Bio-management Options for Ecosystem Services, Carbon Sequestration and Climate Change Adaptation in Saline Environment

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Nearly one billion hectares of arid and semi-arid areas of the world are salt affected and remain barren due to salinity or water scarcity. These lands can be utilized by adopting appropriate planting techniques and integrating trees with tolerant crops, forage grasses, oil yielding crops, aromatic and medicinal plants. Biosaline agroforestry provides various ecosystem services such as the improved soil fertility, carbon sequestration, and biomass production. Provisioning services relating to biomass production have been well studied in different biosaline agroforestry. Tree plantations and agroforestry enrich the soil in organic matter and exert a considerable ameliorative effect on soil properties. The soil microbial biomass serves as a useful indicator of soil improvement under salt stress. By integrating trees with the naturally occurring grassland systems on highly sodic soils, the soil organic carbon content increased from 5.3 Mg ha⁻¹ (in sole grass) to 13.6, 10.9, and 14.2 Mg ha⁻¹, when Dalbergia sissoo, Acacia nilotica, and Prosopis juliflora trees were introduced with grass. The strip-plantations of clonal Eucalyptus tereticornis sequestered

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15.5 t ha\(^{-1}\) carbons during the first rotation of 5 years and 4 months. The soils of biosaline agroforestry could store 25.9–99.3 Mg C ha\(^{-1}\) in surface 0.3 m soil. Maintaining the stores and sink of carbon in agroforestry could play a key role in climate change mitigation as well as help in adaption changing environmental conditions.

Keywords: Climate change; adaptation; carbon sequestration; ecosystem services; salinity; tree plantation.

1. INTRODUCTION

Soil salinity and sodicity are serious land degradation problems in arid and semi-arid regions of the world. The worldwide extent of salt affected soils is about 932.2 million hectares [1]. The excessive irrigation in agriculture has mainly contributed to the increasing problems of secondary salinization, alkalinization and waterlogging [2]. Waterlogging and salinity are a major impediment to the sustainability of irrigated lands and livelihood for the farmers, especially the smallholders in the affected canal irrigated as well as non-irrigated areas. Biodrainage has been found to be effective in controlling waterlogging and salinity in irrigated canal command areas in arid and semi-arid regions [3,4]. Bio-management of saline areas can help in mitigation of rising atmospheric carbon dioxide concentrations through carbon sequestration in the plant-soil system. Estimates of biomass production and the rates of carbon sequestration and exploration of greenhouse gas balance [5] can be useful to understand the potential of agroforestry in climate change mitigation.

The ecosystem services are the benefits that the natural environment provides to humanity. The Millennium Ecosystem Assessment (MEA) defined four categories of ecosystem services, i.e., provisioning services, regulating services, cultural services and supporting services that contribute to human well-being [6]. The Convention on Biological Diversiﬁcation, the Millennium Development Goals, and other international agreements has clearly indicated a relationship between biodiversity conservation, poverty alleviation, and human well-being [7]. The main services from agro-forestry ecosystems include habitat provision, pollination and seed dispersal, clean water, flood mitigation, biodiversity, carbon sequestration, climate regulation, oxygen production, nutrient cycling, genetic resources for crops, and spiritual, cultural, recreational and tourism values [8]. The critical ecosystem services such as the maintenance of soil fertility, carbon sequestration, biomass production, and the regulation of soil water flows are essential for bio-management of saline environments. It has been well recognized that services and beneﬁts provided by agroforestry practices occur over a range of spatial and temporal scales [8].

In recent years, the increase in carbon dioxide (CO\(_2\)) in the atmosphere has gained a lot of attention due to its potential to influence the climate pattern of the world. The increase in CO\(_2\) concentration in the atmosphere has been largely attributed to fossil fuel burning, deforestation and change in land use. For the first time in human history, CO\(_2\) concentration in the atmosphere has passed the milestone level of 400 parts per million (ppm) in the year 2013. Climate Regulation refers to the influence that ecosystems have on the global climate by emitting greenhouse gases to the atmosphere or extracting carbon from the atmosphere. The agroforestry systems could be an important sink for carbon storage, which is an indicator of regulatory ecosystem services. Management practices that favor carbon sequestration in agroforestry also tend to enhance resilience in the face of climate variability, and are thus likely to enhance long-term adaptation to changing climates [9]. Soil carbon sequestration is an important factor in the greenhouse gas emissions balance and is strongly related to site conditions (e.g., Soil structure, initial soil carbon content, climate), structure of agroforestry and soil management. The improvement of soil carbon in forestry and agroforestry systems offer substantial global greenhouse gas mitigation potential. Carbon sequestration in the soil-plant system has numerous co-beneﬁts through improvements in ecosystem services of the terrestrial biosphere amounting to several trillions of U. S. Dollars [10]. About 630 Mha of unproductive croplands and grasslands could be used for agroforestry worldwide with a potential to sequester 391,000 Mg C ha\(^{-1}\) by 2010 and 586000 Mg C ha\(^{-1}\) by 2040, whereas carbon sequestration potential in Indian soil is estimated to 39.3 to 49.3 Tg C yr\(^{-1}\). The available estimates of carbon stored in agroforestry range from 0.29 to 15.21 Mg C ha\(^{-1}\) yr\(^{-1}\) above ground, and 30–
2. THE PROBLEM OF SALT-AFFECTED AND WATERLOGGED SOILS

The natural saline environments can be found on all continents, the increase of salt affected soils in recent decades is directly or indirectly caused by human behavior and activities. The main causes are irrigation practices, over extraction of groundwater in coastal areas and rising sea level because of climate change. Estimations for the global area of salt-affected land range from 400 Mha to 960 Mha [12], depending on the datasets, and the classification systems used. Recently, it has been reported that approximately one billion hectares of land are salt affected worldwide [13], of which approximately 76 million hectares (Mha) are affected by human-induced salinization and sodification [14]. In India, 9.38 million hectares land is salt affected out of which 3.88 million hectares is alkali/sodic soils [15]. In Pakistan, about 6.3 million ha is affected by different levels and types of salinity, out of which nearly half are under irrigated agriculture [16]. Depending upon the soil’s physical and chemical nature, salt affected soils are mainly of three types, i.e., saline, alkaline/sodic and saline–sodic soil. The main properties of saline, sodic and water logged soils based reference [17,18] are summarized in Table 1.

The saline soils have white encrustations on the surface and have high concentrations of soluble chlorides and sulphates of sodium, calcium and magnesium as dominant salts. These soils have a pH below 8.2 and electrical conductivity greater than 2- 4dSm⁻¹ at 25°C, and sodium absorption ratio of the soil solution <15. Saline soils usually remain flocculated due to the presence of excess salts; have a high osmotic pressure of soil solutions which induces physiological drought, tissue injury due to direct toxic effects of individual ions and complex interactions between sodium, calcium and magnesium. In northern India, a large area of canal irrigated areas has gone out of cultivation. The waterlogged areas support the growth of Prosopis juliflora, Desmostachya bipinnata, Sporobolus marginatus and Suaeda fruticosa.

The alkali soils contain excess of salts capable of alkaline hydrolysis such as sodium carbonate, sodium bicarbonate (NaHCO₃) and sufficient exchangeable sodium on the cation exchange sites in the soil. The sodic soils are characterized by high soil pH (saturation soil paste pH > 8.5 and often approaching 11, exchangeable sodium percentage (ESP) > 15 and varying electrical conductivity (ECe < 2- 4 dSm⁻¹). The presence of a high exchangeable sodium percentage in soils imparts poor physical conditions to soils, low infiltration of water and dispersion of soil organic matter. The precipitation of calcium in alkali soils causes deposition of thick CaCO₃ layer known as kankar pan. The adverse climatic conditions in arid and semi-arid regions induce the precipitation of CaCO₃ [19]. The sodic soils support sparse growth of vegetation of salt tolerant grasses. Desmostachya bipinnata, Sporobolus marginatus and Diplachne fusca have been reported to grow in sodic soils of the Indo-Gangetic plains [20].

Table 1. Some important properties of saline, sodic and waterlogged soils relevant to plant survival and growth

| Property                   | Saline                                                                 | Sodic                                                                 | Waterlogged                  |
|----------------------------|------------------------------------------------------------------------|-----------------------------------------------------------------------|------------------------------|
| ECe⁺                       | > 2-4 DS/m                                                             | < 2-4 DS/m                                                            | n.a.                        |
| ESP⁺                       | < 15                                                                  | > 15                                                                 | n.a.                        |
| pH                         | < 8.2                                                                 | > 8.2                                                                | pH fluctuations             |
| Major products             | Na, Cl, S04 predominate                                               | Na, C03, HC03 predominate                                            | Anaerobic respiration end   |
| Physical structure         | Flocculated                                                           | Dispersed                                                            | Variable: low 02 concentrations |
| Soil water                 | Osmotically-induced water stress likely to subsoil                     | Reduced access                                                       | Excess supply               |
| Essential nutrients        | Imbalance                                                             | Imbalance                                                            | Imbalance                   |
| Other                      | Often high Na:Ca                                                      | high Na:Ca                                                          | n.a.                        |

*ECe= electrical conductivity of water extracted from a saturated soil paste; n.a. = not applicable; c ESP = exchangeable sodium percentage.
Waterlogging may be defined as stagnation of water on the land surface or where the water table rises to an extent that soil pores in the crop root zone become saturated, resulting restriction in normal circulation of air leading to decline in the level of oxygen and increase in the level of carbon dioxide [21]. Much of the world’s saline land is also subject to waterlogging (saturation of the soil) because of the presence of shallow water-tables or decreased infiltration of surface water due to sodicity [22]. Waterlogging adversely affects crop productivity in about 4.7% Mha irrigated soils of the Indo-Gangetic Plains of North India comprise 2.5 Mha sodic soils and about 2.2 Mha affected by seepage from irrigation canals [23,24].

