Chapter 16
Climate Change, Carbon Sequestration, and Coconut-Based Ecosystems

P. K. Ramachandran Nair, B. Mohan Kumar, and S. Naresh Kumar

Abstract Climate change, a key global environmental issue of the day, refers to the gradual increase in temperature of the Earth's atmosphere. It is believed to be caused by the increase in atmospheric concentration of carbon dioxide and other greenhouse gases (GHGs). Concerned by the serious consequences of anthropogenic climate change, several global initiatives have been launched to address the issue. They fall under two broad categories, climate-change mitigation and adaptation, aimed at reducing GHG emissions and their negative impacts, respectively. Carbon sequestration, the prominent mitigation strategy, refers to capturing atmospheric carbon and securing it in long-lived pools, such as through photosynthesis by plants. Climate-smart agriculture is the rallying theme for adaptation strategies, which is a combination of site-specific management activities. Most climate-change mitigation and adaptation studies in agriculture so far have focused on annual crops, with little attention being paid to perennials such as coconut. Coconut-based ecosystems offer good possibilities for enhancing carbon sequestration through crop combinations involving a variety of plants including food crops, tubers, vines, and tree crops. For climate-change adaptation, the annual intercrops planted under coconuts could be managed for optimum benefits for the whole system. A holistic approach focusing on the overall productivity and sustainability of the whole system rather than the palm alone is needed to make the coconut-based agroecosystems resilient to climate change.

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K. U. K. Nampoothiri et al. (eds.), *The Coconut Palm*
*(*Cocos nucifera *L.) - Research and Development Perspectives*,
https://doi.org/10.1007/978-981-13-2754-4_16

16.1 Introduction

"Climate change" was probably unheard of a 100 years ago when coconut research was initiated in India. Although memorable climatic events such as floods and droughts may have been talked about, climate change may not have been thought of as an item of coconut research agenda. Today, climate change is a prime research agenda in all agricultural research endeavors including coconut research. After years of gridlock, a new United Nations' agreement on sustainable development bolstered the fight against environmental degradation, and nearly 200 countries signed a historic agreement on climate change. Thus, climate change and discussions and action plans surrounding it are happening in a big way.

Climate change, and the companion term global warming, refers primarily to a gradual increase in the average temperature of the Earth's atmosphere and its oceans, a change that is believed to be permanently changing the Earth's climate. Field investigations on the impacts of climate change on agricultural systems have mostly been limited to cereals and other short-duration species; such studies have not been extended in a significant manner to tree crops, in general, and to coconut in particular. Nevertheless, some projections can be made on the potential impact of climate change on coconut-based ecosystems, based on the current insights and understanding from other studies. The primary objectives of this chapter are to make some such projections and suggest some such strategies for minimizing the adverse effects.

It is important that the commonly used technical terms on the topic are explained and the causes, consequences, and strategies for climate-change mitigation and adaptation (M & A) are discussed in some detail at the outset. This chapter explains those details, presents the global spread of coconut-based ecosystems, briefly reviews the current state of knowledge on climate-change impacts and M & A strategies for agricultural systems, and makes some projections on climate-change scenarios for coconut-based ecosystems.

16.2 Climate Change: The Language, Extent, Causes, and Consequences

Some of the commonly used terms used in climate-change discussions are explained in this section. These details and explanations are compiled from various sources, the most significant being the Intergovernmental Panel on Climate Change (IPCC; www.ipcc.org). Additional reference sources include Simpson (2016) and FAO's (Food and Agricultural Organization; www.fao.org) Climate-Smart Agriculture (CSA) Sourcebook (http://www.fao.org/3/i3325e.pdf).

16.2.1 The Extent of Climate Change

The Earth continues to be warmer than it was several decades ago. According to NASA (the US National Aeronautical and Space Administration: https://www.nasa.gov/), all 10 warmest years in the 134-year documentation have all happened since 2000 (with the exemption of 1998); 2010 and 2005 ranked as the warmest years on record. The average global temperature has increased by about 0.8 °C (1.4 °F) since 1880 and 0.6 °C (1.0 °F) since 1970 as per the January 2014 assessment of NASA's Goddard Institute for Space Studies (GISS). The IPCC has projected that mean global temperatures could escalate between 1.4 and 5.8 °C by the year 2100. Studies conducted in India indicate that in the past 100 years, annual mean maximum temperatures over India increased by about 0.71 °C (INCCA 2010). Similarly, the minimum temperature has been rising at a rate of 0.29 °C/10 years. During 1871–2017 period, India faced 29 deficit and 20 excess monsoon years. Among these, as many as 17 deficit monsoon years and 6 excess monsoon years occurred in the post-1960 period.

It is worthwhile in this context to point out the difference between variability and change. *Variability* in weather is the difference between anything that occurs normally and that actually occurs. Variations can be observed between various time periods such as days, weeks, months, and years. *Change* is the trend in average conditions (of temperature, rainfall quantity and pattern, wind parameters, etc.) in one direction or another. Variability does not necessarily bring about increase or decrease from mean over a period of time; but change does.

