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Influence of latitude on the light availability for intercrops in an agroforestry alley-cropping system

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Abstract

Light competition by trees is often regarded as a major limiting factor for crops in alley-cropping agroforestry. Northern latitude farmers are usually reluctant to adopt agroforestry as they fear that light competition will be fiercer in their conditions. We questioned the light availability for crops in alley-cropping at different latitudes from the tropic circle to the polar circle with a process-based 3D model of alley-cropping agroforestry. Two tree densities and two tree line orientations were considered. The effect of the latitude was evaluated with same-sized trees. The relative irradiance of the crops was computed for the whole year or at specific times of the year when crops need more light. The heterogeneity of crop irradiance across the alley was also computed. Surprisingly, crop relative irradiance of summer crops at high latitudes is high, at odds with farmers' fears. Best designs were highlighted for improving the crop irradiance: North-South tree lines are recommended at high latitudes and East-West tree lines at low latitudes. At medium latitudes, North-South tree lines should be preferred to achieve an homogeneous irradiance of the crop in the alley. If we assume that trees at northern latitudes grow slower when compared to southern latitudes, then alley-cropping agroforestry is highly advisable even at high latitudes with summer crops.

Keywords

Alley-cropping systems, light availability, latitude, design, tree row orientation, virtual experiment

Introduction

Why are high latitude farmers so reluctant to agroforestry? Competition for light between trees and crops is the greatest fear of most farmers when considering agroforestry adoption. It is usually assumed that the reduction of the total annual incoming radiation and the lower elevation of the sun in the sky at high latitudes (above 45° Latitude) would result in an enhanced competition for light between the trees and the crops. As a consequence, farmers often assume that agroforestry is not feasible at high latitudes, and is better fit for low latitudes. However, when considering the actual growing season of crops (spring and summer), some aspects are less obvious: while at high latitudes the direct sun beam comes from various directions during the long days in spring and summer, its path on the sky vault (from East to West) and day length remain relatively unchanged during the year at low latitudes.

Current agroforestry practices in Europe are mostly maintained at Southern Mediterranean latitudes (Eichhorn et al. 2006) and most traditional agroforestry systems were dropped by northern latitude farmers. It is also striking that agroforestry is more successful in the tropics than in the temperate zone (Ong et al. 1991), but this may be more related to less mechanisation constraints than to the light budget of the crops.

Both facts may support that radiation availability is limiting the adoption of agroforestry at high latitudes. Another recent assumption is that North-South tree lines should be preferred to allow for a more homogeneous irradiance of the crops in the alleys at temperate latitudes (Dufour et al. 2013), but the effect of latitude was not included in that study. Using a numerical simulation model, we question these paradigms, and look for their validity domain at different latitudes.

Alley cropping agroforestry (annual crops associated to lines of trees within agricultural fields) is an interesting alternative to mainstream agriculture. It has the potential to increase the income of farmers while tackling environmental issues such as soil, water and biodiversity protection (Dupraz 2005). It also has a high potential of storing soil organic carbon (Cardinael et al. 2015) and protecting crops against climatic hazards due to climate change (Calfapietra et al. 2010; Dupraz 2013). In some European countries such as France, alley-cropping agroforestry is nowadays the main innovative agroforestry system that is adopted by farmers (Liagre et al. 2009) and promoted by the government (Ministère de l'Agriculture 2016).

In alley-cropping agroforestry systems, crops face high levels of spatial and temporal heterogeneity for light, water and nutrients availability due to the wide-spaced trees (Gillespie et al. 2000; Mulia and Dupraz 2006). This results from the partial interception of radiation by tree canopies, and by the partial capture of soil resources by tree root systems that do not colonize the whole plot. Heterogeneity peaks when the trees are medium-sized, but is lower when the trees are very small (small impact of the trees) or very large (homogeneous impact of the trees). The success of such a practice stands in the ability of crops and trees to minimize competition by extracting resources at different locations or times (Thevathasan and Gordon 2004; Tilman and Snell-Rood 2014). As an example fine roots of intercropped walnut trees may colonize deeper soil layers than in a monoculture context, reducing direct root competition with the crop (Cardinael et al. 2015). Complementarity may also occur aboveground: the intercropping of Paulownia trees with wheat was successful in China, as there is minimum shading during the crop growing season due to the late leafing of Paulownia trees (Chirko et al. 1996). However, some experiments have suggested that light competition may be the major limiting factor in many systems such as maize (Friday and Fownes 2002) or cotton alley-cropping (Zamora et al. 2009). The spatial pattern of tree shading on crops has been studied with rows of Paulownia trees (Liu 1991), but the impact of latitude was not evaluated. The effects of solar radiation reduction on wheat grain yield have been assessed with field experiments using artificial shading or mature agroforestry systems. Application of shade during 20 to 30 days before anthesis induced a decreased of the dry weight of spikes (Abbate et al. 1997). Crops subjected to artificial shade conditions also experienced a decrease of grain weight along with an increase of protein content (Demotes-Mainard and Jeuffroy 2004; Dufour et al. 2013). Such studies indicate that if we want to study the impact of trees on crops at different latitudes, we should also consider the processes of competition influencing the day to day and year to year changes in phenology and physiology of both the crops and the trees. We should pay particular attention to the times when low irradiance may critically limit the crop development and yield: i) when flowering is at stake (around the spring equinox for winter crops and the summer solstice for summer crops), and ii) when grain filling is concerned (around the summer solstice for winter crops and the autumn equinox for summer crops).

Many studies have focused on the light interception by hedgerows of fruit trees such as olive trees (Connor et al. 2009; Connor et al. 2016) demonstrating that the fruit yield was influenced by hedgerow orientation and hedgerow side in case of East-West orientation of the tree lines. But these studies did not account for the patterns of the radiation transmitted to the ground, and did not take into consideration the impact of latitude (Trentacoste et al. 2015).

The only published modelling study of the relative ground-level irradiance in an alley-cropping agroforestry system at various latitudes showed an increase of the crop irradiance at low latitudes, and a strong interaction between time of year, latitude and shading patterns in the case of East-West oriented tree lines (Jackson and Palmer 1972; Jackson and Palmer 1989). However, some very simplifying assumptions were included in that study: the hedgerows were fixed parallelepipeds (flat top and vertical sides, no growth) with no gaps between tree canopies and did not transmit any radiation. With such assumptions it was not possible to assess the impact of growing trees with an increasing size over the years, with seasonal variations of leaf area, with gaps between trees, with the shade of trunks and branches in winter. In this regard, field experiments using artificial shade on wheat led to the conclusion that modelling studies should consider, in addition to tree lines configuration, realistic shade patterns created by trees (Dufour et al. 2013). We therefore propose an improved modelling approach that simulates the light availability at the day time step, in agroforestry systems with growing trees (size, shape, leaf area, phenology) over a 40 year period. In this study we analyse the radiation availability at the crop level, at different latitudes of the northern hemisphere and for various configurations of the tree plantation design.

