7 Factsheet Agroforestry

Designing agroforestry systems | Tree planting patterns

Guide for planting trees on farms

WAGENINGEN UNIVERSITY & RESEARCH

Contents

Figure 1 | Shows several different patterns that can be chosen when designing a new system, each will be more or less suited to the different goals of a farm.

1| The importance of planting patterns

There are many important choices to make when designing agroforestry systems and the planting pattern is one of them. There are thousands of options and choosing the right layout will have a huge impact on the yield and quality of the field crops, trees and livestock in addition to the ease of management. The different planting patterns shown in Figure 1 give an idea of the different choices that can be made with regard to planting patterns. Here we will consider the different planting patterns that can be implemented and their suitability for different;

- Contexts – location, existing layout, slopes, climate (last frost date), machinery, labour
- Goals – production, transition to tree crops, microclimate, biodiversity, carbon storage
- Crops – arable, fodder, fruit, nuts, timber, biomass
- Livestock – dairy, chickens, pigs

When these are known it becomes much easier to choose a suitable planting pattern. For instance where the desire is to transition from field crops to an orchard, the plant spacing will more strongly reflect the needs of the trees and the final orchard layout with the optimal spacing for the trees. Where the desire is to have a long-term system with both tree and field crops, then wider alleys will often be chosen that allow sufficient sun for the field crop to grow, even when the trees are fully mature. The key choices for the tree planting pattern regard the: tree spacing, tree species and cultivar spatial diversity, tree row orientation and planting shape. Each of these four choices affects a multitude of factors including; tree-crop interactions, yield, mechanisation, labour, pollination and biodiversity. In this factsheet, we will discuss these key choices so that more informed decisions can be made regarding the most suitable choice for a farm.

2| Tree spacing

The ideal spacing depends on the tree crop and the other crops and livestock on the farm. The key choices to consider are; close or wide tree spacing, tree strip width, number of rows and fixed or temporal tree spacing.

2.1 *Close or wide spacing*

One of the key choices when designing an agroforestry system is the spacing between the tree strips. As shown in Figure 2, the strips can be spaced closer together, or wider apart, with the optimal spacing dependent on the tree and field crop, livestock, goals and context of the farm.

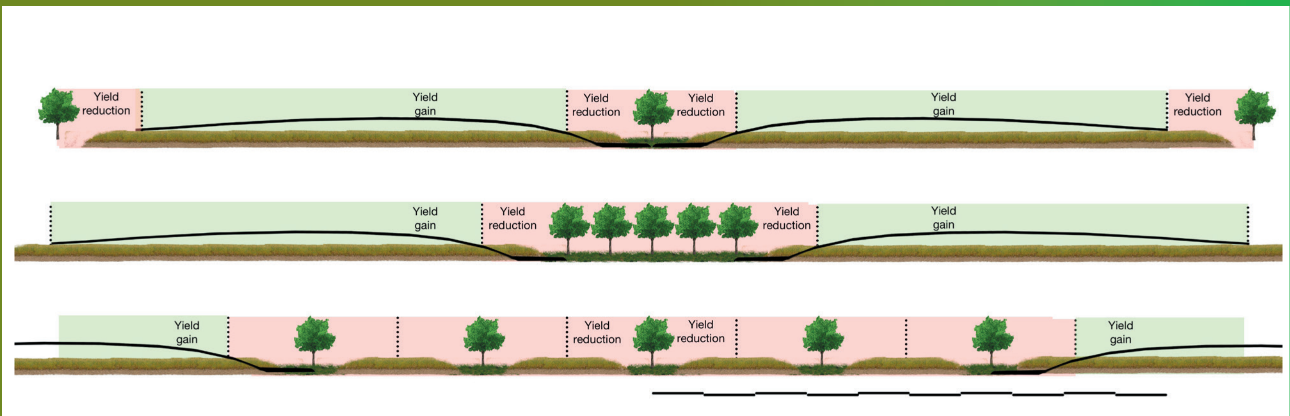
- Where sun-loving field crops are grown, or where the field crop remains the most important crop, a wider spacing of rows will often be more suitable. This reduces the proportion of field crop area under competition for light and will allow the continued cropping of crops with high light requirements. Conversely, where the tree crop is more important and where the crops in the rotation don't suffer too much from competition (mainly winter crops) then closer spacing can be more suitable.
- For those with livestock the spacing of the tree rows affects the protection from heat stress and cold but also the provision of forage (Lin, McGraw et al. 1998) which effects weight gain and milk yields (Jordon, Willis et al. 2020). For chickens, closely spaced rows can help reduce losses to predator birds and encourage ranging.
- Where the farm goal is to transition to tree crops or forest farming then even closer spacing will be more suitable as the field crop is likely to be temporary to provide income in the first years before the tree crop becomes established and can be harvested.
- The local conditions also affect the optimal spacing as in dryland conditions, where water is limiting, the closer spacing can reduce evapotranspiration, thus supporting the growth of the field crop.

Figure 2 | Example of different planting distances between the tree rows

2.1.1 *Crops*

When designing a planting it is important to know that tree strips can both increase, or decrease, the performance of field crops dependent on whether they compete or facilitate with each other and vice-versa. Trees can compete with the field crop for: light, water and nutrients. However they can also facilitate growth by; improving the microclimate, protecting from extreme weather, supporting nutrient cycling and improving pollination. By designing a layout that emphasises the area of yield gain and minimises the area of yield reduction a more successful planting can be created. This is most relevant where continued cropping of the field crop is desired (see Figure 3){Carrier, 2019 #32}.

