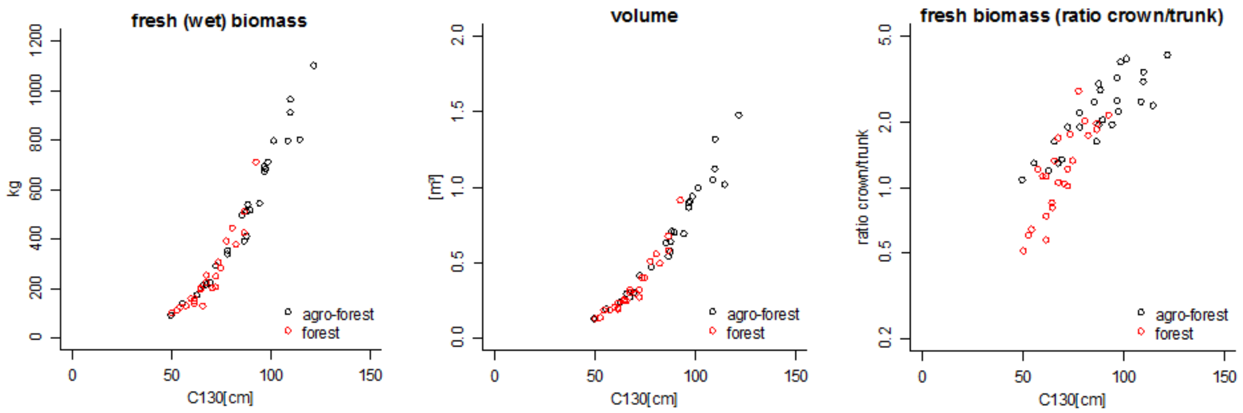
- An agricultural control plot (no trees) located to the south of the agroforestry planting.
- A 700 m long agroforestry plot (the stand thinned to final tree density - 50 trees/ha): the inter-row tree spacing is 14 m, and 14 m between separate trees within each row (the owner did thinning in winter 2015-16). The crop cultivation width in the alleys will be 9 m.
- A 700 m agroforestry plot (102 trees/ha): the inter-row tree spacing is 14 m (cultivation width = 9 m) and 7 m within the row.
- An agroforestry plot: new site with walnut and fruit trees.

Initial results

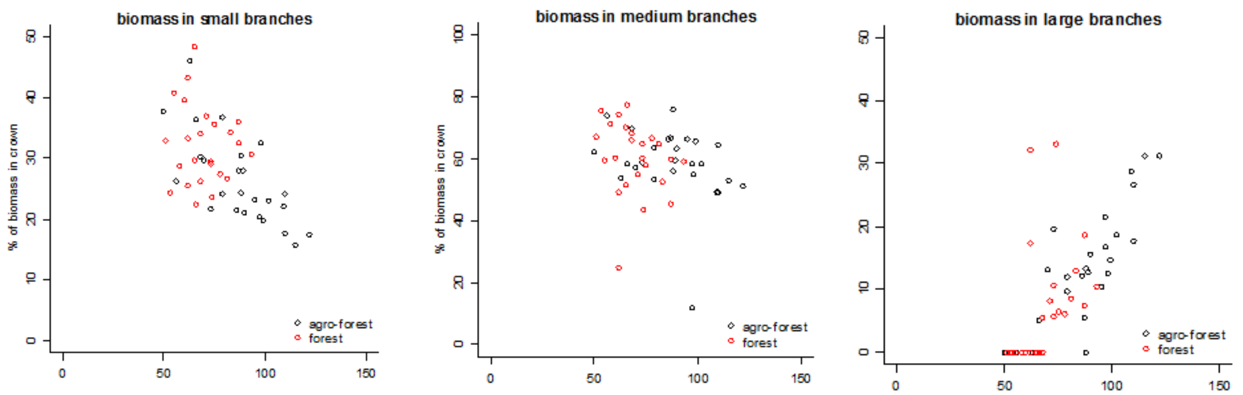
Table of biomass, volume and density of trees cut and analysed in this study

	Trees cut (n)	Fresh biomass (kg)	Dry biomass (kg)	Volume (m^3)	Water content ($kg\ m^{-3}$)	Wet density (%)	Infra-density ($kg\ m^{-3}$)
Agroforest	26	521	297	0.69	44	752	426
Forest	24	257	145	0.34	45	742	417

- The trees from the agroforestry plot selected in this study had on average about twice the biomass of the trees from the forest part for biomass (wet or dry) and volume.



