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The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2022; 11(3): 1936-1944

www.thepharmajournal.com
Received: 02-01-2022
Accepted: 05-02-2022

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Agroforestry-alternative land management for sustainable development

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Abstract
Agroforestry is a land management system that increases production and ecological stability and contributes to the sustainable development of the agroecosystem. It addresses the nation's land stewardship needs by converting degraded lands, protecting sensitive lands and diversifying farm production systems. Deliberate planting of the tree, shrub and herbaceous legumes in rotation with food crops has become a central and integral part of land management practices for replenishing soil fertility in nutrient-depleted small-scale farms. However, owing to the limitation of site for the crop growth in terms of growth resources, efficient utilization of resources is a key for the success of agroforestry systems. The productivity of any vegetation system mainly depends on biomass production and carbon storage potential in their different components, which are affected by nature, age of plant and other climatic, edaphic, topographic and biotic factors. In this context, the biomass production and allocation in agroforestry systems need to be understood to manipulate them for higher gain. Hence, an attempt has been made in this review to explore productivity components of agroforestry and the factors influencing biomass production and allocation. With this knowledge, managers can apply suitable silviculture and management practices to manipulate the biomass production within the system and allocate them as beneficial to the farmer both economically and ecologically.

Keywords: Agroforestry, sustainable, productivity, biomass production, allocation

Introduction
Agroforestry is defined as a complex land-use system where woody perennials are deliberately integrated into farmlands by various spatial arrangements and temporal sequences. Agroforestry may often be considered a practical application of ecological principles based on biodiversity, plant interactions, and other natural regulation mechanisms. Numerous studies report that plant communities with some degree of genetic heterogeneity to have advantages over pure stands. In agroecosystems, biodiversity may: (i) contribute to constant biomass production and reduce the risk of crop failure in unpredictable environments, (ii) restore disturbed ecosystem services, such as water and nutrient cycling, and (iii) reduce risks of invasion, pests, and diseases through enhanced biological control or direct control of pests leading to the sustainable management of the systems. Investigation of competitive or complementarity interactions concerning capture and resource partitioning among the crop components is essential to improve the system's overall productivity and sustainability. This has to be carried out with particular reference to limiting factors of crop growth such as nutrients and water. This review makes a small attempt to throw light on biomass production and allocation patterns in agroforestry which can be a sustainable way of managing the systems.

A. Biomass Production in Agroforestry
Sustainable development is referred to the both ecological and economic development of the system without deteriorating the natural resources. Increased productivity of a system will definitely pay a way towards the sustainable development of the farmer. The biomass production and its storage rate in vegetation systems play an essential role in quantifying the system output, sustainability and determining the carbon sequestration rate for mitigating climate change problems. Estimating biomass is also a prerequisite for assessing the status of the agroecosystem, flux of biological material, understanding the basic dynamics and its productivity. The productivity of forests is based on the height, diameter, and total aboveground biomass, and is influenced by the association of different vegetation components,

area coverage, age, site factors and growth characteristics of tree species vary with climate, soil, temperature and rainfall (Lodhiyal *et al.*, 2002) [31]. Assessment of biomass helps determine the productivity, carbon stock, carbon sequestration, and nutrient cycling performance of tree species. Although biomass has long been of principal importance and interest in forestry, a research study of forest productivity and biomass was given impetus by Ovington (1956), who developed a relationship between the phenology of trees and dry matter production which depends on the site conditions. Biomass is also an essential aspect of studies of the carbon cycle (Ketterings *et al*., 2001) [23]. Incorporating trees and live stocks in agroforestry mimics it as a multifunctional primary forest with all the productive and protective functions. Further, the total biomass productions from the system are comparable to the net primary productivity of the natural forests (Nair, 1993) [39]. The reasons for this are assumed that in agroforestry systems, the combined effect of species selection and management should, theoretically, result in higher rates of biomass production than in monocultural systems. It is assumed that in agroforestry systems, the combined effect of species selection and management should result in higher biomass production rates than in monocultural systems (Sharrow and Ismail 2004; Kirby and Potvin 2007) [59, 24].