In addition to the average irradiance, the spatial homogeneity of light available at crop level within the cropped alley is an important factor to ensure homogeneous crop physiology and maturity, allowing the farmer to manage the crop easily. Therefore the spatial homogeneity of the irradiance of the crop was also assessed.

Materials and methods

The Hi-sAFe agroforestry model

Long term field experiments involving latitude are not feasible. We therefore decided to adopt a virtual experiment approach, using a numerical process-based model of agroforestry systems. We used the Hi-sAFe model that includes a 3D light competition module between trees and crops (Talbot 2011). The model is spatially explicit, allowing comparing various planting designs including tree density, tree rows orientation, plantation design (rectangular, quincunx) and pruning intensity.

The light competition module in Hi-sAFe

The Hi-sAFe model (Dupraz 2005), implemented with the Capsis platform (Dufour-Kowalski et al. 2012), allows the computation of the development and growth of trees and crops based on light, water and nitrogen competition. The model was calibrated and evaluated by Talbot (2011) and Talbot *et al.* (2014). Various plantation designs can be simulated, allowing comparisons between different tree densities (distance between tree rows and between trees on the row), tree rows orientations, tree pruning heights and frequencies, and plot design (rectangular or staggered rows). The agroforestry system is represented by a rectangular scene divided in 1 m² cells that can either host a crop, a tree, or both. Computation of the light interception is performed by a 3-D light competition module between trees and crops that was previously validated with field measurements (Dufour et al. 2013). All light calculations are made for each 1 m² cell of the scene for both the diffuse and direct radiation. The global daily radiation provided by the climate records is first split into direct and diffuse radiation (Bonhomme 1993). All calculations are made for the Photosynthetically Active Radiation (PAR), considered as a constant proportion of the daily solar radiation. The direct radiation interception by trees is computed with a ray-tracing algorithm (Talbot and Dupraz 2012). The trees are represented by a conic trunk and an ellipsoid crown, linked to the diameter at breast height and to the trunk height by allometric relationships. Every thirty minutes, the sun position is updated on the celestial vault and a beam trajectory is computed on each cell. When the trees are small and their canopy diameters are similar to the cell dimensions, more rays (4 or 9 depending on the accuracy required) are computed for each cell. The attenuation of the radiation by the crown of trees is given by the Goudriaan's approximation (turbid medium approximation). Leaf clumping corrections were shown to be not essential and ignored (Talbot and Dupraz 2012). Because of the high computation time required by the ray-tracing method, this is called only when the tree leaf area has changed by more than 5% and/or the sun elevation has changed by more than 2° since the last call (Talbot 2011). The interception of light by the trunk and branches is also calculated when the trees are leafless, assuming a cone shape for the trunk and a density of woody branches in the canopy. Conversely, when the tree is leafy the interception by the branches is neglected. The diffuse radiation received by the crop is computed from the proportion of sky unobscured by the trees and the Standard Overcast Sky model of sky luminance (Hutchison et al. 1980).

By running at the day time step on long periods, the Hi-sAFe model takes into account a dynamic tree phenology (leaf area) and size, including pruning effects. It also considers the variations of the intensity of the radiation as a function of the sun elevation, allowing a synthesis of the various geometrical effects in time and space that is not intuitive.

Simulation of light interception at various latitudes

We computed the radiation available for crops in an alley-cropping system at five latitudes (25°, 35°, 45°, 55°, 65° Latitude North), two distances between tree lines (17 versus 35 m) and two tree row orientations (North-South, East-West). The simulated agroforestry system included a winter durum wheat crop alley, separated by 1 m wide tree lines of *walnut-hybrid* deciduous trees (*Juglans regia x nigra* type) and weeds. Trees were spaced 7 m on the tree line, resulting in a planting density of 84 and 41 trees.ha^{-1} with 16 m and 34 m wide cropped alley respectively, in line with tree densities recommended for temperate agroforestry (Dupraz et al. 2018). The European regulations enforce densities of mature trees between 30 and 200 trees per hectare, but most European countries limit the maximum values to 100 trees.ha^{-1} to maintain full crop payments. Therefore distances between tree lines lower than 15 m would not be acceptable by member states of the European Union. 30 to 100 trees.ha^{-1} can be achieved with distances between tree lines between 15 and 40 m, and distances on the tree line between 8 and 12 m. This is why we chose two options in the modelling study that represent fairly this range. In addition, with higher tree densities, the yields reduction for the intercrops would be rather dramatic when the trees get large, and the system would not be adopted by farmers. We compared two densities that may be considered as a low one and a large one, both complying with European regulations of the Common Agricultural Policy.

The pruning scheme was as follows : every two years, 30% of tree height, until the pruned trunk reached 4 m. We calculated the relative irradiation of the crop (ratio of incoming radiation at the crop level divided by the incoming radiation on the plot) at the day time step and m² scale, and aggregated it at various time (month, year, decades) and spatial (m², cropped alley, total plot) scales. Spatial variability was calculated as the coefficient of variation of the relative irradiation of the 1 m² cells of the cropped alley.

In order to assess the impact of latitude and tree row orientation on the crops at various time periods, corresponding to different phenological stages of both trees and crops, we calculated the relative irradiance available at ground level during four months of the year (March and December: leafless trees; June and September: fully developed leaves). In order to avoid particular days (e.g. one very cloudy day) we chose to do the calculation for the whole month, which gave average values that are more robust than values calculated only on the very day of the solstice or equinox. We will present the irradiation values obtained when the trees reach the final size corresponding to the minimum irradiation values for the crop.