16.2.2 Causes of Climate Change: Greenhouse Gases

Climate change (global warming) is thought to be caused by the rise in atmospheric concentration of greenhouse gases (GHGs). The key GHGs are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Among these, CO_2 is the major and most common one, but other gases are more powerful: methane is 25 times and N_2O nearly 298 times more potent than CO_2 (IPCC 2014). These are called GHGs because of their effect in the atmosphere, where they intercept the outgoing long-wave radiation from the Earth's surface. Solar energy (short-wave radiation) is absorbed by Earth's objects and reradiated back as long-wave radiation (heat). Trapping of GHGs in the atmosphere prevents the long-wave radiation escaping from the Earth back into space, in a manner analogous to the glass ceiling of a greenhouse that permits sunlight to pass in but traps the sun's heat within.

Atmospheric concentration of CO_2 has augmented from the preindustrial concentration of about 280 ppm to the current level of approximately 400 ppm, increasing at an average of 2 ppm per year (Fig. 16.1). This increase is thought to be caused by human activities, including burning of fossil fuels (about 60% of total) such as coal, gas, and oil for industrial and other purposes; agriculture, forestry, and other

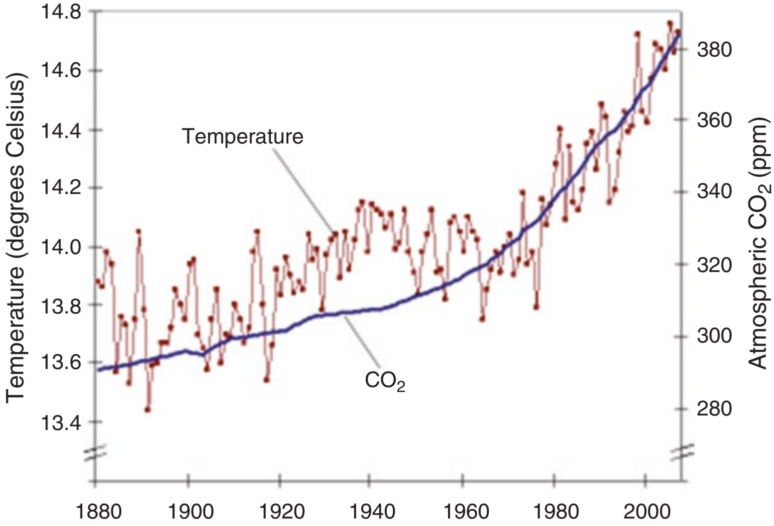

Fig. 16.1 Average global temperature and atmospheric carbon dioxide concentrations, 1880–2007. (Source: NASA GISS and NOAA/ESRL (USA))

land-use activities (AFOLU) including deforestation (approximately 24%); and transportation (about 14%). The full effect of warming is likely to continue into the foreseeable future as long as emission of GHGs continues unabated. Therefore, it is important to reduce GHG emission levels.

Climate-change "deniers" argue that the Earth's climate has always been changing; however, correlation is not the same as causation, i.e., although there is a correlation between increases in GHG concentration and atmospheric temperature, no direct cause-effect relationship has been established between the two, and that global temperature, in spite of its variability between years, has increased only by a mean of less than 1 °C in the past 130 years. The climate-change deniers also argue that most of the climate-change predictions are built on flawed computer models, and the so-called global consensus on climate change is generated more by political and executive pressures and coercion rather than solid scientific data. But the vast majority of the world and public opinion as well as scientific consensus are moving with the conviction that climate change is a real global issue and it needs to be addressed with deserving seriousness.

16.2.3 Impacts of Climate Change

Listed below are the key potential consequences of global temperature increase (climate change):

1. *Rainfall patterns*: Air temperature increase leads to increased evaporation of moisture (water) from soil and water bodies (rivers, lakes, and oceans). Moreover, warmer air holds more moisture than cooler air. Together, these cause more water to move through the global climate system leading to extra rainfall. The surge in rainfall, however, will be distributed unevenly: Less in drier areas and more in wetter areas. The total quantity of rainfall, its distribution, and the pattern (onset of rainy and dry seasons) will be unpredictable. All these effects are now of common occurrence throughout the world.
2. *Sea-level rise*: Similar to the phenomenon of warmer air holding more moisture, the volume of water expands with increase in temperature, leading to rise in sea levels. Ocean levels have levitated 20 cm over the past century, and higher levels of sea-level rises in the future are predicted. About a seventh of the world's human population live within about 10 m of sea level.
3. *Melting of glaciers and permafrost*: Increase in air and ocean temperatures causes melting of glaciers and ice caps, leading to further sea-level rise. As the temperature rises and permafrost melts, bacterial activity will increase leading to faster decomposition of organic matter and release of CO_2 and methane caught in a frozen condition in the Arctic Ocean floor.
4. *Inundation of low-lying islands*: Addition of large volumes of water to world's oceans will lead to inundation of low-lying islands (as has happened may 2016 in Solomon Islands in the Pacific Ocean: http://www.scientificamerican.com/article/sea-level-rise-swallows-5-whole-pacific-islands/).
5. *Ocean currents and El Niño/La Niña*: When ocean surface becomes much warmer than normal, an El Niño is said to occur; a La Niña happens when the reverse situation occurs resulting in lowering of sea surface temperatures. During an El Niño episode (as in 2014–2015), heavy rains and strong tropical storms may occur in some faraway areas and drought in others.
6. *Indirect effects*: These include effects on pollinators, pests and diseases, weeds and invasive species, and other ecosystem and environmental services.