- Fresh biomass and volume increase non-linearly with the circumference at breast height (130 cm).
- Many of the smaller forest trees had less biomass in the crown than in the trunk (ratio below 1). This did not occur with any of the trees in the agroforestry section.
- The large trees in either section had 2-5 times as much biomass in the crown as in the trunk.
- The larger forest trees and the smaller agroforestry trees had similar biomass ratios between crown and trunk.
-



C130 [cm] C130 [cm] C130 [cm]

This set of graphs shows the part of biomass in the crown contained in small branches (7 cm > Ø ≥ 4 cm), medium branches (20 cm > Ø ≥ 7 cm) and large branches (Ø ≥ 20 cm) :

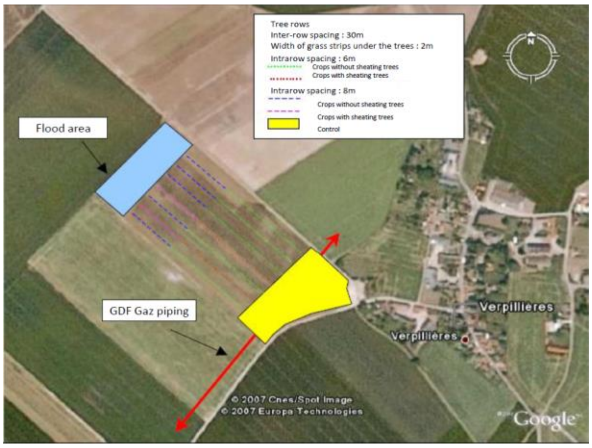
- The percentage of biomass in small branches decreased with trunk circumference (C130).
- In general, the points of the forest and agroforesty trees are mixed for low and medium C130.
- For larger C130, there are only agroforestry trees.

3.8 Agroforestry for arable farmers in Northern France

Innovation

Determining the effect of agroforestry system age on weed abundance and species richness in conventional and organic systems

Map of system



Tree species are Norway maple (*Acer platanoides),* wild service tree (*Sorbus torminalis),* hybrid walnut tree (*Juglans × intermedia*), wild cherry (*Prunus avium*), wild pear tree (*Pyrus sp.*), wild apple tree (*Malus sp.*), sycamore (*Acer pseudoplatanus*), black locust (*Robinia pseudoacacia)*

Tree component

The Picardy field site comprises about 70 ha under agroforestry, divided in seven fields. Between 6 and 12 species of trees were planted in each field; the first one in 2007 and the last one in 2014. Each field has at least two rows of trees, with a within rows spacing of 5 m or more (for wood production) between trees. An example tree mixture is: Norway maple (*Acer platanoides),* wild service tree (*Sorbus torminalis),* hybrid walnut tree (*Juglans × intermedia*), wild cherry (*Prunus avium*), wild pear tree (*Pyrus sp.*), wild apple tree (*Malus sp.*), sycamore (*Acer pseudoplatanus*), and black locust (*Robinia pseudoacacia).* The spacing between the rows varies between 25 m and 75 m.

Crop component

The crop alley varies between 25 m and 75 m. The crop in the alleys are typical for the region, with wheat as the main crop. Most of the time, the first crop in the rotation is oilseed rape, followed by wheat or barley, and potatoes or sugar beet. Production potential is normal to high for the region, depending of the depth and quality of the soil.

Initial results		
	Conventional crop management	**Organic crop management**
Influence of rows	A few transects were measured for the presence of weeds. In recently planted fields: there were as many weeds near tree rows as in crop alleys. In older fields: there were more weeds near grass strips. It seems that there is an influence of tree rows and grass strips on the presence of weeds over the years.	Important weed dispersal into the field with grass strips under the trees (stock of weeds), especially near the tree strips. Best results were obtained from mulching.
Other factors	No influence of the type of crop.	Influence of the type of crop and the environment (excluding the effect of the hedges)
Agrochemical use	No differences for weed killing between conventional fields and fields with trees.	

3.9 Silvoarable Agroforestry in the UK I

Innovation

Development of agroforestry adapted wheat populations (i.e. 'alley-edge' selected lines will perform better in the 'alley-edge' plots than 'alley-centre' lines)