In the case of northern Europe, competition for light, water and nutrients cause the field crop yields to be lower close to the tree row. On average, yields are 70% of a monocrop up until a distance of 1.6 times the tree height (referred to as "H"). For example, for a 5 m tree the competitive zone usually ranges up until 5*1.6=8 m from the tree row (Van Vooren, Reubens et al. 2016) (see also Figure 3 and Table 1). Competition occurs on both sides of the tree row and may differ slightly between one side and the other due to local conditions (Swieter, 2019). Further from the tree row the competition is less and at a distance of 1.6*H the crop yields are generally the same as in a unsheltered monocrop. After this point the facilitatory affects outweigh the competition and yields can increase above the level of an unsheltered monocrop. Yield increases of 5-100% of monocrop yields can be obtained depending on the context and crop (Taksdal 1992, Nuberg 1998, Van Vooren, Reubens et al. 2016, Zheng, Zhu et al. 2016). Field crop yields often reach a maximum at the distance 3*H and fall steadily until 10*H. Consequently, it is likely that tree strip spacings between 6*H and 10*H will maximise the proportion of cropping area which benefits from the improved microclimate and minimise the area under competition. Shade-tolerant and wind-sensitive crops will be more feasible at the closer spacing of 6*H and 8-10*H more suitable for shade intolerant crops. For most farmers looking to continue growing warm season arable crops these 8-10*H are likely to be optimal, though there will be exceptions. This means, for example, that for trees that are 10 m tall spacings of 60-100 m may be best to create the optimal ratio between facilitation and competition for the field crop. Further example tree row-distances for different tree heights are shown in Table 1. Though this may be the optimal distance for the field crop this does not mean that it is the optimal distance for the performance of both the tree & field crops, or economically.



Figure| 3 Shows the common zone of yield reduction and yield gain of the field crop due to competition and facilitation between the tree and crop under normal circumstances.

Table 1| General guideline of the distance from the tree line where competition and facilitation between field crops and trees are expected to take place for trees of different heights. When choosing a distance also keep in mind that a tree may take 50 years to reach its final height or that biomass crops such as short rotation willow coppice will vary in height from 30 cm to 8 m every 3-5 years.

Tree height	Competition up to distance 1.6* H	Optimal protection at 3*H	Dis-tance at 6*H	Facilitation negligible by 10*H
m	m	m	m	m
1	1.6	3	6	10
2	3.2	6	12	20
3	4.8	9	18	30
4	6.4	12	24	40
5	8	15	30	50
10	16	30	60	100
15	24	45	90	150
20	32	60	120	200
25	40	75	150	250
30	48	90	180	300

Spacings less than 6*H are likely to be sub optimal for the field crop except in special circumstances. These special circumstances include;

- For shade-tolerant crops
- When growing crops under extreme conditions (such as heat, drought, strong winds)
- When growing very wind-sensitive crops
- When the tree and annual crops differ in their primary growing season (such as winter wheat)
- For crops adapted to forest conditions such as medicinal plants, or mushrooms

The competition and facilitation depend on the local context and weather (sunlight, water, wind etc.) and the crop species involved. Whereas in northern Europe light is likely to be the most important factor in determining crop yields, closer to the equator water or nutrients may be more limiting, this can make closer spacing feasible. Simultaneously, crop yields limited by water availability can benefit from the improved microclimate provided by trees. In extreme cases this can lead to higher yields closer to the tree row as shown in Figure 4. This has been shown to occur in some cool season grasses (Feldhake 2001). Though this is infrequent, increased temperatures and droughts caused by climate change may make this effect more common in the future.

20% (Pardon, Reubens et al. 2018) and can allow for closer spacing, especially if the tree crop is valuable. The winter barley/wheat - walnut system in France is a good example of this. Other circumstances where closer spacing can be successful is for; crops sensitive to wind and wind-blown soil (such as sugar beet, alfalfa and lettuce), cool season grasses, and when the farm is transitioning to forest crops (such as mushrooms, ginseng and goldenseal).

Besides the effects on field crops it is also important to consider the effect of spacing on the tree crop yields. Though there is limited information on this topic, results from orchards provide some initial indications. In general, tree crop yields of fruits, nuts, timber or biomass also benefit from a more protected microclimate in a similar way to arable crops and grasses. Research of monoculture apple and pear orchards show that tree crop yields are often highest at 3*H from a shelter and gradually fall to monoculture levels by 10*H (RHEE, 1959). Protection at intervals between 4*H and 10*H is often beneficial to total tree crop yields and yield benefits of 70-200% can be achieved (RHEE 1959, Heiligmann, Schneider et al. 2006) (see Figure 5). Shelter can improve growth and thus reduce the years to harvest for the tree crop, and additionally also provide better conditions for pollination.

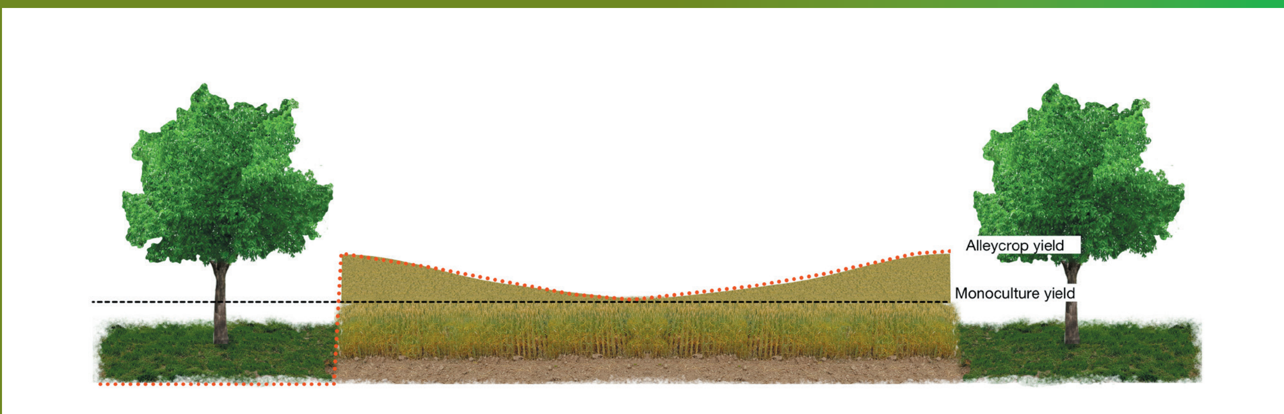


Figure 4| In some cases, depending on the crop and weather conditions, the field crop yields are higher closer to the tree row.

Another important consideration is the crop species involved. Certain field crops only suffer limited yield reduction in the competitive zone (1.6*H) when trees are added, or greatly benefit from the protection from wind. This often occurs when the growth period of the two crops have minimal overlap such as with winter crops (winter wheat, winter barley, field beans, oilseed rape) and a late leafing tree such as walnut. In this case the yield reduction in the competitive zone may only be 10 -

For fruit crops it can also improve product quality by reducing wind damage. Consequently, where the tree crop is sensitive to wind damage and provides a valuable crop, the total economic yield may be improved with closer spacings. Alternatively, where wider spacings are maintained between the tree strips, the tree crop may benefit from having multiple tree rows in the strip as shown in Figure 11. Location, tree species, and cultivars will all effect the suitability of the tree crop to closer, or wider, spacings between the rows. Further experience is required to provide more concrete recommendations that take into account these factors.