16.2.4 Carbon Sequestration

Carbon sequestration is the important strategy for reducing atmospheric concentrations of GHGs, especially $CO_{2,}$ and thereby global warming. The United Nations Framework Convention on Climate Change describes it "as the process of removing carbon (C) from the atmosphere and depositing it in a reservoir, or the transfer of atmospheric CO_2 to secure storage in long-lived pools" (UNFCCC 2007). Plants of all types, especially trees, and soil are important in C sequestration. Plants take up atmospheric C for photosynthesis and store the product of photosynthesis in plant parts. The soil is a major C sink; globally, soil to 1 m depth is estimated to contain 2300 Pg (1 petagram = 10^{15} g = 1 billion ton) consisting of 1550 Pg as soil organic C (SOC) and 750 Pg as inorganic C. This total soil C pool is threefold higher than the atmospheric pool (770 Pg) and 3.8 fold higher than the vegetation pool of 610 Pg.

16.2.5 Climate-Change Mitigation and Adaptation

Mitigation signifies the technological change and substitution that decrease GHG emissions through avoiding emissions and sequestering GHGs. Mitigation strategies include:

- Avoiding or reducing the emissions through increasing input-use efficiency by adopting sound management of nutrients and water and decreasing losses through appropriate soil and water conservation strategies.
- Sequestering CO_2 in terrestrial biosphere such as in biomass aboveground and belowground and soil C pools.

Adaptation refers to initiatives and actions to decrease the susceptibility of natural systems to climate change, by developing strategies to reduce the adverse consequences. These include:

- Enhancing soil resilience (augmenting SOC pool, restoring degraded lands).
- Adopting efficient land-use practices such as agroforestry and conservation agriculture.

16.3 Coconut-Based Ecosystems

Climate-change-related discussions pertaining to specific ecosystems or regions need to be contextualized because many of the manifestations of climate change and strategies for coping with them have to be specific according to the characteristics of the system and region in consideration. With that in view, it is important to review briefly the overall global distribution and management of coconut ecosystems.

16.3.1 Characteristics and Distribution

The coconut palm (*Cocos nucifera* L.), the most widely cultivated of all palms and one of the earliest among domesticated plants, has been described with various adulations and accolades, indicating the usefulness of its various parts and products. The palm has been and still is an intimate part of the bio-cultural legacy and economic well-being of the populations of its principal growing regions. As Purseglove (1972) states, coconut's uses are legion; every part of the palm is useful to man in one way or another.

Coconut is presently grown in over 93 countries (FAO 2018). The area under coconuts is difficult to estimate accurately because of the lack of standardized procedures for estimating areas when the species grows both naturally in scattered stands at varying densities and is planted and nurtured as a crop either alone (Fig. 16.2) or in combination with various other species (Fig. 16.3). This situation also raises doubts about the accuracy of repeatedly used area statistics. Equally unsatisfactory is the situation about its production statistics because a major share of the production is consumed locally in the households without the products entering any form of marketing channels. Nevertheless, statistics on area and production have traditionally been compiled by local, regional, national, and international agencies; the most widely cited and supposedly authentic are the FAO statistics (http://faostat.fao.org). Coconuts are common in countries of the tropical regions especially in coastal areas of Africa and the LAC (Latin America and the Caribbean), mostly in natural stands but also substantially in planted and managed stands. The vast majority of such planted and managed stands of the palm are in smallholder

Fig. 16.2 Sole stand of coconuts. Photograph of a sole stand of about 40-year-old coconut palms at the Coconut Research Institute, Lunuwila, Sri Lanka, 7.5 m × 7.5 m spacing, 175 palms per hectare, showing the high level of light (solar radiation) availability and low shading on the plantation floor, indicating the opportunities for intercropping. (Photo: P. K. R. Nair 1984)

Fig. 16.3 An intensively managed multi-species crop combination with coconuts at ICAR-Central Plantation Crops Research Institute in Kasaragod, India. The species other than the coconut palm include: Banana (*Musa* sp.), Black pepper (*Piper nigrum*), Pine apple (*Ananas comosus*), and nutmeg (*Myristica fragrans*). (Photo: M.A.Nair)

farms of less than 5 ha; the farms in Asia, the main coconut-growing region of the world, are much smaller.

16.3.2 Common Land-Use Features of Coconut-Based Ecosystems

Being a mono-stemmed woody perennial with no cambium, the principal stem (trunk) of the palm does not grow radially with age. In an even-aged (planted) stand of palms, this characteristic growth form permits substantial light infiltration into the understory, as the palm increases in height with age (Fig. 16.2). It is quite common to see younger coconut palms and a variety of shade-tolerant other species growing under tall (older) palms. Thus, smallholder farms of coconut that predominate the coconut areas comprise mostly of palms together with an array of other species of all types: herbs, shrubs, vines, and trees (Fig. 16.3). These multi-species, smallholder production systems, managed as family-farm enterprises, have been acclaimed as “an agroecological marvel” (Nair 2017). While the area estimates of coconut ecosystems are likely to be inaccurate as explained above, they could even be more inaccurate for intercropping systems involving coconuts. Exceptions to this general rule of smallholder farms are found in commercial holdings, as in large "coconut estates" that were developed in the Pacific islands by the European settlers during the twentieth century and a large number of smallholder plantations established later in those areas by local farmers (Bonnemaison 1996). In such situations, uniformity in spacing, mostly 7.5 m square (Fig. 16.2), and even-aged palms (with about 180 palms per ha) are the norm.