Simulations were performed at a daily time step over a period of up to 40 years (years 1995 to 2035), until the tree DBH reached a 50 cm threshold. The final trees had an approximate 19 m height, a crown radius on the tree line of 3.5 m (canopy closure) and a crown radius across the cropped alley of 8.5 m (canopy closure) for 17 m wide alleys, and 10 m (no canopy closure) for 35 m wide alleys. While the first 20 years of the climatic data used in the simulation (1995 to 2015) were recorded at our experimental plot of Restinclières (43.71°N, 3.86°E), data for the remaining years were randomly sampled (without replacement) from the same dataset. Input daily global radiation was adjusted for each simulated latitude by multiplying the radiation measured in Restinclières by the ratio of the extra-terrestrial radiation at the target latitude and at the latitude of Restinclières on a daily basis. The daily extra-terrestrial radiation at each latitude was computed with function extrat() of the “sirad” package for R software. As we focussed on light competition, we considered simple assumptions such as same soil, same crop, same tree species and same weather at all latitudes, with only the radiation corrected to be adjusted to the corresponding latitude. Crop yields and tree growth patterns were not analysed as we concentrate on ground irradiance at different latitudes caused by same-sized trees. In this approach, consistency between radiation and other climate variables is broken, but this has no impact on the radiation budget under the trees that is the core of this study. It allows having same sized trees with the same phenology at all latitudes, which is a methodological choice. Using actual weather data for each latitude would have blurred the conclusions, as each site is unique regarding its climate, depending on elevation, distance to the sea or to mountain ranges, local topography, etc. By using identical trees, we can isolate the effects of latitude and plantation geometry.

If cloudiness was latitude dependent, it would impact the ratio of direct/diffuse light, and our results may be disputed. We searched the bibliography for such a relationship and did not find any evidence of it. Cloudiness is much higher around the equator, but this area was not included in our study. Between 25 and 65° latitude North, no relationship between latitude and cloudiness could be found. We therefore decided to keep cloudiness stable (and equal to cloudiness in our reference site) for this study, and this was achieved by the scaling procedure that we used.

Output variables

Relative irradiance

We discuss the daily relative irradiance on the crop. This is the ratio between the incident PAR at the crop level under the trees and the incident PAR above the trees. We integrated the relative irradiance on the crop at various time (month, year) and spatial scales (m², cropped alley, entire plot). We compared the different factors (latitude, distance between tree lines and orientation of these lines) by plotting radiation patterns against tree size, not time.

The annual integral of the relative crop irradiance may not be a sensible variable when discussing the behavior of crops with short growing seasons or of crops with some stages that are specifically sensitive to low levels of irradiance, such as flowering. In order to explore the worst competition level for the crop, we analyzed the impact of large mature trees (50 cm DBH). DBH is closely correlated to tree height and tree crown diameter and is therefore a very good proxy for tree competition for light. The irradiance level at four times of the year was documented: winter and summer solstices and spring and autumn equinoxes.

Coefficient of variation of the relative irradiance

The spatial variability of the irradiation of the crop was computed as the coefficient of variation of the relative irradiance at the m² scale on the cropped alley. We focussed on the variability in June, when it is expected to be higher, due to the combination of high leaf areas of trees and high elevation of the sun in the sky.

It can be noted that the simulation results have a stochastic component : it comes from the stochastic weather variables used for the simulations. For example, some years with a low rainfall pattern result in water stresses on the trees that reduce their leaf area to adjust to the stress, resulting in a higher irradiation of the crops. This will not happen at the same tree DBH for the different runs of the model, as the tree DBH depends on the latitude (radiation availability), tree competition (different at 17 and 35 m wide tree lines or different tree row orientation). It is therefore normal that the dots on the lines are scattered. This is why we used moving averages to ease the interpretation.

Results

Relative irradiance at the crop level for the whole year

As expected, crop irradiation decreased with tree growth. For trees of equal size, tree density had a much larger impact on relative irradiance than latitude or tree row orientation (Figure 1).

Figure 1 : Variation of the annual relative irradiance of the crops as a function of the tree DBH. Three levels of latitude are plotted for an East-West and North-South tree line orientations. The distance between the lines of trees was set to 17 m (Left : 84 trees.ha^{-1}) and 35 m (Right : 41 trees.ha^{-1}). The relative irradiance was averaged on a year on the cropped alley. Curves were smoothed with a moving average on 5 points.

Effect of latitude

The annual relative crop irradiance decreased when latitude increased, with a more dramatic effect between temperate and polar latitudes. This impact was negligible until the tree DBH reached 10 cm. The tree shades are projected much farther from the tree lines when the sun elevation decreases and, in case of very low sun elevations, the solar beams are intercepted by several tree lines before reaching the crop. However, the impact of latitude on the annual relative irradiation was moderate (Figure 1): only 13% and 16% decrease for 25 cm and 50 cm DBH trees for 17 m wide spaced tree lines respectively when comparing the tropics and the polar circle

Effect of the distance between the tree lines

Wider spaced tree lines increased steadily the relative crop irradiation (Figure 1). As expected, the reduction of the number of trees on the plot increased the light available for crops at all latitudes. The relative irradiance of crops increased by 35% and 23% when the distance between East-West trees lines was increased from 17 m to 35 m, at Latitude 65°and 25° respectively. A wider tree spacing is therefore very efficient to increase crop irradiation at high latitudes. Trees at low density grew faster than trees at high density, but this effect is not discussed in this paper as we compare crop irradiation for trees with the same size.

Effect of tree line orientation

Tree line orientation had opposite effects at high and low latitudes (Figure 1). At low latitude (25°, close to the tropic circle), the crop irradiance was higher with East-West tree lines. At northern latitude (65°, close to the polar circle), the relative irradiance was very similar with both orientations, but slightly higher with a North-South orientation.

Higher relative irradiance at southern latitudes with East-West oriented tree lines can be explained by the sun trajectory on the celestial vault (Figure 2). At such low latitudes, the sun path stays close to the East-West axis during the whole year. With an East-West tree line, long shades produced during the mornings and afternoons are projected on the neighbor trees, while the shades around midday are very short due to the position of the sun close to the zenith. This results in high mutual shading between trees and low shading of trees on the cropped alley. With North-South tree lines, more shade is projected over the cropped alley.

Figure 2 : Sun path at the summer solstice (dashed), equinox (solid) and winter solstice (dotted-dashed) for latitude 65° (left) and 25° (right) as seen from the center of the alley with North-South (top) and East-West (bottom) tree lines. At 65° latitude North, the sun does not rise at the winter solstice. These images are shot from the center of the alley at the reference walnut-wheat system in Restinclières (tree lines spaced by 13 m, tree height 8m). They help to understand the low impact of latitude on the relative crop irradiation at the summer solstice with North-South tree lines, or the high impact of East-West tree lines on the radiation capture in winter at low latitudes.