FIgure 5| Shows the effect of shelter on the growth of black walnut trees after 11 years. The tree grown with shelter for the first 4 years (right) is substantially larger than the exposed tree (left). Reproduced from (Heiligmann, Schneider et al. 2006)

2.1.2 *Livestock*

Trees can provide livestock with several benefits such as shelter from extreme weather, protection from predators and the provision of alternative food (Jordon, Willis et al. 2020). The optimal design for combining trees and livestock can differ to the design for crops and trees. However, in many cases grazing animals and field crops (such as maize, lucerne, alfalfa, field beans, wheat, soya etc.) will both exist on a farm, meaning both will need to be taken into account, especially where field crops are rotated with temporary grassland. Where field crop production is to be maintained when the trees have reached their maximum size then spacings of at least 6*H are likely to be necessary. Closer spacings may result in declining forage yields after 6-10 years. This is especially so for warm season forage, whereas cool season grasses are more tolerant of shade (Pent 2020) and sometimes benefit from cooler conditions in the summer months (Lin, McGraw et al. 1998). In some cases, though total forage yield is reduced, the nutritional composition can change resulting in higher protein content, which may compensate for the reduced yield. This effect combined with the protection from wind and heat stress can result in agroforestry having the same average daily gain for grazing sheep and cows despite producing an extra product (Jordon, Willis et al. 2020). This will depend on the location and tree crops present. Spacing needs to account for the different needs of: livestock, crop and management. Simple changes in the planting pattern such as those shown in Figure 6 will have a large impact on the shelter, light, shadow and the efficiency of mechanisation. For free ranging chickens and pigs where the forage is of less importance, then closer spacings are likely to be more successful allowing greater production from the tree crop. For chickens, a higher cover of trees has been shown to increase ranging (Bestman, Hermansen et al. 2017). The optimal spacing should also account for fencing needs, stock management and crop mechanisation to allow efficient management of the farm.

Figure 6| Two different approaches to silvopasture. Left, widely spaced single trees, providing dappled shade. Right, closely spaced double rows providing more intense shading and shelter whilst also providing a higher efficiency for management operations.

2.1.3 *Mechanisation*

Machinery is another important consideration when designing the planting pattern. The strip widths for arable, fodder and tree crops should account for the machine widths which are used on the farm (1.5 m, 3 m 4.5 m, 6 m, 12 m, 24 m etc.) for the different management operations, such as tillage, weeding, mowing, fertilizing, spraying, harvesting and pruning. The width of the field crop strip should be designed as a multiple of the machinery widths used to ensure optimal labour efficiency (see Figure 7 and Figure 8).

Another important consideration for strip width is the accessibility for unloading during harvesting. Where chaser bins or field bins are used the design should account for how fast the harvester fills up and the access of the chaser bin for unloading. Consider what side the auger will be on and if this is accessible for the chaser and not inconvenienced by the tree rows. In some cases shorter runs can be advantageous for efficient unloading.

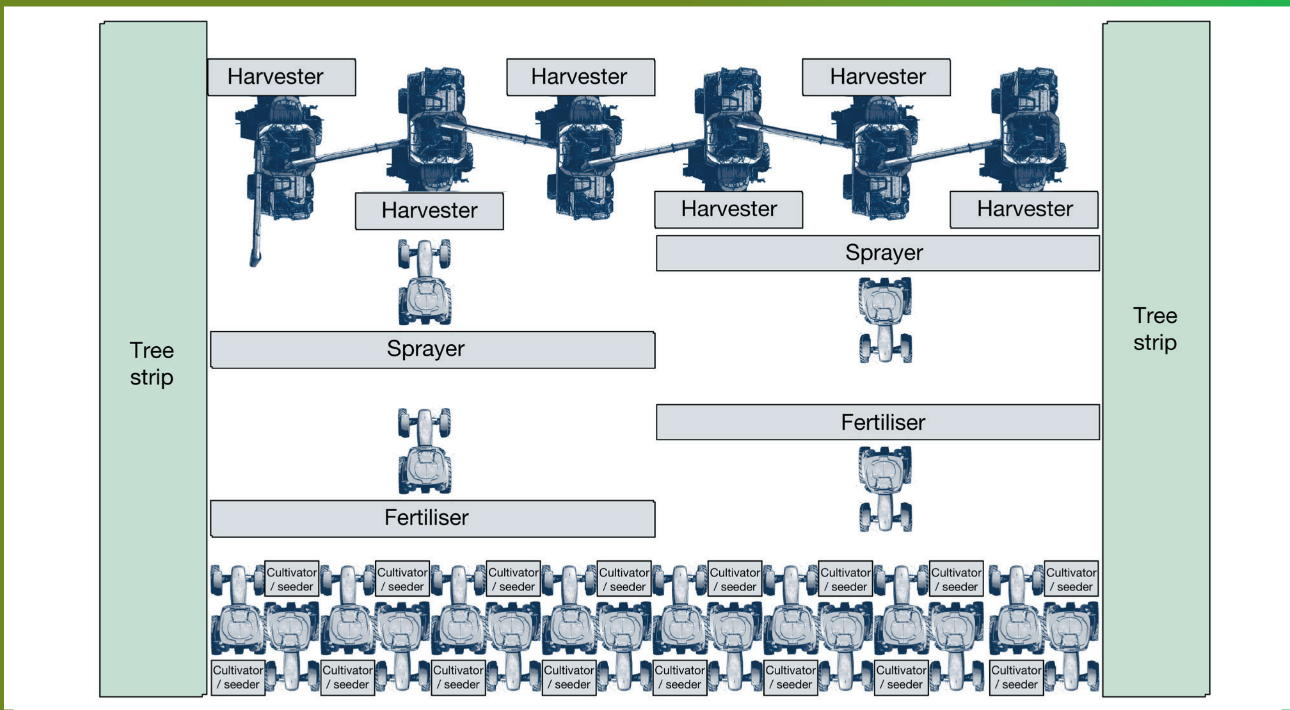


Figure 7| The distance between the tree strips is designed to accommodate the working widths of different farm machinery such as; cultivator, seeder, spreader, sprayer and harvester to ensure efficient field operations.