Spring wheat CCPs in the willow silvoarable system, 2016

Aerial view of hazel silvoarable system at Wakelyns

Map of system

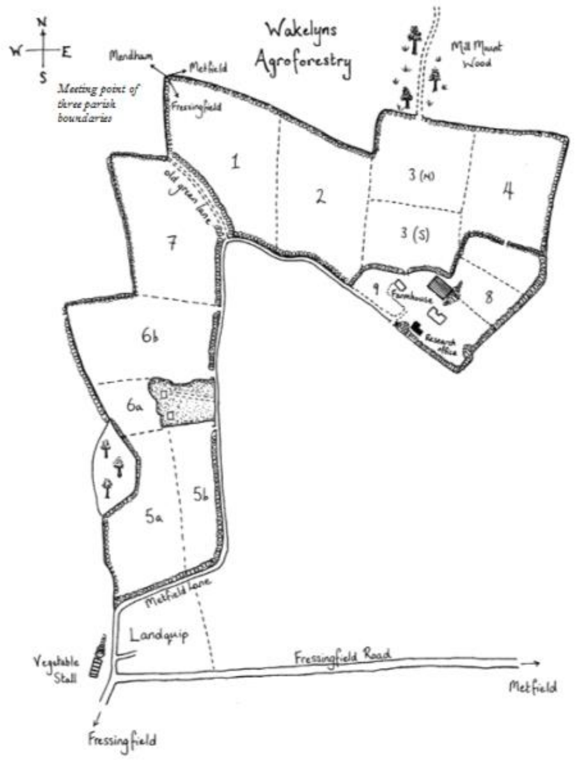
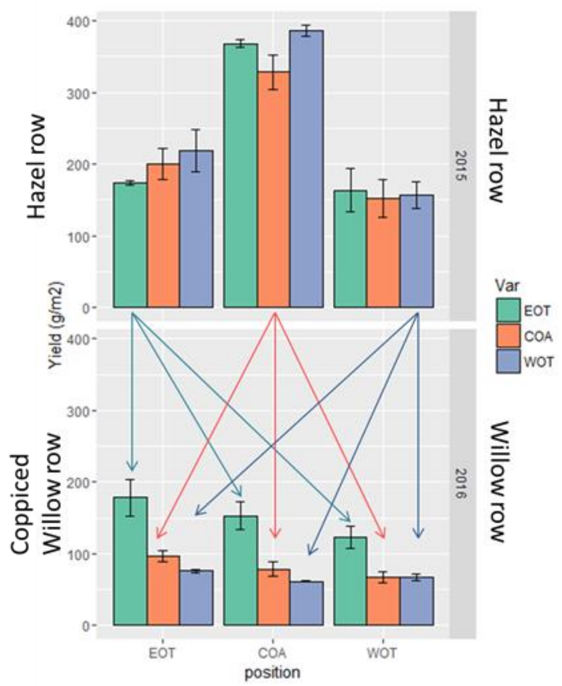


Figure to the left. Map of Wakelyns Agroforestry (SRC systems are in Field 4 (Hazel) and Field 5 (Willow)

Fields and tree systems

1. Far Field • 2+ ha • tree rows planted Feb '94 to 310 trees of 7 timber species (Ash, Wild Cherry, Italian Alder, Small-leaved Lime, Sycamore, Oak, Hornbeam)
2. Water Field • 2+ ha • tree rows as Far Field plus 42 apple trees of 21 old varieties
3. Home Field • 2+ ha • tree rows partially planted, starting in 2001, to fruit and nut trees (plum, cherry, apple, pear, quince, apricot, peach, hazel), each of multiple varieties
4. **Hazel Field • 2+ ha • tree rows planted Feb '95 to 1200 hazel bushes, each individual genetically distinct; each row coppiced every 5-6 years**
5. **Willow Field • 4ha • tree rows planted Mar '98 to a mixture of 5 fast-growing willow varieties; each row coppiced every 2-3 years**
6. Vineyard (6a) and Mid Field (6b) • 3+ ha • No trees yet
7. North Field • 3+ ha • tree rows planted in Feb '01 to 20 walnut trees and in Jan '02 interspersed with varieties of plum; other walnuts and plums have been added occasionally since then, and one row is not yet planted
8. Old Paddock (sometimes used for compost-making)
9. Kitchen Garden

Tree component	Crop component
The SRC willow (*Salix viminalis*) was planted in 1998. The willows were planted in a double row system with 1.2 m between trees and 1.5 m between double rows. The total with of the tree row (including buffer) is 3 m. The hazel was planted in 1995 in a similar design with 1.5 m between trees and 1.5 m between double rows. Biomass production of the SRC willow has been measured since 2011 and the hazel since 2014. Willow is harvested on a 2 year rotation, with every other row being harvested in a particular year (i.e. 50% of the rows are harvested each year). Hazel is harvested on a 5 year rotation, with only one side of the twin row being cut in any year. With the willow, the twin rows within each tree row are cut and so stools from alternate rows (east/west) are sampled. With the hazel, only one of the twin rows (east or west) is cut in any year and so all stools are from the same side.	The crop alley is about 10 m wide. The 2014 cereal trials of a spring oat variety (Canyon), a spring barley variety (Westminster), a spring triticale variety (Agrano), two spring milling wheat varieties (Paragon and Tybalt), an equal mixture of Paragon and Tybalt and a spring wheat Composite Cross Population (CCP) have been reported in Fradgley and Smith (2015).
Initial results	
	In 2015, an experiment was established to test material selected in contrasting environments near to and away from the agroforestry tree rows. A replicated cross-over experiment aimed to compare performance of selected material in each environment based on the hypothesis that wheat lines will perform best in the environment from which they were selected (i.e. 'alley-edge' selected lines will perform better in the 'alley-edge' plots than 'alley-centre' lines). A spring wheat composite cross population (CCP) was grown in plots across a willow system agroforestry alley in 2014. Plots of bulk CCP were harvested separately from plots on either side of the alley, adjacent to the tree rows (East of Trees (EOT), West of Trees (WOT)) and the alley centre (Centre of Alley (COA)). In spring 2015, plots measuring 1.2 m by 10.2 m were drilled in a replicated cross-over trial in a hazel SRC agroforestry system to test the effect of the population adapting under natural selection to each environment. Yield measurements (t/ha, hectolitre weight (g), and thousand grain weight (TGW)) were carried out in autumn 2015 when the plots were harvested. The trial was repeated in 2016, using the same experimental design, but in the willow SRC alley cropping system. The willow SRC on the west side of the alley had been coppiced to the ground in January 2016; the willow SRC on the east side of the alley was in its second

