A mosaiced agroforestry landscape

A mosaic of tree and crop species in an agroforestry landscape in Tosari, Pasuruan, East Java, Indonesia

Photo: World Agroforestry/Ni'matul Khasanah

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CHAPTER FIVE

Belowground resource sharing in mixed tree–crop systems: methods to better understand belowground interactions

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Highlights

- Research in agroforestry moved from a descriptive stock-taking phase to efforts to understand and quantify processes in the sharing of growth resources, above- and belowground
- Root distribution and structure are key to understanding of the interactions and processes involved
- Deployed methods range from basic but labour-intensive invasive approaches (coring, trenching, excavating and rhizotrons) to more sophisticated, expensive but non-invasive methods: X-ray Computed Tomography (CT), Gamma-ray Computed Tomography, Neutron Tomography, Magnetic Resonance Imaging (MRI) and Nuclear Magnetic Resonance (NMR)
- Despite the advances, root research in mixed crop-tree systems remains challenging because of the difficulty in finding the relevant spatial and temporal scales for real-world high heterogeneity soil conditions

5.1 Introduction

Cropping systems based on carefully designed species' mixtures over time (in terms of crop sequences) and/or space (within a farm or landscape) reveal many potential advantages under various conditions, both in temperate and tropical agriculture[1,2,3,4]. In general, annual crops are expected to be relatively shallow-rooted while perennial plants, including trees, can have roots extending deep below the crop root zone, giving a foundation to the safety-net hypothesis[5]. The safety-net hypothesis (intercepting mobile nutrients leaching from crop root zones) complements the nutrient-pump hypothesis (uptake of deep soil resources of relatively immobile nutrients)[6,7]. However, the actual situation of relative root distributions is more complex[8,9,10] and dynamic with seasonal shifts in the soil depth from which water and nutrients are taken up[11]. In some situations, trees and crops compete for nutrients and water in the same soil layer[12,13], even though the impact on crop performance and yield may vary according to rainfall[14] and nutrient availability[15,16,17]. Therefore, the potential benefits of trees in mixed systems depends on complex spatial and temporal interactions involving a large number of factors[18,19,20]. Strong positive effects (for example, through increased nutrient availability) can be offset by strong negative effects (for example, via shading), making optimization complex and context dependent[21].

The past decades of agroforestry research have revealed many interacting processes in the sharing of, and competition for, belowground resources, made progress in their quantification and established tools to study mixed tree–crop systems, as this chapter shows. However, the manner in which net effects depend on context still requires empirical verification of simulation models.

5.2 Complexity of the structure of agroforestry practices

Modern agriculture has been characterized by the promotion of sole crops in rotations or monocultures with the use of external inputs (germplasm, fertilizers, pesticides), which did not reach poor farmers living in the most vulnerable agro-ecologies, leading to deforestation when new areas of land were claimed for agriculture. This has resulted in reduced ecosystem services' delivery: 1) provisioning services (food, fuelwood, fibre, biochemical, and genetic resources); 2) regulating services (climate, disease control, water regulation and purification); and 3) supporting services (soil formation, nutrient cycling, primary production and provision of habitat). Such decline highlights the critical role of trees in farming systems, as attested by findings of a structured review of the roles of trees on farms for provisioning of ecosystem services in sub-Saharan Africa[22]. The majority of studies reviewed showed beneficial effects of trees on crops (58%), such as enhancing water and nutrient cycling, in particular in semi-arid areas. In 28% of the reviewed studies, no effects were found and, in 15%, crop yields were declining owing to tree–crop competition, for example, modification of the microclimate[23].

Traditional mixed farming systems are repositories of principles that can, if understood and correctly applied, make modern agricultural systems more productive and more resilient[24]. In other words, it is about getting the mixtures fitting well into the context such that trees acquire resources that crops would not otherwise use[25]. Studies of traditional systems that combine trees, crops and livestock on the same land unit have shown greater efficiency in using resources (water, nutrients and light)[4,26] than an exclusively annual-crop-based agriculture while they also are more resilient to climate change[24].

Such conclusions come from a long process that started by descriptive categorization of agroforestry systems and quantification of their benefits (production, effects on soils etc.). In contrast, experiments in which fast-growing, shallowly rooted trees were combined with cacao were found to make the cacao more vulnerable to dry years[27].