At northern latitudes, the sun location on the celestial vault has less preferential directions, particularly close to the summer solstice, when its path remains low on the horizon all day long. During the longest days of the year, the sun is creating long shadows that extend east and west of the trees during mornings and afternoons, and north of the trees at midday. Midday light intensity is much higher when the shadows of trees are projected on neighboring trees with North-South tree lines. The Hi-sAFe model allowed to integrate all these effects and to compute that North-South tree lines allow a slightly higher irradiance on the crop at high latitudes.

Effects of different time periods of the year on the relative crop irradiation

The calculations used final 50 cm DBH trees, with a very strong impact on radiation availability for the crops (Figure 3). In March and December, the trees are leafless and cast a shade on crops with their trunks and branches, capturing 25% to 45% of the radiation at most latitudes. During this leafless period, North-South tree lines allow a higher relative irradiance at high and medium latitudes. At high latitudes, the radiation captured by the tree trunks and branches is not negligible, as the sun beams cross many tree lines before reaching the crop.

Figure 3 : Relative irradiance on crops in March, June, September and December, when the DBH of trees reached 50 cm. Relative irradiances were calculated on the cropped alley. The distance between the tree lines was 17 m (left) or 35 m (right)

In June and September, trees are leafy, capturing 55% to 75% (17 m wide alleys) or 25 to 50% (35 m wide alleys) of the sun irradiation that would have reached the crop. In particular, in June (summer solstice), while the light intercepted by North-South oriented tree lines produces quite constant relative crop irradiance at all latitudes, East-West tree lines let a more variable radiation reaching the crop. The way the sun trajectory is hidden by the tree lines largely depends on their orientations. While North-South tree lines hide the sun trajectory quite similarly at all latitudes (Figure 4, top), the effect of East-West oriented tree lines largely changes with the latitude (Figure 4, bottom). In addition to the sun trajectory, the sun elevation (zenith angle) has a major impact on the amount of radiation intercepted by the tree lines. For high sun elevations (low latitudes) East-West tree lines allow the trajectory of the sun to be visible by the crop almost all day long. Regarding September (summer equinox), North-South tree lines provide more light to the crops than the East-West ones at high and medium (temperate regions) latitudes, while the opposite is true at low latitudes.

Figure 4. Sun path at 25° of latitude North (dashed line) and 65° of latitude North (dotted-dashed line) between North-South (top) and East-West (bottom) oriented tree lines, as seen from the centre of the cropped alley (left) or close to the tree line (right). Picture shot in a poplar alley cropping system with tree lines spaced 16 m and tree height 20 m

Heterogeneity of the relative irradiance at the crop level in June

The coefficient of variation of the crop relative irradiance in June was computed on the cropped alley (Figure 5). The light intercepted by the trees and the resulting heterogeneity of crop irradiance changed with the tree size. When the trees are very small, there is logically no heterogeneity in crop irradiation. Heterogeneity increases with tree size, but not in a simple way: it depends on latitude and, above all, on the tree line orientation.

Figure 5 : Coefficient of variation of the relative irradiance of the crop as a function of the DBH of the trees for the month of June at three latitudes, for two tree line orientations (North-South and East-West) and two distances between tree lines (17 and 35 m). Curves are smoothed with a moving average on 5 points.

Effect of latitude

Heterogeneity decreases for increasing latitude (Figure 5) especially with East-West tree lines. The Hi-sAFe model can be used to integrate the sun position and beam energy across the day, at any location or time of the year, allowing the computation of non-intuitive results. The sun trajectory at high latitudes follows a much wider azimuth range than at low latitudes (Figure 2). Therefore, at high latitude, the projected shadows rapidly move over the cropped alley during the day, resulting in a quite uniform irradiance. The opposite is true at low latitudes, where the sun trajectory stays almost always in the southern half-hemisphere of the sky vault, resulting in some very shady and some very sunny parts of the cropped alley.

Effects of tree lines orientation

North-South tree lines spectacularly reduced the variability of crop irradiation (Figure 5) at all latitudes. At high latitudes (25°), a coefficient of variation as high as 40% was predicted with East-West tree lines, but decreased to 10% when using North-South tree lines. This reduction is due to the canopies of the trees masking the sun path (Figure 4. Sun path at 25° of latitude North (dashed line) and 65° of latitude North (dotted-dashed line) between North-South (top) and East-West (bottom) oriented tree lines, as seen from the centre of the cropped alley (left) or close to the tree line (right). 4). With North-South oriented tree lines, all crops experience both full sun and full shade during a day, independently of the position in the alley, resulting in a quite uniform daily irradiance across the alley. Conversely, with East-West oriented tree lines, the crop can be in full sun or full shade for the whole day, depending on its position in the alley. This results in very high coefficients of variation of crop irradiation in the cropped alley.

It is worth noticing that the relation between tree size and the heterogeneity of the radiation reaching the crop changed with the orientation of the tree lines. While with East-West tree lines the heterogeneity steadily increased with tree size, with North-South oriented tree lines the heterogeneity peaked for medium sized trees. However, with North-South tree lines, the variability was always very low (<12%), independently of the tree size.

Effects of the distance between tree lines

Surprisingly, at high latitudes the variability of crop irradiation was the same with close (17m) or remote (35m) tree lines. Conversely, at low latitudes the variability was significantly reduced with remote tree lines (Figure 5). Remote lines reduced and stabilized the heterogeneity of the radiation at a value below 25% for all latitudes. This reduction resulted from the higher proportion of the cropped alley exposed for long times to the direct radiation of the sun.

Discussion

Feasibility of agroforestry

The reduction of the crop relative irradiation was not as large as feared at high latitudes during the summer. This was the result of the compensation effect of the lower sun elevation by the longer sun path in the sky. Many studies indicate that a 30% reduction of irradiance may not decrease the yield of most shade tolerant crops, especially in dry environments. This was evidenced for tropical fodder crops (de Andrade et al. 2004), for wheat (Li et al. 2010; Xu et al. 2016; Yadav et al. 2017), for several tropical crops including taro (Pouliot et al. 2012; Sanou et al. 2012). Global dimming of the air may have reduced the average radiation reaching crops by 13% without any yield reduction (Stanhill and Cohen 2001). A 50% reduction of irradiance has a stronger impact on crop yields, but allows often a 80% to 100% relative yield for shade tolerant species such as barley, taro or fodder grasses, while intolerant species will often decrease their yield proportionally to the light reduction. Crop varieties where shade avoidance mechanisms have been cancelled (Wille et al. 2017) will even perform better in the shade, as they will not invest in useless stem elongations in search of additional light (Gommers et al. 2013). This is why it is usually assumed that crops adapted to shady environments may cope with up to 50% of reduction in irradiance, and will perform with only a minor decrease in yield at 80% relative irradiance (Ong et al. 1991). With 41 trees.ha^{-1}, the 50% threshold was never reached in our simulations (Figure 1), showing that agroforestry should be feasible at high latitudes with widely spaced tree lines. With 84 trees.ha^{-1} the relative irradiance of the crops remained above 80% for the whole growth cycle at low latitude, and for more than half the tree life cycle at very high latitudes (Figure 1). Even at latitude 65°, it would never go below the 50% threshold if the final size of the trees would not exceed 40 cm DBH.