	year of re-growth. In 2015, there was a significant effect of location on yield ($F_{2,17}$= 48.89, p<0.001) and hectolitre weight ($F_{2,17}$= 4.81, p<0.05). Yields and hectolitre weights were significantly higher in the centre of the alley than at either edge. There were no significant differences between the different populations for any of the yield parameters, and no significant interactions between the populations and their locations. This suggests that in the first year, there was no adaptation of populations to their selected locations (i.e. EOT populations did not perform any better in the EOT locations than in the other locations). In 2016, there was significantly higher yield (p=0.000) East of trees than West of trees, i.e. West side has more limiting condition than East side. This is likely to be because the Western tree row (i.e. adjacent to the EOT bed) was coppiced in January 2016 so there was less shading (and potentially less competition for water/nutrients?) in adjacent crops compared with the east side of the alley where crops competed with second year willow re-growth. What is striking is that the population selected on the East side (EOT), i.e. the 'least limiting conditions', yields more than twice that of the two others (p=0.02) in every position in the alley. However, yields were very low.

3.10 Silvoarable agroforestry in the UK II

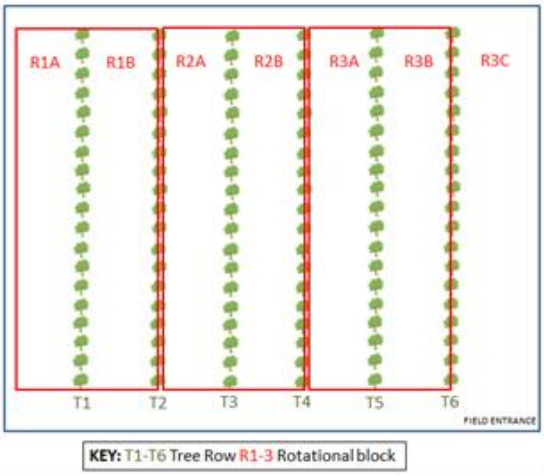
Innovation

Managing the tree understorey for increased food production and biodiversity

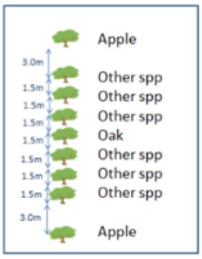

Daffodils in the tree understorey, spring 2016


Rhubarb in the tree understory, Sept 2016

Map of system



Field map and tree row design.



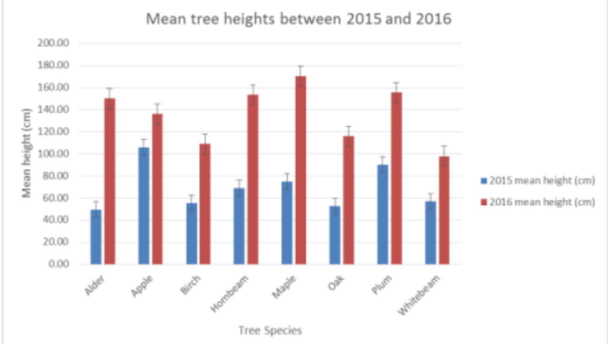
Row code	T1	T2	T3	T4	T5	T6
2015	Legume and herb mix planted in July 2013	Long term beetle bank	Grass, vetch, red clover	Natural regeneration	Legume and herb mix planted in July 2012	Legume and herb mix planted in July 2012
2016	To be planted with globe artichokes mid-late summer 2016	Long term beetle bank	Herbaceous flowers for cut flowers	Rhubarb crowns planted spring 2016	Daffodils and narcissi planted Dec 2015	Daffodils and narcissi planted Dec 2015