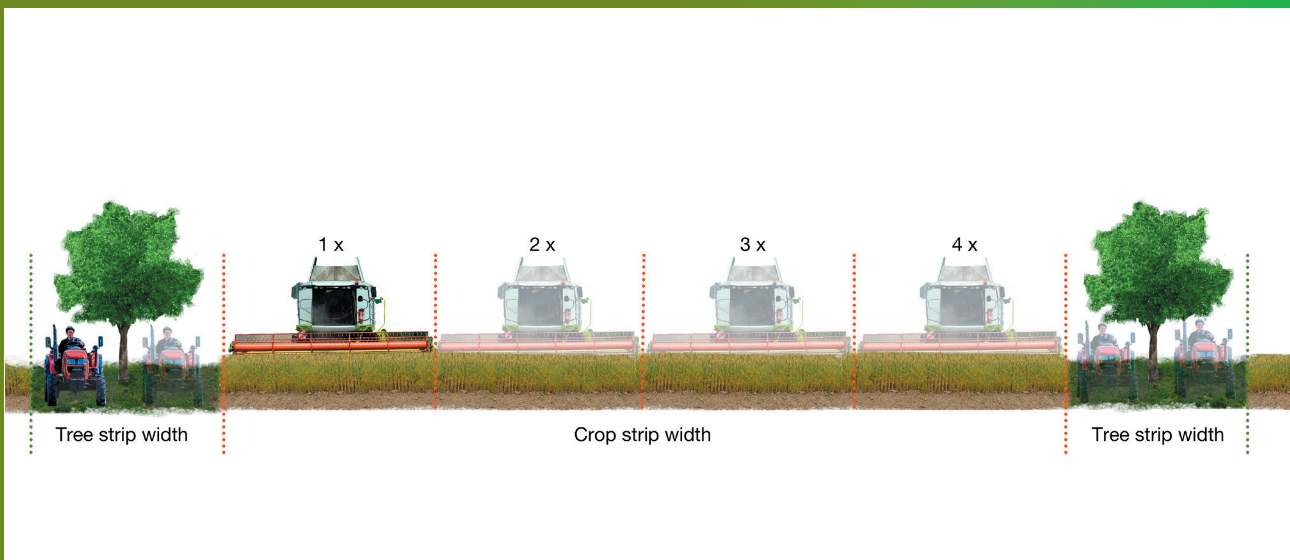


Figure 8| The strip widths of both the tree and field crops should accommodate the needs of the crop and the different machinery used.

Irrigation is another important consideration when choosing the plant spacing as it is costly and generally reserved for high-value crops. Some irrigation techniques such as sprinkler irrigation (often a radius from 30-60 m) or lateral move irrigation (30, 45, 54 m) cover large areas. The planting pattern should be designed to accommodate this (see Figure 9). If the tree strips are closer together than the diameter of the irrigation, they will also be irrigated with the field crop. This is unlikely to be a good investment for timber or biomass crops. In the case of lateral move irrigation, the tree strip spacing also needs to be wide enough to allow access. Where drip irrigation, or flood irrigation are used this is less of a constraint. For sprinkler systems, the combination with a hose and reel with a traveling sprinkler gun cart allows for even irrigation through the crop, which is much more difficult for static systems.

Figure 9| The irrigation of field crops with hose and reel traveling sprinkler or lateral move irrigation. The wider spacing of tree strips makes the irrigation of field crops more efficient and feasible.

2.2| ***Tree strip width***

When designing the tree strip width the main considerations are accessibility for machinery, suitability for harvesting and strip permanence. Where timber trees are grown, strips of 2 m are often necessary (1 m either side of the tree). This reduces the chances of damage during field crop operations. For fruit and nut crops the widths of at least 3 m are likely to be necessary to allow for management. Where the tree crop is harvested from the ground (walnut, hazelnut, cider apples) the tree strip needs to be at least as wide as the canopy and potentially broader to account for wind throw (see Figure 10). For some crop rotations the tree strip can be kept small and a harvest strip for the trees prepared following the harvest of the field crop (winter wheat, winter barley, seed potatoes, early onions). For late harvested crops such as potato and sugar beet this is not possible and so a permanent strip is necessary to harvest such tree crops. Where the tree crop takes several years to mature the strip can also be kept narrower for 5-10 years before the strip is necessary for harvest. This should be planned for in the design to reduce the double working of machinery where possible (see Figure 7). Naturally, when planting multiple rows in the tree strip, the tree strip will be wider (see Figure 11).

Figure 10| Strip width should be carefully considered to ensure that mechanised operations can take place and that it is suitable for the tree crop harvest. Handpicked and timber crops can have narrower strips than nut crops harvested from the ground. Left: taller nut trees with ground harvesting will need proportionally wider strips to account for windthrow. Middle: with smaller trees this is less of an issue. Right: for timber trees and handpicked trees the strips can be thinner.

2.3| *Number of rows*

Choosing the number of tree rows is another key choice during the design process. As shown in Figure 11, trees can be planted in single, double, or multiple rows within the tree strip. The optimal choice depends on many factors.

Figure 11| Single (left), double (middle) or multiple rows (right).

Where a fixed number of trees is necessary (for minimum viable sale and investment) then multiple rows can allow for wider spacing between the tree strips on a given area of land. This can be valuable to support the continued production of sun demanding field crops (maize, potato, sugar beet). The tree-crop interactions are likely to be similar in a single or multiple row system although the microclimate may change slightly with the additional rows. However for the trees the additional row is likely to have a substantial effect. It is known that tree growth and yields (fruit, nut, wood, biomass) improve in a protected microclimate. This has been shown for apples, pears and walnuts with yield improvements of 20% to 70% (RHEE 1959, Norton 1988, Balandier and Dupraz 1998, Heiligmann, Schneider et al. 2006). Additionally, having two or multiple rows can be beneficial for the pollination of both insect pollinated and wind pollinated tree crops as pollinator trees can be more easily spread through the rows. For mechanisation the multiple rows can simplify the operations and in the case of crops harvested from the ground (such as walnut, hazelnut, chestnut and some fruit crops) it can reduce the loss of fruit and nuts in the field crop, or the need for wider strips to allow for harvesting. For conventional farmers where pesticide drift can be an issue, multiple rows can also provide for a better buffer between the field crops and the trees. This is also relevant for the design of agroforestry buffers for waterways which can also benefit from having multiple rows to reduce runoff into streams and rivers.

