Short-Rotation Forestry: Implications for Carbon Sequestration in Mitigating Climate Change

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Abstract

The unceasing loss of natural forest ecosystems and pressure on limited biomass production for fuel and timber has led to a search for a new platform. During the past few decades, plantation forestry has expanded around the world to meet the demands of biomass production, especially for energy consumption, with the aim to replace fossil fuels. In this context, short-rotation forestry (SRF; or fast-growing tree plantations) has played a major role due to its rapid growth. The potential of forest ecosystems to mitigate climate change has been the focus of many international organizations. However, to adapt and mitigate climate change, the potentialities of SRF need to be addressed: the majority of SRF is used for energy production, thereby releasing carbon dioxide (CO_2) to the atmosphere; thus, the conversion into durable products is urgently required. The carbon sequestration (C_{seq}) potential of different short-rotation plantations around the world has been assessed by different researchers to be 1.3–8.0 Mg C/ha/year. Similarly, studies have observed that carbon content in the soil tends to change with the establishment of SRF; most of the studies showed a declining trend of soil organic carbon, with a maximum of 20% in the initial years and followed by improvement of soil carbon up to 57%. However, the impacts of SRF on soil sustainability and biodiversity are another limitation on the acceptability of SRF in terms of its long-term sustainability. The proper management and implementation of policy incentives to maximize the importance of carbon credits could increase the sustainability of SRF and be considered as a future approach to mitigate climate change. Other afforestation and reforestation activities on wasteland, unproductive arable land, and agroforestry could also widen the scope of SRF to curb such climate change issues.

Keywords

Short-rotation forestry · Carbon sequestration · Climate change

Abbreviations

C	Carbon
CDM	Clean development mechanism
CO_2	Carbon dioxide
C_{seq}	Carbon sequestration
GHG	Greenhouse gas
MAI	Mean annual increment
SOC	Soil organic carbon
SRF	Short-rotation forestry
SRP	Short-rotation plantation

1 Introduction

In short-rotation forestry (SRF), fast-growing forest tree species are cultivated at a high density, with the aim of producing high biomass and growth within the shortest possible time span. SRF has been defined as the growth of high-density, fast-growing tree species plantations with the primary objective of producing high woody biomass (Christersson 2005). The tree species grown in SRF attain an exploitable diameter within 5–15 years (short rotation), whereas conventional tree species reach this diameter after 60 years or more (Hanson 1991). Fast-growing tree species produce a mean annual increment (MAI) of at least 15 m^3 per ha per year or attain a height increment of at least 60 cm per year (Dwivedi 1993; Cossalter and Pye-Smith 2003).

SRF aims to overcome the escalating industrial demands of commercially important wood species in the pulp, paper, furniture, and transportation sectors, among others, as quickly as possible. Biomass is the fourth largest energy source in world and contributes 14% of the energy to the total energy sector (Rockwood et al. 2004). In industrialized countries, 3% of the total energy consumed comes from fuel wood (Hall et al. 1999); in developing countries, 86% of the total wood consumed is used for fuel (WEC 1999). Nowadays, many countries are facing shortages of wood and wood-based resources because of the severe deforestation that occurred with the advent of industrialization, human development, and ever-increasing human populations (Jhariya and Yadav 2018). A major challenge for most developing countries is the shortage of fuel wood, whereas woody raw material for forest-based industries is a major concern in developed countries. Therefore, industrialized countries have started using modern biomass energy systems; however, in developing countries with very low incomes, people still have to depend on wood as fuel (Rockwood et al. 2004).

In 2016, global trade was 125 million m^3 for industrial round wood, 144 million m^3 for sawn wood, 87 million m^3 for wood-based panels, and approximately 109 million tons for paper and paper board (FAO 2016). This trade is expected to grow 5–8% every year from ever-increasing demands. Thus, the promotion of SRF on wastelands and community lands will pave the way for meeting the raw material demands of forest-based industries and for fuel wood, as well as help to preserve our forests from overexploitation (Pathak et al. 1981; Christersson 2005; Meena et al. 2016; Raj et al. 2018a, b). SRF is intended to optimize resource use efficiency in an environmentally safe and economically sound manner (Landsberg et al. 1997). Ultimately, SRF may substitute for the deforestation of tropical forests and temperate forests and would promote the conservation of forest resources required for mitigation of climate change and human health.

To establish SRF, a high density of genetically improved, locally adapted, and clonally propagated planting materials are deployed (Tuskan 1998). These plantations are established after extensive site preparation with adequate nutrient and fertilizer doses, along with intense weed control and pest management (Tuskan 1998). The growth increments of SRF vary by site quality, species selection, and intensity of management, but range from 6 to 21 Mg/ha/year dry matter in non-irrigated plantations and up to 30 Mg/ha/year dry matter in irrigated land (Wright and Tuskan 1997). Once the SRF crop matures, it is harvested and allowed to regenerate from coppice or replaced by using cuttings of new seedlings.

Because wood is a renewable source of energy, it can be easily substituted for other fuels (Segrest et al. 2001). SRF is considered to be carbon-neutral, indicating that it does not increase carbon dioxide (CO_2) in the atmosphere but helps in carbon sequestration (C_{seq}) (Tuskan and Walsh 2001). More than 100 species have been identified as SRF species (El Bassam 1998). In India, the recommended SRF for various agro-climatic regions include *Acacia* species such as *Acacia auriculiformis* (Earleaf acacia), *Acacia nilotica* (Babool), *Acacia catechu* (Khair), and *Acacia mangium* (Mangium); *Albizia* species such as *Albizia lebbeck* (Black siris) *and Albizia procera* (White siris); *Parkinsonia aculeate* (Jerusalem thorn), *Azadirachta indica* (Neem), *Ailanthus excelsa* (Indian heaven tree), *Casuarina equisetifolia* (Beech oak), *Eucalyptus camaldudensis* (Longbeak eucalyptus), *Leucaena leucocephala* (Subabool), *Melia azedarach* (Bakain), *Prosopis cineraria* (Khejri), *Prosopis juliflora* (Kikar), *Terminalia arjuna* (Arjun), *Populus deltoides* (Poplar), *Robinia pseudoacacia* (Black locust), and *Salix* species (Willow) (Rockwood et al. 2004).

The total growing stock in the Indian forest is 5822.377 Million m^3, and the MAI of 0.7 m^3/ha is far lower than the global average MAI value (2.1 m^3/ha). Imports of wood are increasing every year, from $630 million in 2003 to $2.7 billion in 2013 in India (FAO 2016). The total import of wood and wood-based products constituted of 328.2 billion Indian rupees in 2016–2017 (https://www.statista.com/statistics/625460/import-value-of-wood-india/) (Fig. 1).

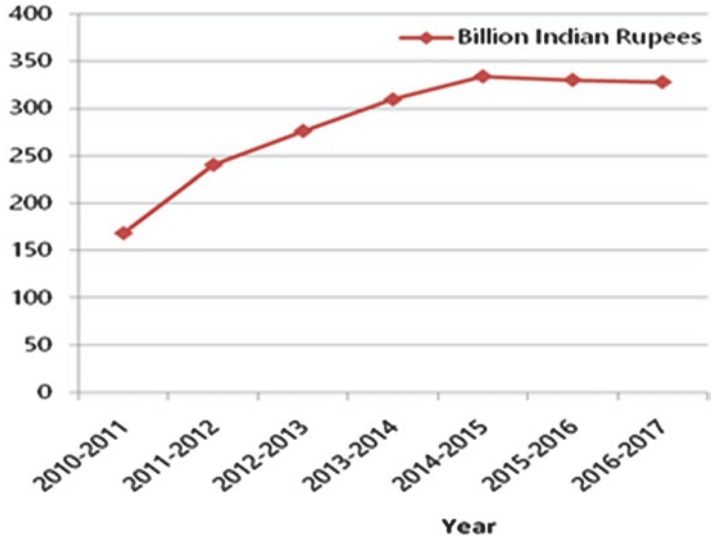

Fig. 1 The increasing import value of wood and wood-based products in India. (Data sourced from: https://www.statista.com/statistics/625460/import-value-of-wood-india/)

In this scenario, the increasing demand for raw material to be used in pulp, paper, furniture, and wood-based industries in India has led to the increased import of raw material; however, this is not a sustainable solution. Indian forests are not sufficient enough to fulfill the increasing demand for wood-based raw materials. In addition to the degraded conditions of forests, low growing stock, poor increments, less technological inputs, and excessive human pressures due to population explosions, industrialization, and urbanization, we cannot impose more pressure on these precious forest resources required for human survival; instead, conservation is required (Lal 2010; Jhariya 2014; Verma et al. 2015). Therefore, to bridge the gap between the demand for wood as a raw material and its supply, fast-growing and genetically superior SRF species are attracting attention. Many industries, such as the Western India Match Company Limited, ITC India Limited, West Coast Paper Mill Ltd., Tamil Nadu Newsprint and Papers Limited, Ballarpur Industries Limited, and Bharatiya Agro Industries Foundation, have started growing SRF species to meet their raw material requirement (Chauhan et al. 2017a).