Tree component

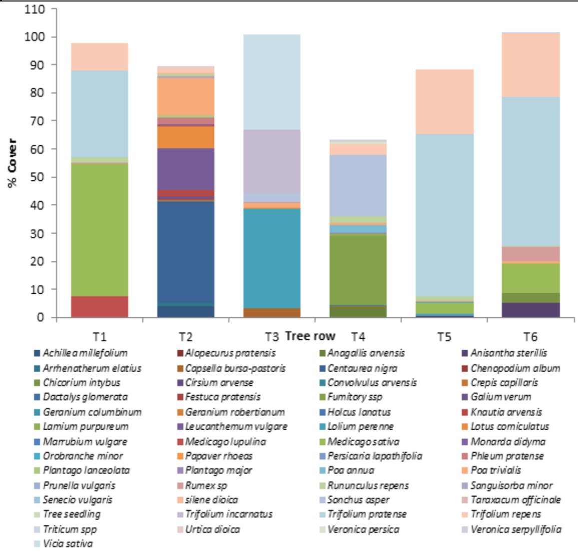
In the rows, 447 trees were planted of 8 species; apples (18 varieties); field maple (*Acer campestre*); whitebeam (*Sorbus aria*); Italian alder (*Alnus cordata*); oak (*Quercus robur*); black birch (*Betula lenta*); hornbeam (*Carpinus betulus*); Myrobalan/cherry plum (*Prunus cerasifera*). Trees were planted into existing ground vegetation in March 2015, and woodchip mulch applied around each tree to reduce weed competition. There are six tree rows that separate seven 20 m wide and 150 m long alleys (see Figure above).
Trees were measured in June 2015 and June 2016.

Crop component

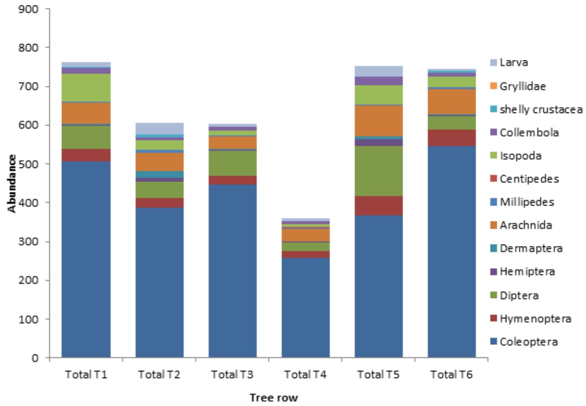
Initial results



In terms of species, the alder and field maple trees showed the greatest height increment between 2015 and 2016 (100 cm and 95 cm respectively). The apple trees showed the least growth at an average of 30 cm increase over the year (Fig left).



Plant biodiversity was assessed in the tree understorey in June 2015 to provide a baseline against which to monitor changes to biodiversity as the agroforestry system matures. A total of 53 plant species were identified. The plant composition varies according to the tree row (Figure at the left) and tree row 2 (long term beetle bank) had the highest diversity with 28 different species. Each row is characterized by two (tree row 5) to four (tree rows 1 and 2) dominant species and a varying number (but less than 25% of the row total plant abundance) of other rarer species. Among the dominant species there are: *Medicago sativa, Trifolium repens* and *Trifolium pratense* for tree row 1; *Centaurea nigra, Leucanthemum vulgare, Achillea millefolium, Lotus corniculatus, Poa trivialis* in tree row 2; *Vicia sativa, Lolium perenne, Trifolium incarnatum* in tree row 3; *Sonchus asper, Fumaria spp* in tree row 4, *Trifolium repens* and *Trifolium pratense* for tree rows 5 and 6.



Total invertebrate abundance was also assessed in each tree row in June 2015. In all tree rows, Coleoptera was the most abundant invertebrate order caught in the pitfall traps. Proportions of other orders differed according to tree rows. Regarding Coleoptera, and focusing on Carabidae, the highest abundance was located in tree row 6 (n = 442), decreasingly followed by tree row 1 (n = 300), 3 (n = 260), 5 (n = 247), 2 (n = 218) and 4 (n = 203). A minimum of seven different species were recorded in tree row 1 and a maximum of 10 species in tree row 3. The most abundant species in tree rows are increasingly: *Harpalus rufipes* (n = 87), *Pterostichus madidus* (n = 186), *Pterostichus melanarius* (n = 449) and *Poecillus cupreus* (n = 700).