3. AGROFORESTRY SYSTEMS FOR SALT-AFFECTED SOILS

Several approaches, including chemical amendments, tillage operations, crop assisted interventions, tree plantations, and Phytoremediation have been used to reclaim sodic and saline- sodic soils. The sodic soils have been reclaimed by growing salt tolerant grasses, protecting natural vegetation cover and adopting reclamation forestry [25]. Several workers have used plant assisted approach for the amelioration of sodic soils [26].

The sodic soils have a narrow spectrum of flora and are characterized by low species diversity and single species dominance [27]. For the different sodic grassland communities (pH ranging from 8.9 to 10.10), species richness, species diversity and species evenness have been found to decrease with increasing sodicity [27]. Grasses such as Cynodon dactylon, Sporobolus arabicus, Imperata cylindrica and Aeluropus lagopoides dominate the saline or saline arid habitats of the Salt Range in Pakistan [28].

Some examples of Bio-saline agro-forestry systems for salt affected areas in India are summarized in Table 2. These are agro-forestry systems for high soil sodicity with calcareous hard pans + fresh ground water (GW); high soil sodicity + sodic GW; permanent waterlogged saline soils; temporary waterlogged saline soils; saline or neutral soil; saline groundwater or aquifer. The agro-forestry systems range from silvi-agro to agro; halophytic trees to remediate soil + conventional agro-ecosystem; agro-silvi-aqua-pasture, trees for bio-drainage (prevention); permanent Agro-forestry system: agro-silvi-pasture trees for bio-drainage; permanent Agro-silvi-pastoral and pastoral-silvi systems.

Forestry and agro-forestry systems on salt-affected soils or bio-saline (agro-forestry systems) may be an alternative land use option as some tree species are less susceptible to soil salinity/sodicity, and their cultivation can help regenerate these soils [5]. Examples of species tolerant to soil salinity, soil sodicity, or both are Acacia nilotica, Eucalyptus camaldulensis, Eucalyptus tereticornis, and Prosopis juliflora [29]. Several studies focused on sodic soils and found agro-forestry systems to be an economically viable land use option [30].

The integration of salt tolerant trees with naturally growing grasses has been reported to be a viable land use option for improving the biological productivity and fertility of highly sodic soils [31,32]. Monoculture plantations on degraded lands could improve the soil condition and enrich the species diversity of herbaceous plants [33]. Re-vegetation of salt wastelands has been found to ameliorate soil conditions and improve soil biological activity. Creation of new forests on barren land has contributed significantly to soil amelioration in the degraded sodic soil of the Indo-Gangetic plains [34].

Kaur et al. [31] analyzed plant biomass production, carbon storage in the soil-plant system in different silvopastoral systems of Prosopis juliflora, Dalbergia sissoo, and Acacia nilotica used for rehabilitation of sodic soils. In these systems, increased input of plant residue into the soil played a significant role to improve soil properties and fertility of highly sodic soils [31]. The tree plantations and Silvo-pastoral agro-forestry systems, raised on sodic soils have been found to improve soil carbon and microbial activity through input of organic matter from above ground and below ground parts of the plants [31,32].

Thirty tree species were evaluated for saline water irrigation (EC 8 – 10 dSm⁻¹) in a highly calcareous soil at Hisar. Findings of the study showed that tree species like Acacia nilotica, Acacia tortilis, Acacia farnesiana, Azadirachta indica, Azadirachta tortilis, Eucalyptus tereticornis, Pithecellobium dulce, Prosopis juliflora, Prosopis cenesaria, Tamarix articulata and Feronia limonia hold promise with saline water irrigation. These workers have also reported that various grasses including Panicum laevifolium, Panicum antidotale, Panicum virgatum, Panicum maximum, Cenchrus ciliaris, and Cenchrus setigerus and Brachiaaria mutica showed good performance under saline water irrigation [35].
Table 2. Some examples of Bio-saline Agro-forestry systems for salt affected areas in India. (GW= Ground Water)

| Saline Environments                                                                 | Occurrence                  | Preferred Agro-forestry system, the role of trees                                                                 | Study areas               |
|-------------------------------------------------------------------------------------|-----------------------------|-----------------------------------------------------------------------------------------------------------------|---------------------------|
| High soil sodicity with calcareous hard pans + fresh GW                             | Haryana, UP, Bihar, Punjab  | Temporary Agro-forestry system, from silvi-agro to agro; Halophytic trees to remediate soil + conventional agro-ecosystem | Lucknow, India            |
| Permanent waterlogged saline soils (canal command areas with extremely poor drainage or geomorphological basins with hardpan and shallow GW<2m) | Haryana, Rajasthan, Punjab | Permanent Agro-forestry system: agro-silvi-aqua-pasture Trees for bio-drainage (prevention); agro & pasture with salt tolerant species (+pond is advisable) | Sampal Rohtak, India      |
| Temporary waterlogged saline soils (shallow GW<4m)                                  | Haryana, Rajasthan, Punjab  | Permanent Agro-forestry system: agro-silvi-pasture Trees for bio-drainage (prevention); conventional agro & pasture with salt tolerant species | Gudha, India: subsoil water level is permanent topsoil is temporary |
| Saline or neutral soil; saline groundwater or aquifer (rainfed, no other major influx of surface water) | Rajasthan, Punjab           | Permanent Agro-silvi-pastoral and Pastoral-silvi systems. Trees have a role in the protection and production, soil improvement | Hisar, India Bhudhawa, India Kharya Sodha, India |
| Saline-sodic topsoil, sodic subsoils, waterlogged, slight                           | Haryana state, India        | Existing agro-forestry system with alley cropping                                                                | Puthi, Haryana state, India |
| Sodic soil, presence of precipitated CaCO₃ layer at Various soil depths, low soil permeability and impeded drainage. | Haryana state, India        | Tree plantations and silvopastoral agro-forestry systems, Trees have a role in the protection and production, soil improvement | Bichian, Haryana state, India |
Beneficial effects and potential uses of *Prosodies* species are: agroforestry systems, control of soil erosion, sand dune stabilization, desalinization, prevention of salinization, nitrogen fixation, recycling of nutrients. *Prosopis* can grow in a soil salinity regime up to sea water salinity. All species of *Prosopis* can tolerate ECe = 10 ds/m salinity with no reduction of growth. In India the most common *Prosopis* species are *P. juliflora* and *P. cineraria*. *Prosopis* growth on salty soils results in their amelioration to such an extent that it can even be used for arable farming after removing *Prosopis* trees [36]. It was reported that afforestation tends to improve biological production by increasing soil organic matter contents and availability of soil inorganic nitrogen in *Acacia*, *Eucalyptus* and *Populus* based agroforestry system [37]. Afforestation by salt tolerant tree species has been found to reclaim salt lands, along with the increase in the size of carbon sinks in the plant-soil system [38].

4. **BIODRAINAGE FOR RECLAMATION OF WATER-LOGGED AREAS**

Bio-drainage may be defined as “pumping of excess soil water by deep-rooted plants using their bio-energy” [39]. The biological drainage uses the transpirative capacity of vegetation an especially trees, to cope with elevated ground water table in the landscape by enhancing their discharge and reducing their recharge. The bio-drainage system consists of fast growing tree species, which absorb water from the capillary fringe located above the ground water table. The absorbed water is translocate to different parts of plants and finally more than 98% of the absorbed water is transpired into the atmosphere mainly through the stomata [40]. This combined process of absorption, translocation and transpiration of excess ground water into the atmosphere by the deep rooted vegetation conceptualizes bio-drainage. Bio-drainage is a natural system, in which tree plantation strip absorbs deep percolation losses of irrigation water applied to the neighbouring crop strip and dispose excess water through evapotranspiration. In other words the concept of bio-drainage is based on evapotranspiration from tree plantation strips located adjacent to the irrigated crop strips [41]. There are different views on the effectiveness and sustainability of bio-drainage for land reclamation. Some important bio-drainage studies on world and national level are reviewed below. The ground water table underneath *Eucalyptus* plantations remained lower than the ground water table in the adjacent fields [39]. The average ground water table in the plantations was 4.95 m and the average ground water table in the control located in adjacent fields was 4.04 m [39].

A large number of species are reported in literature as being salt tolerant. However, the level of salt tolerance differs between species, but also within species and between provenances. For instance, different provenances of *Eucalyptus camaldulensis* show different levels of salt tolerance. Some salt tolerant tree species under waterlogged saline conditions are given in Table 3.

Saline soils suffer from excessive concentration of salts, high water table often leading to water logging, and occurrence of poor quality underground waters in many areas [42]. Poor root zone aeration caused by the high water table (water logging) and excess presence of salts, which operate simultaneously, impair the success of plantation on such soils. The planting techniques should be such that the salt concentration in the root zone remains at a low level and the plants are able to escape the adverse effects of high salinity. Though a series of experiments techniques of plantations on waterlogged saline soils were developed, i.e bund plantations to control water logging; in waterlogged areas near canals planting cloned *Eucalyptus* on bunds (of ~ one meter height) on farmer’s field (in two lines in a space of 1m x 1m ) proved very useful, which not only controlled rise in water table but also helped to generate revenue after 5 years of plantation [43]. In saline areas, lining of poly-sheets on bunds helped in controlling the development of salinity.