This chapter explores the scope and potential of SRF with respect to biomass production, as well as the role of policy and other related incentives available to different land users in general. More specifically, climate change mitigation and adaption approaches through SRF, the dimensions on C_{seq} potential, ecosystem sustainability, soil, and biodiversity, etc. will be discussed in this chapter. Overall, this chapter attempts to expand the potentialities of SRF while challenging the climate change effects and considering future implications on a positive note.

2 Extent of SRF

SRF plantations are now a major source of raw material for wood-based industries in India and other countries. Most SRF in India includes poplar, eucalyptus, and beech oak (Chaturvedi 1998; Christersson and Verma 2006). Earleaf acacia is a species grown in humid tropical regions of northeast India, which has been reported to give higher pulp and fodder yield at 4-year rotations. *Tectona grandis* (teak), *Gmelina arborea* (gamhar), beech oak, mangium, poplar, willow, *Eucalyptus tereticornis* (forest red gum), subabool, and *Melia composita* (Hill neem) SRF have been used in the pulp and paper industries in the tropical plains, southern, and northeast humid tropics of India (Christersson and Verma 2006).

Species such as subabool, bakain, eucalyptus, and poplar hybrids are extensively raised in subtropical foothills of India (Christersson and Verma 2006). In temperate and sub-temperate regions, SRF includes planting black locust, *Acacia mollissima* (black wattle), and *Morus alba* (white mulberry) (Christersson and Verma 2006). In the semi-arid and arid regions of India, kikar and babool are planted. The Indian heaven tree, *Anthocephalus cadamba* (kadam), is also being promoted in India as an SRF species, especially in northern India. According to India's country report (2016), approximately 317,800 ha in India are estimated to be covered by poplar. Eucalyptus was introduced in India in the later part of the eighteenth century; it is currently estimated to be grown on more than 3 million

Table 1 Area, productivity, and rotation age of commercially important SRF species (Cossalter and Pye-Smith 2003)

Species (area)	Main countries raising these species	Rotation age (years)	MAI m^3/ha/year
Eucalyptus grandis (flooded gum) and *Eucalyptus hybrids* (3.7 Mha)	Brazil, India, South Africa, Uruguay, Congo, and Zimbabwe	5–15	15–20
Eucalyptus species (Tropical region) (1.55 Mha)	Vietnam, Myanmar, Madagascar, China, India, and Thailand	5–10	10–20
Eucalyptus species (Temperate region) (1.90 Mha)	Uruguay, Chile, Portugal, Spain, Australia, South Africa, and Argentina	10–15	5–18
Acacia species (1.40 Mha)	China, Indonesia, Malaysia, Vietnam, India, Philippines, and Thailand	7–10	15–30
Gmelina arborea (Gamhar) (0.1 Mha)	Costa Rica, India, Malaysia, and Solomon Islands	12–20	12–35
Poplar species (0.9 Mha)	India, China, USA, Europe, and Turkey	7–15	11–30

hectares, 80% of which is under agroforestry. India also has about 10% of the world's eucalyptus plantations (http://www.tnpl.com/web_pdf_files/Socio-Economic-and-Environmental-Impact.pdf).

Most SRF species are raised on farms and other non-forestry land. The government is focusing on raising SRF in problematic areas and farms to meet demands for fuel, wood-based industries, and paper industries and to reduce pressure from natural forests. *Populus trichocarpa* (black cottonwood), poplar, and other exotic hybrids are grown in rotations up to 6–7 years in Canada and the United States (Steenackers 1990; Dickmann et al. 2001; Ram and Meena 2014), with annual production up to 20 tons per hectare (Heilman and Stettler 1985). Hybrids of aspen (*Populus tremula*) crossed with quaking aspen (*Populus tremuloides*) have been observed to produce 20 m^3 per hectare per year (Christersson and Verma 2006).

In the Philippines, gamhar and acacias are grown commercially for SRF (Diaz and Tandug 1999; Christersson and Verma 2006), whereas bamboo species and hybrid poplars are being cultivated in China as SRF. Currently, 4.6 million hectares of eucalyptus plantations exist in China, with 60–70% of these plantations being under short rotations of 5–7 years (Zhou et al. 2017; Ashoka et al. 2017). Some example of SRF plantations with their area, productivity, and rotation ages are presented in Table 1.

3 Importance and Scope of SRF

SRF can provide enormous benefits when grown on wasteland, agricultural land, marginal land, and roadsides. The main benefits include pollution control, C_{seq}, ecological restoration of degraded sites, overcoming the rising demands of wood-based industries for raw material, phyto-remediation of polluted and heavy metal loaded soils, and providing a renewable source of energy, particularly for bio-energy and bio-fuel. The high growth rate of SRF species leads to higher biomass production, make them amenable for all of the previously mentioned purposes. The high MAI attained by these SRF species provides early returns to farmers and high quantities of raw materials to industries. Therefore, SRF is win-win situation for both farmers and industries.

In Brazil, SRF hybrid species of *Eucalyptus grandis* (flooded gum) crossed with *Eucalyptus urophylla* (Timor mountain gum) have been reported to yield dry biomass of 10–12 tons/acre/year. Flooded gum trees have been observed to provide total green biomass of more than 30 tons (Stricker et al. 2000). Poplar generally produces dry biomass of 5 tons/acre/year (Mercker 2007). *Pinus taeda* (loblolly pine), a fast-growing pine species, is capable of producing an average of 4 dry tons/acre/year if grown up to a 20-year rotation (Mercker 2007). Poplars in short rotation periods of 6–8 years are capable of yielding about 20–25 m^3/ha/year (Saddler 2002). Poplar hybrids can provide a total aboveground yield up to 500 m^3/ha in a 12-year rotation (Saddler 2002). In India, subabool has been reported to produce 112 t/ha of biomass, whereas forest red gum produces 96 t/ha in and babool produces 52 t/ha (Singh and Toky 1995).

A short rotation of willow has been reported to yield 3–7 tons/acre/year of dry biomass (Mead 2005). *Liquidambar styraciflua* (American sweetgum) and *Platanus occidentalis* (American sycamore) plantations have been observed to produce dry biomass up to 1 and 2.3 tons/year on 7-year rotations, respectively (Davis and Trettin 2006). For fast-growing species such as gamhar under 6-year rotations, yields of hardwood ranged between 40 and 120 m^3/ha on poor-quality and good-quality sites, respectively (Agus et al. 2001). This indicates that good site quality is a prerequisite for achieving higher productivity with these SRF species.

For the reclamation of waterlogged areas in India, species utilized for SRF include eucalyptus, *Casuarina*, arjun, karanj (*Pongamia pinnata*), willow, siris, poplar, *Acacia, Prosopis* and *Syzygium cumini* (Jamun) (Pandey et al. 2015). Willow species have been used for the removal of heavy metals such as cadmium; the high evapo-transpiration rate of such species facilitates phyto-remediation. Moreover, using trees for remediation is cost-effective and also provides other benefits to people (Aronsson and Perttu 2001).

In the long term, SRF improves soil properties by enriching soil with nutrients, enhancing soil organic carbon (SOC), and improving soil biological activities. After planting willow and poplar species, the total organic carbon and total nitrogen content have been reported to reach 4.0 g per kg and 0.2 g per kg in 12 years on sandy soil. Higher dehydrogenase activity in soil along with decreases in bulk density and increases in soil porosity has been observed in SRF (Kahle et al. 2007; Meena et al. 2017).

In addition to higher growth rate, biomass production and the renewable nature of SRF have great potential to capture a huge amount of carbon (C) at a fast rate. High annual C_{seq} in eucalyptus plantations (130.98 tC/ha/year) and poplar (18.59 tC/ha/year) and mixed plantations (21.83 tC/ha/year) of these two species has been observed (Sarangle et al. 2018). Similarly, plantations of fast-growing tree species, such as Timor mountain gum tree and *Acacia crassicarpa* (northern wattle), were shown to accumulate more C in their biomass than other long-rotation plantations of the same age (Chen et al. 2015).

Economic returns are also high for fast-growing short-rotation species due to the huge biomass production for industries and other bioenergy and biofuel purposes. One study carried out in China found that net present values range from $1024 to $6925/ha, equivalent annual incomes range from $120 to $623 ha/year, and internal rates of return range from 13.2% to 29.3% for popular plantations (18,032 ha) (Wang et al. 2014). Similarly, plantations of forest red gum tree can produce 201.64 m^3/ha, which is equivalent to Rs.1210 432/ha after 8 years (Jalota and Sangha 2000). Therefore, SRF has the potential to provide high economic returns to farmers and other involved agencies.

There is lot of scope for SRF in India to meet demands for energy resources, biodiesel, and raw materials for wood-based industries. In addition, the high biomass production of SRF makes it a desirable option for mitigation and adaptation for climate change. Moreover, SRF has the capability to provide early returns to farmers, which therefore make it a good option for generating income in a short period of time. SRF can be used on wastelands for their reclamation and restoration, on agricultural land as boundary plantations, as part of agroforestry, and on village community land under joint forest management to improve a community's economic status (Singh et al. 2014; Raj and Jhariya 2016a, b, Raj et al. 2016).