Where single rows can have an advantage is in the early stage of a planting, as it is easier to keep a part of the tree strip under field crop production for the first years (before it is needed for harvesting, see Figure 13). In doing so the field crop production area is increased. Ideally this should fit the working widths of machinery as shown in Figure 7. Single rows can also be preferable when tree crops are grown which do not require a strip to allow for activities such as harvesting, such as timber crops, or when the arable crop does not interfere with harvesting operations (grass on a dairy farm or wheat harvested before a nut crop, thus allowing the ground to be prepared for harvesting of the tree crop).

The area between the tree rows in a double row alley cropping can also be temporarily cropped as shown in Figure 12, however the feasibility is dependent upon the crops and machinery used on the farm. This can be more difficult than when using single rows (Figure 13). Another consideration is that where the same number of trees are grown on one field the double row has a smaller area of tree-crop competition (Figure 3). This can be a useful option for farmers looking to achieve a certain number of hectares of tree crop production, without spacing strips at less than 6*H that can result in greater competition with field crops.

Figure 12| Example of double row planting at different stages. In the beginning (left) it is possible for temporary cropping between the double row depending on the crops and machinery on the farm, in later stages this is no longer possible.

Figure 13| Example of single row planting at different stages (left to right) with the potential for temporal cropping between single rows.

2.4| ***Fixed or temporal planting pattern***

Another choice regards whether to have a permanent planting pattern, or one that changes over time. Tree crop yields are generally related to the amount of canopy. Consequently, for certain nut, fruit and biomass tree crops it is valuable to have a higher initial planting density than the final plant stand as this reduces the number of years until commercial harvesting can take place. For instance double or triple the final tree density is planted and then tree rows are removed or thinned as the trees mature (see Figure 14). This is especially relevant for nut and timber trees, as many fruit crops have dwarfing rootstock available and so can be planted at higher densities without thinning.

Figure 14| Example of hazelnut planted at higher row density (left) and as the trees mature (year 7-10+) the middle row is removed (right).

A higher initial planting density can also be valuable for timber crops as it allows the selection of the best trees for timber. It is also common where nurse crops are used. Nurse crops are crops used to support the growth of the main tree crop. An example is the combination of Black Walnut for timber and Black Alder as a nurse crop. The alder provides shelter from wind, nitrogen fixation and reduces lateral light for the walnut (see Figure 15). This supports the walnut growth and encourages long straight timbers with few side branches. Depending on the growth and spacing, the alder is gradually thinned, and eventually removed completely to provide space for the walnut. The alder thinnings and harvest provides an early crop that can help offset the management costs of the walnut plantation (Bohanek and Groninger 2005).

Figure 15| An example of a temporal timber planting. Here black alder acts as a nurse crop for black walnut (for timber). The alder protects the walnut from wind and encourages long straight timber during the early growth (left). Eventually the alder is harvested with the walnut is left to mature (right). Some farmers are also exploring combining hazelnut and walnut in this manner to achieve an early and a later nut crop.

Where the tree crop is the most important crop then the field crop may be the temporary element of the agroforestry system. The spacing is optimised for the tree crop and the field crop provides income in the early years before the tree crop is productive. In the first years after tree planting field crops with high light requirements can still be grown. These are followed by progressively more shade- tolerant field crops and finally the field crop strips are replaced by shade-tolerant grass or forest farming (see Figure 16). This can include the production of crops such as mushrooms, ginseng and goldenseal.

Figure 16| Transition from arable cropping (left) to a tree focused cropping system or forest farming (right). Field crops with high light requirements are replaced by shade-tolerant field crops and finally by grass or forest farming.

Figure 17| Example of a mixed farm in transition from high-value field crop (left), to winter crops (middle) and finally to grazed pasture when the trees are more mature (right).

For mixed farms with livestock, the temporary element may be the type of arable crop and the inclusion of livestock. In the first years higher value crops with high light requirements are grown, as the trees mature more shade-tolerant and winter crops are grown and finally a transition to pasture is made (see Figure 17). In this way the trees can become established before the animals can get close to them. Additionally, because the field crops are cultivated it can encourage the tree roots to grow deeper and compete less with the field crop or pasture

2.5| **Guidelines for tree spacing**

Table 2| A summary is given of different design choices and when they are likely to fit different goals, context and crop and livestock aspects.

Choices	Context	Goals	Crops	Livestock
Closer row spacing: <6*tree height	• Rainfed conditions (risk for drought) • Very windy conditions • Light is not main yield-limiting factor	• Tree crop as main crop • Full transition to tree crops • Forest farming • Increasing biodiversity	• High-value tree crops • Mainly shade-tolerant/ winter field crops • Wind-sensitive field crops • Forest farming	• Encourage ranging in chickens • Shelter provision • Balanced shade and light where trees are widely spaced in the row (Figure 6)
Wider row spacing: 6-10 * tree height	• Sheltered locations • Light is the most yield- limiting	• Combined arable and tree crop production • Ease of mechanisation and irrigation	• Sun-loving field crops • More wind-tolerant tree crops (not planted in multiple rows or in shelter)	• Grazing animals to allow for pasture production • For ease of stock management and fencing
Single rows	• Sheltered locations	• Maximise field cropping area	• Timber crops • Transition to tree crops/ orchard • Tree crops that take many years to first harvest	• Grazing of fodder trees, with tree protection
Multiple rows	• More extreme conditions (temperature, water, wind)	• Ease of management and mechanisation	• Tree crops sensitive to wind for growth, pollination and fruit forming • Tree crops that are quick to first harvest	• Effective shelter provision
Fixed strip	• Dependent on long -term mechanisation	• Ease of management and mechanisation	• Tree crops that are quick to produce their first harvest • Timber crops	-
Temporary strip	-	• Maximise field cropping area	• Field crop can be harvested before the tree crop • Slower growing trees such as walnuts	-
Fixed planting pattern	-	• If optimal for the tree crop	• Fruit and nut trees planted at final density (e.g. with dwarfing rootstock)	-
Temporary planting pattern	• More extreme conditions (temperature, water, wind)	• Support and manage tree growth • Provide rapid early yields	• Nurse trees for timber crops or fruit/nut crops • High density plantings which are thinned	-

3| **Tree species and cultivar spatial diversity**

If multiple tree crops or cultivars are chosen then the choice is whether or not to mix them and if so how. Species and cultivars can be mixed within the row and/or between the row/s as shown in Figure 18. The optimal type of mixing is dependent on the crops, livestock, farm goals and context. Mixing is essential to tree crops that require pollination and can also be valuable for slow growing timber crops where a nurse crop is grown to support their growth and provide an earlier harvest. Where fodder hedges are grown for livestock, then diverse mixtures can support animal health and also provide shelter from temperature extremes. Alternatively, for the tree crops that need to be harvested, different crops/ cultivars can be grown in different fields and the animals rotated from one to the other allowing the crops to be harvested. Naturally where the goal is to support biodiversity or ensure easy management then the level of mixing is likely to be very different. With regards to context, where there are considerable risks from disease or late frosts then higher levels of mixing may be attractive. This can also be attractive when a trial planting is grown to determine which cultivars to grow on a larger scale.