Impacts of two 18 years old *Eucalyptus tereticornis* plantations located 350 m apart were studied on water table draw down and salt distribution in the soil profile in canal irrigated alluvial sandy loam soil with sub surface calcium concretion waterlogged areas having ground water table between 3 to 6 m at Dhob-Bhali, Rohtak in Haryana state of India [44]. There was a lowering of ground water table underneath the plantations (0.91m) than the ground water table underneath the adjacent fields without plantation throughout the two year study. The ground water table underneath the plantations was affected up to a maximum depth of 5.63 m below the ground level and the spatial extent of lowering of ground water table underneath the adjacent fields was up to a distance of more than 730 m from the edge of a plantation. The drawdown in the
ground water table was mainly because of the combined cone of depression developed by both the plantations similar to two pumping wells [44].

To evaluate the impact of parallel strip plantations of paired rows of clonal Eucalyptus tereticornis on waterlogging, farm productivity and carbon sequestration in waterlogged areas, a field study was carried at Puthi, Hisar, Haryana [45]. In this study, four parallel strip plantations of clonal Eucalyptus tereticornis (Mysore gum) were raised in December 2002 on four ridges constructed in north-south direction in 4.8 ha canal irrigated waterlogged fields of farmers. The strip plantations were spaced at 66 m and each strip plantation contained 2 rows of trees at a spacing of 1 m x 1 m resulting in a density of 300 plants ha⁻¹. The ground water table underneath the strip plantations remained lower than in the adjacent fields and the drawdown in ground water table was 0.85 min 3 years. The shapes of drawdown curves of ground water table in both transects were similar to the combined cone of depression of 4 pumping wells working simultaneously for a long period indicating that 4 strip plantations of clonal E. tereticornis were also working as bio-pumps. Water table draw down could mainly be due to the luxurious water use by Eucalyptus.

The annual rate of transpiration by 240 surviving trees per ha was 268 mm annum⁻¹ against the mean annual rainfall of 212 mm. The strip plantations generated 46.6 t ha⁻¹ fresh roots and shoot biomass and sequestered 15.5 t ha⁻¹ carbon during the first rotation of 5 years and 4 months. The Benefit-cost ratio of the first rotation of strip-plantations was 3.5:1 and it would be many folds for next 3 to 4 rotations due to the negligible cost of coppiced Eucalyptus. Wheat yield in the inter-space of strip plantations was 3.4 times the yield in adjacent waterlogged areas without plantation. It was mainly because of lowering of the water table and improvement in soil properties. There have been a number of trials in Tasmania to assess the performance of trees and shrubs in soils with moderate to high salinity, combined with seasonal waterlogging. A number of Eucalyptus, Allocasuarina and Acacia species have been reported to perform well [29].

The greenhouse gas balance of bio-saline (agro) forestry on different types of salt-affected soils in South Asia and their economic performance (in terms of the net present value (NPV) and the production costs (COP) has been studied [5]. The bio-saline (agro) forestry system in different conditions included 1) a rice-tree agro-forestry plantation on coastal saline soils in Bangladesh, 2) a rice-wheat- tree agro-forestry plantation on waterlogged, salt-affected soils in India, and 3) a forestry plantation on saline-sodic soils in Pakistan [5]. Bio-saline AF-systems combined the advantages of AF-systems with the utilization of halophytes (salt tolerant trees) in combination with the conventional food crops, or halophytic fodder crops and grasses [5]. The main characteristics of the three studies of bio-saline (agro) forestry in South Asia are given in Table 4, [5].

5. ECO SYSTEM SERVICES OF BIOSALINE AGROFORESTRY

The ecosystem services are the benefits that the natural environment provides to humanity. The Millennium Ecosystem Assessment (MEA) highlighted the condition of ecosystem and ecosystem services, and distinguished four broad categories of ecosystem services, i.e., provisioning, regulating, cultural, and supporting services [6], Fig. 1.

The MA provisioning services describe the processes that yield foods, fibers, fuels, water, bio-chemical, medicinal plants, pharmaceuticals, and genetic resources. The cultural services

| Very Tolerant (25-35 dS/m) | Tolerant (15-25 dS/m) | Moderately tolerant (10-15 dS/m) |
|--------------------------|-----------------------|-------------------------------|
| Acacia farnesiana         | Acacia nilotica       | Cassia siamea                 |
| Melaleuca hal australis   | Acacia tortils        | Casuarina cunninghamiana     |
| Parkinsonia aculeate      | Casuarina equisetifolia| Dalbergia sissoo             |
| Prosopis juliflora       | Eucalyptus camaldulensis| Eucalyptus tereticornis     |
| Tamarix aphylla           | Eucalyptus campae     | Melia azedarach              |
| Tamarix troupil           | Eucalyptus occidentalis| Samanea saman                |
|                          | Eucalyptus sargentii  | Sesbania bispinosa           |
|                          | Pithecellobium dulce  | Sesbania sesbana             |
|                          | Prosopis cineraria    |                               |

Table 3. Some salt tolerant tree species for water logged saline conditions
Table 4. The main characteristics of the three studies of bio-saline (agro) forestry in South Asia [Reference 5]

|                          | Case study 1                                      | Case study 2                                      | Case study 3                                      |
|--------------------------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| Location                 | Coastal zone of Khulna Division, Bangladesh       | Puthi, Haryana state, India                       | Shorokot, Punjab province Pakistan                 |
| Soil conditions Type of Salt-Affectedness; Severity (topsoil) a | Saline; Ranges from moderate to extreme           | Saline-sodic topsoil, sodic subsoils, waterlogged, slight | Saline-sodic; Extreme                              |
| Topsoil properties: ECE (dS m⁻¹) pH SAR (mmol L⁻¹) | 6-25 <8.5 13-14.4                                 | 4.3-7.9 8.6-8.9 15-54                             | 8.2-8.9 25-110                                    |
| (Agro)forestry system    | alley cropping b                                  | Existing agroforestry system with alley cropping b | Existing compact tree plantation                   |
| Tree species             | E. Camaldulensis                                  | E. tereticornis                                    | A. nilotica                                       |
| Agricultural crops; tree density (trees ha⁻¹) | Rice; 200                                        | Rice and wheat; 200                                | Not applicable; 1730                              |
| A share of land used for agricultural crop (%) | 92                                               | 96                                                | 0                                                 |
| Lifetime of plantation (years), Number of rotations | 20; Two                                          | 15; three                                        | 10; one                                           |
| Biomass use              | Fuel wood, timber                                 | Fuel wood timber                                  | Fuel wood, timber                                 |
| Reference system         | Single-season cropping, rice                      | Rice-wheat production system                      | Land is unused due to soil conditions              |

comprise a set of largely non-material benefits of the environment, including recreation and tourism and the spiritual, religious, esthetic, and inspirational well-being. The regulating services are the benefits obtained from the regulation of ecosystem processes; include erosion control or soil stabilization, water purification, and waste treatment; air quality maintenance, climate regulation, hydrological flows, and natural hazard protection. The Supporting services are those that are necessary for the production of all other ecosystem services (Fig. 1).

Fig. 1. Major ecosystem service provided by biosaline agroforestry [Reference 6]
Ecosystem goods and services depend on ecosystem structure and processes. Structural components in ecosystems include trees, crops, soil, topography and animals. Ecosystem processes include the flow of water, animal life cycles, photosynthesis, nutrient cycles and others. These structural components and ecosystem processes support ecosystem functions such as soil accumulation, habitat creation, and buffers to flooding. Ecosystem functions generate benefits to people called ecosystem goods and services [49]. For conservation of biodiversity, it is important to show the relationship between biodiversity and ecosystem services (Fig. 2) and the importance and value of ecosystem services provided by sites important for bio-diversity. Ecosystem services are generated as a result of interaction and exchange between biotic and abiotic components of ecosystems. Since most of the ecosystem services are not part of commercial market, they are often given little weight in policy decisions. Trees in agro-forestry can be used for timber, pulp, firewood, fodder, honey and other products (e.g. Leaf oils and tannins), shelter and shade, wind, water and water table erosion control, wildlife corridors and aesthetics.

6. PROVISIONING SERVICES FROM AGRO-FORESTRY

Provisioning services are the products obtained from ecosystems, including genetic resources, food, energy, timber, fibre, and fresh water. Provisioning ecosystem services, improve local well-being by providing clean water and productive agricultural systems. Agroforestry practices can provide significant amounts of timber and fuel wood on marginal salt lands. In bio-saline agroforestry, some provisioning services are more readily appropriated by human society, which gives economic and social benefits. If the trees are used as fodder or as shade trees, they can be planted scattered over the fields that are used as pastures, but can also be planted in blocks or as timber belts. The trees can be directly browsed by cattle or the leaves and pods can be harvested to feed cattle. A well-known species that are favored in agro-forestry systems are Prosopis Cineraria: it fixes large amounts of nitrogen and does not affect growth of plants under the canopy [22]. Other improvements in soil conditions include reducing water erosion (and thereby nutrient losses) through improving water infiltration, reducing impacts by water droplets, intercepting rain and snow, and physically stabilizing soil through the roots and leaf litter.

The generally crooked stems and branches of P. juliflora make good fuel-wood with a calorific value of 18.9 to 19.9 MJKg⁻¹ and provide excellent charcoal [22]. Charcoal from P. juliflora wood is used extensively. In India a planting of 2500 plants/ha gave about 13 t/ha from cut side-branches after 40 months of growth. The tentative biomass production in ten years was 260 t/ha. P. juliflora planted at 10,000 plants per hectare on a high alkaline soil resulted in an annual increment of 47 t/ha of biomass each year with a rotation of 7 years. The annual increment in a plantation with 5000 plants per ha under the same conditions was 28 Mg per ha [36]. Pod yields of P. juliflora range from 2 t/ha to 8 t/ha in optimum conditions [50].