4 Important SRF Species in India

In India, earleaf acacia, khair, mangium, babool, black siris, white siris, neem, Jerusalem thorn, Indian heaven tree, beech oak, longbeak eucalyptus, subabool, bakain, khejri, kikar, arjun, poplar, black locust, bamboo species, kadam, Gamhar, pink cedar (*Acrocarpus fraxinifolius*), and willow species are the most important SRF species (Rockwood et al. 2004). These species show high productivity and can be grown in the different soil types and agro-ecological zones of India (Tables 2, 3, and 4).

5 SRF for Higher Biomass Production

To meet the demands of the pulp, paper, furniture, packaging, veneer, and plywood industries, raising SRF tree species is an eco-friendly and viable solution (Martin and Nordh 2009). In many countries, such as Sweden, willows are commercially raised to meet energy demands. Tree species such as poplar, pine, birch (*Betula spp.*), and eucalyptus species are being used in China commercially to meet the demands of various wood-based industries (Chen et al. 2015). Now, the focus is on renewable energy sources that can meet demands sustainably without deteriorating the environment. Therefore, SRF is being promoted by various governmental and

Table 2 Important SRF species and their productivity

Species	Family	Productivity	References
Dalbergia sissoo	Fabaceae	9–15 m^3/ha/year (10-year rotation)	FAO (2001)
Acacia auriculiformis	Fabaceae	8–35 tons/ha/year (10-year rotation)	Schmerbeck and Naudiyal (2014a, b)
Acacia mangium	Fabaceae	46 m^3/ha/year (9 -ear rotation)	Patil et al. (2012)
Acacia nilotica	Fabaceae	3–4 m^3/ha/year	Mohapatra et al. (2005)
Albizzia lebbeck	Fabaceae	66 tons biomass (after fifth year)	Yadav (1986)
Casuarina equisetifolia	Casuarinaceae	11 m^3/ha/year (12- to 15-year rotation)	Ray (1971)
Eucalyptus camaldudensis	Myrtaceae	8–12m^3/ha/year (10- to 20-year rotation)	Mohapatra et al. (2005)
Leucaena leucocephala	Fabaceae	30–55 m^3/ha/year	FAO (2001)
Melia azedarach	Meliaceae	15–17 m^3 /ha/year (15-year rotation)	(http://www.worldagroforestry.org/sites/default/files/Timber%20demand%20supply-Northwest-No6.pdf)
Prosopis juliflora	Fabaceae	4.9–8.4 kg/tree/year	Chaturvedi et al. (1988)
Populus deltoides	Salicaceae	20–25 m^3/ha/year (8- to 10-year rotation)	Mohapatra et al. (2005)
Robinia pseudoacacia	Fabaceae	23 m^3/ha (at 10-year rotation age)	NAS (1983)
Salix viminalis (basket willow)	Salicaceae	20–30 tons of biomass (10–15 tons of seasoned wood) per hectare per year	Rajoriya et al. (2016)
Gmelina arborea	Verbenaceae	12 and 50 m^3/ha, MAI in 5–8 years	FAO (2001)
Anthocephalus cadamba	Rubiaceae	20 m^3/ha/year (at 9-year rotation	Krisnawati et al. (2011)

Table 3 SRF species suited for various soil types in India (Benwood 2011)

Species	Soil sites
Populus deltoides	Sandy to fine loam
Leucaena leucocephala	Variable soils
Melia composita	Fertile and sandy loam
Eucalyptus hybrids	Sandy loam, alluvial soils are preferred
Robinia pseudoacacia	Acidic soils and sloping land
Morus alba	Sandy loam to clay loam
Prosopis juliflora	Saline, sandy soils
Gmelina arborea	Sandy loam and deep soil
Ailanthus excelsa	Porous sandy loam
Casuarina equisetifolia	Red gravelly loam, coastal and saline soils
Terminalia arjuna	Moist locations and sandy loam soils
Tectona grandis	Deep black soil, black clay and black loamy soils

Table 4 Zonewise distribution of various SRF species in India (Benwood 2011)

Species	Distribution
Acacia auriculiformis	Humid tropical regions in the north
Acacia mangium	Eastern India and the humid tropics
Acacia mollissima	Southern India
Populus deltoides	Irrigated agro-ecosystem in northwestern states
Leucaena leucocephala	Throughout the country
Eucalyptus hybrid	Throughout the country
Robinia pseudoacia	Temperate northwestern Himalayas
Morus spp.	Temperate northwestern Himalayas
Prosopis juliflora	Arid and semi-arid areas
Gmelina arborea	Northeastern humid tropics
Bamboo species	Throughout the country, with most species in the northeastern states
Anthocephalus cadamba	Northeast regions and southern states of India
Ailanthus excelsa	Central India, arid regions, and northern part of peninsular India
Casuarina equisetifolia	Coastal areas and salt-affected soils
Terminalia arjuna	Lower Himalayan tracts and eastern India
Cryptomeria japonica	East Himalayas and humid regions

non-governmental agencies as a solution for meeting demands for wood products and combating climate change.

SRF species are high above-ground biomass (18–50 t/ha), which makes them suitable for bridging the gap between the demand for and supply of wood. In India, 90% of industrial round wood demand is met from fast-growing species outside forests. *Populus* spp., *Eucalyptus* spp., *Acacia* spp., subabool, *Melia dubia* (Malabar neem), willow, and beech oak are being promoted in India and are gaining the interest of farmers and industries. When grown at high density, these SRF species can provide farmers with high returns.

Sachs and Low (1983) reported 22 oven-dry tons of biomass/ha/year under a 6-month rotation in a flooded gum tree plantation at very high density (17,200 trees/ha). Two years after planting *Eucalyptus camaldulensis* (river red gum) at 5000 trees per acre, the plantation yielded 16 dry tons of biomass per acre per year.

With 9-year-old poplar, the total biomass (above-ground and below-ground) varied from 71.50 tons/ha to 251.50 tons/ha, depending upon plant density (Puri et al. 1994). For multipurpose bio-energy crops such as arjun (41.62 tons/ha), neem (19.22 tons/ha), kikar (56.50 tons/ha), karanj (26.60 tons/ha), Beech oak (42.10 tons/ha), South American mesquite (27.75 tons/ha), babool (50.75 tons/ha), forest red gum (31.77 tons/ha), *Pithecellobium dulce* (32.25 tons/ha), and *Cassia siamea* (kassod) (21.65 tons/ha), high biomass production has been observed (Singh et al. 2010). For 1-year-old seedlings of some fast-growing species, such as *Samanea saman* (40.07 tons/ha/year), *Erythrina variegata* (32.02 tons/ha/year), *L. leucocephala* K-8 variety (45.52 tons/ha/year), and black siris (27.40 tons/ha/year) high biomass was recorded, which indicates their suitability as high biomass production species (Ponnamal and Gnanam 1988).

During a study on the biomass production potential of four SRF species on a 4-year rotation, *Betula pendula* (silver birch) was observed to produce high dry biomass up to 3.3 tons/ha/year, *Acer pseudoplatanus* produced dry biomass of 1.2 tons/ha/year, populous hybrid *P. trichocarpa* × *P. deltoides* produced dry biomass of 4.2 tons/ha/year, and *Salix viminalis* (basket willow) produced 3.5 t of dry biomass ha/year (Walle et al. 2007).

In a hybrid of *E. torelliana* × *E. citriodora*, hybrid vigor and high standing volume production was reported at the rotation ages of 7, 10, and 23 years. Standing volumes of 0.18 m^3, 0.53 m^3, and 3.03 m^3 and yields of 16.17 m^3/ha/year, 33.12 m^3/ha/year, and 82.79 m^3/ha/year were observed at 7-, 10-, and 23-year rotations, respectively (Kumar et al. 2010). *Eucalyptus* plantations have been reported to produce pulp up to 5.9–10.9 t/ha/year (Fenton and Romero 1995; Bertolucci et al. 1995). Forest red gum and beech oak have been reported to produce 20 times more at high densities of 40,000 plants per hectare (Rai and Srinivasan 2012).

In SRF with willow coppice in Kashmir, a higher fresh biomass yield of 15.55 tons/ha/year was obtained after 4 years of plantation, which increased to 23.41 tons/ha/year after 3 years when willow coppice was grown a second time (Masoodi et al. 2014; Yadav et al. 2017b). Thus, SRF can yield high biomass, thereby meeting the demands of wood-based industries.

6 Economic Importance of SRF

SRF is an ecologically and economically viable option for meeting the demands of wood-based industries, reducing pressure on forests, and providing higher and early returns to farmers in comparison to commercial forestry. However, farmers may be reluctant to adopt SRF because of the long gestation period of trees in comparison to food crops, a lack of availability of planting materials, a lack of market intelligence about demand and supply of wood-based products, and mostly because the small size of land holdings. However, SRF is profitable for both farmers and wood-based firms because it provides high returns. The crops grown will of superior genotypes; therefore, uniform growth rates and quality are achieved. Many paper, pulp, and wood-based industries of India, such as Western India Match Company Limited, ITC India Limited, West Coast Paper Mill Ltd., Tamil Nadu Newsprint and Papers Limited, Ballarpur Industries Limited, and Bharatiya Agro Industries Foundation, are now also encouraging farmers to take up SRF to fulfill their demand for raw materials.