Agroforestry systems utilize the land effectively where the emphasis is placed on perennial crops which yield benefits over a long period. Furthermore, well-designed agroforestry systems maximize beneficial interactions of the crop plants while minimizing unfavorable interactions. Agroforestry systems produce multiple products, including food, fiber, fuel, income, shade, and other ecosystem services, all of which need to be simulated for a comprehensive understanding of the overall system to emerge. Tree crop interactions between components of an agroforestry system are often needs to be complementary. In a system with agrisilvicultural system, the trees provide shade and/or feed while the animals provide manure. Thus, agroforestry systems reduce the risks and increase the sustainability of both small- and large-scale agriculture. The benefits of the tree–crop interactions on increased productivity, improved soil fertility and microclimate, nutrient cycling and soil conservation and advantages of weed and pest control demonstrate agroforestry's multifunctional role.

Crop Productivity in agroforestry

In comparison to conventional agricultural systems, the integration of trees and arable crops on the same land has been increasingly justified that the system's productivity can be enhanced along with increased environmental benefits. The agroforestry system is consistent with the model of sustainable agriculture in terms of environmental conservation. However, considering that agroforestry systems have a planning horizon of several decades, the productivity of such systems for their components needs to be periodically assessed for forthcoming risk assessments and adaptation scenarios in the near future. The enhancement of crop productivity in agroforestry is evident by the studies and is attributed to the fact of positive effects from tree crop interaction and efficient use of natural resources. Diversification of cropping systems and efficient use of resources help to restore and augment crop yield with increased environmental quality. The Land Equivalent Ratio (LER) is used to assess crop or agronomic productivity, which is the relative area of land required in monocrops to produce the same yield as in an intercrop or agroforestry system. Monoculture systems are considered as having LER value of 1, while LER higher than 1 indicates a higher productivity in polyculture systems.

$$LER = \frac{Crop\ yield\ in\ agroforestry}{Crop\ yield\ in\ monoculture} + \frac{tree\ yield\ in\ agroforestry}{tree\ yield\ in\ monoculture}$$

Lehmann *et al.* (2020) [28] recorded the observations on a network of five agroforestry systems with arable crops, livestock and biomass trees was studied to assess the range of agricultural products in each agroforestry system in Europe. Agronomic productivity was measured using Land Equivalent Ratio (LER). Values for LER ranged from 1.36–2.00, indicating that agroforestry systems were more productive by 36–100 per cent compared to monocultures.

Soil productivity

Agroforestry tends to protect soil from several adverse effects. Most agroforestry systems constitute sustainable land use and help to improve the soil in a number of ways. Some of the beneficial effects of agroforestry system for which enough experimental evidences is available include reduction of loss of soil as well as nutrients through reduction of runoff, addition of carbon and its transformation through leaf, twigs, bark falls, etc., improvement of physical conditions of soil such as water-holding capacity, permeability and drainage and moderating effect on extreme conditions of soil acidity and alkalinity (Nair, 1984) [36]. Under the tree cover, the fertility of soil improves, which checks soil erosion, adds soil organic matter, and replenishes the nutrients through effective recycling mechanisms. Soil fertility improvement under agroforestry systems occurs mainly through the addition of plant biomass and nutrient pumping from deeper layers. Conservation of soil and water resources is better conserved under any trees than keeping large areas of land barren or even under grass cover (Monalisa *et al.*, 2020) [34]. Further, agroforestry mimics, to a greater extent, the natural ecosystems in its nutrient cycling patterns which are represent self-sustaining and efficient nutrient cycling systems. These are considered to be"closed" nutrient cycling systems as they are characterized high nutrient turnover rate and with relatively little loss or gain of the actively cycling nutrients. However, in contrast most of the agricultural systems represent 'open" or "leaky" system with comparatively high nutrient losses. Nutrient cycling in agroforestry systems falls between these “extremes” (Nair *et al*., 1995) [37]. Thus, the land-use systems play a tremendous role in influencing the nutrient flows, and overall soil quality (Sharma, 2019) [58]. Sharma (2019) [58] computed the chemical soil quality index for the soils under agroforestry systems to evaluate the impact of systems on soil properties. In this case study, it was clearly understood that the land-use systems helped in increasing the soil organic carbon content, cation exchange capacity, exchangeable cations, total nutrients as well as hydrolysable N pools of soil over the arable land. Thus, the tree based agriculture play an important role, not only in improving the productivity and overall returns from the system, but also protects the soil from further degradation and improve the quality of the soil across the profile layers. Further, the nutrient analysis under three different agroforestry systems viz, Agri-horticulture system (AH), Agrisilviculture system (AS) and Agri-Horti-silviculture system (AHS) of north-western Himalayas revealed that the altitudinal variations in certain Physico-chemical characteristics of agroforestry systems soil at cold desert high altitude. Bulk density, particle density, and total nitrogen percentage, available potassium (K), exchangeable Ca and Mg was higher at Dry temperate high hills. Similarly, Pore Space percent, soil pH, organic carbon percentage (OC) and extractable phosphorus (P) were found to be higher at high hills temperate dry and cold. The soils of cold deserts are suitable for various agroforestry systems. Agroforestry play important role to make attention soil science researcher and agroforesters to study the various combination of tree species which can help to improve soil fertility as well as cultivation practices at cold desert (Salve *et al*., 2018) [54].