Fig. 2. Conceptual framework of ecosystem services [adapted from reference 48]
Kaur et al. [31] reported bole and branch wood production in different Silvo-pastoral systems of *Prosopis juliflora*, *Dalbergia sissoo*, and *Acacia nilotica* used for rehabilitation of sodic soils. In silvopastoral agroforestry systems, involving *Acacia nilotica* + *Desmostachya bipinnata*, *Dalbergia sissoo* + *Desmostachya bipinnata* and *Prosopis juliflora* + *Desmostachya bipinnata*, the bole wood that can be used as timber was 4.62 to 9.78 Mg ha\(^{-1}\) and branch biomass production varied between 4.16 to 20.82 Mg ha\(^{-1}\)\ year\(^{-1}\) [31], Table 5.

Timber and fuel wood biomass in clonal *Eucalyptus tereticornis* plantations in different spacing in shallow water table areas after four years at Hisar (based on 55 Kumar, 2014) showed timber production of 11.17 to 28.65 Mg ha\(^{-1}\) as shown in Table 6 [51].

Biomass accumulation has been studied in a farmer’s plantation model of bio-drainage in northwestern India [4]. An abandoned waterlogged area (water table up to 2 m) on a farm at adjacent to Balsam and the canal at HAU Hisar was planted with ten tree species (Table 7). After 6 years of establishment of the plantations, the cone of depression of the water table beneath the plantation strips was observed, the decline in water table was found to be 20 cm over the entire area [4]. The aboveground and belowground biomass accumulation after 6-yr was greater in different clones of *Eucalyptus tereticornis* (102 to 186 Mg ha\(^{-1}\)) as compared to other tree species (12 to 95 Mg ha\(^{-1}\)).

Table 5. Timber and fuel wood production in silvopastoral systems after six years on a sodic soil in Bichian, northwestern India [Based on reference 32]

| Silvopastoral system | Bole (Mg ha\(^{-1}\)) | Branches (Mg ha\(^{-1}\)) |
|----------------------|------------------------|---------------------------|
| *Acacia nilotica* + *Desmostachya bipinnata* | 5.04 | 4.16 |
| *Dalbergia sissoo* + *Desmostachya bipinnata* | 4.62 | 6.29 |
| *Prosopis juliflora* + *Desmostachya bipinnata* | 9.78 | 20.82 |
| *Acacia nilotica* + *Sporobolous marginatus* | - | - |
| *Dalbergia sissoo* + *Sporobolous marginatus* | 0.23 | 0.25 |
| *Prosopis juliflora* + *Sporobolous marginatus* | 7.90 | 11.55 |

Table 6. Timber and fuel wood biomass in clonal *Eucalyptus tereticornis* plantation in different spacing in shallow water table areas after four years at Hisar [based on reference 43]

| Tree spacing | Components | Biomass (August 2011) (Mg ha\(^{-1}\)) |
|--------------|------------|--------------------------------------|
| 1m x 1m (300 tree ha\(^{-1}\)) | Timber | 28.65 |
| | Fuel wood | 1.52 |
| 1m x 2m (150 trees ha\(^{-1}\)) | Timber | 15.28 |
| | Fuel wood | 1.84 |
| 1m x 3m (100 trees ha\(^{-1}\)) | Timber | 11.17 |
| | Fuel wood | 1.57 |

Table 7. The aboveground and belowground biomass accumulation in different species after 6-yr on water logged soils at Hisar [Reference 4]

| Plant species | Aboveground biomass (Mg ha\(^{-1}\)) | Belowground biomass (Mg ha\(^{-1}\)) | Total Plant Biomass (Mg ha\(^{-1}\)) |
|---------------|-------------------------------------|------------------------------------|-----------------------------------|
| *Callistemon lanceolatus* | 10 | 2 | 12 |
| *Eucalyptus tereticornis*, Clone-10 | 109 | 27 | 136 |
| *Eucalyptus tereticornis*, Clone-130 | 146 | 36 | 186 |
| *Eucalyptus tereticornis*, Clone-3 | 82 | 20 | 102 |
| *Eucalyptus hybrid* | 84 | 21 | 105 |
| M. azaderach | 41 | 10 | 51 |
| *Pongamia pinnata* | 30 | 7 | 37 |
| *Prosopis juliflora* | 76 | 19 | 95 |
| *Tamarixaphylla* | 63 | 16 | 79 |
| *Terminaliaarjuna* | 10 | 2 | 12 |
7. SOIL ENRICHMENT AND BIOAMELIORATION

Soils deliver provisioning, regulating, cultural and supporting ecosystem services, and are regulated by the physical, chemical and biological properties of the soil [52]. The ability of soils to deliver the ecosystem services directly depends on soils regulatory services of filtering and detoxifying water, soil biodiversity, decomposition of organic materials, regulation of fluxes of greenhouse gases, and plant-soil nutrient cycles [52]. The growing of tree plantations on salt affected soils has been reported to exert ameliorative effects, especially on sodic soils. Incorporation of organic matter into soils through root growth and litter fall and their decomposition leads to reduction in sodicity and thus higher infiltration and leaching of reaction products.

*Acacia nilotica* and *Eucalyptus tereticornis* plantations were noted to have a considerable ameliorative effect on soil properties when planted on alkali soil [53]. The soil organic carbon content increased to about double the initial value for *Eucalyptus* but tripled under *Acacia* Plantation. Twenty year old plantations of *Prosopis juliflora*, *Acacia nilotica*, *Eucalyptus tereticornis*, *Albizia lebbeck* and *Terminalia arjuna* could ameliorate the alkali soil by adding organic matter through litter to the extent that arable crops could be grown successfully on the soil. At the other alkali soil site, *Terminalia articulata* ameliorated the soil by inducing the maximum reduction of sodicity and pH values followed by *Prosopis juliflora* and *Acacia nilotica* [54]. It was also reported that the break –even points occur within the life cycle of tree plantations and these occurred in 9 and 11 years after the plantations of *Banksia grandis* and *Pinus radiate*, respectively. Nevertheless, most salt-affected soils, being low in carbon at planting, can provide for environmental benefits not only in terms of carbon accumulations and ameliorations of soils, but also their direct benefits through their effects on the greenhouse gas carbon dioxide.

*Prosopis Cineraria* grows successfully in highly saline (ECe > 15 DS/m) and alkaline soils (pH values up to 9.8). It is highly drought tolerant; its taproot can reach groundwater at 20 meters depth. It is an excellent fuel (calorific value of sapwood: 20.9 MJ/kg), and also gives high-quality charcoal (5,000 kcal/kg) [22]. Due to its deep root system, mono-layered canopy and ability to fix atmospheric nitrogen *P. cineraria* is extensively used as an agro-forestry tree throughout arid and semi-arid India. The tree has a boosting effect on the yield of crops growing in its vicinity. The crops draw their moisture and nutrients from the top 50-60 cm of soil while the tree gets its nutrients from a deeper horizon. In addition, the tree provides shade to crops during summer [55]. The tree is favoured for agro-forestry as it fixes large amounts of nitrogen and does not affect growth of plants under the canopy. In silvi-pasture agro-forestry systems, soil organic matter, biological productivity and carbon storage were greater in agro-forestry than grass only systems [31]. In these systems, increased input of plant residue into the soil played a significant role to improve soil properties and fertility of highly sodic soils. With the increase in age of *Prosopis juliflora* and *Dalbergia sissoo* plantations from 3 years to 9 years on sodic soils, there was an increase in soil porosity, decrease in bulk density of soil, improved soil aggregation, and increase in mean permeability of soil due to increase in the levels of soil organic matter [56].

Soil microbial biomass is an important component of soil organic matter comprising 1-3% of total soil organic matter [57]. It is a labile fraction of soil organic matter and conserves nutrients for plant growth [58]. The microbial biomass primarily depend on the rates of nutrient fluxes and has been used as an index of soil fertility. Salinity under arid conditions has a harmful influence on the size and activity of soil microbial communities and their activity are greatly influenced by salinity [60].

Using various combinations of gypsum, Karnal grass, and cropping systems on sodic soils, Batra et al [61] have found an increase in dehydrogenase activity and microbial biomass carbon in alkali soils. The effect of salinity on the microbial and biochemical parameters of salt affected soils of coastal regions of the Bay of Bengal [62]. These workers have shown that microbial biomass and microbial activities decreased with an increase in salinity, resulting in poor crop growth of salt affected coastal soils [62].

8. NITROGEN CYCLING

Nitrogen is essential to the survival of all life forms and often limits productivity, decomposition and the long-term accumulation of carbon in
terrestrial ecosystems. Nitrogen is a key element in biogeochemical processes and often limits net primary productivity in major terrestrial ecosystems [63]. Forests account for 80% of the world’s plant biomass and are therefore constituted a main driver and component of the Earth’s biogeochemical cycles [64]. Forest ecosystems show a high net primary productivity that is generally limited by the availability of nitrogen [65]. Thus, nitrogen cycling is a key factor to understand the structure and functioning of ecosystems. Soil and vegetation are the respective primary and secondary sinks for N in terrestrial ecosystems. Litter production determines the amount and quality of N returned to the forest floor and mineral soil. The trees in agro-forestry systems can actually increase the supply of nutrients within the rooting zone of crops through fixing biological nitrogen gas (N₂) and retrieving nutrients from below the rooting zone of crops. This is important as many salt-affected soils are also characterized by low soil fertility.