Chaudhary and Chaudhary (2012) planted 12,000 poplar trees of superior genotype at Chaudhary Farm in Pilibhit, Uttar Pradesh, India. After harvesting trees every 7 years, high yields of 1000 quintal of timber per acre have been obtained, along with economic returns of Rs. 100,065 per acre per year.

In poplar-based agroforestry, high net returns were reported for poplar and sugarcane intercropping (Rs. 64,355/ha/year) followed by poplar and turmeric intercropping (Rs. 59,543/ha/year) and poplar and rainfed wheat (Rs.18,719/ha/year). Poplar mono-cropping generated Rs. 20,188/ha/year, whereas a traditional rice-wheat-crop rotation could obtain Rs. 22,970/ha/year as the net income (Chahal et al. 2012). This underscores the hypothesis that two-tier cropping is more profitable than mono-cropping.

Chauhan et al. (2015) found high economic returns from poplar block plantation in comparison to boundary plantation and sole cropping of rice and wheat with a Benefit:Cost ratio of 3.30, 1.90, and 1.61, respectively. Beech oak intercropping at 4-year rotation with groundnut has been found profitable, with net annual returns of Rs. 88,827/ha/year in comparison to traditional rice cultivation returns of Rs. 68,381/ha/year (Saravanan and Vijayaraghvan 2014). Beech oak clonal propagation for poles and pulp gives a higher B:C ratio (3.88–5.05) than beech oak seedlings (1.66–1.91) (Saravanan and Vijayaraghvan 2014). Growing willow coppice in Kashmir valley at high density provided gross and net income after two-time cultivation of trees on the same land (4-year rotation) equivalent to ₹8,76,750 and ₹4,96,255 per hectare, with a net present worth of ₹2,00,663 and a B:C ratio of 1.73 at a discount rate of 12% (Masoodi et al. 2014).

Further promoting SRF on farmers' fields and community land under the Clean Development Mechanism (CDM) of the Kyoto Protocol can help farmers to earn revenues from the sale of carbon credits. As SRF has high biomass production capacity and 50% of the dry biomass is carbon, SRF has high C_{seq} potential. Such SRF projects can be taken up under CDM, and these carbon credits can be sold to developed countries to offset their carbon emission reduction targets. Therefore, SRF is economically viable because it provides quick and high returns; in addition, being renewable, it can serve as a permanent option for steady income streaams.

7 Policies and Initiatives Related to SRF

Over the last few decades, there has been universal concern over the inevitable effects of climate change, especially on vegetation ecosystems, due to the unavoidable phenomena of global warming and climate change. Climate change mitigation and adaptation activities through the adoption of tree-based systems have been considered as a holistic solution. The concept of using fast-growing tree species could prove a viable option to mitigating the challenge of climate change by a faster rate of biomass accumulation, thereby capturing CO_2 in the woody biomass as well as reducing the pressure on natural forests (Chauhan et al. 2017b). In addition, afforestation and reforestation activities would help to reclaim degraded land and wastelands by providing the services of C_{seq} on one side and conservation of land resources on the other side. Thus, the regulation of tree plantation activities by implementing proper plantation policies with the aim to improve the tree cover area should be given top priority. For example, in India, the National Forest Policy 1988 set up the goal to maintain 33% of the total geographical area as forest and tree cover area. In an attempt to increase the tree cover area in India, the government has taken initiatives and started programs such as the Green India Mission (2014) and National Agroforestry Policy (2014). In the context of SRF, the main purpose is for higher biomass production and replacement of fossil fuels. The National Biofuel Policy 2008 of India was one of the major steps taken by the government, and *Jatropha curcas* was one of the short-rotation tree species identified in this aspect (Basavaraj et al. 2012).

The government of Australia initiated the Carbon Credit Act 2011 with respect to plantation forestry, with the aim to reduce carbon emissions and benefit farmers by selling their carbon credits. Other policies with respect to plantation forestry have been implemented in various countries, but their norms and regulations vary by region and may be very rigid for farmers and other stakeholders. Therefore, governments and concerned authorities should review the regularization and user-friendliness of adopted policies. Other than the implementation of policy, some incentives can be provided to benefit land users directly or indirectly. Incentives such as the regulation of market prices, supply of planting material, exemption of taxes, and financial or loan support would be helpful to farmers, but the nature and amount of incentives provided vary from country to country. In this regard, Enters et al. (2004) highlighted the incentives required for the evolution of plantation in developed and developing countries. More incentives are required for developing countries at the initial phase of plantation development. The accessibility of incentives by different beneficiaries in developed countries is very promising and attractive in nature in comparison with developing countries.

Mola-Yudego and Pelkonen (2008) in Sweden reported that the implementation of policy incentives increased the farmers who adopted short-rotation willow plantation by 70% during 1986–1996. This proved that providing incentives to farmers not only encourages farmers to adopt SRP but also serves as a future strategy to achieve more biomass production. Lindegaard et al. (2016) also reported the importance of SRP policies for growers and emphasized that there is an urgent requirement to disseminate the information and educate the farmers and policymakers to impart the benefits derived from SRP. Governments and concerned authorities also need to provide financial support with the aim to implement the policies for the long term.

Enters (2004) studied the impact of policy and incentive availability with respect to plantation activities for different land users in the Asia-Pacific region. The author outlined three main stages during the process of plantation establishment: the initiation phase, acceleration phase, and final or maturation phase. The type of incentives to be provided depends on the developmental phase of the plantation. For example, direct incentives at the initiation phase of plantation will help to achieve successful plantation programs; later, direct incentives may be replaced by other kinds of incentives. It was also highlighted that the structure and function of social and political factors can affect the availability of incentives. Thus, the implementation of effective policy initiatives and other incentives will be helpful in stimulating the expansion of plantation forestry.

8 Impact of SRF on Soil Sustainability

Soil plays a crucial role in the overall growth and development of a plant. Nutrient reserves in the soil ecosystem provide support that has a pronounced effect on a plant's productivity. In other words, the level of soil fertility or the nutrient status of soil has a significant impact on plant growth and productivity. The sustainability of soil resources, which helps to fulfill the nutrient requirements from the soil system, needs to be critically examined. Furthermore, the self-sustainability of soil nutrient reserves is also required to be maintained or improved with every plantation activity (Jhariya et al. 2018; Kumar et al. 2018). Tree-based land use systems provide greater soil sustainability than do treeless or agricultural systems. In an agricultural system, different management activities, such as tillage, the application of fertilizers, and pesticides use, influence the nutrient status of the soil, especially SOC storage in the soil (Chen et al. 2004; Guo and Gifford 2002).

It is important to understand the nutrient status of the soil where afforestation or reforestation activities are planned. Afforestation and reforestation activities are expected to increase the soil organic C_{seq} potential of the site (Sauer et al. 2012). With the introduction of SRF in an area, there will be significant changes in the soil properties. Generally, SRF and fast-growing species plantations are established where the land is to be converted from arable land, abandoned land, wasteland, or degraded land. In a few cases, SRF is introduced where lands are covered by natural forests, pasture lands, or grasslands.

According to the previous land use pattern, the impact of SRP on soil properties may be negative or positive. In this regard, Guo and Gifford (2002) reported that the SOC stock of different land use systems changed according with the change in their previous land use pattern. They found that a 10% decrease of SOC when original pasture land was converted to plantation and more SOC loss (13% decrease) when native forest was shifted to plantation forestry. Interestingly, however, an increase of

Table 5 Soil carbon changes after introduction of SRP

Short-rotation forestry/plantation	Former land use pattern	Soil depth (cm)	Time span (years)	Change in soil carbon (%)	References
SRF poplar (Italy)	Agriculture (maize- wheat)	0–10	9–10	57% increase	Bene et al. (2011)
Poplar, aspen, and willow (Germany)	Arable land	10–30	7–9	15% decrease	Jug et al. (1999)
Hybrid aspen (Estonia)	Arable land	0–30	5–15	10.4% increase	Lutter et al. (2016)
Pinus radiata (New Zealand)	Pasture	5	5	16% decrease	Chirino et al. (2010)
Eucalyptus nitens (New Zealand)	Pasture	5	5	8% decrease	Chirino et al. (2010)
Cupressus macrocarpa (New Zealand)	Pasture	5	5	2% decrease	Chirino et al. (2010)
Cupressus lusitanica (Ethiopia)	Abandoned Farmland	10	20	25% increase	Poultouchidou (2012)
Eucalyptus saligna (Ethiopia)	Abandoned Farmland	10	20	20% increase	Poultouchidou (2012)
Poplar spp. (USA)	Agriculture	32	12	No change	Coleman et al. (2004)
Pinus radiata (Australia)		15	5	19–2.7% decrease	Smethurst and Nambiar (1990)
Meta-analysis (many species covered)	Agricultural land	< 10	5	3.46% decrease per year	Paul et al. (2002)

18% SOC occurred by the time the crop area was changed to a plantation. For the overall development of soil quality as well as for maintaining soil productivity, the role of soil organic matter is very critical; thus, it should be considered as a key parameter in deciding the soil quality (Teepe et al. 2003; Verma et al. 2010).