Resource use efficiency in Agroforestry systems

Exploitation of interactions between woody and non woody (herbaceous or annual crop) components is the key to the success of all agroforestry systems. Hence, it is prudent for a agroforestry manager to have a better understanding of the interactions provides an impetus for improvement of traditional, as well as evolving, systems. In agroforestry, tree and agricultural crops are combined together, and they compete with each other for growth resources such as light, water, and nutrients. The resource sharing by the components may result in complementary or competitive effects depending upon the nature of the species involved in the system based on their spatial arrangement and on the climatic factors. Components may influence the growth of their neighboring species not only adding or removing of some factor, but also by affecting conditions for acquisition of nutrients such as temperature, light, wind movement or by altering the balance between beneficial and harmful organisms. Hence, each component has its own strategy to efficiently acquire the resources in an agroforestry system which in turn is reflected in the increased productivity and sustainability of the system as a whole.

a) Efficiency in Light utilization patterns

In general, when the amount of available light (PAR) increases, photosynthesis increases up to a certain level. A great number of studies report that the tree shade, by reducing the photosynthetically active radiation (PAR) intercepted by crops, leads to a decrease in yield. The reduction of PAR increases with the time (22 per cent lower during wheat flowering, 56 per cent at maturity) (Li *et al.,* 2008) [29] and the yield of intercrop can decreased by more than 50 per cent (Dufour *et al.,* 2013) [13]. Even the best plant varieties developed for the increased productivity are all bred under full sun, and therefore they are not the best adapted to shade conditions. Hence, management of light conditions is crucial in agroforestry systems to realize the expected increased productivity.

Management for Increasing Radiation Interception

Manipulation of light conditions is the management practice that can induces changes in photosynthetic patterns in the agroforestry system. In order for a plant community to use solar radiation effectively, most of the radiation must be absorbed by green, photosynthetic tissues, while the selection of species and their arrangement and management determine the photosynthetic efficiency of the whole plant community, the angle, disposition, number, size, and arrangement of leaves are important factors that determine the photosynthetic area and capacity of individual plants (Nair, 1984) [38]. It is very sensible to understand the variation and management of light interception in multispecies plant communities, e.g., home gardens, which have multiple strata of leaf canopies. The conditions and methodologies used in radiation studies in monocropping and annual crops are clearly not met in intercrops or agroforestry systems because of the extensive horizontal and vertical variation in canopy structure introduced by the intimate mixture of species with differing planting dates and arrangement, heights and maturity dates. Transmitted radiation under trees shows variability in space and time that may have implications for the under storey. Canopy management practices like pollarding (method of pruning at a height which keeps away from the grazing animals), lopping (trimming and various sections of the trees) and pruning (removing the branches of the trees) ensures proper light penetration into the canopy on the lower layers. The suitable tree canopy management options have minimized competition between the components for critical resources and also maintained vigour and biomass production ability of tree species for a longer duration. Physiological data, for example, photosynthesis, transpiration, water use efficiency, light transmission ratio for components under different agroforestry systems (data not included) indicated that shade appeared to be more critical for crop production, although root competition can not be ruled out completely. Many previous reports describe the dominance of tree components under agroforestry systems (Lawson and Kang 1990, Ong *et al*. 1991, Williams *et al*., 1995, Jose *et al*. 2000, Thakur and Dutt 2003, Rao *et al*., 2004) [27, 44, 66, 21, 62, 52]. However, the management of tree canopy minimizes competition to the agricultural crops, which is desirable per se.