Nitrogen cycling in silvopastoral systems in a highly sodic soil showed that the nitrogen pool in vegetation was 32.47% and 29.52% of the soil pool in Prosopis juliflora + Desmostachya bipinnata and Prosopis juliflora + Sporobolus marginatus silvopastoral system, respectively, on a sodic soil at Bichian (Fig. 3). The return of nitrogen in litterfall varied from 0.0 75 to 0.14 Mg N ha⁻¹ yr⁻¹. The turnover of fine root biomass returned 0.019 to 0.037 Mg N ha⁻¹ yr⁻¹. The return of total nitrogen to the soil was 0.11 to 0.177 Mg N ha⁻¹ yr⁻¹. Total nitrogen uptake was 0.156 to 0.277 Mg N ha⁻¹ yr⁻¹. Thus, nitrogen sequestration in the system was 0.046 to 0.10 Mg N ha⁻¹ yr⁻¹, which was 28.84 to 36.10% of total uptake of the nitrogen in the agro forestry system [31].

9. CARBON STORAGE AS AN INDICATOR OF ECOSYSTEM SERVICES

The agro-forestry systems could be an important for carbon storage in the soil-plant system, which is an indicator of regulatory ecosystem services. The plants sequester carbon from the atmosphere and influence the patterns of climate. Climate Regulation refers to the influence that ecosystems have on the global climate by emitting greenhouse gases to the atmosphere or extracting carbon from the atmosphere. The various pools of carbon in the agro-forestry systems include above ground woody biomass, below ground biomass, litterfall, ground floor litter and soil carbon. Carbon sequestration in agro-forestry systems has been discussed as follows. The agro-forestry systems have appreciable carbon sequestration potential in the soil, which could play an important role in climate change mitigation and adaptation. Maintaining the stores and sink of carbon in agro-forestry could play a key role to reduce future emission of greenhouse gases.

10. CARBON SEQUESTRATION

Carbon sequestration involves the removal and storage of carbon from the atmosphere in vegetation, and soils through physical or biological processes. Carbon sequestration refers to the transfer of atmospheric carbon dioxide in the long-lived pools and storing it in soil pool for a sufficient period of time. Carbon sequestration can occur in plant biomass, organic and inorganic carbon in surface soil and carbon storage in soil profiles. In terrestrial ecosystems (i.e. soils, trees and other vegetation), C sequestration are a natural process based on photosynthesis and humification of biomass [10]. Every year, ~121 Pg (Pg = petagram = 10¹² g ) of CO₂-C from the atmospheric pool is photosynthesized into plant biomass , out of which ~60 PgC is returned back to the atmosphere by plant respiration and the remaining 61.6 PgC by soil respiration. Plant biomass and soil organic matter constitute the major pool of carbon in terrestrial ecosystems. The biotic pool in vegetation stores about 610Pg C at any given time, Fig. 4.

The total amount of carbon in the world’s soil organic matter is estimated to be 1500 to 1580Pg C [66]. The global soil carbon pool of 2500 Gt C that comprises about 1550 Gt of soil organic carbon and 950 Gt of soil inorganic carbon [66]. Globally, the terrestrial heterotrophic respiration is responsible for returning about 60 Pg C year⁻¹ to the atmosphere [67].

11. CARBON SEQUESTRATION IN PLANT BIOMASS IN THE AGRO-FORESTRY SYSTEMS

The Agro-forestry has potential to store carbon in plant biomass and wood products besides being a self-reliant and risk proof system required for sustainable land management, microclimate moderation and rehabilitation of degraded land and carbon sequestration [68]. The degraded croplands and pasturelands have the potential to improve them using agro-forestry as well as sequestering carbon in such systems.
Deep-rooted trees are important for incorporating the SOC pool in the sub-soil and enhancing soil structure. Perennials with deep root systems also use more water and can improve the drainage conditions. The trees on salt-affected soils have the potential for carbon sequestration by increasing soil carbon and plant biomass production [31,32]. In an age sequence of Prosopis plantations, trees have been found to ameliorate highly sodic conditions by alleviating sodium toxicity and improving the build-up of soil fertility. These workers have found an annual rate of increase of 1.4 Mg C ha\(^{-1}\) yr\(^{-1}\) over a 30 year period of the plantation. There is a large potential of sequestering carbon in soil and vegetation by protecting native vegetation, and adopting silvopastoral agro-forestry systems on salt affected soils.

In South western Australia, estimated rates of C sequestration in biomass of *E. globulus* over a 10 year period ranged from 3.3 to 11.5 Mg C ha\(^{-1}\) year\(^{-1}\) [69,70]. These are markedly high rates of C sequestration, especially on a large scale.
watershed. Biomass and carbon sequestered by 5-yr and 4-month-old clonal *E. tereticornis* on waterlogged soils at Puthi, Hisar, North-west India was 15.5 Mg ha\(^{-1}\) [45], Table 8.

Soil carbon sequestration potential in 0-30 cm soil layer ranged from 6.839 to 27.09 in some agroforestry systems and grassland systems of salt-affected soils (Table 9).

The silvo-pastoral systems on saline-sodic soils showed carbon sequestration potential ranging from 20.393 to 19.930 Mg C ha\(^{-1}\). The *Eucalyptus* based agro-forestry on waterlogged soils showed soil carbon storage of 15.823 Mg C ha\(^{-1}\). Compared to baseline of the cropland, the net carbon sequestration amounted to 4.452 Mg C ha\(^{-1}\) over a period of four years. Carbon storage in plant biomass (Mg C ha\(^{-1}\)) and carbon flux in net primary productivity (Mg C ha\(^{-1}\) yr\(^{-1}\)) of clonal *Eucalyptus tereticornis* agro-forestry and tree plantation at different spacing in shallow water table areas in Puthi, north-west India [43] showed that total carbon storage in plant ranged from 5.85 to 16.46 Mg C ha\(^{-1}\) (Table 10).

Carbon flux in net primary productivity was 2.01 to 4.7 Mg C ha\(^{-1}\) yr\(^{-1}\). Carbon sequestration in plant biomass in sole plantation was very high and amounted to 91.84 Mg C ha\(^{-1}\) (Table 10). Biomass production from bio-saline agro-forestry in waterlogged, saline-sodic soils in India was found to sequester 6 Mg CO\(_2\)eq. ha\(^{-1}\) over the 15 year lifetime of the plantation [5]. The emissions from agrochemical and fossil fuel use could be compensated by carbon sequestration in belowground biomass and soil. The economic value of the carbon sequestration is small and ranges between 0.003 and 0.046 kV ha\(^{-1}\) depending on the carbon credit price assumed.

### 12. SOIL CARBON SEQUESTRATION IN AGRO-FORESTRY SYSTEMS

Even at low concentration, SOC is important to improving soil fertility, increasing water permeability, enhancing aggregation, and accentuating soil biotic activity. Thus soil organic matter is an important indicator of soil quality and the ecosystem services that it provides. Improving SOC Pool is an important strategy of reclaiming salt affected soil. The goal is to create a positive ecosystem C budget. There are several technologies which have proven effective in enhancing the SOC pool (Fig. 5).

Mishra and Sharma [56] reported that with the increase in age of *Prosopis juliflora* and *Dalbergia sissoo* plantations from 3 years to 9 years on sodic soils, there was an increase in the levels of soil organic matter. There was a measurable increase in the SOC pool to 150 cm depth after planting *Eucalyptus* on sodic soils. The rate of soil carbon sequestration was 1.1 to 1.5 Mg C ha\(^{-1}\) year\(^{-1}\). Trees have also been grown in association with salt tolerant grasses through agro-forestry systems. Experiments conducted in the Indo-Gangetic plains showed that growing mesquite (*Prosopis juliflora*) and

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**Fig. 5. Strategies to reclaim salt-affected soils for salt tolerant, soil carbon storage and leaching**
other perennials is an effective strategy for increasing the SOC pool in salt-affected soils. Establishing mesquite on an alkaline soil in North Western India increased its SOC concentration over a 74-month period from 0.18% to 0.43% in 0-15 cm depth, and from 0.13% to 0.29% in 15-30 cm depth. Establishing mesquite in association with Kallar grass (Leptochloa fusca) increased SOC concentration over a 74-month period from 0.19% to 0.58% in 0-15 cm depth compared with 0.12% to 0.36% in 15-30 cm depth. Change in bulk density and organic carbon concentration and organic carbon pool less than four years Eucalyptus plantations at Puthi research site of water logged areas, Hisar up to 0-90 cm soil depth was 32.63 to 29.02 Mg C ha⁻¹ (Table 11).

The soil carbon sequestration in some agro-forestry systems in 0-30 cm soil on salt affected soils as reported by different workers is given in Table 9. In the Prosopis juliflora + Desmostachya bipinnata and Prosopis juliflora + Sporobolus marginatus agri-silvopastoral systems on sodic soils at Bichian, north-west India, the soil carbon pool was: 13.431 Mg C ha⁻¹, Prosopis juliflora + Desmostachya bipinnata; 9.621 Mg C ha⁻¹, Prosopis juliflora + Sporobolus marginatus [31]. The soil carbon sequestration in Acacia nilotica and Salvadora persica silvopastoral systems on saline-sodic calcareous soils Hisar, India varied from 20.393 to 19.930 Mg C ha⁻¹. The soils stored 74.774 to 73.06 Mg CO₂ ha⁻¹, which could account for 73.927 carbon credits/ha for soil carbon sequestration. Assuming $10 Price for one Carbon Credit, the monetary value of carbon storage comes out to be ranging from ~ 739 US $/ha.