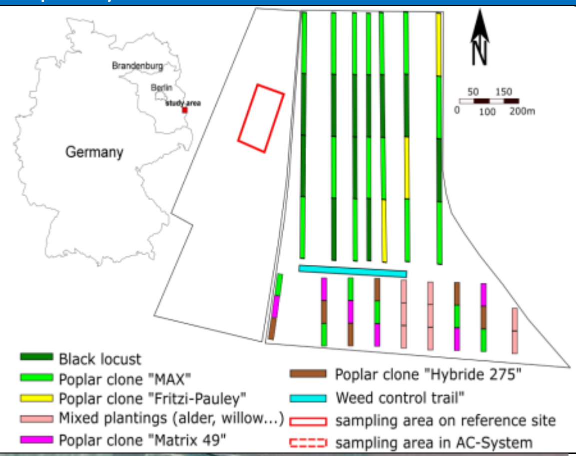
3.11 Alley cropping in Germany

Innovation

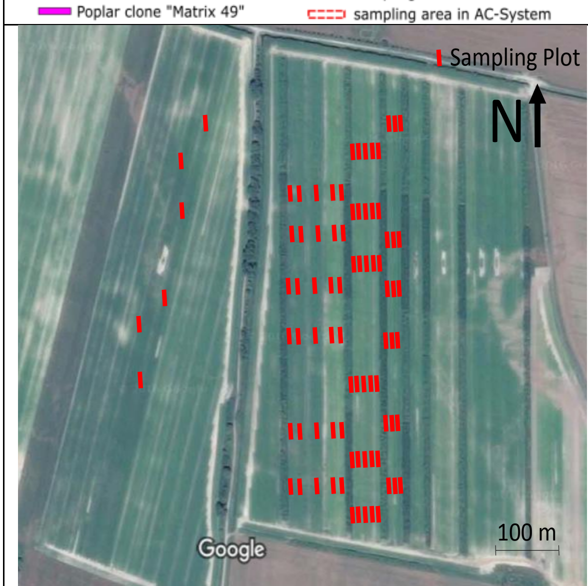
Determining the effect of tree hedgerows on crop yield

Alley cropping with winter wheat and poplar/black locust hedgerows

Map of system



Coloured lines indicate tree rows (for species see legend). Tree species are Poplar clone ‘Max’ (*Populus nigra L.× P. maximowiczii*), Poplar clone Fritzi-Pauley (*P. trichocarpa*), Poplar Matrix 49 (P. maximowiczii × P. trichocarpa), Poplar Hybrid 275 (P. maximowiczii × P.) and Black Locust (*Robinia pseudoacacia*).



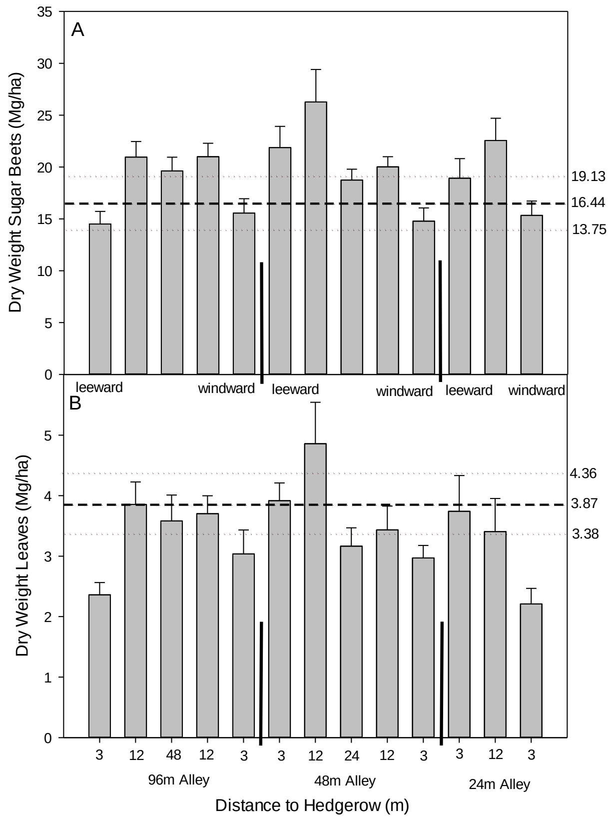
The harvest took place between 30th Sep and 6th Oct 2015. The three western alleys were used for the sugar beet harvest (Figure at the left). Sampling plots varied between 3-5 m^2 and consisted of 3 rows and were 8 sugar beets long. For the 96 m and 48 m alleys plots were located at 3 m, 1 2m and in the middle of the crop alley, for the 24 m alley plots were only located at 3 m and 12 m (also middle) from the crop alley.