An on-station phase of research, where external variation could be partially controlled, helped to identify mechanisms of the tree–soil–crop interactions and critically test key hypotheses of safety-net functions[28,29,30] and the synchrony of nutrient supply by mineralization and crop demand[31]. However, findings of studies on interactions revealed that belowground niche differentiation did not hold everywhere as there were trade-offs between the beneficial effects of trees on soils and competition with crops for soil resources[32,33]. Indeed, many studies showed that root distribution of most of the tree species coincided with the upper soil layers occupied by annual crops[8,34,35] and that tree root systems may be highly opportunistic and reactive[36]. This property of accumulating maximum fine roots in the upper soil profile gives the plant an easy access to moisture and nutrients from the most fertile topsoil while the primary roots growing deeper help in extracting more moisture[37]. The fact that niche differentiation was found to not occur everywhere[38,39] triggered a range of studies on tree–crop root competition about ways to manage them through, for instance, root pruning[40,41] or crop competition[42]. Such efforts revealed that competition may induce changes in the phenology, activity and distribution of the roots of one of the competing species in such a way that competition is reduced or avoided[43;44,45;46].

5.3 Methods for research on belowground interaction at plot level

Research on belowground interactions emerged from the evolution of agroforestry science and the corresponding changes in research paradigms from descriptive studies to those on processes in growth resources sharing[47]. Thus, it was only during the 1990s that research on soils and root processes in agroforestry systems were emphasized[48,49]. Such research covered root distribution, water and nutrients content and uptake. Various categories of studies have been conducted, including observation of existing practices, field trials, station experiments and modelling[13,50]. This diversity of types of studies has also involved various experimental designs, including transects from one tree or shrub for scattered naturally regenerated trees (parklands, dehesa, farmer-managed natural regeneration) or from a line/row of trees for planted ones.

5.3.1 Root distribution

Because of the important role of roots in taking up water and nutrients for plant growth, they have attracted the attention of scientists both in studies of natural ecosystems and cultivated agro-ecosystems[51]. The studies started with very rudimentary methods, like core sampling and samples washed to extract roots, soil profiles to describe root distribution, excavating to study root system structure up to the recent use of imagery techniques. More broadly, methods have evolved from invasive field methods to non-invasive ones that are mostly restricted to laboratory conditions.

Invasive methods have helped describe root system architecture and distribution as an indication of the volume of soil explored and potential resource uptake. Basic methods for observing and quantifying tree and crop root biomass and length involve:

- Core soil sampling/monoliths and washing roots from soil[52] combining sieves or more automated root washers. Extracted roots are used to estimate a range of variables (weight, length, root length density, specific root length etc) manually or by scanning equipment and related software
- Trenching to use the wall profile for root distribution studies[53]
- Excavation around an individual tree to a certain depth and distance (up to the limits of the crown width) that allows observations of root architecture. This method is labour intensive

- Root pruning by trenches as a root management tool to limit competition for water and nutrients[38,54]
- Rhizotron technology allowing direct observations of fine root dynamics, including production, mortality, decomposition and turnover[55;56,57,58]. The forms vary from transparent tube to transparent plexiglas pane, or inflatable tubes[59]. However, the rhizotron approach has some limitations, including its inability to provide information regarding the chemical composition of fine roots and the rhizosphere, the difficulty of installing the tubes in stony soils, and soil disturbance caused by tube installation[60]. Inflatable rhizotrons avoid the gaps that tend to form between rigid structures and soil particles, improving visibility of roots and making turnover rates more realistic

Invasive methods can provide a range of information on roots interacting with soil profiles and companion plants but uptake functions are also controlled by root age and specific interactions in the rhizosphere[61,62,63,64] that require different methods. Non-invasive methods are meant to provide further insights into dynamic interactions because they cause no damage to the root systems. The use of 3D visualisation techniques to measure roots in soil started in the early 1990s and they include X-ray Computed Tomography (CT), Gamma-ray Computed Tomography, Neutron Tomography, Magnetic Resonance Imaging (MRI) and Nuclear Magnetic Resonance (NMR)[65,66]. A more detailed description of these techniques emphasized their continued development and limitations[60].