b) Efficiency in utilization of water

The complementary interaction between the crop component is judicial for the sustainable development of agroforestry systems. Thus role of climate is highest in determining the efficiency of an agroforestry systems. In situations, where the the area receives high rainfall, moisture will not be a limiting factor. However, conditions of limited rainfall, trees may compete for water which may be detrimental to the crop, at the root zone. Hence, it is essential to work towards the productive use of rainfall to enhance biomass production on farms. In arid and semi-arid regions, crops normally utilize less than half of the annual rainfall productively, where most it will be lost as runoff, evaporation or drainage. Improved water use efficiency in agroforestry systems are achieved when the tree can access groundwater that is not accessible to the companion crop.

Management for increased water use efficiency

The general knowledge of the presence of deep root systems in the soil profile by the trees will not give a sufficient idea about the water use by different agroforestry components. Without the periodic recharge of soil water by rainfall the system is not sustainable. Design and management of agroforestry systems requires explicit knowledge of climate, the depth of groundwater and soil water volume. Tree species from arid environments utilized in agroforestry systems in areas with strong seasonality in rainfall. Unfortunately, the data on differences in the spatial distribution of roots between tree and crop species which is a key to complementarity in agroforestry systems is lacking. Rooting patterns for trees and crops are usually similar, and although trees have deeper roots than crops, there is little spatial separation. Complementarity in agroforestry must depend on the distribution of the water resource, not on the distribution of roots. To achieve this, the trees and crops must capture a greater proportion of available resources than equivalent sole stands, and/or use them more efficiently to produce dry matter (Cannell *et al.,* 1996) [9]. It is vital that trees are complementary rather than competitive with associated crops (Ong *et al.,* 1996) [47]. Complementarity may be either spatial or temporal; the former occurs when trees and crops exploit different resource pools, for example, when deep-rooted trees exploit water and nutrients which annual crops cannot access (Cannell *et al.,* 1996) [9]. Temporal complementarity occurs when trees and crops impose demands on available resources at different times, for example, when trees are deciduous during part of the cropping season or continue to extract water during the dry season (Broadhead *et al.,* 2003, Ong *et al*., 2006) [4]. Although attempts to reduce water uptake by trees through silvicultural management practices such as shoot pruning have proved at least partially successful for some species, their application has been limited (Jones *et al.*, 1998; Namirembe, 1999; Elfadl and Luukkanen, 2002; Ong *et al*., 2002) [20, 40, 14, 64]. Several studies have shown that exclusion of tree roots from the crop rooting zone may increase crop yield in the humid tropics by preventing the extension of tree roots into the cropping zone, thereby avoiding competition (Singh *et al.,* 1989; Corlett *et al*., 1992; Okorio *et al.,* 1994; Hocking and Islam, 1998) [60, 11, 43, 18]. Under such conditions, trees may use their deeper roots to exploit residual water reserves and continue growth when absorption from the crop rooting zone decreases or ceases. Previous studies have shown that ploughing the 0-20 cm soil horizon destroys fine roots, confining tree roots to the deeper horizons and decreasing competition between trees and crops (Schroth, 1999; Newaj *et al.,* 2001) [57, 41].