The results for specific times of the year are very helpful to design cropping systems. The annual average is not appropriate to design a system based on a seasonal crop. East-West tree lines are definitely more suitable to increase the radiation on the crop at low latitudes at all times of the year, while North-South tree lines are more appropriate at high latitudes for summer crops (usually, there is no winter crop at high latitudes). The tiny irradiance gain predicted at high latitudes in June and December with East-West tree lines does not justify using such an orientation. The same conclusion applies to the gain in irradiance predicted at low latitudes during the winter solstice period with North-South tree lines.

Comparison with other studies

Some simulation studies of light availability for crops in agroforestry systems are available, but they never considered the impact of latitude (Dauzat and Eroy 1997; Van Noordwijk and Lusiana 1998; Zamora et al. 2009). We found only one study on the relative irradiance of crops at different latitudes in an orchard hedgerow system (Jackson and Palmer 1972; Jackson and Palmer 1989). The authors assumed parallelepiped, opaque and fixed hedgerows (no tree growth), and calculated irradiance only in the "clear alley", outside of the vertical projection of the hedgerows, but not under the trees. They investigated three latitudes (0, 30, 50°) and 3 hedgerow orientations (N-S, E-W, SE-NW). Surprisingly, they found the same relative annual irradiance in the alley at all latitudes with N-S hedgerows, which might be the consequence of their very simplifying assumptions: opaque hedgerows and no variations in leaf area. Our more detailed model shows on the contrary that the relative irradiance of crops with North-South tree lines decreases steadily with latitude (Figure 3). They found different patterns of crop irradiance with East-West oriented hedgerow, depending on latitude and time of the year. Such broad conclusions are in agreement with our study. However, by taking into account more realistic and growing shapes of trees, by including porous tree canopies, by considering gaps between tree canopies and by considering a dynamic pruning scheme, we showed that East-West oriented tree lines result in higher variations of the crop relative irradiance with latitude as compared to North-South tree lines (Figure 3). Jackson and Palmer (1972) evidenced a uniform relative irradiance on North-South oriented inter-rows for hedgerow higher than the width of the alley on June 21st. Our simulations confirmed this uniformity for 17 m wide alleys and a tree DBH of 50 cm (corresponding to a tree height of about 20 m) during the month of June: the coefficient of variation in June is typical of an homogeneous relative irradiance with North-South tree lines (Figure 5).

Practical recommendations

Crop irradiation is a key factor for crop success. Crop sensitivity to low irradiation may be high at some phenological stages such as germination, flowering and grain filling. Well-designed agroforestry systems should allow a sufficient relative irradiation during the whole crop cycle, but also a sufficient relative irradiation during critical stages. Our virtual experiment allows recommendations to be drawn about the best design of alley-cropping systems at different latitudes (Table 1). Winter solstice (December) is the time of germination and early growth for winter crop, spring equinox (March) corresponds to winter crops flowering and germination of summer crops. At summer solstice (June) winter crops fill their grains and summer crops bloom and finally autumn equinox (September) is the time of summer crops grain filling. In order to maximize the crop irradiance during the grain filling phases of winter and summer crops, North-South tree lines should be preferred at high latitudes (>50°), and East-West tree lines at low latitudes (<40°). At high latitudes, East-West tree lines are not advisable for summer crops because of the low levels of irradiance that would reach the crop in late summer. Regarding temperate latitudes (40° to 50°), the tree line orientation had no significant impact on crop irradiation at most key phenological stages, such as flowering or grain filling. At these latitudes, tree phenology is more important in determining the radiative conditions of winter crops, and late leafing trees will be preferred to allow for proper crop irradiation at time of flowering. The Saint-Jean walnut tree may be the best example : it opens its buds in mid June, leaving plenty of time for spring crops to mature in full sun. But these trees need to be propagated by grafting. Another option to play with tree and crop phenology to avoid low irradiance at critical moments for the crop yield would be to look for early leaves-dropping trees that would allow grain filling of late summer crops and germination of the next winter crop in the full sun. However, most temperate deciduous trees do not have an early leaf drop.

Table 1 Looking for best practices in alley cropping agroforestry: what is the best tree line orientation?

Finally, at high latitudes winter crops are unlikely because of the snow cover and the lack of light. At low latitudes the dry and humid seasons govern crop management and do not coincide with summer and winter. The rules for designing agroforestry systems in the tropics should therefore take into account the interaction between the rainfall pattern and the relative irradiation pattern described in this study.

Trees and crops are dealing with absolute values of irradiation, not relative values. Some high levels of relative irradiation could lead to limiting values of absolute irradiation, if the absolute incoming radiation intensity is low. But the absolute value of daily irradiation is not always lower at high latitudes (Table 2). The extraterrestrial irradiation is about the same at all latitudes in summer (Figure 6). The absolute value of irradiation at ground level is highly controlled by the local cloudiness. This explains for example that the monthly annual irradiation in April is higher in Canada than in South China or the Amazon basin.

Table 2: Influence of latitude on the annual extraterrestrial and ground-level radiation (Anon, 2018).

Figure 6 : Extraterrestrial radiation throughout the year at different Northern latitudes

It is therefore not possible to give a universal rule about the influence of latitude on the absolute radiation availability for crops, and the relative approach used here can easily be transferred to local conditions when the cloudiness pattern is known. These results emphasise that, depending on the system design, agroforestry can be successfully implemented at all latitudes (Table 1). If we assume that agroforesters favor crops to secure an annual income, North-South tree lines at temperate and high latitudes and East-West tree lines at low latitudes are the best options.

Assuming different tree growth rates at different latitudes

Comparing the latitudes with same-size trees may be questioned. Trees grow slower at Northern latitudes, due to the lower radiation, but also to lower temperatures that shorten the growing season. The decrease of the relative irradiance on crop at high latitudes could be compensated by the reduced light capture by slower growing trees in such regions. To assess this hypothesis, the average crop relative irradiance in June was plot against a tree size index (Figure 7). We assumed that the final tree DBH decreased linearly with latitude from 50 cm at 25° to 30 cm at 65°.