In the Western Australian wheat belt, the restoration of native eucalypt forests for managing degraded agricultural landscapes is a critical part of managing dry land salinity and rebuilding biodiversity. Harper et al. [72] conducted two 26 year old reforestation experiments with four Eucalyptus species (E. cladocalyx var nana, E. occidentalis, E. sargenti and E. wandoo) compared with agricultural Field. SOC stores (to 0.3 m depth) ranged between 33 and 55 Mg ha⁻¹, with no statistically significant differences between tree species and adjacent farmland [72]. In contrast, the reforested plots contained additional carbon in the tree biomass (23–60 Mg ha⁻¹) and litter (19–34 Mg ha⁻¹), with the greatest litter accumulation associated with E. sargentii. Litter represented between 29 and 56% of the biomass carbon and the protection or utilization of this litter in fire-prone, semi-arid farmland will be an important component of carbon management [72]. These workers emphasized the importance of considering a litter in reforestation carbon accounts.

### 13. CLIMATE CHANGE MITIGATION AND ADAPTATION

Climate change mitigation refers to activities that reduce GHGs in the atmosphere or enhance the storage of GHGs stored in ecosystems. Adaptation to climate change is focused on actions that reduce or eliminate the negative effects of climate change or take advantage of the positive effects [73]. Agroforestry functions that support climate change mitigation and adaptation are summarized in Fig. 6.

While delivering other production and natural resource services, bio-saline agro-forestry has the potential to address climate change mitigation and adaptation needs on salt-affected and waterlogged soils. In the tropics, the potential of agro-forestry for climate change mitigation and adaptation is well recognized [74]. The woody biomass component represents the major portion of easily observed and measured the new carbon in the agro-forestry systems [75]. The bulk of this C is generally contained within the above ground woody parts (bole and branches). For example, above ground woody biomass carbon in Prosopis juliflora + Desmostachya bipinnata silvopastoral systems, bole and branches comprised 82% of the total biomass carbon in six year old systems [31].

#### Table 8. Biomass and carbon sequestered by 5-yr and 4-month-old clonal E. tereticornis on waterlogged soils at Puthi, Hisar, North-west India (Reference 45)

| Tree component | Dry biomass (Mg ha⁻¹) | C (%) | C sequestered (Mg C ha⁻¹) |
|----------------|-----------------------|-------|--------------------------|
| Timber         | 22.1                  | 47.0  | 10.4                     |
| Fuel wood      | 0.8                   | 43.5  | 0.3                      |
| Twigs and Leaves | 1.1               | 43.9  | 0.5                      |
| Roots          | 8.9                   | 48.0  | 4.3                      |
| **Total**      | **32.9**              | **15.5** |
Table 9. Soil Carbon sequestration in some agro-forestry systems in 0-30 cm soil on salt affected soils

| Agro-forestry System | Site | Soil Carbon sequestration (Mg C ha⁻¹) | Soil CO₂ sequestration (Mg CO₂ ha⁻¹) | Reference |
|----------------------|------|--------------------------------------|--------------------------------------|-----------|
| *Prosopis juliflora* + Desmostachya bipinnata Silvopastoral system | sodic soils at Bichian, north-west India | 13.431 | 49.247 | [32] |
| Desmostachya bipinnata Grassland | -do- | 9.355 | 34.302 | [32] |
| *Prosopis juliflora* + *Sporobolus marginatus* silvopastoral system | -do- | 9.621 | 35.28 | [32] |
| *Sporobolus marginatus* Grassland | -do- | 7.529 | 27.606 | [32] |
| Eucalyptus plantation* | Sodic soil of UP, India | 24.56-27.09 | 90.05-99.33 | [71] |
| Baseline* | Sodic soil of UP, India | 20.70 | 75.90 | [71] |
| Eucalyptus Clonal | Puthi, Haryana state, India | 15.827 | 58.03 | [43] |
| Agro-forestry on waterlogged soils | -do- | 11.355 | 41.635 | [43] |
Table 10. Carbon storage in plant biomass (Mg C ha\(^{-1}\)) and carbon flux in net primary productivity (Mg C ha\(^{-1}\) yr\(^{-1}\)) of clonal *Eucalyptus tereticornis* agro-forestry and tree plantation at different spacing in shallow water table areas in Puthi, north-west India [based on reference 43]

| Tree spacing         | Components                  | Carbon storage (Mg C ha\(^{-1}\)) | Carbon flux (Mg C ha\(^{-1}\) yr\(^{-1}\)) |
|----------------------|------------------------------|-----------------------------------|---------------------------------------------|
| 1m x 1m (300 tree ha\(^{-1}\)) | Above ground biomass        | 11.63                             | 4.47                                        |
|                      | Belowground biomass         | 4.83                              | 0.23                                        |
|                      | **Total**                   | **16.46**                         | **4.70**                                    |
| 1m x 2m (150 trees ha\(^{-1}\)) | Above ground biomass        | 6.25                              | 5.48                                        |
|                      | Belowground biomass         | 2.26                              | 0.26                                        |
|                      | **Total**                   | **8.51**                          | **5.74**                                    |
| 1m x 3m (100 trees ha\(^{-1}\)) | Above ground biomass        | 4.25                              | 1.73                                        |
|                      | Belowground biomass         | 1.6                               | 0.28                                        |
|                      | **Total**                   | **5.85**                          | **2.01**                                    |
| Sole Plantation      | Above ground biomass        | 67.6                              | 22.74                                       |
|                      | Belowground biomass         | 24.24                             | 4.09                                        |
|                      | **Total**                   | **91.84**                         | **26.83**                                   |

Table 11. Change in bulk density and organic carbon concentration and pool under four year *Eucalyptus* plantations at Pithy research site, Hisar

| Tree spacing | Soil depths (cm) | Organic carbon (%) | Bulk density (g cm\(^{-3}\)) | SOC Pool (Mg C ha\(^{-1}\)) |
|--------------|------------------|--------------------|------------------------------|----------------------------|
| 1m x 1m      | 0-15 (15)        | 0.45               | 1.31                         | 8.84                       |
|              | 15-30 (15)       | 0.38               | 1.39                         | 7.92                       |
|              | 30-60 (30)       | 0.23               | 1.44                         | 9.94                       |
|              | 60-90 (30)       | 0.13               | 1.52                         | 5.93                       |
|              | **Total**        |                    |                              | **32.63**                  |
| 1m x 2m      | 0-15 (15)        | 0.42               | 1.33                         | 8.37                       |
|              | 15-30 (15)       | 0.37               | 1.41                         | 7.82                       |
|              | 30-60 (30)       | 0.21               | 1.44                         | 9.07                       |
|              | 60-90 (30)       | 0.10               | 1.49                         | 4.47                       |
|              | **Total**        |                    |                              | **29.73**                  |
| 1m x 3m      | 0-15 (15)        | 0.39               | 1.34                         | 7.83                       |
|              | 15-30 (15)       | 0.32               | 1.39                         | 6.67                       |
|              | 30-60 (30)       | 0.22               | 1.45                         | 9.57                       |
|              | 60-90 (30)       | 0.11               | 1.50                         | 4.95                       |
|              | **Total**        |                    |                              | **29.02**                  |
| Control      | 0-15 (15)        | 0.30               | 1.49                         | 6.70                       |
|              | 15-30 (15)       | 0.20               | 1.55                         | 4.65                       |
|              | 30-60 (30)       | 0.15               | 1.61                         | 7.24                       |
|              | 60-90 (30)       | 0.07               | 1.67                         | 3.50                       |
|              | **Total**        |                    |                              | **22.09**                  |

Soil carbon stocks have been found to be positively affected by agro-forestry systems compared to conventional cropping systems, tree plantations or grass only systems [76]. However, there could be high variability in terms of methods of soil sampling and actual accrual of new carbon derived from both internal and external sources with reasonable accuracy [77]. Net increase of C in soils using C-sequestering activities generally does not continue for many years; soil organic carbon (SOC) levels are assumed to stabilize at a new steady state after 20 years [78]. Thus, understanding of carbon cycling within agro-forestry systems, as well as our knowledge gaps need to be addressed to enable accurate and full carbon accounting contributed by agro-forestry systems [76].

Impacts of agro-forestry systems on nitrous oxide (N\(_2\)O) and methane (CH\(_4\)) emissions need to be
considered. Studies on these GHGs in agroforestry systems are limited [73]. Agro-forestry includes many agricultural activities that affect emissions of these GHGs (e.g., fertilization, liming, tillage, and livestock management). Integrating agro-forestry into agricultural operations, reduce N\textsubscript{2}O emissions by eliminating nitrogen (N) application on the part occupied by trees. Additionally, emissions may be further reduced through tree uptake of excess nitrogen [79]. The roots of trees have the potential to take up excess N spatially and temporally that would otherwise be available for N\textsubscript{2}O emissions on- or off-site. Silvopasture may offer several options for reducing CH\textsubscript{4} and N\textsubscript{2}O emissions [80]. The integration of tree components in silvopasture could result in diminished N\textsubscript{2}O emissions due to increased nutrient use efficiency. Agro-forestry practices offer many opportunities to increase carbon sequestration, potentially reduce other GHGs, and help maintain production at the landscape level [73].