Intercropping under or between coconuts with a variety of other useful species is a common practice in most coconut-growing regions of the world. Nair (1979) has articulated the chronological sequence of the growth of coconut palms in Kerala (India) and the potential for growing a wide spectrum of intercrops at various growth stages of the palm. Reports on intercropping and the array of crops grown in different countries and regions abound. "The species so intercropped consist of food crops including roots and tubers, fruit trees, tree-plantation crops, medicinal plants, multipurpose trees, and others that provide multiple products such as food, fuel, fodder, timber, medicine, and such other basic necessities, and help meet the cash requirements of the growers" (Kumar 2007; Lamanda et al. 2006). Such integrated farming systems are generally characterized by higher productivity, better returns, and improved social functionality than many commercial farming systems (Tipraqsa et al. 2007).

16.3.3 Growth Habits of Coconut Palm in Relation to Multispecies Systems

The amenability of coconut stands for intercropping depends primarily on the growth stages of the palm. Based on the amount of light transmitted through coconut canopy during the palm's growth stages, Nelliat et al. (1974) divided the life span of the palm into three distinct phases from the perspective of intercropping in a sole stand of palms (see Chap. 7 for details).

Managed multi-species, multi-strata systems with the coconut palm and a wide variety of other economically useful plants are now quite common on the west coast of India (Fig. 16.3). The central hypothesis underlying the functioning of such agroecological marvels (Nair 2017) is the "niche complementarity hypothesis" (Harper 1977). It implies that "a larger array of species in a system leads to a broader spectrum of resource utilization making the system more productive and leads to better and more efficient use and sharing of resources." Some farmers, however, are apprehensive of the effect of competition for growth factors such as light, water, and nutrients between coconuts and associated plants. A compilation of the available reports, nonetheless, indicates that intercropping trees in the interspaces does not exert strong negative effects on the yield of coconut palms unless such trees grow taller and reduce light availability to coconut crown (Kumar 2007).

16.3.4 Integrated Animal and Fish Production Systems with Coconuts

Apart from the multi-species, multi-strata tree, shrub, and field crop systems, the generic coconut-based integrated farming popular in the Asian courtiers also involves animals such as cow, goat, poultry, duck, rabbit, pig, and aquaculture (production of shrimp, fish, prawn, etc.). Historically, considerable attention has been given to the integration of cattle with coconut, especially with the traditional Tall variety of palm in Southeast Asia and the Pacific (Plucknett 1979; Devendra and Thomas 2002). Reviewing the constraints to farmers' attitude to the acceptance of this traditional practice, Mack (1991) and UNESCO (1979) reported that grazing livestock in coconut stands also necessitates the agriculturalist to learn animal husbandry and pasture management techniques, which could sometimes dissuade farmers from adopting the practice.

16.3.5 Ecosystem Services of Coconut-Based Systems

Multi-strata, multi-species coconut ecosystems offer a variety of ecosystem services such as provisioning, regulating, supporting, and cultural functions as described by the UN Millennium Ecosystem Assessment Report (MEA 2005). In addition to the production of fruits, nuts, vegetables, spices, and medicinal plants (provisioning services), improvements in soil organic matter status and moisture holding capacity and consequential yield increases have been demonstrated (Kumar 2007). For example, soil moisture retention was better in the cacao + coconut systems than in the cacao + *Gliricidia sepium* system (Osei-Bonsu et al. 2002). Furthermore, global warming and the resultant accelerated soil organic matter oxidation could accelerate degradation of the nutrient-poor tropical soils; however, such problems are less likely to manifest in multi-strata production systems than in sole stands of coconuts.

Thus, coconut-based ecosystems around the world consist, in general, of predominantly small-to-medium-holder farm enterprises involving not only coconuts but a variety of other crops and trees grown in intimate associations and managed at various levels of intensity for multiple products and services. These systems are ecologically and structurally complex and economically and socially rather unique in terms of their history, structure, function, dynamics, outputs, and societal values and importance. As such, they present an interesting subject for climate-change mitigation and adaptation studies.

16.4 Climate-Change Mitigation and Adaptation Strategies for Coconut-Based Ecosystems

Consequent to the emergence of climate change as a major environmental issue on the global agenda about 20 years ago, numerous studies, reports, and action plans have emerged at all levels.

16.4.1 Impacts of Climatic Stresses and Projected Climate Change on Coconut Plantations

Coconut, being a perennial crop, lives through the climate change and may face several climatic stresses during its life span of 60–70 years. Although the effects of mean change in temperatures are difficult to predict, the consequences of extreme events on coconut palm have been demonstrated in a few studies. For example, Rajagopal et al. (1996) reported that coinciding dry spells with sensitive stages of inflorescence development such as primordial initiation, ovary development, and button-size nut stages will cause severe loss to coconut yield. Changes in temperature affect coconut yield mainly through the effect on phenological development process (Chmielewski and Rötzer 2001). In a cross-pollinated crop such as coconut, climate variability might influence phenology and peak flowering time. This is because the palm is susceptible to climatological changes throughout the period from primordium initiation to maturity of nuts (approximately 44 months). Consistent with this, Rajagopal et al. (1996) noted that under rain-fed farming situations, nut production was significantly affected by the duration of dry spells at sensitive phases and the dry spells during primordium and ovary development stages were particularly crucial.