Figure 7 : June relative crop irradiance in the alley plotted against tree size at three latitudes, with two tree line orientations and two tree line distances. The standardized growth index increased from 0 (tree planting) to 1 (final tree size). Final DBH was assumed to decrease linearly from 50 cm at latitude 25° to 30 cm at latitude 65°.

With such tree growth differences, the relative irradiance of intercrops was higher at high latitudes than at low latitudes at the summer solstice with North-South tree lines, and unchanged with latitude with East-West tree lines. Although such results depend on the pattern of tree growth slowdown with latitude, we evidenced a compensation mechanism that cannot be overlooked. Agroforestry at Northern latitudes may be favored by smaller trees than at low latitudes.

Conclusion

The feasibility of agroforestry systems at high latitudes was evidenced and we suggest several practices to improve the light availability for intercrops at different latitudes. As expected, a large distance between the tree lines increased the intensity and decreased the heterogeneity of crop irradiance at all latitudes. However, as wood yield is proportional to plantation density, a trade-off between tree density and crop yield should be investigated using criterion such as the Land Equivalent Ratio (Dupraz 1998). This criterion could be supplemented by taking into account thresholds of acceptability for the heterogeneity of crop irradiance. For a given tree density, in order to increase crop irradiation, we recommend to set the tree line orientation to North-South at high latitudes and East-West at low latitudes. At medium latitudes, the tree line orientation had no significant impact on crop irradiation at most key phenological stages of the crops. Flowering or grain filling occur during times when the relative irradiance of the crops is quite the same with the two orientations. This novel result is at odds with the conclusions of some previous studies (Dufour et al. 2013; Molto and Dupraz 2014) that advised North-South tree lines at all latitudes. We may also question if, for the same level of daily irradiance, the morning light or the afternoon light may have distinct impacts on the crops. This could be assessed by computing separately the irradiation of the crops in the morning and in the evening. Some field experiments with paulownia and wheat have evidenced a higher yield for wheat plots located East (receiving mostly morning light) of a North-South tree line (Chirko et al. 1996) as compared to plots located west of the tree line. This can be explained by the fact that in the morning, the Vapour Pressure Deficit (VPD) is low and the plant water status still high while during the afternoon, VPD is high and a stomatal closure is often happening. Therefore there is a higher risk that photosynthesis can be stopped by stomatal closure during the afternoon and thus photosynthesis could be more efficient in the morning. However, as the model outputs are only at the daily time step, the optimization of tree line orientation taking into account the hourly variation of light interception was not addressed in this paper. Our conclusions are based on the crop relative irradiance, but in places where the absolute incoming irradiance is low (and this happens in cloudy sites at all latitudes) it may result in levels of absolute irradiation that could be limiting for the growth of the crops, even when the relative irradiance is high. At high latitudes, summer crops are the rule, and we demonstrate that they can benefit from a high relative irradiation in agroforestry systems during the summer, when the absolute radiation is also high. However, several additional factors may be included in the assessment of light availability on the crop zone in agroforestry systems, such as the slope of the field, the height of tree pruning, or the use of local climate series that reflect more accurately the local cloudiness pattern. Therefore, recommendations for managing agroforestry systems could be further improved by taking into consideration more characteristics of the field such as its topography, tree management, and the actual crop and tree phenology.

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Influence of latitude on the light availability for intercrops in an agroforestry alley-cropping system

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Figures and Tables

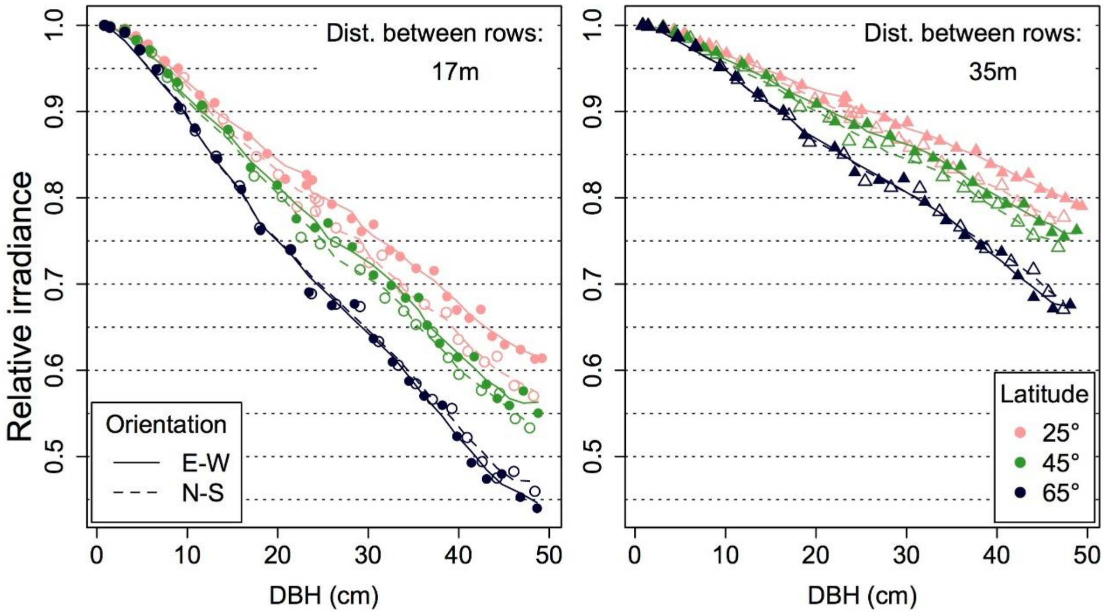

Figure 1 Variation of the annual relative irradiance of the crops as a function of the tree DBH. Three levels of latitude are plotted for East-West and North-South tree line orientations. The distance between the lines of trees was set to 17 m (left : 84 trees.ha^{-1}) and 35 m (right: 41 trees.ha^{-1}). The relative irradiance was averaged on a year on the cropped alley. Curves were smoothed with a moving average on 5 points.