5.3.2 Soil water content and uptake

Sampling patterns for soil-water measurement vary according to the studied agroforestry practice: transect, random etc. Methods used can measure water content, water potential or its drainage. For water content, the oldest and most accurate method is gravimetry (weighing fresh and dried samples). More sophisticated and automated tools were developed but they all use surrogates as proxies for soil-moisture content[87]. Although changes in water content in the surface soil horizons are commonly measured gravimetrically, more sophisticated techniques allow rapid automated measurements. Time Domain Reflectometry (TDR)[67] is commercially available with substantial advances in its use to measure soil-water content and bulk soil electrical conductivity[68,69]. A variety of TDR probe configurations provides users with site- and media-specific options. Advances in TDR technology and other dielectric methods offer the promise not only of less expensive but also more accurate tools for electrical determination of water and solute contents[70] that can be used to measure soil-water content. Another technique for measuring surface soil-water content is the Surface Insertion Capacitance Probe (SCIP)[71]. Although this approach was initially manual, it has also undergone tremendous development and can be automated and remotely controlled using a wireless network[72]. Despite the fact readings may be sensitive to supply voltage, temperature and bulk soil electrical conductivity, SCIP sensors are low cost and can be deployed in wireless network, allowing coverage of large spatial areas[73,74].

At depths below 15 cm, soil water content has often been measured using neutron probes[75,76]. The neutron probe is one of the most appropriate approaches for soil-water balance studies because access tubes can be installed without disturbing the soil profile outside the tube, except in gravelly or stony soils, and the access tubes can be of indefinite length. This technique has some limitations for changes in water content at shorter periods than a week.

Water potential can be measured using tensiometers. However, tensiometers have the disadvantage that they only work for water potentials down to c. -80 kPa and so may be off-scale for much of the time in semi-arid or arid regions. Soil-water potential can also be measured using gypsum blocks[77], which function down to much lower water potentials (around -1500 kPa) but may exhibit hysteresis and must be properly calibrated to obtain accurate readings. The high maintenance requirements of gypsum blocks limit their research capability. Uncalibrated gypsum blocks were used to provide qualitative information regarding two-dimensional soil drying and wetting patterns in agroforestry systems during several rainy seasons in Kenya[78]. Various other approaches for monitoring soil-water content[79,80] include gamma-ray attenuation, capacitance probes, pressure plates, ground-penetrating radar and remote sensing of soil-surface properties.

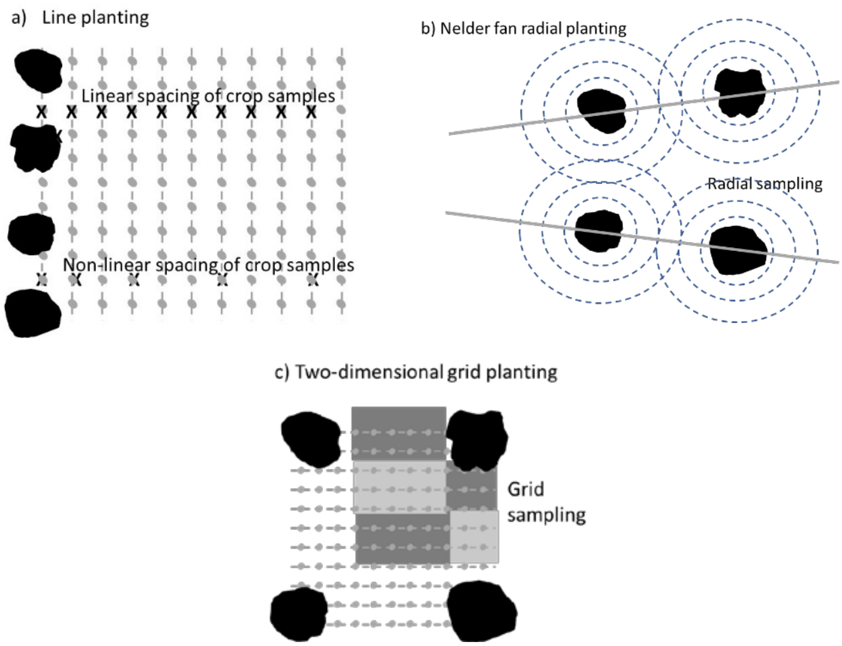

Figure 5.1 Examples of soil-water content sampling patterns used in mixed tree–crop systems
Note: Measurement points (x) can be arranged (a) perpendicular to the tree line, (b) at radial distances from individual trees and (c) in a two-dimensional grid[81]

Six approaches for determining drainage[82] are porous cups, porous plates, capillary wicks, pan lysimeters, resin boxes and lysimeters. The most basic approach is the use of lysimetry to capture drainage-water volumes using buried containers over various time periods. Several types of lysimeter have been employed, including pan lysimeters, equilibrium-tension lysimeters and wick lysimeters, each with their own advantages and disadvantages[83]. Recently developed passive-wick lysimeter using an inert wicking material, such as fibreglass or rock wool[83,84] can be linked to dataloggers to transmit drainage data to a remote host[85]. Collecting soil-pore water or drainage water will also allow for chemical analysis, for example, of pH, plant nutrients and other elements[86]. Drainage volumes can be estimated indirectly[87] and through modelling approaches[88,89].