Furthermore, such effects may manifest over the long term, given the long reproductive phase of the palm. For instance, drought affected coconut yield for the succeeding 4 years (Naresh Kumar et al. 2007). Consecutive drought years caused not only severe yield reduction but also left about 200,000 palms dead in Coimbatore district of Tamil Nadu and Tumkur district of Karnataka, India; productivity loss was approximately 3500 nuts ha^{-1} $year^{-1}$ (Naresh Kumar 2010). Likewise, the cyclone of 1995 reduced productivity by ~4100 nuts ha^{-1} $year^{-1}$ in Andhra Pradesh state of India (Naresh Kumar et al. 2008).

Naresh Kumar et al. (2008) developed a process-based simulation model for climate-change impact assessments for coconut in India, originally called “InfoCrop-coconut,” now named “CoCoSim.” It takes weather, soil, management, and varietal characteristics into account to simulate the growth and yield of coconut. Results of such simulation studies indicate that climate-change impacts on coconut yield in India will have considerable spatial variations (Naresh Kumar and Aggrawal 2013). According to these projections, coconut productivity may improve in the western coastal zone (consisting of Kerala, parts of Tamil Nadu, Karnataka, and Maharashtra), northeastern states, islands of Andaman and Nicobar, and Lakshadweep, if present levels of water and crop management are maintained. On the flip side, nut yield is predicted to diminish in Andhra Pradesh, Odisha, West Bengal, Gujarat, and parts of Karnataka and Tamil Nadu owing to climate change. Krishnakumar (2011), however, reported that productivity of a perennial crop like coconut would be more susceptible to climatic variability (e.g., summer droughts) rather than climate change, viz., rising temperature and declining rainfall. Nevertheless, such impact assessments may help adapt plantation crop management to climate change and maximize positive impacts while minimizing the negative impacts.

16.4.2 Mitigation and Adaptation Strategies

As far as the agricultural and other land-use issues pertaining to climate change are concerned, the most significant issues on which efforts are focused on are climate-change mitigation and adaptation (M & A). As explained earlier, mitigation refers to technological transformation and substitution that reduce GHG emissions through avoiding emissions and sequestering GHGs, whereas adaptation refers to “initiatives and measures to reduce the vulnerability of natural systems against climate change,” by developing strategies to reduce the negative impacts. Although mitigation and adaptation are different concepts, the terms and action plans surrounding them are so related and intertwined that the terms are usually used together as M & A and sometimes synonymously for one another. Several strategies have been suggested for addressing the two issues individually as well as together, and the most prominent “rallying themes” are carbon sequestration for mitigation and “climate-smart agriculture (CSA)” for adaptation. These are discussed in detail here in relation to coconut-based ecosystems.

16.4.2.1 Carbon Sequestration

To reiterate, the fundamental concept of carbon sequestration in relation to land-use systems is that plants capture or absorb CO_2 from the atmosphere for photosynthesis and store the products of photosynthesis in their different parts. Depending on the nature of utilization of these parts (products), the C so stored may be retained in “long-lived” pools such as stem (timber). When plant parts fall to the ground either through natural processes such as leaf (and litter) fall or through management operations such as residue incorporation, mulching, and green manuring, they decompose, and some or most of the carbon could be “lost” back to the atmosphere, with a relatively small part becoming a part of soil organic matter (SOM).

General Situation in Land-Use systems Following the realization of the importance of C sequestration as a climate-change mitigation strategy, there has been a veritable explosion of such studies in land-use systems of all types. Numerous reports are available on C sequestration potential of various land-use systems, including tree-based systems, from different parts of the world. For example, extensive estimates of global forest biomass have been prepared, mostly as the product of estimated stem-wood volume and species-specific wood density and other "correction factors"—to calculate whole-tree biomass. Carbon content is taken as 50% of the whole-tree biomass, and the belowground components are generally ignored in such estimations. Although whole-tree harvesting, followed by determining the component weights and summing up the amount of harvested and standing biomass, has traditionally been used for obtaining more precise estimates of tree biomass stocks, the cumbersome nature of the method restricts its application to experimental studies only.

Allometric equations constitute yet another widely used method in forestry for estimating volumes of standing forests. It is based on biophysical attributes of trees and validated by measurements of destructive sampling occasionally. These are developed as regression equations linking easily measurable parameters such as tree diameter at breast height, total height or commercial bole height, and occasionally wood density as the independent variables and total dry weight as the dependent variable.