In general, during the early phases of plantation, SOC content seems to decline and then begins to build up with the passage of time. This may be due to more disturbances in the soil at early stages due to the tree establishment process, less litter fall accumulation, and a high mineralization rate (Paul et al. 2002; Jug et al. 1999; Makeschin 1994). Changes in soil C content after introduction of SRF and fast-growing tree species are presented in Table 5. It can be seen that there were more changes in soil C content when the arable land was changed to plantation; in addition, the soil C storage or accumulation seems to change along with species planted as well as the previous land use pattern. The response of different tree species growing in same environmental condition has the potential to create a varying C accreditation pattern in the soil. For example, Abate (2004) claimed that *Cupressus lusitanica* exerts a higher quantity of SOC than *Eucalyptus globulus* due to its higher production of litter mass and coarse roots. Litter fall and decomposition processes play a major role in the development of SOC in the plantation system; however, the rate of litter accumulation depends on species and climatic factors, among others. Due to differences in their litter fall patterns, the quality of litter and rate of decomposition will have a significant impact on the amount of C sequestered in the soil; this has proven to be species specific (Vanguelova and Pitman 2011; Jhariya 2017a, b).

In addition to SOC, other physical, chemical, and biological properties of soil are inclined to change after the establishment of SRP. For example, in Germany, Jug et al. (1999) observed reductions in the soil pH and cation exchange capacity of soil after the establishment of poplars and willow. Similarly, reductions in soil pH after the establishment of SRF in different locations in Europe were reported (Ritter et al. 2003; Uri et al. 2011; Lutter et al. 2015). However, Muys et al. (1992) had observed an increase in soil pH with the plantation of *Alnus glutinosa*, *Prunus avium*, *Fraxinus excelsior,* and *Tilia platyphyllos*. Change in the soil reaction can be determined by the action of the species planted with the adaptability of the site and could modify the soil nutrient dynamics with passage of time. Therefore, for sustainability of the SRP, an understanding of soil pH and its dynamics is very important because soil mineralization and other microbial activity have been affected by soil pH, which influences the overall soil nutrient cycling (Lutter et al. 2016; Jhariya 2014; Meena and Meena 2017).

The biological properties of soil in terms of microbial populations and their activity have also played a significant role in maintaining soil fertility and productivity. Like SOC, microbial activity in the soil decreases during the initial stages of plantation because there are more disturbances in the soil; however, in later phases, the microbial activity shows a significant increase (Minor et al. 2004). Improvements in soil ectomycorrhizal fungi in different plantations of species, such as willow and poplar, have been recorded in comparison with arable land (Baum et al. 2009; Rooney et al. 2009). Soil with a higher microbial biomass is expected to have higher SOC and is considered to be one of the early sensitive indicators of a soil system (Jenkinson et al. 2004). The amount and quality of litter added to the soil would preferably affect the rate of decomposition by influencing the activity of soil microbes. Generally, it is believed that soil microbial biomass tends to change with the shifting of land use patterns as the substrate availability and other growth favoring condition is frequently changed.

Mao and Zeng (2010) observed a change in soil microbial biomass C, with reductions during the early development of plantations and a tendency to increase with the passage of time. The positive impact of plantations on soil microbial biomass C is evident from the works of Kahle et al. (2010) and Pellegrino et al. (2011). SRF has been proven to improve soil biodiversity by increasing microbial populations and thus influencing the soil nutrient cycling. The effects of SRP in terms of soil sustainability can be determined by the maintenance of balance between the nutrient removal during harvesting and nutrients addition by fertilization (Vanguelova and Pitman 2011). During the harvesting period of the plantation, there will be heavy disturbances in the soil, with exports of nutrients from the soil. For example, O'Connell and Glove (1999) reported that more than 500 kg N/ha was removed from the soil of an 8-year-old *Eucalyptus globulus* plantation during harvesting. Therefore, for long-term soil sustainability under SRP, harvesting practices that lead to less disturbance in soil should be considered, in addition to leaving the leaf litter and other waste materials after harvesting (Ranger and Belgrand 1996).

9 Impact of SRF on Biodiversity

The constant loss of biodiversity due to human interference has resulted in a decrease in forest area as well as an increase of atmospheric CO_2 (Cairns and Meganck 1994; Gross 2016). Forests and other natural ecosystems have a strong linkage to building up biological diversity, which form a series of webs and maintain the overall stability of the terrestrial ecosystem. During the last two decades, people have started to realize the impact of losing biodiversity, compromising the services of the ecosystem with human satisfaction (Cardinale et al. 2012).

Deforestation, illicit felling, and burning inside forests have been done intentionally by humans while in search of their requirements for food, fodder, fuel wood, and timber, which has tremendous effect on forest biodiversity (Jhariya et al. 2012, 2014; Kittur et al. 2014a, b). In this regard, plantation forestry aims to reduce the pressure on limited natural forestry as well as serve the demands for tangible products derived from the forests. It is generally expected that undisturbed or natural forest ecosystems will have more biodiversity than plantation systems. Stephens and Wagner (2017) have argued that plantation forests have less biodiversity than natural forests, but higher diversity than agricultural or other land use systems. Similarly, Bremer and Farley (2010) claimed that the level of biodiversity in plantations may be higher when compared with agricultural land and degraded areas but lower than natural forests and grasslands; they also indicated that plantations consisting of native indigenous tree species will have more diversity than exotic plantations. Sustainable forest management aims toward long-term sustainability by conserving and maintaining the biological diversity of natural resources. Carnus et al. (2006) reported that plantation forestry can increase diversity while meeting the demands for fuel wood and timber; they also suggested that plantation forestry should be managed in such a way that the economic outlook is not the top priority but the diversity of the plantation is also considered.

It is apparent that the effects of plantations on biological diversity may be either positive or negative. For example, a negative or lower level of biodiversity in plantations was reported by various authors (Paritsis and Aizen 2008; Makino et al. 2007; Raman 2006). On the contrary, an increase in biodiversity inside plantations has been described in other reports (Tomasevic and Estades 2008; Stephens and Wagner 2017). It is obvious that the level of biodiversity is significantly influenced by management intensity (Braun et al. 2017; Carnus et al. 2006) and other factors such as land use history, management practices, and species planted (Bremer and Farhey 2010; Carnus et al. 2006).

The influence of SRF on the level of biodiversity will also have a significant impact, as general plantation forestry does. In this regard, few studies have been

Table 6 Possible SRF influences on biodiversity

Category of species	Level of biodiversity	Possible impact
Plant vegetation	Medium to good	Initial decrease in plant species richness followed by an increase in species richness over a course of time when the initial disturbances are stabilized followed by appropriate management practices
Arthropods	Medium	Possible loss of arthropod population when a native species is replaced by an exotic species; the selection of species would significantly influence arthropod diversity and species produced; flowering before harvesting would help with arthropod diversity. Potential to increase the biodiversity of arthropods whenever mixed species plantations are established
Bird	Medium	Bird populations in the plantation would be dependent upon the plantation stand dynamics. Comparable increase in bird populations when plantations are established adjacent to agricultural lands or former arable lands.
Mammals	Medium	Plantation stand dynamics also influence on the population of mammals. Prey-predator relationships inside the plantation also signify the biodiversity level in the plantation.

carried out and thus little information is available. In general, SRF is mainly composed of homogenous or single species, unlike a natural forest, thus creating low species richness. In other words, only the species that is favored by a plantation may persist and others may be lost. Hardcastle et al. (2006) attempted to determine the possible impact of SRF on biodiversity status, as shown in Table 6.

10 SRF and Climate Change

With the increasing impact of climate change owing to increased greenhouse gas (GHG) emissions coupled with increasing demands for fuel, tree-based raw materials for various industries, and tree-based eco-friendly fuel, a sustainable solution is needed that can mitigate climate change, help in adapting the environment to climate change, and fulfill demands for fuel and wood-based raw material. SRF is one such eco-friendly option for fulfilling all of these objectives. SRF has high biomass production potential within a short period of time; therefore, SRF can sequester more C at faster rate than conventional forestry. A major cause of pollution and GHG emissions is the use of fossil fuels for producing energy; fossil fuels have negative impacts on the environment and are also non-renewable resources. Moreover, the availability of fossil fuels will decrease in near future (Eduardo et al. 2017). Thus, shifting to a renewable, eco-friendly source of energy that can mitigate energy demand is required. SRF is the best option because bio-energy from biomass is known to reduce GHG emissions along with being a sustainable supply of energy (British Forestry Commission 2007).

Zurbaa and Matschullata (2015) compared SRF (willow- and poplar-based) with rapeseed cultivation as energy sources and studied the ratio between soil respiration and combustion heat released (per hectare) from products of rapeseed, willow, and poplars. Poplar and willow SRF showed low ratios. Therefore, such species can be promoted as a source of energy for meeting energy demands. Further studies must be carried out to evaluate the suitability of various SRF species for energy production. High biomass production of 18–50 t/ha has been reported in SRF species, which makes them suitable for bridging the gap between demand and supply of wood. *Populus* spp., *Eucalyptus* spp., *Acacia* spp., subabool, Malabar neem, willow, beech oak, arjun, neem, *Erythrina variegata*, karanj, *Prosopis alba* (South American mesquite), kassod, black siris, silver birch, and basket willow have been observed to produce high biomass and therefore can meet escalating energy demands in an eco-friendly manner (Sachs and Low 1983; Ponnamal and Gnanam 1988; Walle et al. 2007; Rai and Srinivasan 2012; Dadhich et al. 2015).