Stable isotopes (D, ^{18}O, and ^{13}C) provide valuable non-invasive methods for determining of the soil layers of water uptake[90]. Soil and plant water potential[91] or ground-penetrating radar and plant ^{18}O ratio[92] to produce more accurate information.

5.3.3 Soil nutrients and uptake

Measurement designs for soil nutrients either in situ or by soil sampling are similar to those used for root distribution and soil-water content. Taking soil samples at various distances and depths, analysing them and comparing the situations with agroforestry practice without (control) has been the most common approach. Trees component of agroforestry practices are in general expected to directly contribute to carbon (photosynthesis and biomass recycling) and nitrogen (N_2 fixation and biomass recycling) and indirectly by taking up other nutrients from deep soil layers and recycle them in upper soil layers through the litter and root decay. Laboratory analyses have so far provided the most accurate data but there is on-going development of devices allowing in situ measurement of the concentrations of soil nutrients. Such devices still have a number of limitations. For laboratory approaches, wet chemistry is being combined with Near Infrared (NIR) methods[93,94,95], which allows analyses of thousands of samples and in very short periods of time. NIR methods still require a lot of improvement about the accuracy of the measurements.

For the uptake, again like water, stable isotopes (such as ^{15}N and ^{31}P) have been used for testing the safety-net hypothesis of niche differentiation between components of agroforestry practices ([28,96,97]). Other soil parameters measured in studies about the belowground interactions include soil texture, pH, bulk density, porosity, fauna abundance and diversity[13].

5.4 From plot to farm and landscape: modelling approaches for scaling

Models are a way of understanding the implications of processes we know sufficiently well to structure and parameterize the models[13]. These models are approaching the interactions from three different angles: separating positive and negative effects, establishing the resource balance, and modelling the resource capture[21].

5.4.1 Plot-level models of belowground tree–crop interactions

Plot-level models 'without roots' can be adequate to relate available resources to uptake at field scale at a monthly or annual timescale. However, models that use spatial details of root distribution are required for accounts of competitive or resource-constrained systems and can be classified in four classes[98,99]:

i) models that ignore root dynamics and use time-independent root distributions;
ii) models that incorporate simple root dynamics described by a generic distribution model independent of both aboveground processes and soil conditions;
iii) models that simulate root-system growth in response to conditions in the aboveground parts of the plant but without an interaction with soil environment; and

iv) models that simulate the growth of a root system that senses and reacts to local soil conditions as well as to the conditions in the aboveground part of the plant.

Most agronomical or forestry models at the plot scale include a one-dimensional root model and constrain the root distribution by a negative exponential decrease with distance (vertically and laterally) from the plant base[104]. A step forward was achieved with recent models that describe root systems in 2D or 3D, dynamically, and consider dynamic responses to local soil conditions. Two models designed for agroforestry systems include these features: 2D for WaNulCas[102] and 3D for Hi-sAFe ([100,103,101]). The Hi-sAFe model includes a continuum representation to simulate the growth of both fine and coarse root systems in 3D heterogeneous soil conditions and was designed with a 3D 'voxel automata' approach[36]. The Hi-sAFe root model is driven by the diffusion of fine roots across a soil compartmentalised in voxels, and linked by a coarse root system that is self-generated by the model. It provides a generic and flexible root model that can react to the soil heterogeneity that is always induced by the competing rooting systems of trees and crops[102].

5.4.2 Upscaling to farm and landscape levels

Almost all the studies of belowground interactions have been conducted at the plot level while key issues are at farm and landscape levels, bringing in more complexity. To address such complexity, several agroforestry models were developed (Table 5.1). However, they all show intrinsic limitations, including insufficient flexibility, restricted ability to simulate interactions, extensive parameterization needs, lack of model maintenance and with updating and investments needed[8,37,103]. Even though models that are maintained can now in their advanced versions describe root systems in 2D or 3D and dynamically consider changes in soil conditions[100,104,105], efforts are still needed to move from plot level to landscape scale.