Based on such extensive studies reported from different forest- and other tree-based systems, it is well accepted that tree-based systems such as forestry and agroforestry have greater potential to sequester C compared to single-species crop or pasture systems (Nair et al. 2009, 2010). Primarily, this assumption and calculations are based on the higher amounts of aboveground biomass (and therefore carbon) stored in these systems, even if only a (small) part of such stored C could be considered as C stored in secure long-lived pools (which, by definition, is sequestered C). The estimates of C stocks in agroforestry systems (AFS) varied from 0.29 to 15.21 Mg ha^{-1} year.$^{-1}$ aboveground and 30–300 Mg C ha^{-1} for the top 1 m layer of the soil profile (Nair et al. 2010). Recent studies involving diverse AFS under varied ecological conditions also corroborate the fact that tree-based systems, compared to treeless systems, have higher soil C stocks especially in the deeper soil layers at close proximity to the tree than farther away from it, and species richness and tree density are major determinants of soil organic C content. Besides, C3 plants (trees) contributed more C in the silt + clay fractions of soil that represents the more stable C than C4 plants, in deeper soil profiles (Nair 2012a). However, environmental conditions and system management are two predisposing factors that determine the amount of C sequestered in AFS depends.

Carbon Sequestration Potential of Coconut-Based Ecosystems Reports on carbon sequestration potential of coconut palms and coconut-based ecosystems are, in general, scanty and superficial. Some reports suggest that tree plantation crops represent remarkable carbon pools based on the conjecture that trees retain much more carbon per unit land area than other categories of vegetation and coconut has great potential as a carbon sink (Ranasinghe and Silva 2007). Many of these reports, however, are too general in nature and not based on scientifically rigorous investigations. Indeed, detailed studies on the NPP (net primary productivity) of coconut palms and coconut-based ecosystems are rare. In one of the early reports on this subject, Nelliat et al. (1974) estimated the total annual biomass production of a sole stand of coconuts with 175 adult palms (in full bearing stage) to be in the range of 14.2 Mg ha^{-1} for an annual average production level of 60 coconuts per palm, 18.7 Mg ha^{-1} for 100 nuts per palm, and up to 35.5 Mg ha^{-1} for the very high production level of 250 nuts. These estimates appear to be too simplistic given that the differences in values among the three production levels are attributed solely to the nuts, the biomass production by other plant parts such as leaves, stem, and roots being assumed to be the same across all production levels, which is a questionable assumption. Navarro et al. (2008) reported that under optimal crop nutrition in a high fertility site without any drought problems, the total NPP of coconut + grass understory was 32 Mg ha^{-1} year.$^{-1}$. Simulation studies (Naresh Kumar et al. 2008) indicated a total dry matter production potential in the range of 52–62 Mg ha^{-1} $year^{-1}$, which was close to the potential dry matter production of coconut monocrop (51 Mg ha^{-1} $year^{-1}$) reported by Corley (1983).

Navarro et al. (2008) from published values of NPP deduced that coconut plantations exhibit high productivity typical of the tropical humid evergreen forest ecosystems. Nevertheless, biomass C stocks were lesser than for forests, because a major share of C allocation was reportedly going into labile or easily decomposable components such as fruits (nuts), leaves, peduncles, and fine roots. Moreover, many of these parts such as fruits and leaves, being economically useful, are removed from the farm so that their contribution to soil organic matter pool and soil carbon sequestration may not be substantial compared to that of stands of other trees. Kumar and Takeuchi (2009) and Kumar (2011) estimated the aboveground C stock of mixed tree species (>20 cm girth) in 839 homegardens of southwestern coast of India to be in the range of 16.3–35.2 (mean 24.3) Mg ha^{-1}; these included coconuts and a number of fruit trees, both of varying stand densities. Carbon storage by coconut palms in mixed stands will, understandably, be considerably higher than in sole stands of coconuts, especially when the mixed species are trees (e.g, compare Figs. 16.2 and 16.3).

Saha et al. (2010) reported one of the rare studies on soil carbon sequestration in coconut stands compared with other common land-use systems such as homegardens, natural forests, rubber (*Hevea brasiliensis*) plantation, and an agricultural field (rice paddy) in the humid lowlands of Thrissur district of Kerala, India (10°0′–10°47’ N latitude and 75°55′–76°54′E longitude; 2780 mm rainfall per year; soils: inceptisols). On the whole, SOC content up to 1 m depth decreased in the order forest > HGS = rubber ≥ HGL ≥ coconut > rice paddy (Fig. 16.4) [HGS and HGL refer to small and large homegardens, with the former less than 0.4 ha area and the latter more than 0.4 ha but usually less than 1.0 ha; both stands include intimate association of several types of plants including fruit trees, around the homestead; HGS has a higher density of plants than the HGL]. Comparing the SOC stock at different soil depth classes, forest had the highest stock of SOC and the rice paddy

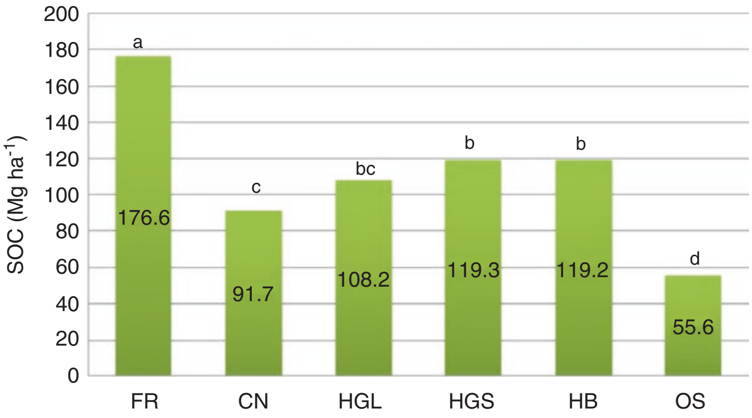

Fig. 16.4 Stock of soil organic carbon (SOC) down to 1 m depth six land-use systems in Madakkathara *Panchayat*, Thrissur, Kerala, India. The land-use systems are forest, FR; coconut grove, CN; large homegarden (> 0.40 ha in area), HGL; small homegarden (<0.4 ha in area), HGS; rubber plantation, HB; and rice paddy field (OS). The lowercased letters indicate differences ($p = 0.05$) in SOC among the systems to 1 m soil depth. (Source: Saha et al. (2010); reproduced with authors' permission)