When choosing to mix it is important to consider the effects on tree-crop interactions, yield, mechanisation/ labour, pollination and biodiversity. In general trees are mixed for biodiversity, pollination, temporal cropping or nurse crops and kept more uniform to for mechanisation and labour.

3.1| ***Cultivar mixing***

Mixing different cultivars of the same species is the most simple form of mixing. This will have limited impacts on the tree crop interaction but substantial effects for; pollination, spreading risk (in the case of crop failure by one cultivar), and mechanisation (or labour). For pollination, pollinator trees are generally required within a certain distance for sufficient pollination. For instance; 15 m for hazelnut (Olsen 2013), 60 m for chestnut (Hunt, Gold et al. 2009) and 100 m for walnut (Wertheim 1981). Where single tree rows are chosen this will generally require the mixing of trees in the row (see Figure 18, rows A,B and C). Where multiple rows are used these can be shared between the rows (see H) or production and pollinator rows can be alternated (see I). By sharing the pollinators between the rows the percentage of pollinator trees vs main crop trees may be reduced. For optimizing mechanisation the main considerations regard whether the cultivars are harvested at different times (early and late cultivars), or produce a slightly different product (quality). Where this is the case it can be helpful to alternate the rows (see D, E, I) as the efficiency of mechanised harvest and grading can be improved.

3.2| ***Species mixing***

Where different tree species are mixed the impacts are more substantial. Generally there is more mixing for; biodiverse hedges, fodder hedges, shelter belts, temporal cropping, nurse crops, poly cropping and systems such as forest gardens (Food Forests). Achieving commercially viable systems that are highly mixed requires careful consideration of pollination, spreading risk, mechanisation and sales.

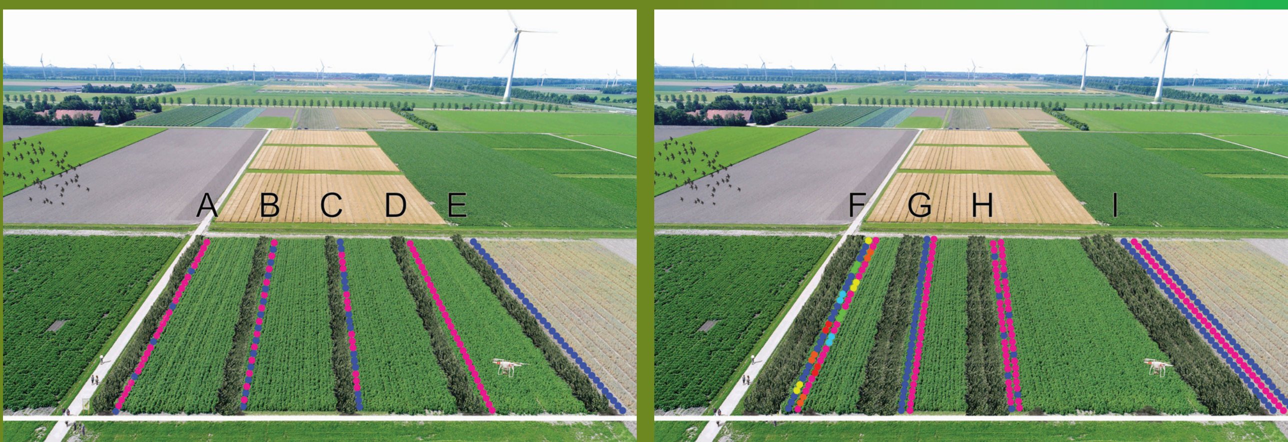


Figure 18| A few examples of different mixing patterns (A-I) within a planting. Mixing can be of species, or cultivars and there are many alternative combinations possible. The different colours indicate different species or different cultivars.

Where species are mixed within the row (see B & C) the percentage of pollinators per species is likely to need to increase. When mixing between the rows this is less of an issue (see G & I). Mixing in the row can also reduce mechanisation efficiency as the pruning, irrigation, fertilisation and harvest can differ substantially between crops with current machinery. Again, between the rows this is less of an issue.

Another important consideration is the minimal economically viable sales and investments for machinery. In many cases several tons of product are necessary before sale and mechanisation becomes feasible. Consequently, highly mixed systems such as forest gardens are currently not easy for mechanisation and sales. However, such systems could be viable for self-harvest CSA systems.

3.3| *Guidelines for species and cultivar spatial diversity*

Table 3| A summary is given of different design choices and when they are likely to fit different goals, context and crop and livestock.

Choices	Context	Goals	Crops	Livestock
Cultivars mixed in the row	• Conditions not suitable for pollination	• Trialling different cultivars • (Bio)diversity • Pest and disease control	• Pollinated tree crops when not pollinated between rows • Tree crops with simultaneous maturation and similar quality attributes • Disease prevention • Timber crops	• Early and late cultivars for a more even feed or fodder production
Cultivars mixed between the rows	• Where the slope, soil or climate changes significantly between the strips, an alternative cultivar/ rootstock can be more suitable • Closer tree strip spacings of multiple tree rows per strip when pollination is needed	• Ease of harvesting and mechanisation • Increased proportion of productive cultivars	• Harvesting crops with different maturation or quality attributes	
Cultivars mixed in and between the row		• Trialling different cultivars	• For crops with different maturation or quality attributes such as a row for industry and a row for fresh use • For tree crops with different pollination groups	
Species mixed in the row	• Self-harvest farm (CSA) • Low degree of mechanisation	• Product diversity • Biodiversity • Aesthetics • Temporal cropping (see 2.4)	• Timber trees	• Fodder hedges • Different levels of shelter
Species mixed between the rows	• Where the slope, soil or climate changes significantly between the strips, an alternative species can be more suitable	• Ease of harvesting and mechanisation whilst increasing product diversity • Spread risk and labour • Temporal cropping (see 2.4) • Nurse cropping • Trialling different crops		• Rows with different uses such as fodder hedges and biomass hedges for woodchip bedding
Species mixed in and between the row	• Self-harvest farm (CSA)	• Biodiversity		• Fodder hedges • Medicinal hedges