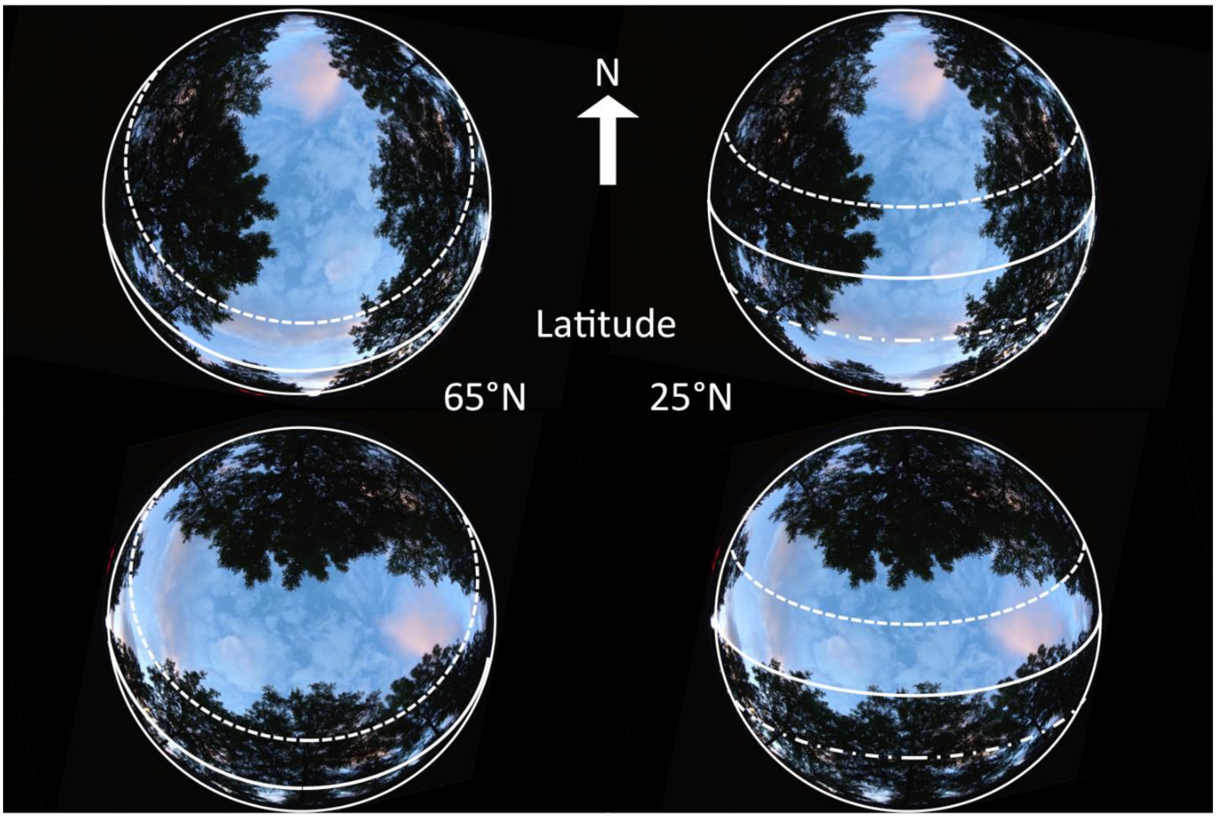

Figure 2 : Sun path at the summer solstice (dashed), equinox (solid) and winter solstice (dotted-dashed) for latitude 65° (left) and 25° (right) as seen from the center of the alley with North-South (top) and East-West (bottom) tree lines. At 65° latitude North, the sun does not rise at the winter solstice. These images are shot in winter from the center of the alley at the Restinclières farm (tree lines spaced by 13 m, tree height 8m). They help to understand the low impact of latitude on the relative crop irradiation at the summer solstice with North-South tree lines, or the high impact of East-West tree lines on the radiation capture in winter at low latitudes.

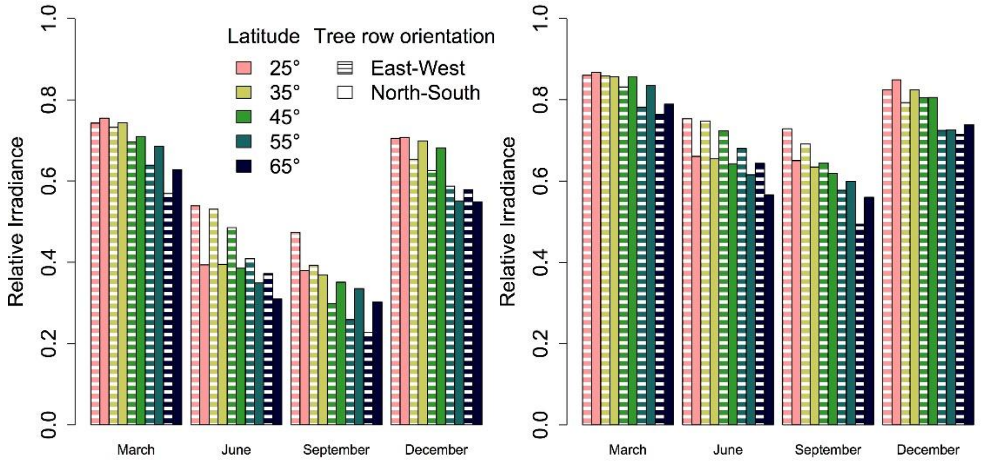

Figure 3 Relative irradiance on crops in March, June, September and December, when the DBH of trees reached 50 cm. Relative irradiances were calculated on the cropped alley. The distance between the tree lines was 17 m (left) or 35 m (right)

Figure 4. Sun path during the summer solstice at 25° (dashed line) and 65° (dotted-dashed line) of latitude North between North-South (top) and East-West (bottom) oriented tree lines, as seen from the centre of the cropped alley (left) or close to the tree line (right). Picture shot in a poplar alley cropping system with tree lines spaced 16 m and tree height 20 m

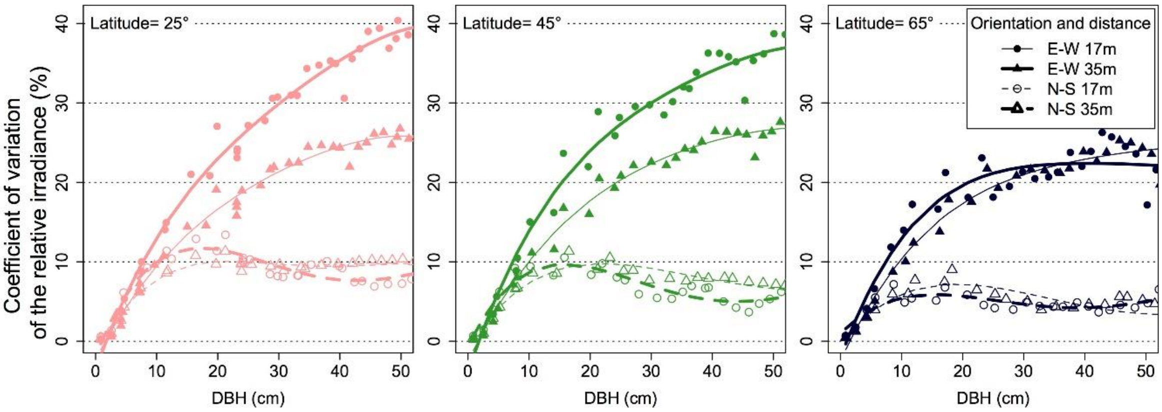

Figure 5 : Coefficient of variation of the relative irradiance of the crop as a function of the DBH of the trees for the month of June at three latitudes, for two tree line orientations (North-South and East-West) and two distances between tree lines (17 and 35 m). Curves are smoothed with a moving average on 5 points.