c) Efficiency in utilization of nutrients

An increased productivity under agroforestry is ascribed to increased complementarity in resource-capture i.e. trees acquire resources that the crops alone would not. This is based on the ecological theory of niche differentiation; different species obtain resources from different parts of the environment. The concept of nutrient pumping in agroforestry is that the tree roots extend into portions of the soil profile (B and C horizon) that may not be accessible to annual crop root systems and that tree crops extract nutrients from these portions of the profile. These nutrients are then translocated to above ground plant parts (*i.e.,* leaves, branches, stem, etc.) and to a much larger root mass in the surface horizons (A and B horizons). Litterfall completes the nutrient translocation from lower soil horizons to the soil surface. This will lead to greater nutrient capture and higher yields by the integrated tree-crop system compared to tree or crop monocultures (Smith, 2010) [61]. Recycling of nutrients through crop residues does not offset these losses, and a decline in productivity of a system would be expected without any external nutrient inputs in the form of inorganic fertilizers. Apart of the biomass removal, soil erosion and leaching also play an important role in nutrient depletion from the system. In agricultural system, much of the crop biomass is removed during the harvesting. Similarly complete tree utilization approach found certainly to remove a sustainable amount of nutrients from the tree based system. Disentangling "nutrient acquisition strategies" and “nutrient transfer processes” is important to encourage positive nutrient interactions in agroforestry systems. Distinguishing structural and functional characteristics of tree root systems, comparative to crop roots, remains a foundation of agroforestry.

Management for increased nutrient acquisition in agroforestry

The belowground indicators (root system distribution patterns and individual root functional traits) and processes (nutrient interception and chemical/ biological rhizosphere dynamics) at the tree-crop interface in agroforestry systems reveals that tree component of an agroforestry system can unlock nutrient advantages by reducing the losses by leaching, nitrogen fixation, nutrient pumping and modifying the rhizosphere zones in its physical and chemical properties to improve the nutrient availability. Tree roots stratified below the crop root zone capture unused nutrients that move down the soil profile. This spatially stratified action in the soil profile is based on the niche partitioning hypothesis to maximize closed nutrient cycles in agroforestry systems (Ong and Leakey 1999) [45], typically for very mobile nutrients such as nitrate ($NO3-$) moving in soils via mass flow. Associated with the safety net process is nutrient pumping - the acquisition of both mobile and weathered minerals deeper in the soil profile (Lehmann 2003), the translocation of nutrients to litter tissue, the deposition of litter on the soil surface via litterfall, and the addition of nutrients to the topsoil via decomposition processes (Mafongoya *et al.* 1998) [32]. Overall positive effects from nutrient pumping is, arguably, conditioned on the biomass-ratio hypothesis (Grime 1998) [15]; ecosystem processes such as decomposition are largely dependent on the most dominant species in the community, often the tree component. Within the zone of tree and crop root interactions, fine lateral roots are characterized by a range of nutrient acquisitive traits and conservative traits, thus forming a dominant axis of nutrient acquisition strategies among and across species (Weemstra *et al*. 2016; Isaac *et al*. 2017) [65, 19]. Finally, this zone of interspecific interaction is also characterized by an array of chemically and microbially mediated mechanisms (Kurppa *et al.* 2010; Hinsinger *et al.* 2011) [26, 17] that result in site-specific nutrient competition or facilitation.

Overcoming soil fertility depletion is fundamental to arresting the ever declining crop yields. Poor soil fertility translates to low crop production, increased impoverishment of rural households, further weakening their ability to invest in improved soil management. The effects of poor soil management are creating larger problems through increased food insecurity, soil erosion and siltation of water systems, deforestation and desertification through agricultural expansion into marginal lands, and social stresses due to excessive urban immigration. Combinations of organic fertilizers, like mulch from agroforestry, with inorganic fertilizers have often been suggested (Sanchez, 1994; Palm *et at.,* 1997) [49], the paramount reason being the amount of available biomass is limited. Well-managed agroforestry can provide greater inputs of organic matter to semi-arid farming systems. However, even with the intensification of dryland agroforestry available organic fertilizers are not likely to contain enough nutrients, especially P (Buresh *et al*., 1997) [7], to cope with both crop needs and soil deficiencies.