Agro-forestry can add a high level of diversity on degraded lands with an accompanied increased capacity for supporting numerous ecological and production services that impart resiliency to climate change impacts [73,74]. The mixing of woody plants into crop, forage, and livestock operations provides greater resiliency to the interannual variability through crop diversification as well as through increased resource-use efficiency [81]. Agro-forestry increases soil porosity, reduces runoff, and increases soil cover, which can improve water infiltration and retention in the soil profile, thereby reducing moisture stress in low rainfall years [82].

14. CONCLUSION

Soil carbon sequestration in salt-affected soils are critical to formulate management strategies for their ecological restoration and for improving soil productivity so as to meet increasing demands of human society for food, fodder, biomass energy, and industrial products. Implementing appropriate management practices to build up soil carbon stocks in grasslands could lead to considerable mitigation, adaptation and development benefits. Carbon sequestration also provides associated ecosystem co-benefits such as increased soil, water holding capacity, better soil structure, improved soil quality and nutrient cycling, and reduced soil erosion. Under water logged conditions in saline environments, tree-based systems can reduce the water table by pumping out excess water more rapidly than only cropland systems. Agro-forestry systems can offer greater economic stability and reduce risk under climate change by creating more diversified systems with greater income distribution over time.
The sparse research conducted to-date for climate change mitigation and adaptation through agro-forestry has mainly focused on carbon sequestration in woody biomass. However, the complexity in agro-forestry that provides its potential for meeting GHG objectives and providing the resiliency for attaining the production and the other ecosystem service goal need be worked out under different climatic and soil conditions. Agro-forestry has the potential to affect numerous production and ecosystem services such as aesthetics, recreation, microclimate, carbon sequestration; natural pest control, pollination, water quality, soil erosion prevention and that will be impacted by climate change. Thus, climate change -integrated tools along with ecosystem functioning and services will be needed to ensure sustainable agro-forestry in saline environments.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Szabolcs I. Salt-affected soils. Florida, USA,CRC Press. 1989;274.
2. Qadir M, Tulehelle A, Akhtar J, Larbi A, Minhas PS, Khan MA. Productivity enhancement of salt-affected environments through crop diversification. Land Degradation and Development. 2007;19:429-453.
3. Ram J, Garg VK, Toky OP, Minhas PS, Tomar OS, Dagar JC, Kamra SK. Biodrainage potential of Eucalyptus tereticornis for reclamation of shallow water table areas in North-West India. Agroforestry System. 2007;69:147-165.
4. Toky OP, Angrish R, Datta KS, Arora V, Rani C, Vasudeven P, Harris PJC. Biodrainage for preventing waterlogging and concomitant wood yield in arid agro-ecosystems in North-Western India. Journal of Scientific Industrial Research. 2011;70:639-644.
5. Wicke B, Edward SWM, Akanda R, Stille L, Singh RK, Awan AR, Mahmood K, Faaij APC. Biomass production in agroforestry and forestry systems on salt affected soils in South asia: Exploration of the GHG balance and Economic performance on three case studies. 2013;127:324-334.
6. MEA (Millennium Ecosystem Assessment). Ecosystems and human well-being: Biodiversity synthesis. Washington, D.C.: World Resources Institute; 2005.
7. Turner WR, et al. Global biodiversity conservation and the alleviation of poverty. Bioscience. 2012;62:85-92.
8. Jose S. Agroforestry for Ecosystem Services and Environmental Benefits. Springer Science, The Netherlands. 266p. Forest Ecology and Management. 2009;133:231-247.
9. FAO. Global forest resources assessment 2010. Main report. FAO Forestry Paper 163. Rome; 2010.
10. Lal R. The potential for soil carbon sequestration", In: Nelson, GC (eds.), Agriculture and Climate Change: An Agenda for Negotiation in Copenhagen, Brief 5, Focus 16, International Food Policy Research Institute, Washington DC; 2009.
11. Jose S, Bardhan S. Agroforestry for biomass production and carbon sequestration: An overview. Agroforestry System. 2012;86:105-111.
12. FAO. The state of food insecurity in the world. High food prices and food security threats and opportunities. Rome; 2008.
13. Wicke B, Smeets E, Dornburg V, Vashev B, Gaiser T, Turkenburg W, Faaij A. The global technical and economic potential of bioenergy from salt-affected soils. Energy & Environmental Science. 2011;4:2669-2680.
14. Oldeman LR, Hakkeling RT A Sombroek WG. World map of the status of human-induced soil degradation - An explanatory note - Global Assessment of Soil Degradation, GLASOD. Wageningen: International Soil Reference and Information Centre; Nairobi: United Nations Environmental Programme. Retrieved 24.10; 2008. Available:http://www.isric.org/isric/webdocs/Docs/ExplanNote.pdf.1991
15. IAB. India Agriculture in Brief, 27th Edition, Directorate of Economics and Statistics Department of Agriculture and Cooperation, Ministry of Agriculture of India, New Delhi. 2000;36.
16. Qureshi AS, PG McCormick, Qadir M, Aslam Z. Managing salinity and waterlogging in the Indus Basin of Pakistan. Agricultural Water Management. 2008;95:1-10.
17. Marcar NE, Khanna PK. Reoferestation of salt affected and acid soil. Ln: Nambar EK, Sadanandan Brown AG (eds) Management of Soil, Nutrient and water in
and nitrate assimilation in pea leaves. Acta Societatis Botanicorum Poloniae. 1988; 57:457–463.
28. Chaudhary AA, Hameed M, Ahmed R, Hussain A. Phytosociological studies in Chumbi Suresa Wild Life Sanctuary, chakwal, Pakistan. Species diversity. International Journal of Agricultural Biology. 2001;3:369-374.
29. Marcar N, Crawford D. Trees for saline landscapes, rural industries research and development corporation (RIRDC), Canberra, Australian Capital Territory; 2004.
30. Zhang J, Xing S, Li J, Makeschin F, Song Y. Agroforestry and its application in amelioration of saline soils in eastern China coastal region. Forestry Studies in China. 2004;6:27-33.
31. Kaur B, Gupta SR, Singh G. Carbon storage and nitrogen cycling in silvopastoral systems on a sodic soil in northwestern India. Agroforestry Systems. 2002a;54:21-29.
32. Kaur B, Gupta SR, Singh G. Bioamelioration of a sodic soil by silvopastoral system in northwestern India. Agroforestry Systems. 2002b;54:13-20.
33. Singh AN, Raghubanshi AS, JS Singh. Plantations as a tool for mine spoil restoration. Current Science. 2002;82:1436-1441.
34. Tripathi KP, Singh B. The role of revegetation for rehabilitation of sodic soils in semi-arid sub tropical forest, India. Restoration Ecology. 2005;13:29-38.
35. Tomar OS, Minhas PS, Sharma VK, Singh YP, Gupta RK. Performance of 31 tree species and soil conditions in a plantation established with saline irrigation. Forest Ecology and Management. 2003;177:333-346.
36. Singh G, Singh NT. Mesquite for the revegetation of salt lands, Central Soil Salinity Research Institute, Karnal. 1992;24.
37. Singh; 1995.
38. Singh G, Singh NT, Dagar JC, Singh H, Sharma VP. An evaluation of agriculture, forestry and agroforestry practices in a moderately alkali soil in northwestern India. Agroforestry System. 1997;37:279–295.
39. Ram J, Dagar JC, Singh G, Lal K, Tanwar VK, Shoeran SS, Kaledhonkar MJ, Dar SR, Kumar M. Biodrainage ecofriendly technique for combating waterlogging and

Tropical Plantation Forests. ACIAR Monograph No 43, Canberra, Australia; 1997.
18. Marcar N, Ismail S, Hussain A, Ahmad R. Trees, shrubs and grasses for saltlands: An annotated bibliography. ACIAR Monograph No. 56. ACIAR, Canberra. 1999:316.
19. IRRI. Increasing productivity of intensive rice systems through site-specific nutrient management, Dobermann A, Witt C, Dawe D (Eds), Enfield, N.H. (USA) and Los Baños (Philippines): Science Publisher s pp 410. International Rice Research Institute (IRRI). 2004:410.
20. Gupta SR, Sinha A, Rana RS. Biomass dynamics and nutrient cycling in a sodic grassland. International Journal of Ecology and Environmental Sciences. 1990;16:57–70.
21. Setter TL, Waters I, Sharma SK, Singh KN, Kulshreshtha N, Yaduvanshi NPS, Ram PC, Singh BN, Rane J, MC Donald G, Khabz-Saberi H, Biddolph TB, Wilson R, Barclay I, Mclean R, Cakir M. Review of wheat improvement for waterlogging tolerance in Australia and India: The importance of anaerobiosis and element toxicities associated with different soils. Journal Annals of Botany. 2009;103:221-235.
22. Qureshi RH, Barrett-Lennard EG. Saline Agriculture for Irrigated Land in Pakistan: A Handbook. Monograph No. 50, Australian Centre for International Agricultural Research, Canberra. 1998:142.
23. Minhas PS, Dagar JC. Agroforestry uses of inland salt-affected landscapes. CAB Review: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources. 2007;2:10.
24. Singh AK. Nutrient management in problem soils, In: Enhancing Nutrient Use Efficiency in Problem Soils. Singh G, Qadir Ali, Yaduvanshi NPS and Dey P (eds.), CSSR, Karnal, India. 2009;1-21.
25. Singh G, Gill HS. Ameliorative effect of tree species on characteristics of sodic soils at Karnal. Indian Journal of Agricultural Science. 1992;62:142–146.
26. Qadir M, Qureshi RH, Ahmad N. Amelioration of calcareous saline-sodic soils through phytoremediation and chemical strategies. Soil Use Management. 2002;18:381–385.
27. Sinha SK, Srivastava HS, Mishra SN. Effect of lead on nitrate reductase activity
salinity. Technical Bulletin: CSSRI/Karnal/9/2008;24.