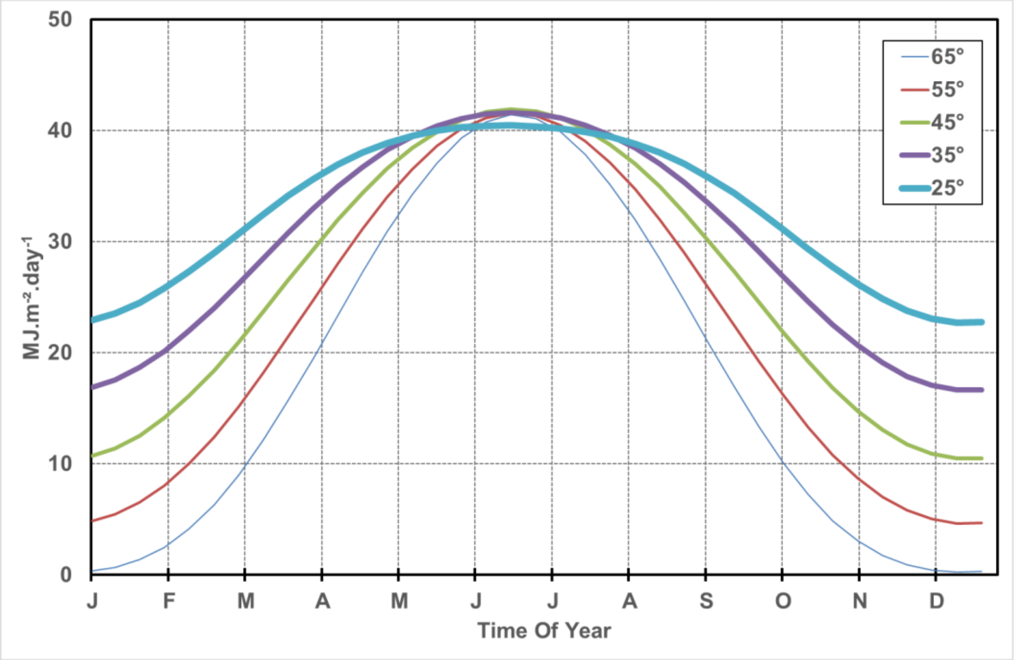

Figure 6 : Extraterrestrial irradiation throughout the year at different Northern latitudes

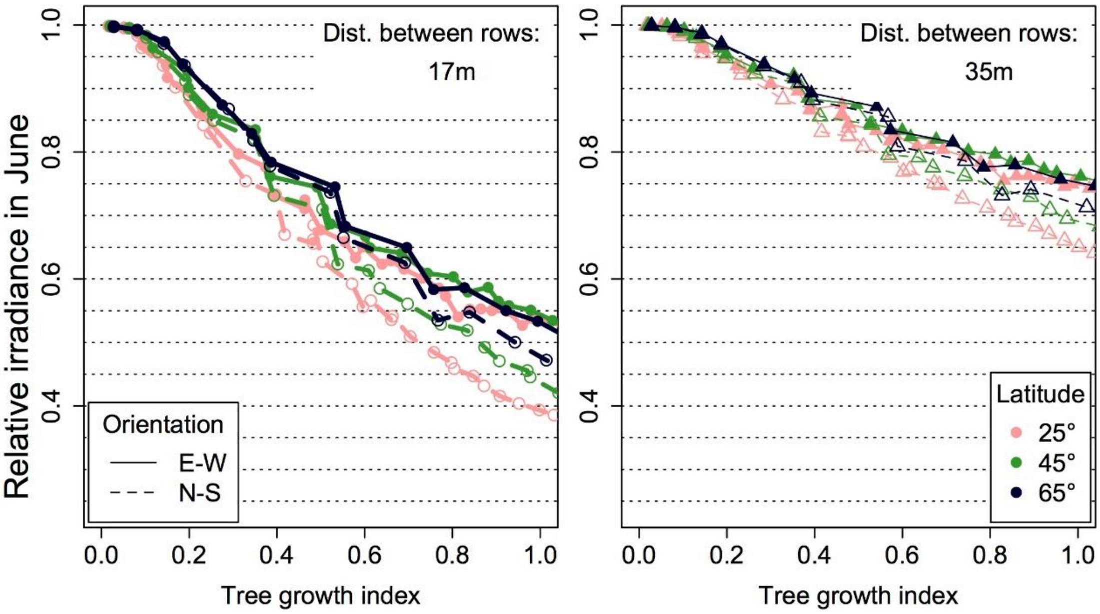

Figure 7 : June relative crop irradiance in the alley plotted against tree size at three latitudes, with two tree line orientations and two tree line distances. The standardized growth index increased from 0 (tree planting) to 1 (final tree size). Final DBH was assumed to decrease linearly from 50 cm at latitude 25° to 30 cm at latitude 65°.

Table 1 Looking for best practices in alley cropping agroforestry: what is the best tree line orientation?

	Increase light availability	**Reduce light heterogeneity**	**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

The number of crosses indicate the relative impact for each criterion : +++ = high impact; ++ = moderate impact; + = low impact

Table 2 : Influence of latitude on the annual extraterrestrial and ground-level radiation. Ground-level variation is mainly explained by local cloudiness. Reference : Wikipedia (https://en.wikipedia.org/wiki/Solar_irradiance)

Latitude	Extraterrestrial Radiation (kWh.m^{-2} and relative value to 45° Lat. North)	Lower ground level radiation (high cloudiness areas) (kWh.m^{-2})	Higher ground level radiation (low cloudiness areas) (kWh.m^{-2})
65°	1876 (0.69)	800	1100
55°	2299 (0.84)	900	1500
45°	2727 (1.00)	1000	2000
35°	3104 (1.14)	1100	2500
25°	3408 (1.25)	1100	2600