Another benefit of SRF is that it can be integrated with traditional agroforestry practices, leading to crop diversification; in addition, SRF conserves soil, water, and biodiversity, thereby enhancing ecosystem resilience (Rowe et al. 2009). Additional priorities being given to fuels include more climate resilience, more production to bridge the gap between the demand and supply of fuels, and increased C_{seq} in comparison to conventional agriculture (Sims et al. 2006). SRF has been designated as a cost-effective way to improve resilience because the diversification of crops reduces pest and insect attacks and act as a habitat for various macroflora and microflora (Walker 1995); this biodiversity acts as a buffer against environmental variability because the response will be different due to greater diversity (Yachi and Loreau 1999; Elmqvist et al. 2003).

Because of the higher C_{seq} potential of SRF, it is the best option for mitigating climate change. The C_{seq} rate in SRF-based agroforestry system is higher than that of other species because it helps with above-ground and below-ground C_{seq} in trees and sequesters more C in soil. The mean C storage (t C/ha) in various tropical SRF (rotation age 3–20 years) species has been observed to range from 8 to 59 (t C/ha) (Schroeder 1992). In addition, an increase in SOC has been observed in most SRF-based land use systems. In this way, SRF is climate smart option for meeting energy and wood-based raw materials demand.

11 Carbon Sequestration Potential of SRF

The ever-increasing impact of climate change has fueled an imbalance in ecosystem productivity and sustainability. The issue of global warming with increases in atmospheric CO_2 and other GHG concentrations have become hot topics. There has been a considerable increase in CO_2 concentration, which is approximately 40% greater than in pre-industrial time (IPCC 2013) and still increasing. Uncontrollable human behavior and its related activities have created natural resource crises. In addition, the release of CO_2 contributes significantly to increased CO_2 concentrations in the atmosphere, which are expected to be approximately

1.2 PgC/year, or 12% of the total CO_2 emitted from anthropogenic sources (van der Werf et al. 2009; Yadav et al. 2017).

The alarming rise in CO_2 concentration during the past few decades requires a strategy to mitigate and adapt to the challenging climate change issues. The importance of forests and other natural vegetation in the conservation and sustainable use of natural resources has been realized. Even though the forest ecosystem represents only 30% of the world's geographical area (FAO 2006), it is contributing more than 75% of the C reservoir of the terrestrial ecosystem (Bolin and Sukumar 2000). The sustainable management of forest ecosystems could lead to more space for C storage in tree components, such as leaves, stems, and roots, as well as in the soil ecosystem. Unfortunately, the pace of deforestation and desertification is constantly increasing and becoming a major concern across the globe. Therefore, plantation forests have become a strategy to meet the multifarious demands of society, unleash pressure on the natural forest ecosystem, and mitigate the global atmospheric C budget (Cunningham et al. 2015).

Forests and other tree-based land use systems have extensive potential to capture atmospheric CO_2 and store ir in their biomass (above and below ground) as well as in the soil ecosystem. This strategy is considered to be a viable option toward the mitigation of climate change. However, the natural forest ecosystem has not been managed properly and the principles of sustainable forest management system are not executed most of the time. Plantation activities have been started across the world, with the main aim to produce higher biomass production for replacing fossil fuel. The United Nations Framework Convention on Climate Change (UNFCC 1998) reported that plantation forestry is a potential mitigation option for GHGs under the activities of afforestation, reforestation, and deforestation, as highlighted in the Article 3.3 provisions of the Kyoto Protocol.

The potentiality of forest and related activities in terms of mitigating climate change can be achieved through following strategies, as stated by Ravindranath et al. (2000): carbon conservation, C_{seq}, and carbon offsetting. According to this, SRF is a part of C offsetting technology; a C offsetting idea was originally proposed by Dyson (1977). Afforestation and reforestation programs can regulate the C cycling of the terrestrial ecosystem, thus providing a potential option to curb climate change. It has been reported that an SRP area of 40 million hectares could reduce the annual C emission by approximately 0.072 Gt (Singh and Lal 2000). It is believed that managed forest plantations have more efficient C storage than natural plantations. Plantations of fast-growing species with intensive management would possibly capture and store more C than other systems (Chauhan et al. 2017b). Therefore, it is necessary to understand the C fluxes inside the plantation forestry, as depicted in Fig. 2. It is noted that C storage in plantation forestry is for the short term as compared with forest ecosystems, due to frequent harvesting.

C_{seq} in SRF indicates the removal and storage of C in tree biomass and soil ecosystems. C_{seq} denotes the amount of C balance that is taken and stored during photosynthesis and lost during respiration (Montagnini and Nair 2004). Originally, the concept of SRP originated with the production of higher biomass to replace fossil fuels (Laureysens et al. 2004a, b). Studies on SRF C_{seq} potential have received

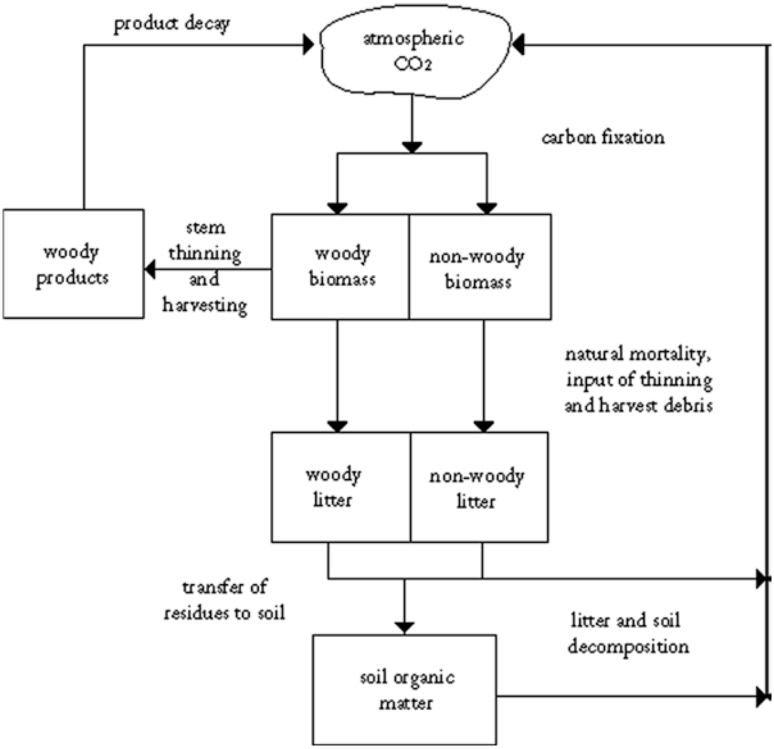

Fig. 2 C cycle in a plantation forest ecosystem. (Cannell 1995)

increasing attention in the last few decades around the world. However, information on C pools and fluxes inside SRF plantations is still meager (Grigal and Berguson 1998; Zha et al. 2004). The emergence of SRF could provide a potential option to mitigate climate change through C_{seq} due to its fast-growing nature (Vitousek 1991). The C storage potentials of some of the fast-growing tropical tree species are presented in Table 7.

Several afforestation and reforestation projects of the CDM can also expedite the introduction of SRP, with a view to optimize the concept of C_{seq}. Under CDM projects, the annexure I countries (developed countries that are bound by emission reductions) are allowed to purchase credits (carbon emission reductions) earned by annexure II countries (generally developing or underdeveloped) so as to meet their target setup per the Kyoto protocol.

The scope of SRF or fast-growing species can be expanded with the introduction of new plantations in degraded areas or wastelands. Agroforestry, a sustainable land use system in which tree components are deliberately cultivated along with agricultural crops, has the potential to sequester C to a considerable extent (Jhariya et al. 2015; Singh and Jhariya 2016; Meena et al. 2015). The dimension of short-rotation or fast-growing species can be explored in an agroforestry system where

Table 7 Examples of tropical forest plantations' carbon storage potential (Schroeder 1992)

Species	Final yield (m^3/ha)	Rotation (years)	Mean annual growth (m^3/ha/year)	Wood density (g/cm^3)	Mean carbon storage (tC/ha)
Pinus caribaea	300	15	20	0.46	59
Leuceana spp. (poor site)	72	8	9	0.60	21
Fuelwood crop	140	7	20	0.60	42
Casuarina spp.					
Moderate site	140	10	14	0.83	55
Degraded site	50	10	5	0.83	21
Pinus patula	400	20	20	0.45	72
Cupressus lusitanica	340	20	17	0.43	57
Acacia mearnsii	250	10	25	0.60	78
Cassia siamea	100	10	10	0.58	28
Acacia nilotica					
Moderate site	60	10	6	0.60	17
Degraded site	45	15	3	0.60	12
Azadirachta indica	40	8	5	0.52	8

fast-growing tree species such as poplar, eucalyptus, subabool, kadam, Malabar neem, white mulberry, and Indian heaven tree, among others, can be incorporated. Basically, the introduction of fast-growing species would aim to maximize biomass production with intensive cultivation techniques, thereby assuming that C storage in the agroforestry system will be increased in the short term. The tradeoffs between C storage and biomass production can be maximized by a conversion of monocropping into agroforestry, which can bring a paradigm shift by increasing the C storage residency. Thus, the effects of SRF would be applied for shorter period of time because the harvesting cycle of a tree species is less than that of a traditional forest; most of the C would return back to the atmosphere, but this problem could be solved by use of durable products made from that wood (Schroeder 1992).