Tree component	Crop component
The northern part of the alley cropping system is 40 ha and consists of poplar (*Poplar* spp, varieties Max 1 (*Populus nigra L.× P. maximowiczii*) and Fritzi-Pauley (*P. trichocarpa*) and black locust (*Robinia pseudoacacia*). This part of the experimental site was planted in 2010 and the	The crop alley width varies between 24, 48 and 96 m. The crop alleys are planted with conventional arable crops common to Germany such as sugar beet (*Beta vulgaris*), barley (*Hordeum vulgare*), maize (*Zea mays*), alfalfa (*Medicago sativa*)/SolaRigol (legume and not legume mix for

poplars were replanted in 2011. The research trial consists of seven tree hedgerows that are 11 m wide (four double rows) and approximately 600 m long. The spacing within the row is 0.9m, within the double row 0.75 cm and between the double row 1.8m. The distance between the tree hedgerows varies between 24, 48 and 96 m.

potatoes), potatoes (*Solanum tuberosum*), winter wheat (*Triticum durum*).
Crop spacing and design is according to common agricultural practice. For 2015, the sugar beet crop at the research site in Forst crop densities ranged from 8 to 13 beets m^{-2}.

Initial results



Mean (± SE) dry weight sugar beets (A) and dry weight leaves (B) at different distances from the tree hedgerow and for 3 alley widths 96 m, 48 m and 24 m. Dotted lines indicate the means (± SE) for the crop reference area. (n=6).

Results: Within the agroforestry site, dry weight for sugar beets was smaller in close proximity to the hedgerow. When comparing sugar beet yields within the agroforestry system and the reference site, greater yields were measured at 12 m from hedgerow, at 48 m (96 m alley) and at 3 m east (48 m alley) in comparison with the reference site. Leaf dry weight (B) showed a similar trend with lower values closer to the hedgerow. Across the board, leaf biomass was lower within the agroforestry systems in comparison with the reference site. Only 12 m east of the hedgerow for the 48 m alley the sugar beets produced a greater leaf biomass.

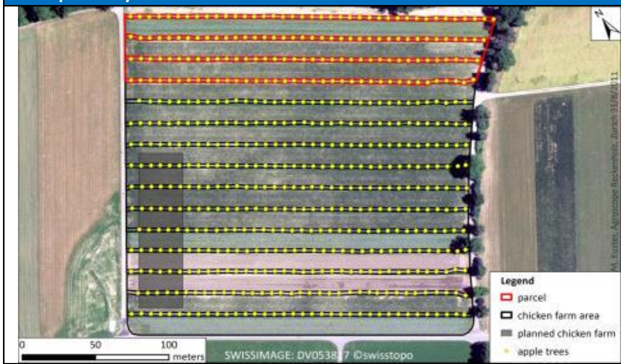
3.13 Silvoarable agroforestry in Switzerland

Innovation

Monitor changes in farmers perception of agroforestry systems

Silvoarable system at Sursee (Luzern, CH)

Map of system



The layout of the experimental area during the 2014-2015 cropping season. The tree rows highlighted in red are included in the monitoring, they are intercropped with a crop rotation consisting of cereals, maize and strawberry. The farmer plans to convert part of the parcel to a chicken farm. It is not sure, however, if and when he can put this plan into practice.

Tree component

In 2009, the agroforestry was planted with 545 apple trees (*Malus domestica*) of two different varieties, *Boskoop* and *Spartan*. The trees are arranged in 15 lines with a tree-strip width of around 3 m while in every strip one tree variety is dominating. Tree density is 100 trees/ha; 2.5 m within the line and 10 between the tree lines. The mean tree diameter was 8 cm in 2011 and 15.9 cm in 2014, the mean tree height was 160.3 cm in 2011 and 201 cm in 2014. Seven trees were replanted in 2014. In 2015 ten trees died because of mice damage, and 15 fell down because of wind, and were replanted. The rabbits are also a problem for the trees, but no system for tree protection has been used.

Crop component

The crop alleys have a width of 10m. The crop component constitutes 78% of the agroforestry surface, of which 33% is manged with winter wheat, the 33% with strawberries and the remaining 12% is rotational fallow. These crops are managed according to the Swiss minimum standard for ecological management (ökologischen Leistungsnachweises, ÖLN, http://www.blw.admin.ch/themen/00006/00049/index.html?lang=de).

Initial results

Table to the left. A farmer's perception of their agroforestry parcel in the period 2011-2015 (no data for 2014). Score scale: -3 (absolutely irrelevant), -2 (irrelevant), -1 (rather irrelevant), 1 (rather relevant), 2 (relevant) and 3 (highly relevant).

A system of scores and a questionnaire were conceptualised to evaluate the perception of the farmers on their agroforestry plots. The score

Year	2011	2012	2013	2015
Tree productivity	1	3	3	2
Regulation functions				
Soil protection	-1	1	2	1
Ground water protection	-1	2	1	3
Local climate conditions	-1	-1	1	2
Climate protection	-1	1	2	1
Shading for cattle	-1	-3	-3	-3
Wildlife protection	2	1	2	nd
Characteristic landscape	2	3	2	3
Economical value				
Income from production	1	3	nd	-2
Income from direct payments	3	3	3	3
Potential risks and limitations				
Light competition	-1	-3	-3	-2
Water and nutrient competition	-1	-3	-3	-3
Root competition	-1	-3	-3	-3
Pest increase	2	3	3	3
Yield loss due to tree litterfall	-2	-3	-3	-3
Limitation for machinery	nd	3	1	-1

nd: not determined

system ranged from -3 to 3 points: -3 (absolutely irrelevant), -2 (irrelevant), -1 (rather irrelevant), 1 (rather relevant), 2 (relevant) and 3 (highly relevant).