B. Biomass allocation in agroforestry systems

Biomass production is a primary function of forest ecosystems that is influenced by interplay of processes: roots capture nutrients from soil, stems and branches provide mechanical support and conduct water with nutrients, and leaves fix carbon (Poorter *et al*., 2012) [50]. Because plants have to balance the allocation of resources to roots, stem, branches and leaves in a way to enable necessary physiological activities for the functioning of these organs, only plants that are successful in acquisition of resources will maintain or achieve a regular growth. The extent to which acquisition and utilisation of resources vary among taxa would define the limit of plant biomass production (Reich, 2002). Therefore, understanding the patterns of biomass partitioning within plants is of high importance in the field of tree physiology and plant ecology, and also has many applications for agriculture/forestry. Biomass allocation has generally been used to capture resource utilisation by plants in empirical and simulation studies. For instance, in water- and nutrients-limited environments, plants decrease the biomass allocates more biomass to organs that have limited access to resources. Similarly, in nutrient-limited soils, more biomass would be allocated to roots to increase the use of water and nutrient resources. Therefore, biomass allocation among plant organs is driven by above and belowground environmental conditions, but plant size, ontogenic trends, species competitive abilities, species identity, and functional traits can also act as potential covariates to define the investment in support tissues. Plant biologists have long recognized that in order for a plant to complete its life cycle, it must function as a balanced system in terms of resource uptake and use (e.g., Mooney, 1972; Agren and Ingestad, 1987) [35, 1]. Communication between carbon gaining and nutrient and water gaining parts of the plant is assumed to be rapid and efficient. Resources obtained from the environment and manufactured in the plant are allocated to various plant parts and functions (growth, reproduction, and defense).

Resource allocation plays a vital role in plant development, yield formation and tolerance to abiotic and biotic stress. Plants have a remarkable capacity to co-ordinate the growth of their organs, so that there is generally a tight balance between the biomass invested in the shoot and that invested in roots. Root systems of plants are the interface between plant and soil and thus gain central importance for the long-term, sustainable functioning of agricultural as well as forestry or agroforestry systems. Consequently, the selection of plant species and the design/ management of agroforestry systems has to take root functions such as competition, effects on nutrient and water cycling, carbon input and allelopathy into account. Similarly, the aboveground parameters, canopy structure, leaf phenology, stem straightness of trees also improve soil characteristics, increases productivity and modify micro-climate. The ratio of belowground biomass to the aboveground biomass (root-shoot ratio) is the parameter that most directly reflects biomass allocation by plants. Generally, biomass allocation of plants follows "functional equilibrium" concept, which states that plants increases their growth by enhancing the uptake of most limiting factor (Brouwer, 1963) [5]. That is, if the limiting factor for growth is below ground resources such as nutrients and water, they allocate relatively more biomass to roots and will allocate more biomass to shoots if the limiting factor for growth is above ground resources such as light and carbon dioxide. Thus, adaptive strategies of trees in agroforestry system could be well understood by knowing the resource allocation pattern. The study conducted by Liu *et al.* (2012) [30] on 31 cultivars of apples raised under two different water regimes highlighted that all the plants under drought stress reallocated biomass from shoots to roots and their root: shoot were higher. Varella (2002) [64] observed that lucerne (*Medicago sativa* L.) plants when exposed to different light regimes, shaded plants tend to transfer the photosynthates to shoot portion and such plants showed morphological changes such as increase in stem height, intermodal length and leaf to stem ratio. These finding are inconsistent with the theory of functional balance.

In the case of nutrient or water stress condition, critical physiological processes regulating resource acquisition and plant growth occur belowground (Coyle and Coleman, 2005). Hence in many of the sub-tropical dry forests, root share accounts for a considerable portion of total biomass (27-68%). Variations in belowground biomass proportions during tree growth are controlled by resource availability and development (ontogeny). With the increase in availability of belowground growth resources (nutrients and water), biomass allocation shifts from root to shoot (Coyle *et al.*, 2008) [12]. This change in biomass allocation to roots in response to availability of resource accord with the optimum partition theory which suggest that plant must allocate biomass to the organ that acquires the most limiting resources (Brouwer, 1963) [5]. Plants allocate their biomass in an optimal pattern if all above- and below-ground resources that a plant requires are limiting growth to an equal extent (Bloom *et al.*, 1985) [2]. Based on the biomass allocation pattern, biomass production can be broadly divided into above ground biomass production and below ground biomass production.