However, the profitable advantages of short-rotation species—ensuring early returns, providing secure income for farmers' income, and capturing C (atmospheric) at faster rate in a shorter period of time—can be crucial while curbing the climate change. The rate of C sequestering is affected by the inherent quality of tree species to store C both in growing and wood products and soil recalcitrant C content (Montagnini and Nair 2004). SRF is established to meet biomass consumption and energy production, while at the same time attention has been shifted to the C_{seq} potentiality in the foreseeable future. However, the establishment of plantations may be dependent on various factors such as climatic, socio-economic, edaphic, and other management interventions related to SRF. Thus, SRF can be view optimistically as an option for long-term C_{seq}.

Gera (2012) reported that fast-growing poplar block plantations in India can sequester 1.33 tC/ha/year without wood products and 2.41 tC/ha/year with wood products. In Uttarakhand, India, Kanime et al. (2013) also assessed the C_{seq} potential of six different tree species plantations, where poplar block plantations

Table 8 C_{seq} potential (above and below ground) of selected SRF around the world

Country	Species	C_{seq} potential (Mg C/ha/year)	References
China	Poplar and willow	3.45	Meifang et al. (2017)
Italy	*Salix alba*	1.3	Calfapietra et al. (2015)
Italy	*Populus alba*	2.0	Calfapietra et al. (2015)
Italy	*Populus×euramericana*	2.0	Calfapietra et al. (2015)
India	*Eucalyptus tereticornis*	6.0	Kaul et al. (2010)
India	*Populus deltoides*	8.0	Kaul et al. (2010)
USA	Hybrid poplar	1.8–3.0	Updegraff et al. (2004)
Canada	Willow (*Salix spp.*)	2.96	Zan et al. (2001)
Sweden	Salix	3.5	Rytter (2012)
Sweden	Poplar	4.0	Rytter (2012)

(2.75 MgC/ha/year) and shisham plantations (2.73 MgC/ha/year) achieved the highest C_{seq} potential. The lowest (0.84 MgC/ha/year) C_{seq} rate was observed in forest red gum boundaries. Fang et al. (2007) reported that 10-year-old poplar plantations in China have the capacity to store 6.23 tons/ha/year of C. Some examples of the SRF C_{seq} potential around the world are presented in Table 8.

Soil C_{seq} potential could add another dimension to the long-term sustainability of SRF. There is huge scope for C_{seq} potential in soil because soil contains the largest C pool in the terrestrial ecosystem, with approximately 1500–1600 pg C in 1 m soil (Post et al. 1982; Amundson 2001). The great potential of C_{seq} is drawing considerable attention for climate change mitigation and adaptation approaches. In general, tree-based land use systems have more SOC than treeless systems. The dynamics of soil organic matter are frequently associated with disturbances in the soil system due to changes in land use or cropping patterns, which ultimately affect soil organic C_{seq} (Jobbagy and Jackson 2000; Guo and Gifford 2002; Degryze et al. 2004).

Afforestation and reforestation programs optimize the value of soil's C_{seq} potential by converting degraded and wasteland areas into bio-energy production plantations. The application of proper management practices, species characteristics, prevailing climatic conditions, edaphic factors, and previous land use pattern will have a significant influence on the C storage potential of a plantation (Post and Kwon 2000). There are reports suggesting that SOC stock shows variations among different plantations of fast-growing species. For example, Keith et al. (2015) assessed the soil C stock changes in different plantations consisting of 9 coniferous and 16 broad-leaved SRF. The authors found that coniferous species had more SOC stock compared with broadleaved SRF, indicating that the effects are species-specific as well as soil type interactions. Species with the potential to produce higher root biomass will have more SOC sequestration in the soil (Lorenz and Lal 2005).

Paul et al. (2002) indicated that there was a positive change in the organic matter content of approximately 0.06 tons/ha/year after the establishment of afforestation activities in former arable lands. Similarly, Post and Kwon (2000) claimed that the afforestation of arable land with different species had a mean positive change in soil

C accumulation of approximately 0.34 tons/ha/year. The soil organic C_{seq} under SRF of willow and poplar was assessed by Rytter (2012) in Sweden; reported that poplar plantations (0.52 MgC/ha/year) had more soil C_{seq} value than did willow plantations (0.41 MgC/ha/year). A study conducted by Deckmyn et al. (2004) revealed that poplar in SRP had more emission reduction potential than mixed oak-beech forest. However, there are reports of no changes or decreases in soil C after afforestation. For example, Dowel et al. (2009) observed that there was decreased soil C content during the first 5 years of plantation, but also stated that losses did not persist as the age of plantation increased. Losses or no change in soil C during the early stages of plantation were also reported by Coleman et al. (2004) and Ulzen-Appiah et al. (2000). In the short term, increases in soil C after afforestation did not show significance improvement for at least 30 years, signifying that more C stocks in soil are present in older plantations (Vesterdal et al. 2002).

In long-rotation plantation, there is longer C storage than in fast-growing SRF, which is self-explanatory and reported in several studies (Sharma et al. 2016; Kaul et al. 2010; Sihag et al. 2015). Compared with natural forests, fast-growing SRP has been established where lands are degraded, on former arable land, or under agroforestry systems. In such cases, fast-growing SRP can account for short-term C storage reservoirs. Because of the fast-growing nature of SRF, there may be high net annual accumulation of C in the biomass, but it tends to reach equilibrium biomass shortly (Kaul et al. 2010). It is evident that growing hybrid poplars for very short rotations (4–6 years) may cause a loss in soil C. The cultivation of such species with a minimum rotation of 12 years could greatly help to sequester soil C (Hansen 1993).

12 Climate Change Mitigation and Adaptation Through SRF

The changing climate and its potential effects on mankind and vegetation of various forms have caused authorities to investigate solutions to tackle these unwanted problems. Mitigation and adaptation activities are being considered to combat the effects of climate change and to meet sustainable development goals. In general, mitigation activities attempt to reduce the unwanted effects of climate change, either by reducing the emission of GHGs or implementing interventions that will increase the sink of GHGs. Adaptation aims to reduce the degree of susceptibility of climate change or adapt to the changing climate by implementing different interventions (IPCC 2002; Locatelli et al. 2015).

Several mitigation and adaptation strategies in the agriculture and forest sectors have been explored in the literature. The forest ecosystem contains a significant amount of total earth C and plays a moderating role in the global climate. Following the emergence of IPCC in 1988, approaches have been made to curb climate change. The forestry sector is considered as a potential area to cope with the unwanted effects of climate change. Strategies and actions have been described in IPCC assessment reports, with a focus on the potential role of forestry and other related sectors to address climate change mitigation and adaptation. Some notable programs (e.g., REDD, REDD++, CDM) were formed as important mitigation and adaptation approaches related to forestry. Plantation forestry has been expanding at a rapid pace during the past few decades. SRF plantations consist of fast-growing tree species, signifying a huge opportunity to increase the C sink in a shorter period of time, as well as to address the scope of mitigation processes. However, due to their fast-growing nature, the plantations are harvested frequently. The limited C storage in wood and other parts is emitted back into the atmosphere through combustion, thus causing a conflict while attempting to address the role of SRF in climate change mitigation.

Theoretically, SRF will help to reduce GHG emissions in two ways, as described by Samson et al. (1999): (a) increasing the C storage capacity of tree biomass and SOC; and (b) replacing fossil fuels or conserving renewable resources by periodically harvesting under SRF. Because of the importance of SRF in increasing the forest cover area, plantation forestry around the work has focused attention on SRF establishment.

12.1 Mitigation and Adaptation Options with SRF

The following are some important mitigation and adaptation options that can be achieved through SRF:

1. Afforestation and reforestation activities: The pace of afforestation and reforestation activities has been stepped up with the introduction of CDM projects from the Kyoto Protocol. Since then, several afforestation and reforestation activity programs have been expanding across different regions of the world. Plantations with fast-growing tree species have also been extensively used for this purpose. Afforestation and reforestation programs are considered to be potential climate change mitigating options and have been implemented in various parts of the CDM projects.
2. Agroforestry: Trees form the integral part of any agroforestry system. The inclusion of fast-growing tree species in agroforestry systems is a viable and promising option. The inclusion of fast-growing tree species appeals to farmers because of the early economic returns and other intermediate products derived from this system. The C_{seq} potential of agroforestry systems has been studied and reported by different researchers around the world. A poplar-based agroforestry system in the Indo-Gangetic plains of India is one of the important systems in this aspect. Moreover, the area of agroforestry is expanding. Different stakeholders are gaining interest in agroforestry and consider it to be an important climate-resilient cropping system.
3. Industrial plantations: Many developed countries have expanded the scope of plantation forestry by introducing industrial plantations with an aim to provide raw materials for pulp wood and other wood-based industries. The fast-growing nature of SRF has advantages over conventional plantation systems because the trees are harvested at regular intervals of time and the demands of industries can be met. C_{seq} forms the basis for mitigation options, and the plantation of native species should be considered as an adaptation approach for changing climates.