Table 5.1 Different models used to study interactions in mixed tree–crop systems and their main characteristics

Model	Components	Unique features for below-ground modelling	Model source code
Historical			
SCUAF[106]	*N/A*	*Effect of trees on soil conservation and carbon*	**
ALMANAC[107]	Water, carbon, nitrogen	Supply, uptake, competition	**
COMP8[108]	Water, carbon, nitrogen	Supply, uptake, competition	**
CropSys[109]	Water, carbon, nitrogen	Supply, uptake, competition	**
GAPS[110]	Water, carbon, nitrogen	Supply, uptake, competition	**
WIMISA[111]	*Water, carbon, nitrogen*	*Supply, uptake, competition Windbreak Sahel*	**
HyCAS[112]	*Water, carbon, nitrogen*	*Supply, uptake, competition*	**
HyPAR[113]	*Water, carbon, nitrogen*	*Supply, uptake, competition*	**
Still actively maintained			
WOFOST[114]			https://www.wur.nl/en/Research-Results/Research-

Model	Components	Unique features for below-ground modelling	Model source code
			Institutes/Environmental-Research/Facilities-Products/Software-and-models/WOFOST.htm
WaNuLCAS[115]	*Light, Water, nitrogen, phosphorus, carbon*	*Dynamic tree and crop root systems*	http://www.worldagroforestry.org/output/wanulcas/download
APSIM[116,117]	Water, carbon, nitrogen, phosphorus	Crop rotations and land management	http://www.apsim.info/
Hi-sAFe[100,101,118]	*Light, water, nitrogen, 3D above-ground, 3D belowground*	*Dynamic and opportunistic tree and crop root systems*	https://www1.montpellier.inra.fr/wp-inra/hi-safe/en/
YIELD-SAFE[119,120]			http://www.isa.ulisboa.pt/cef/forchange/fctools/content/yield-safe-model
FARM-SAFE			https://www.agforward.eu/index.php/en/web-application-of-yield-safe-and-farm-safe-models.html
LUCIA[121] *Land Use Change Impact Assessment tool*	*Light, Water, nitrogen, phosphorus, carbon*		https://lucia.uni-hohenheim.de/en

NB: * Model still under active development, ** No longer active; N/A: Note Applicable; italic are agroforestry models. WOFOST and APSIM are not but their modular nature has allowed applications in agroforestry

Source: modified from 50

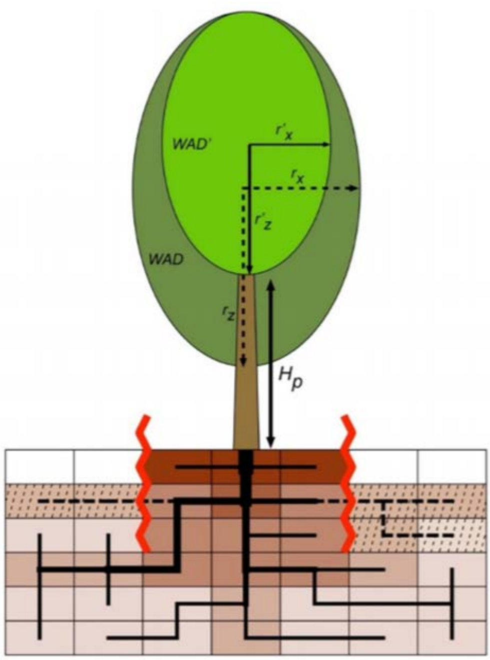

Figure 5.2 101 A simplified, 2D illustration of the branch and root pruning management interventions in sAFe-Tree

Coarse roots are represented by solid lines, with diameter proportional to line thickness. Fine root density is proportional to voxel shading, with darker colors indicating more fine roots. Branch pruning to a height Hp reduces vertical and horizontal crown radii by the same proportion. A reduction in WAD (and consequently LAD) can also be specified. Root pruning occurs along equidistant, parallel lines that straddle the tree (zigzag lines; into the page). Coarse roots that are cut by root pruning (dashed lines) are killed, along with all downstream coarse and fine roots (hatched voxels). It is possible for vertically growing coarse roots to avoid root pruning and maintain roots above the pruning depth, as shown on the left side of the illustrated scene. LAD: leaf area density within the crown; WAD: wood area density within the crown.

5.5 Way forward

Accuracy in the measurements of most parameters involved in belowground interactions is something to continue to pursue. The work on the belowground compartment remains tedious and expensive yet with still a large part of uncertainty in the measurements. Therefore, development of methods and tools to better describe processes in mixed cropping systems should continue. This includes scale of spatial sharing of belowground resources for which modelling has a lot to contribute once processes are well understood.

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