the lowest among land-use systems at all depth classes, and tree-based systems (coconuts, rubber, and the homegardens) came in between the forest land and rice paddy fields (Fig. 16.5). Another aspect of this study examined soil carbon content in different soil fraction-size classes to assess the relative long-term nature of the sequestered carbon. It showed that coconuts and rice paddy, compared with forests and homegardens, had lower amounts of "recalcitrant" C, i.e., C that is strongly held (= sequestered) in the lower soil layers up to 1 meter depth. This suggests that soil carbon sequestration under coconut stands was relatively less compared with that of other tree-dominant systems such as forests, homegardens, and rubber plantation. It shows that in sole stands of coconuts, soil carbon sequestration, the predominant form of carbon sequestered in ecosystems, could be substantially lower than in mixed stands of coconuts especially when coconuts are combined with other tree species such as fruit trees and cacao. This ecological benefit of multi-species and multistoried crop combinations with coconuts is not adequately studied and, naturally, not appreciated.

It is also worth stating in this context that, in general, estimates of C sequestration in ecosystems are based on several assumptions such that the reported values may be lacking in scientific rigor and quality (Nair 2012b). For example, there is profound ambiguity in the perception of this concept of C sequestration when it comes to "long-lived" C pools. Most reports equate C stock to C sequestration, whereas sequestration refers to loading in "long-lived" pools. Furthermore, C content of plant biomass is 42–44%, whereas most calculations take it as 50% for the sake of convenience. The general assumption that all C in soil denotes sequestered C is also incorrect. Fresh C additions to the soil surface through litterfall and exog-

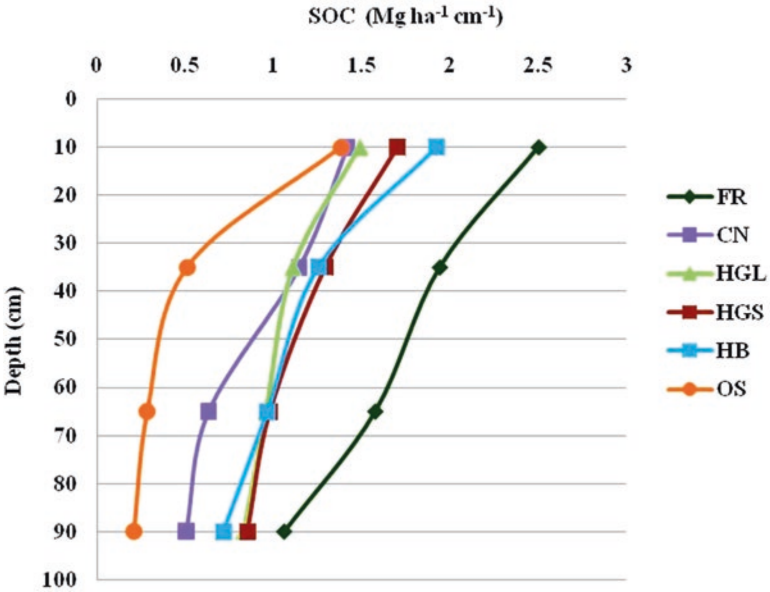

Fig. 16.5 Mean soil organic carbon (SOC) content at different soil depths under six land-use systems in Madakkathara *Panchayat*, Thrissur, Kerala, India. The land-use systems are forest, FR; coconut grove, CN; large homegarden (> 0.40 ha in area), HGL; small homegarden (<0.4 ha in area), HGS; rubber plantation, HB; and rice paddy field (OS). (Source: Saha et al. (2010); reproduced with authors' permission)

enous additions may undergo quick decomposition and release of CO_2, with only a small proportion of C entering the stable "long-lived" pools. If C stocks are augmented through time, that represents C sequestration. Yet another issue is that, in general, roots are believed to represent one-third of the total NPP. However, it is very difficult to measure this fraction, and it may not be true in the case of palms such as coconuts with high proportion of coarse roots than fine roots. Nair and Nair (2014) argue that the high degree of variability and lack of rigor in the reported results of available reports on C sequestration in agroforestry systems limit their potential use for arriving at widely applicable land-management decisions and recommendations.

16.4.2.2 Climate-Smart Agriculture

CSA is a collective rallying theme for various climate-change adaptation strategies. The concept was forged together by FAO in collaboration with a large number of organizations. It is not a solitary farming technology or practice that can be universally applied but is an approach that entails location-specific appraisals to recognize suitable agricultural production technologies and practices. It is comprised of three key objectives: "sustainably increasing agricultural productivity and incomes, adapting and building resilience to climate change, and reducing and/or removing greenhouse gas emissions, where appropriate" (FAO 2013).