4| Tree row orientation

The orientation of the tree row is the last important consideration in the planting pattern design process. Farmers often question if it is better to plant the trees from north to south, east to west, or in another orientation (see Figure 19). The tree row orientation has four important impacts:

- It affects the light and shadow dynamics for both the tree and the field crop
- It has a substantial effect on the microclimate depending upon whether it is parallel or perpendicular to the prevailing winds
- It affects the number of crop rows (based on the field dimensions) and thus the ease of mechanisation
- It can effect erosion, runoff and the capacity to use machinery on sloping terrain.
- In most cases a compromise will have to be made which may differ from field to field.

Figure 19| Example of a design with differing orientation, in this case north-south or east-west orientation.

4.1| *Light*

In terms of light, the orientation affects the availability and intensity of sunlight available to the crop and the distribution of light in the tree canopies within the row. This changes based on the latitude and also the time of year. Suggestions for the best orientation of tree rows for light are shown for different latitudes in Table 4 based on simulations from (Dupraz, Blitz-Frayret et al. 2018).

Table 4| Recommended orientation of tree row at different latitudes based on light availability and heterogeneity (Dupraz, Blitz-Frayret et al. 2018). The number of crosses indicate the relative impact: +++ high impact; ++ moderate impact; + low impact.

	Increase light availability for crops	**Reduce light heterogeneity for crops**	**Increase tree growth**	**Best compromise**
Low latitudes (<35°) (Tropics)	East–West +++	North–South +	North–South +	East-West
Temperate latitudes (35°–50°)	Neutral	North–South ++	North–South +	North–South
High latitudes (>50°) (Boreal/ Austral)	North–South +++	Neutral +	Neutral	North–South

In general, a north-south tree line orientation is recommended for the temperate latitudes for several reasons:

- For the trees this provides a more even light distribution on both sides of the tree (see Figure 20) and reduced temperature extremes. Where trees are orientated east-west there is a sunny and shaded side which may result in fewer flowers on the north side, early flowering on the south side and an increased risk of frost injury (Lombard and Westwood 1976). This may also affect the timing and uniformity of fruit maturity, quality characteristics and the risk of sunburn though the results are not yet conclusive (Lombard and Westwood 1976, Trentacoste, Connor et al. 2015, Trought, Naylor et al. 2017, Maldera, Vivaldi et al. 2021).
- For the field crop the light availability is quite similar for both orientations, in some months the north-south orientation provides just slightly more light (e.g. March and September), and in other months east-west provides more light (e.g. June and December), however the distribution of light is more even with a north-south orientation which makes it the best compromise when it comes to the field crop (Dupraz, Blitz-Frayret et al. 2018).
- For livestock, the more intense shading on the northern side of the east-west orientation may provide more shelter from high temperature extremes and thus be beneficial for the animal. More practical experience is necessary to explore this.

There remains much to learn about the optimal tree row orientation. Further research and practical experience is necessary to provide definitive recommendations that optimise the orientation for different; tree species, latitudes, planting patterns, crops and crop rotations, cultivars, flowering and fruit set times, tree canopy densities (dense or dappled), uniformity in crop ripening, product quality characteristics (such as grain size, protein content, dry matter, fruit colour).

4.2| ***Wind***

When placing windbreaks to protect crops from damaging winds there are two options. The most simple is placing the windbreak perpendicular to prevailing winds. However, when the damage occurs in a particular month such as during the germination of the field crop, flowering, or early fruit development, it can be wise to place the windbreak perpendicular to the wind direction that is dominant at this time of year as this can provide the greatest benefit.

4.3| ***Mechanisation***

The consideration of mechanisation for tree row orientation regards the number of crop rows, necessary turns with machinery and accessibility for the harvester and chaser bins. Most field operations take place in a way that it minimises labour and fits the working widths of the machinery. In many cases this means long runs and fewer turns. However in some cases, dependent on the field layout, crop and machinery, shorter runs with more turns can be more efficient for the harvest. Careful consideration of these options should be made based on the existing field layout. The ability to use machinery is also of importance on sloping sites. In this case the capacity to use machines on the slope and also the desire to reduce erosion can be in conflict.

Figure 20| Effect of east-west (left) or north-south (right) orientation on the distribution of light (Dupraz (2018) as in (Nelissen, Van Daele et al. 2017))

4.4| ***Guidelines for orientation***

Table 5| A summary is given of different design choices and when they are likely to fit different goals, context and crop and livestock aspects.

Choices	Context	Goals	Crops	Livestock
North-south orientation	• Temperate and boreal latitudes with suitable field layouts	• More uniform distribution of light for field and tree crops (temperate climates)	• Crops sensitive to sunburn • Uniform ripening of tree and field crops	
East-west orientation	• Tropical latitudes with suitable field layouts	• Can provide more light in some months of the year	• Crops needing more light in spring and autumn • Crops insensitive to sunburn	• East-west may in some situations provide more accessible shade for livestock in temperate zones
Perpendicular to wind	• Substantial damage from winds • Wind erosion problems	• Wind erosion control • Optimal wind shelter	• Wind and erosion sensitive field- and tree crops	• Reducing wind chill and temperature stress for animals
Dependent on field layout	• Narrow and irregular fields	• Fitting with current farm mechanisation	• Crops with wide working widths	• Supporting animal movement and grazing movements through the field

5| Planting shape

In most cases the shape will be chosen which is the most easy to manage mechanically and fits with existing field boundaries, crop operations and field contours. Where animals are present the trees may be planted in a block to provide additional shelter for the animals. Additional considerations such as erosion, frost, wind and elevation can also effect what is the optimal shape for the field.