In 2011 the farmer compiled the first questionnaire. In the initial year, tree productivity was considered a relevant issue (1). Regulation functions (soil protection, ground water protection, local climate conditions, and climate protection) of the agroforestry system were considered irrelevant or having only a minor influence (-1). The farmer perceived the relevant role of the system for species protection and for contributing to the characteristic landscape (2). The farmer considered the agroforestry parcel very interesting in terms of direct payments (3), but not in terms of fruit and wood production (1). Considering the potential risks of light and water competition between trees and crops, the farmer did not consider these as major issues (-1), but he perceived as relevant the risk of increased pest pressure (2). For instance, in the parcel, the mice were a relevant problem. A minor role was played by the impaired mechanization on the agroforestry parcel (1).

The farmer’s perception has been also monitored in 2012, 2013 and 2015. The perception changed with time (Table), especially regarding the production and regulation functions, for which an increase in the perceived positive effect of the trees was registered.

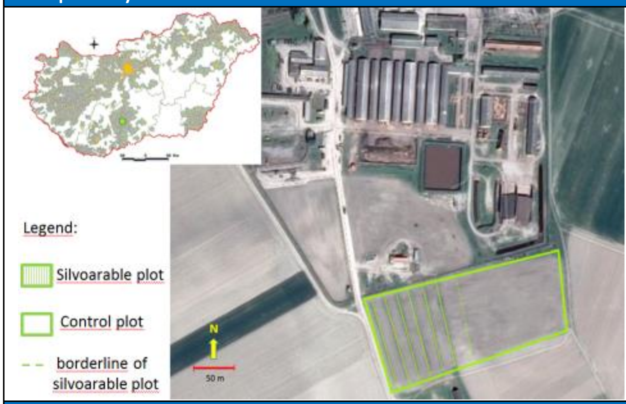
3.14 Arable agroforestry in Hungary

Innovation

Determination of crop yield effects due to tree hedgerows

Summer view of alley cropping with alfalfa and Paulownia hedgerows (2014)

Map of system



The design of the field trial during the 2014-2015 cropping season.
The green line is the border of the field trial. The total area is 2 ha. Half of it is covered by the alley cropping system (striped area), the second half is cultivated in as a conventional monocrop system as control for agroforestry.

Tree component

The tree lines in alley cropping systems consist of Paulownia, which is a fast growing woody crop. The experimental site was first planted in 2012 and after serious damage (caused by standing water) the trees were replanted in 2013. *Paulownia tomentosa* (var. Continental E.) is a variety selected for local conditions. The young trees grow relatively fast, reaching a height of 12-15 m in 5-8 years, under optimal site conditions. This selected variety is observed to be vigorous under local weather conditions while resistant to extreme climate.

The alley cropping system consists of six tree rows that are 2 m wide without crop cover. The distance between the stems is 5 m. The spacing between the tree lines is 14 m, 12 m of which is covered by the intercrop.

Crop component

The crop alleys in between the tree lines are about 12 m wide and are planted with alfalfa (*Medicago sativa*). Decision on the crop species was based on the requirement of a shade tolerant crop and the need for forage.

Crop spacing and design is according to common agricultural practice. The width of intercrop rows has been determined by the technical parameters of the cooperative’s sowing and harvester machines.

Initial results

No.of sample	AF		C	
	fresh yield/m2 (g)	u (m/m%)	fresh yield/m2 (g)	u (m/m%)
1	2.58	73.28	2.97	72.24
2	3.21	72.16	2.73	74.95
3	3.08	71.99	2.92	73.23
4	3.20	76.20	3.09	76.71
Mean	3.02	73.41	2.93	74.28

The table to the left shows the fresh yields and moisture content (u) of alfalfa during summer harvest in 2016. Four samples per agroforestry (AF) and control [C] plots were harvested manually just before machine harvesting. Within the agroforestry system samples were harvested at 0.5, 1.0, and 2.0 m from the hedgerow; and in the middle of the crop alley. Fresh production and moisture content were weight immediately after sampling, using a portable analytical equipment (BOECO *SMO* 01). The result of statistical analysis show that there was no significant effect of sampling position on fresh yield and moisture content of the crop. Preliminary results suggest that the 3 year old trees had no significant influence on the yield and the moisture content of alfalfa during the summer period of 2016.

4 Acknowledgements

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