4. Bioenergy plantations: The concept of SRF originated to replace fossil fuels by producing higher biomass for fuel wood and energy consumption. C_{seq} and soil C improvements under SRP have attracted the attention of different researchers. However, more information is still needed to validate their results.
5. Wasteland development: The areas of plantation forestry can be extended by covering degraded and wasteland areas. The selection of native fast-growing species has an advantage over exotic species. Agricultural lands that have been intensively farmed can turn into unproductive land, which can then be used for plantation forestry. The establishment of plantation forestry on such lands will require sufficient government funding and other facilities. However, considering the needs for the expansion of forests and tree cover, such activities will play a vital role in fightin climate change.

In general, the mitigation and adaption approaches discussed here have great potential in combating the effects of climate change. However, plantation activities (afforestation and reforestation) can cause some unwanted results, which may hamper environmental values and other social issues. Therefore, there is a need to consider the activities of afforestation and reforestation with an aim to increase the C_{seq} potential, conserve SOC, and meet the requirements for fuel wood and other industrial raw materials (IUCN 2004).

13 SRF and Ecosystem Sustainability

The state of an ecosystem is dynamic, not static. Several factors are responsible for the maintenance of ecosystem sustainability. This implies that the ecosystem's processes tend to change over the course of time—not only from interactions among the components of the ecosystem, but also from human interference or external factors that exert an impact on the sustainability of the ecosystem (Chapin et al. 1996). In the context of ecosystem stability or sustainability, it is generally accepted that natural forests are more complex and superior than plantation systems. Some concerns have been raised over plantation forestry, which is causing harmful effects on environmental processes, such as water issues (quality and quantity), biodiversity status, degradation of soil nutrients, and soil fertility, among others. This controversial situation may be an obstacle to the establishment of SRF and affect the potential of SRF. However, despite these controversial issues, SRF has been considered as a sustainable production approach for more biomass and as a potential platform to sequester CO_2. Thus, it can be seen that SRF versus ecosystem sustainability has become a burgeoning debate topic that provokes different opinions and assumptions, making this issue more ethical than scientific. In this regard, Cossalter and Pye-Smith (2003) compiled and shared the perspectives of fast-growing forestry by analyzing the opinions of different scholars who supported and opposed SRF. According to the authors, several important environmental factors have to be considered when analyzing the impact of SRF on the environment, including biodiversity, soil, and water.

Despite these problems related to environmental issues, SRF practices have been increasing day by day, ensuring the demand for wood and other wood products is met. For example, approximately 90% of the demand for wood-based industrial raw materials in India is mostly supplied through fast-growing tree species plantations (Prasad et al. 2009). SRF programs would able to maintain the ecosystem sustainability by exaggerating the tree covers in wastelands and degraded areas; this process will help in the restoration of degraded and fragile ecosystem. Interestingly, SRF not only attempts to meet the demands for wood for various uses, but it also reduces the pressure put on limited natural forests, literally preventing the act of deforestation. According to the World Forest Movement (1999), SRF has issues related to high demands for water, which could be a major setback in the establishment of SRF, especially where the land is considered for agricultural purposes. However, SRF has been reported to be successfully grown with sewage water applications; thus, the problems of water scarcity in the areas of SRF can be compensated for by such activities (Cossalter and Pye-Smith 2003; Roygard 1999). Moreover, the application of sewage water to SRF will help to solve the problem of water scarcity in SRF areas and minimize the crisis of sewage plant treatment. Phytoremediation is another possible benefit of SRF because fast-growing tree species, such as poplars and willows, can help to improve the soil toxicities of different hazardous compounds (Glass 1999). Phytoremediation through poplars and willows has been extensively studied around the world, as reported by Jackson and Attwood (1996), Hammer et al. (2003), and Laureysens et al. (2004a, b). The establishment of SRF on degraded and fragile land also can enhance the biodiversity of a particular area. Zurba (2016) reported that SRF on degraded land can improve an ecosystem's structural and functional quality by 43% and 12%, respectively.

Thus, it is clear that SRF aims to produce higher biomass for energy consumption and reduce the use of natural resources. Furthermore, it should be considered as a C conversion technology in the field of bioenergy to reduce GHG emissions (Styles and Jones 2007). However, the problems of SRF related to environmental issues also need to be addressed. Proper planning and management of SRF will not only satisfy the need for wood but can also improve the environment (Cossalter and Pye-Smith 2003).

14 Future Implications of SRF

The advantages of SRF for the production of higher biomass in general and as a platform for C storage (biomass and soil) need to be investigated. Limited information has been published in the past few decades; thus, more studies need to be conducted. Europe and other developed countries have shifted from the cultivation of agricultural crops to SRF for several reasons, especially for higher biomass energy. Therefore, C_{seq} needs to be emphasized, along with the broader future implications of SRF use around the world. Some of the important steps that need to be highlighted for the future use of SRF include the following:

- The use of native or indigenous tree species and more research on species adaptability need to be addressed.
- Policy incentives, subsidies, and other financial supports need to be strengthened.
- The required project funds need to be allocated to different stakeholders, such as the private sector, nongovernmental organizations, and farmer groups.
- More afforestation and reforestation activities need to be established in wastelands and unutilized lands.

15 Way Forward to Promote SRF in India

Several programs have been introduced to achieve more progress in plantation forestry in general and SRF in particular, with an aim to meet the goals of sustainable development. To advance these activities, the following strategies should be adopted when SRF is to be established:

(a) Commercially important species of SRF should be prioritized in each agro-ecological zone of India by the government in collaboration with research institutes.
(b) Barren land, wasteland, and village community land should be selected for raising SRF species.
(c) Quality planting material for these SRF species should be provided to farmers/villagers for raising SRF.
(d) Equal benefits should be shared among villagers who are raising SRF. A joint forest management model can be adopted for the management, monitoring, harvesting, and sale of these SRF species.
(e) New policies should be framed to cover these activities, and wood-based industries should be linked with the growers for maximum revenue and sustainable utilization of SRF.

16 Conclusion

SRF initially originated to replace fossil fuels by producing higher biomass for fuel wood and energy consumption purposes. Some common fast-growing tree species, such as earleaf acacia, babool, khair, mangium, siris, jerusalem thorn, neem, Indian heaven tree, beech oak, longbeak eucalyptus, subabool, bakain, khejri, kikar and arjun, poplar, black locust, and willow, are generally used for SRP. SRF plantations serve as a major source of raw material for wood-based industries in India and other countries. Some of the forerunners in terms of SRF plantation area around the world include Brazil, China, Indonesia, Malaysia, the United States, India, the Philippines, and Thailand. Among the SRF plantations, *Eucalyptus* spp. covers the most area, with India accounting for approximately 10% of the world's eucalyptus plantations. SRF aims to meet the demands of wood-based industries, reduce pressure on forests, and provide higher and early returns to farmers in comparison with commercial forestry.

The strengthening of policies and other required incentives need to be emphasized when appraising the role of SRF. Soil sustainability in SRF is mainly dependent upon the previous land use pattern. The impact of SRP on soil properties is either negative or positive. Generally, there is an initial decline in SOC, with a later recovery of the SOC in a due course of time. Similarly, SRF plantations also have a significant impact on the biodiversity of a particular site: Because SRF is generally composed of a single species, SRF may have lower species richness than a natural forest. However, the results may be positive when the SRF is established in areas other than natural forests.

Currently, climate change and its associated phenomena have created an imbalance in ecosystem productivity and sustainability. In response to this challenging situation, tree-based land use systems are being considered as a viable option for mitigating and adapting to climate change. In this context, SRF will help to reduce GHG emissions by increasing the C storage capacity of tree biomass, replacing fossil fuels, and conserving renewable resources by periodically harvesting under SRF. However, studies on C_{seq} potential and SOC have been limited in the past few decades, so more information is still needed to validate the results. The introduction of SRF as part of afforestation and reforestation programs under CDM projects, industrial plantations, bioenergy plantations, and agroforestry systems would add another dimension to climate change mitigation and adaptation approaches. Limitations pertaining to the establishment of SRF include environmental and social issues; however, these problems are more ethical than scientific, and most of the issues related to SRF are region specific. Therefore, the proper execution and management of SRF will be highly essential for the successful establishment of SRF. Prioritizing the importance of native species would encourage the involvement of local people. However, the establishment of plantations may be dependent on climatic, socio-economic, and edaphic factors, as well as other management interventions related to SRP. Thus, the implementation of SRF as an option for long-term C_{seq} remains an optimistic viewpoint.

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