Aboveground biomass production

Individual tree biomass values are used to estimate the total biomass of the entire system. Aboveground biomass is the most important visible and dominant carbon pool in vegetation systems aboveground plant biomass comprises all woody stems, branches, and leaves of living trees, creepers, climbers and epiphytes, as well as understory plants and herbaceous growth. For agriculture land, this includes trees (if available), crops and weed biomass. The dead organic matter pool (necromass) includes dead fallen trees and stumps other coarse woody debris, the litter layer and charcoal (or partially charred organic matter) above the soil surface.

It has been observed that the relative amount of biomass present in different organs is not fixed but may vary over time, across environments and among the species (Poorter *et al*., 2012) [50]. Median carbon storage by different agroforestry practises was 9 tC ha^{-1} in semi-arid, 21 tC ha^{-1} in sub-humid, 50 tC ha^{-1} in humid, and 63 tC ha^{-1} in temperate ecozones (Schroeder, 1994) [56].

Pattern of biomass allocation to different aboveground components stem, branch and foliage varies, the per cent contribution of biomass to these component changes with stand age and diameter. The contribution of stem, branch and leaf was found to be greatly influenced by vegetation type, stand age and diameter which influences not only the overall production of biomass but also its partitioning into different components. Chaturvedi *et al*. (2012) reviewed in different agroforestry systems, it was reported that bole biomass contributed to 28 to 86% of total above ground biomass. The percentage allocation of biomass to bole, branch and leaf were 65-76%, 14-19 %, 3-12 % for fast growing tree species. In other tree based systems stem contributed around 76 to 80%, branch 11 to 29% and leaves 3 to 14% of aboveground biomass. Kumar *et al*., (2021) [25] conducted a study to understand biomass allocation in eight different agroforestry components in Himalayan foothills. Among the different aboveground parts allocation of biomass was maximum in stem followed by branch and leaf. The highest stem biomass was recorded in *Eucalyptus tereticornis* (69.43 ± 0.90 Mg ha^{-1}), branch biomass in *Populus deltoides* (5.04 ± 0.35 Mg ha^{-1}), leaf biomass also in *Populus deltoides* (2.21 ± 0.12 Mg ha^{-1}). Biomass accumulation was highest (81.01 %) in the stem of *Toona ciliata*, branch of *Populus deltoides* (5.73%), leaves of *Eucalyptus tereticornis* (2.93%).

Biomass allocation to different above ground parts (leaves and wood) showed clear differentiable patterns to different species, tree size (diameter) and also as response to varying plant functional traits such as leaf area and wood density (Mensah *et al*., 2016) [33]. It was observed that with increasing diameter, lower wood density species tended to allocate more biomass to foliage and less biomass to stems and branches. As tree size increases, more biomass is allocated to branches and foliage compared to stem, because more biomass are invested into height growth to compete for above ground resource such as light. Trees with more biomass in branches can out-compete neighbours by increasing the height and expanding crown area to shade out competitors.

Below ground biomass production

The below ground biomass comprises living and dead roots, soil fauna and the microbial community. There is a large pool of organic carbon in various forms of humus and other organic carbon pools. Knowledge of root biomass is of particular importance for the understanding of root carbon allocation and carbon cycling in different vegetation systems. Roots provide anchorage for the tree and serve the vital functions of absorption and translocation of water and nutrient. Roots provide detrital carbon to soil organisms and are important in immobilizing and processing soil water pollutants and improving soil quality (Groffman *et al*., 1992). Fine and small roots (<5 mm), and coarse roots (> 5 mm) are two major components of belowground biomass, and their vertical distributions define the extent to which they modify soil physical, chemical, and biological properties. Fine roots represent a dynamic portion of belowground biomass, nutrient capital, and a significant part of net primary production in native and managed ecosystems (Buyanovsky *et al*., 1987) [8]. The root shoot ratio varies from species to species, growing stage of species and external climatic conditions. The root and shoot growth also affected by topographic and edaphic conditions.