40. Akram NA, Shahbaz M, Ashraf M. Nutrient acquisition in differentially adapted populations of Cynodon dactylon(L.) Pers. and Cenchrus ciliaris (L.) under drought stress. Pakistan Journal of Botany. 2008;40:1433-1440.

41. Chhabra R, Thakur NP. Biodrainage using trees to control waterlogging and secondary salinization in canal irrigated areas. Proceedings National Conferences on salinity management in agriculture. Central Soil Salinity Research Institute. Karnal, India; 1998.

42. Dagar JC. Opportunities for alternate land uses in salty and water scarcity areas. International Journal of Ecology and Environmental Sciences. 2009;35:53-66.

43. Kumar M. Waterlogging control and carbon sequestration through biodrainage. PhD thesis, Kurukshetra University Kurukshetra. 2012;253.

44. Ram J, Garg VK, Toky OP, Minhas PS, Tomar OS, Dagar JC, Kamra SK. Biodrainage potential of Eucalyptus tereticornis for reclamation of shallow water table areas in north-west India. Agroforestry System. 2007;69:147-165.

45. Ram J, Dagar JC, Lal K, Singh G, Toky OP, Tanwar VS, Dar SR, Chauhan MK. Biodrainage to combat waterlogging, increase farm productivity and sequester carbon in central command areas of northwest India. Current Science. 2011;100:1673–1680.

46. Haines-Young RH, Potschin M. The links between biodiversity, ecosystem services and human well-being. In: Raffaelli, D. & C. Frid (eds.): Ecosystem Ecology: A new synthesis. BES Ecological Reviews Series, CUP, Cambridge. 2010;110-139.

47. Peh KSH, Balmford AP, Bradbury RB, Brown C, Butchart SHM, Hughes FMR, Statters field AJ, Thomas DHL, Walpole M, Birch JC. Rapid assessment of ecosystem services at sites of biodiversity conservation importance. Ecosystem Services. 2013;7.

48. Mace GM et al. Biodiversity and ecosystem services: A multilayered relationship. Trends in Ecology and Evolution. 2012;27:19-26.

49. De Groot RS, Wilson M, Boumans R. A typology for the description, classification and valuation of ecosystem functions, goods and services. Ecological Economics. 2002;41:393–408.

50. Kuiper L, Probos O. Biosaline (agro) forestry: A literature review. Biomass upstream stuurgroep. 2005;17.

51. Kumar M. Waterlogging control and carbon sequestration through biodrainage. PhD thesis, Kurukshetra University Kurukshetra. 2014;253.

52. Palm C, Sanchez P, Ahmed S, Awiti A. Soils: A contemporary perspective. Annual Review of Environment and Resources. 2007;32:99-129.

53. Gill HS, Abrol IP. Afforestation and amelioration of salt-affected soils in India. In: The productive use of saline land (eds. Davidson, N. and Galloway, R.). Proceedings of a workshop held in Perth, Western Australia. ACIAR Proceedings. 1993;42:23-27.

54. Dagar JC, Singh G, Singh NT. Evaluation of forest and fruit trees used for rehabilitation of semiarid alkali/sodic soils in India. Arid Soil Research & Rehabilitation. 2001;15:115-133.

55. Dutton RW (eds.) Prospis Species: Aspects of their Value, Research and Development. CORD, University of Durham, Durham, UK; 1992.

56. Mishra A, Sharma SD, Khan GH. Improvement in physical and chemical properties of sodic soil by 3, 6, and 9 years old plantation of Eucalyptus tereticornis Bio rejuvenation of sodic soil. Forest Ecology Management. 2003;184:115124.

57. Jenkinson DS, Ladd JN. Microbial biomass in soil; Measurement and turnover. In: Soil Biochemistry (E. A. Paul and J. N. Ladd, eds). 1981:5:415-471. Dekker, New York.

58. Singh JS, Raghunath AS, Singh RS, Srivastava SC. Microbial biomass acts as a source of plant nutrient in dry tropical forest and savanna. Nature. 1989;338:499-500.

59. Yuan X, Lin X, Chu H, Yin R, Zhang H, Hu J, Zhu J. Effect of elevated atmospheric CO2 on soil enzyme activities at different nitrogen application treatments. Acta Ecologica Sinica. 2006;26:48-53.

60. Rietz DN, Haynes RJ. Effects of irrigation induced salinity and sodicity on soil microbial activity. Soil Biology & Biochemistry. 2003;35:845–854.

61. Batra L, Kumari A, Manna MC, Chhabra R. Microbiological and chemical amelioration
of alkaline soil by growing Karnal grass and gypsum application. Experimental Agriculture. 1997;33:389–397.

62. Tripathi S, Kumari S, Chakraborty A, Gupta A, Chakrabarti K, Bandypadhyay BK. Microbial biomass and its activities in salt-affected coastal soils. Soil Biology and Fertility of Soils. 2006;42:273-277.

63. Vitousek PM, Howarth RW. Nitrogen limitation on land and in the sea: How can it occur?. Biogeochemistry. 1991;13:87-115.

64. Watson AJ, Bakker DCE, Boyd PW, Ridgwell AJ, Law CS. Effect of iron supply on Southern Ocean CO2 uptake and implications for glacial atmospheric CO2. Nature. 2000;407:730–733.

65. Gruber N, Galloway JN. An Earth-system perspective of the global nitrogen cycle. Nature. 2008;451:293-296.

66. Lal R. Soil carbon sequestration impacts on global climate change and food security. Journal of Science. 2004;304:1623-1627.

67. Schlesinger WH. Biogeochemistry: An Analysis of Global Change. Academic Press. 1991;12: 443.

68. Palsaniya DR, Tewari RK, Singh R, Yadav RS, Dhyani SK. Farmer-agroforestry land use adoption interface in degraded agroecosystem of Bundelkhand region, India. Range Management and Agroforestry. 2010;31:11-19.

69. Harper RJ, Smettem KRJ, Tomlinson RJ. Using soil and climatic data to estimate the performance of trees, carbon sequestration and recharge potential at the catchment scale. Australian Journal of Experimental Agriculture. 2005;45:1389–1401.

70. Harper RJ, Beck AC, Ritson P, Hill MJ, Mitchell CD, Baret D, Smetter KRJ, Mann SS. The potential of greenhouse sink to underwrite improved land management. Ecological Engineering. 2007;29:329-341.

71. Mishra A, Sharma SD, Khan GH. Improvement in physical and chemical properties of sodic soil by 3, 6, and 9 years old plantation of Eucalyptus tereticornis Bio rejuvenation of sodic soil. Forest Ecology Management. 2003;184:115-124.

72. Harper RJ, Okom AEA, Stilwell AT, Tibbet M, Dean C, George SJ, Sochacki SJ, Mitchell CD, Mann SS, Dods K. Re-foresting degraded agricultural landscapes with Eucalypts: Effects on carbon storage and soil fertility after 26 years. Agriculture Ecosystems and Environment. 2012;163:3-13.

73. Schoeneberger M, Bentrup G, Gooijer de H, Soolanayakamahally R, Sauer T, Brandle J, Zhou X Current D. Branching out: Agroforestry as a climate change mitigation and adaptation for agriculture. Journal of Soil and water Conservation. 2012;67:128-136.

74. Verchot LV, Van Noordwijk M, Kandji S, Tomich T, Ong C, Albrecht A, Mackensen J, Bantilan C, Anumampa KV, Palm C. Climate change: Linking adaptation and mitigation through agroforestry. Mitigation and Adaptation Strategies for Global Change. 2007;12:901-918.

75. Schoeneberger MM. Agroforestry: Working tree for sequestering carbon on agricultural lands. Agroforestry Systems. 2009;75:27-37.

76. Kumar BM, PKR Nair (eds). Carbon Sequestration Potential of Agroforestry Systems: Opportunities and Challenges. 2011; Vol. 8: Advances in Agroforestry. New York: Springer; 2011.

77. Nair PKR. Methodological challenges in estimating carbon sequestration potential of agroforestry systems. In Carbon Sequestration Potential of Agroforestry Systems: Opportunities and Challenges. Vol. 8: Advances in Agroforestry. eds. B.M. Kumar and P.K.R. Nair. 2011;3-16. New York: Springer.

78. IPCC (Intergovernmental Panel on Climate Change). IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 4. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use. Prepared by the National Greenhouse Gas Inventories Programme, eds. Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K., Published: IGES, Japan; 2006. Available: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

79. Bergeron M, Lacombe S, Bradley RL, Whalen J, Cogliastro A, Jutras MF., Arp P. Reduced soil nutrient leaching following the establishment of tree-based intercropping systems in eastern Canada. Agroforestry Systems. 2011;83:321-330.

80. Eckard RJ, Grainger C, de Klein CAM. Options for the abatement of methane and nitrous oxide from ruminant production: A review. Livestock Science. 2010;130:47-56.
81. Olson RK, Schoeneberger MM, Schmann SGA. An ecological foundation for temperate agroforestry. In North American Agroforestry: An Integrated Science and Practice, eds. H.E. Garrett, W.J. Rietveld, and R.F. Fisher, 31-62. Madison, WI: American Society of Agronomy, Inc; 2000.

82. Jose S, Holzmueller EJ, Gillespie AR. Tree-crop interactions in temperate agroforestry. In North American Agroforestry: An Integrated Science and Practice. 2nd Ed., ed. H.E. Garrett, 57-73. Madison, WI: American Society of Agronomy, Inc; 2009.

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