The strategies for adaptation to climate change, obviously, are very situation-specific. Jat et al. (2016) discussed crop management technologies in relation to climate-change adaptation focusing on many agronomic management issues including conservation agriculture, pest management, climate-resilient genotypes, early climate warning systems, and crop insurance, all in terms of short-duration agronomic crops. Though the much-referenced FAO-CSA Sourcebook (FAO 2013) also describes similar climate-change adaptation strategies, there is only very limited information presented in the "module" on forestry.

Simulation analysis (Naresh Kumar and Aggrawal 2013) indicates that agronomic management such as soil and water conservation, summer irrigation, drip irrigation, and fertilizer addition can minimize the negative effects of climate change on coconut palms. These will also help to maximize any positive impacts of climate change (e.g., resulting from carbon nutrition) on nut yield. Consistent with this, low-cost practices such as mulching the palm basins with husk/plant detritus, application of composted coir pith, and husk burial have been recommended to conserve soil moisture in palm basins (Naresh Kumar et al. 2006). Drip irrigation was found to save the drought-affected gardens in Tamil Nadu, India, during the consecutive drought years of 1998–2002 (Subramanian et al. 2012). Along with drip irrigation and soil moisture conservation, fertigation will improve the water and nutrient use efficiency in coconut plantations. In addition to the agronomic management, adoption of improved and stress-tolerant hybrids is essential to improve coconut productivity in climatically vulnerable areas.

16.5 Future Directions: Climate-Change M & A and the Coconut-Based Ecosystems

Although climate change is now almost universally accepted as a reality, the existence of a strong and powerful group of "climate-change deniers" should not be ignored. But it cannot be denied that the world has been experiencing substantial climate variability lately even if that may not translate into significant changes when expressed as averages over longer periods of time such as decades. These inter- and intra-seasonal climate variations could have enormous impacts on agricultural production within a season as well as across seasons.

Research on coconuts and other tree crops are modelled for sole stands of species along the same lines as for short-duration agricultural crops. This is inappropriate for crops like coconuts, which exist in natural stands in association with a number of other species in many places. Accurate area estimate is essential for designing any regional management strategy such as climate-change M & A. The production statistics of coconuts are also of doubtful accuracy, which presents a problem in terms of calculating biomass and, therefore, carbon sequestration potential of such systems. These gaps and deficiencies in data gathering and reporting related to coconuts and coconut-based ecosystems will have to be rectified since they have a bearing on the appropriateness of climate-change M & A strategies.

As far as climate-change mitigation is concerned, enhancement of carbon sequestration in the ecosystem is well accepted as a viable strategy. Although some reports suggest that the coconut palm has "high" C sequestration potential, our analysis based on the growth habits of the coconut palm and the pattern of utilization of its products indicates that the palm by itself cannot be rated as a species of high C sequestration potential. On the other hand, "carbon farming" (Toensmeier 2016) through multi-species combinations with coconuts consisting of a variety of annual and perennial species offers tremendous opportunities for enhancing C sequestration in coconut-based ecosystems. This is a satisfactory situation in terms of climate-change mitigation given that such crop combinations are the order of the day in most coconut-based ecosystems. Considering the other ecological benefits of mixed species communities such as biodiversity and ecosystem sustainability, and above all possible economic gains, additional efforts in carbon farming present a "win-win" strategy for coconut-based ecosystems.

Adjusting the dates of planting and harvesting and such other management strategies as a strategy for climate-change adaptation are just not feasible for long-term crops like coconuts. What is feasible, though, would be to capitalize on the climate-change adaptation strategies for the annual crops that are interplanted with coconut. Crop substitutions of even perennial crops grown in association with coconuts could also be thought of as a strategy. For example, if coffee planted with coconuts is seen to be suffering under climate-change-induced higher temperature, it could be substituted by cacao that has better adaptability to higher temperatures than coffee, especially when replanting of old coffee bushes is on the management plan. The response of coconut palm itself to vagaries of climate in terms of various physiological processes and susceptibility to pest and disease incidence needs to be monitored and factored into the strategies.

Carbon substitution projects such as coconut biodiesel initiatives are also being discussed in the context of climate-change mitigation strategies. Coconut oil is used as a feedstock for biodiesel production in some countries such as the Philippines and the South Pacific. But research results on such seemingly novel initiatives are still too scanty that it is too early to include such experimental approaches.

Large-scale effects of climate change such as is sea-level rise will, naturally, have serious adverse impacts on the coconut palm that is traditionally adapted to coastal areas. Total submersion and disappearance of islands as has happened in May 2016 in Solomon Islands are catastrophic events for coping for which no local, short-term, climate-change adaptation strategies are available.

In conclusion, the best strategy for climate-change mitigation and adaptation in coconut-based ecosystems in the immediate future seems to be one of promoting multi-species combinations with coconuts by planting other species under or between coconuts. In order to implement such a strategy, a holistic outlook on coconut-based ecosystem is needed by all concerned: researchers, research administrators, and policy planners at all levels. The emphasis on looking at and planning solely for the coconut palm has to be replaced by one that considers coconut palm as a central component of an ecosystem. Research programs and policies need to be formulated with such a holistic ecosystem concept rather than for just one component of the system.

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