On slopes prone to erosion due to rainwater runoff, placing the trees on contour will reduce erosion and improve water infiltration. However, in doing so it can also trap cold air and form frost pockets. In this case it can be valuable to include gaps or slopes in the tree line to allow cold air to move down the slope, especially where the field and/or tree crops are susceptible to late spring frosts. Where livestock are present an additional consideration is the ease of fencing, stock movement and grazing management.

Figure 21| Curved planting pattern (left) can be suitable on slopes where trees are planted on contour to reduce erosion and improve infiltration. Block planting (right) is sometimes used in livestock systems.

5.1| *Guidelines for planting shape*

Table 6| A summary is given of different design choices and when they are likely to fit different goals, context and crop and livestock aspects.

Choices	Context	Goals	Crops	Livestock
Shape – Block	• For certain field layouts	• Easy management • Shelter for livestock	• Wind-sensitive tree crops may do better in blocks or multiple rows • Timber crops can have straighter trunks and fewer side shoots	• More substantial shelter in different directions
Shape - On contour	• Hilly areas with erosion problems	• Reduce runoff and erosion	• Erosion sensitive crops	
Shape – Irregular	• Irregular existing field layout	• Utilize edges that are not easily mechanised	• Low management tree crops, such as timber	• Provide shelter from multiple directions
Shape – Inclined (not on contour)	• Frost prone areas • Hilly regions	• Reduce frost pockets • Allow management for certain machines	• Tree and field crops sensitive to frost pockets	

6| Conclusion

There is still a great deal to learn regarding the optimal planting patterns for agroforestry systems. The ideas and suggestions here are intended to inspire the development of new and improved agroforestry systems and support designers in making informed decisions about the various choices that are made when developing a system for their specific local settings and goals. As new cultivars, machines and insights are gained no doubt additional systems will be possible. Comments, suggestions and shared experience are welcome and can be submitted to addresses in the colophon.

7| References

Balandier, P. and C. Dupraz (1998). "Growth of widely spaced trees. A case study from young agroforestry plantations in France." Agroforestry Systems 43(1): 151-167.

Bestman, M., et al. (2017). "Lessons learnt-Agroforestry for organic and free-range egg production in the Netherlands." AGFORWARD Report Work-package 5.

Bohanek, J. R. and J. W. Groninger (2005). "Productivity of European black alder (Alnus glutinosa) interplanted with black walnut (Juglans nigra) in Illinois, USA." Agroforestry Systems 64(2): 99-106.

Dupraz, C., et al. (2018). "Influence of latitude on the light availability for intercrops in an agroforestry alley-cropping system." Agroforestry Systems 92(4): 1019-1033.

Feldhake, C. (2001). "Microclimate of a natural pasture under planted Robinia pseudoacacia in central Appalachia, West Virginia." Agroforestry Systems 53(3): 297-303.

Heiligmann, R. B., et al. (2006). "Effects of wind barrier protection on eleven-year growth of black walnut seedlings." Northern Journal of Applied Forestry 23(2): 83-86.

Hunt, K., et al. (2009). "Growing chinese chestnuts in Missouri." Univ. Missouri. Ctr. Agroforestry Publ. AF1007.

Jordon, M. W., et al. (2020). "Implications of Temperate Agroforestry on Sheep and Cattle Productivity, Environmental Impacts and Enterprise Economics. A Systematic Evidence Map." Forests 11(12): 1321.

Lin, C., et al. (1998). "Shade effects on forage crops with potential in temperate agroforestry practices." Agroforestry Systems 44(2): 109-119.

Lombard, P. and M. Westwood (1976). Effect of hedgerow orientation on pear fruiting. II International Symposium on Pear Growing 69.

Maldera, F., et al. (2021). "Row Orientation and Canopy Position Affect Bud Differentiation, Leaf Area Index and Some Agronomical Traits of a Super High-Density Almond Orchard." Agronomy 11(2): 251.

Nelissen, V., et al. (2017). "Teelttechnische impact agroforestry."

Norton, R. L. (1988). "11. Windbreaks: Benefits to orchard and vineyard crops." Agriculture, Ecosystems & Environment 22: 205-213.

Nuberg, I. (1998). "Effect of shelter on temperate crops: a review to define research for Australian conditions." Agroforestry Systems 41(1): 3-34.

Olsen, J. L. (2013). "Growing hazelnuts in the Pacific Northwest: pollination and nut development."

Pardon, P., et al. (2018). "Effects of temperate agroforestry on yield and quality of different arable intercrops." Agricultural Systems 166: 135-151.

Pent, G. J. (2020). "Over-yielding in temperate silvopastures: a meta-analysis." Agroforestry Systems 94(5): 1741-1758.

Rhee, J. (1959). "Windbeschutting van cultuurgewassen, vooral onderzocht voor fruit." Van der Wiel en Co., Arnhem.

Taksdal, G. (1992). "Windbreak effects on the carrot crop." Acta Agriculturae Scandinavica B-Plant Soil Sciences 42(3): 177-183.

Trentacoste, E. R., et al. (2015). "Row orientation: applications to productivity and design of hedgerows in horticultural and olive orchards." Scientia Horticulturae 187: 15-29.

Trought, M. C., et al. (2017). "Effect of row orientation, trellis type, shoot and bunch position on the variability of Sauvignon Blanc (Vitis vinifera L.) juice composition." Australian journal of grape and wine research 23(2): 240-250.

Van Vooren, L., et al. (2016). "Greening and producing: An economic assessment framework for integrating trees in cropping systems." Agricultural Systems 148: 44-57.

Wertheim, S. J. (1981). De teelt van walnoten, Consulentschap iad voor de fruitteelt in de volle grond [etc.].

Zheng, X., et al. (2016). "Assessment of the effects of shelterbelts on crop yields at the regional scale in Northeast China." Agricultural Systems 143: 49-60.

Author | Andrew Dawson & Isabella Selin-Norén
With the cooperation of |
Maureen Schoutsen & Marcel Vijn

Design | Caroline Verhoeven

Figures | Andrew Dawson & Fogelina Cuperus

Contact |
Wageningen University & Research | Open Teelten
E | maureen.schoutsen@wur.nl T | +31(0)320 29 16 40
E | isabella.selinnoren@wur.nl T | +31(0)320 29 11 74

This factsheet is part of the series 'Factsheets Agroforestry'. This factsheet is a result of the 'National research program Agroforestry (2019-2022)' (co-financed by the Ministry of Agriculture, Nature and Food Quality) and the European project AgroMix.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement 862993.