Toky and Bisht (1992) [63] studied root architecture of six year old trees of 9 indigenous and 3 exotic species growing in North western India. The total biomass varied from 2.2 kg in *Accacia catechu* to 30.6 kg in *Populus deltoides*, and top soil contained about 42 to 78% of the total biomass. Borden *et al*. (2017) estimated the belowground biomass and carbon stocks for cocoa grown with shade trees and in monoculture. The results showed that coarse roots in cocoa can hold approximately 6.0 kg C $plant^{-1}$. Cocoa roots contributed 5.4-6.4 $MgCha^{-1}$, representing 8- 16 % of carbon stock in all live tree biomass.

Management Practices to manipulate biomass allocation in Agroforestry

The allocation of biomass to different plant organs depends on species, ontogeny and on the environment experienced by the plant (Porter and Nagel, 2000) [51]. Management practises also can affect biomass production and the allocation of the resources by controlling inter-crop and intra-species competition (Buck, 1986) [6]. Management practises in agroforestry systems can alter resource sharing between woody and crop components in spatial and temporal dimensions such that tree and can affect biomass production and allocation. Some of these practices like irrigation and fertilization can lead to changes resource allocation patterns in trees of agroforestry. As per the study by Noulekoun *et al.* (2017) [42], the biomass accumulation in the fast-growing species (*Leucaena leucocephala* Lam., *Moringa oleifera* Lam., and *Jatropha curcas* L.) was positively impacted by fertilization and irrigation in rainy seasons. The slow-growing species (*Anacardium occidentale* L. and *Parkia biglobosa* Jacq) responded positively to the silvicultural treatments during the dry and second rainy season. The application of fertilizer alone increased the biomass of *P. biglobosa* by up to 335% during the dry season. The author opined that while ontogeny was the main driver of biomass partitioning, increased resource availability induced a larger production of biomass, overall leading to greater aboveground production in all species.

A way forward to increase the biomass Production and Resource efficiency in Agroforestry to attain sustainability

To optimize productivity benefits from agroforestry, more information is needed to better tailor practices to the environment. Information and research needs include:

- Better understanding of how to capitalize on aboveground and belowground structures and processes that improve function performance, such as water and nutrient uptake.
- Better documentation of interactions in agroforestry practices over time, space, and planting options as they relate to production benefits and management strategies.
- Identification of tree and crop combinations and their management that can provide improved ecological services, including microclimate modification, pollination, and biological pest control in support of production.
- Design of innovative agroforestry-based food systems, especially those suitable for marginal lands that can expand opportunities for food production and natural resource protection.

Conclusion

Agroforestry is a low-input system which combines trees with crops in various combinations or sequences. It is an alternative to intensive cropping systems, which rely on large inputs of manufactured fertilizers and other external inputs to sustain production. Agroforestry systems offer a win-win opportunity by acting as sinks for atmospheric carbon while helping to attain food security, increase farm income, improve soil health and discourage deforestation. It also has the potential to reduce risk through diversification of a variety of products, including food, fuelwood and animal fodder. Other perceived benefits include enhanced nutrient and water use efficiencies, reduced nutrient leaching to groundwater, and improved soil physical and biological properties. However, a fundamental requirement of agroforestry is that the trees and crops should complement each other in terms of resource use and not be competitive for resources. Agroforestry systems are labor-intensive and require careful management. They will be more attractive to farmers as a soil fertility management tool where manufactured fertilizers are unavailable or too costly, or where the soils have become degraded through continuous monocropping. Managing the agroforestry for improved resource efficiency is a prerequisite for its success. There is a need to reorient our research priorities and integrated systems with a focus on enhancement system productivity and conserving the resources on a sustainable basis. The use of silvicultural and genetic principles are prudent for the productivity improvement. Attention must be paid to soil and water conservation techniques in relation to agroforestry based interventions for better resource utilization, besides exploring unexploited and under-exploited trees and grasses of high economic values.

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