contribution to the IPCC's Fifth Assessment Report (WGII AR5) has evaluated how patterns of risks related to climate change can be reduced and managed through adaptation and mitigation (IPCC 2014). The following conclusions have been drawn in this report:

- In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans.
- In many regions, changing precipitation and melting snow or ice are altering hydrological systems, affecting water resources in terms of quantity and quality.
- Many terrestrial, freshwater and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances and species interactions in response to ongoing climate change.
- There have been more negative impacts of climate change on crop and animal production than positive impacts.
- Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones and wildfires, have revealed significant vulnerability and exposure of some ecosystems to current climate variability.

It can safely be concluded that change in hydrological systems and rise in temperature and sea level will add more salinity to the soil and underground water in dry regions and coastal regions.

Adaptation Strategies with Special Reference to Saline Agriculture

Adaptation strategies should focus on the development of new resource-use, efficient and multiple stress-tolerant genotypes; development of new land use systems; evolvement of new climate-smart agronomic management strategies for climate change scenario; exploration of opportunities for maintenance/restoration/enhancement of soil properties; popularization of resource conservation technologies; development of spatially differentiated operational contingency plans for temperature and rainfall-related risks, including supply management through market and non-market interventions in the event of adverse supply changes, and value-added weather management strategies for reducing production risks; and development of knowledge-based decision support system for translating weather information into operational management practices, besides using and exploring opportunities for utilization of indigenous traditional knowledge. We need to identify adaptation strategies that may anyway be needed for sustainable development of agriculture. These adaptations can be at the level of individual farmer, society, community farms, village and watershed, at regional or national level. Some of the possible adaptation options related to saline environment are discussed here.

Breeding for Tolerance to Salinity, Waterlogging and Inundation

Increasing agricultural productivity requires the use of frontier technologies through investments in breeding programmes which could spark substantial yield gains in adapting to climate change. Therefore, future breeding efforts would need to address tolerance to multiple stresses like heat, drought, salinity, waterlogging, inundation, cold, frost, elemental toxicities and cultivars resistant to pests and diseases to encounter impact imposed by changing climate. This would require extensive breeding efforts, which will depend on the collection, conservation and sharing of appropriate crop genetic material among plant breeders and other researchers. The genetic resources, especially landraces from the areas where past climates mimicked the projected future climates, could serve as the serving pool for building genes for stress-tolerance. Further, there is a need for a better understanding of wild relatives and landraces, creating trait-based collection strategies and establishing pre-breeding as a public good for providing a suitable response to challenges of global climate change. A combination of conventional, molecular, marker-assisted and transgenic breeding approaches will be required to evolve the desired cultivars and varieties.

For developing salinity-, waterlogging- and inundation-tolerant crops, we would have to understand properly the physiological adaptations. Soil salinity affects plant growth and survival because ions (mainly Na^+ and Cl^- but also Ca^{2+}, Mg^{2+} and SO_4^{2-}) increase in the soil solution to concentrations that adversely decrease the availability of water to the plant due to osmotic effect. Accumulation of these ions in the plant tissue also impairs plant metabolism and growth (Greenway and Munns 1980; Mullen and Barett-Lennard 2010). Plants have different adaptation mechanisms such as the ability to exclude high Na^+ and Cl^- at the root surface, discriminate high K^+/Na^+ referring to the maintenance of K^+ uptake even in the face of very high Na^+/K^+ in the soil solution, exclude ions from the xylem stream through glands, accumulate and tolerate ions in the tissues, adjust osmotically enhanced ability to accumulate ions in older rather than younger leaves and enhanced vigour, and grow fast in congenial conditions and complete life cycle before the development of salinity (Colmer et al. 2005; Mullan and Bannett-Lennard, 2010). These traits associated with salt tolerance enable plants to withstand the adverse water relations caused by salinity, decrease the movement of toxic ions to shoots and help in the survival and growth of the plant in adverse conditions.

Waterlogging tolerance in crops is primarily associated with two major physiological traits (Colmer 2003; Mullan and Bannett-Lennard 2010) that enable plants to avoid soil hypoxia. First is the formation of aerenchyma in the cortex of roots that enable O_2 to be conducted down inside of the root. The second trait is an ability to form a barrier to radial oxygen loss that decreases the leakage of oxygen out of the root, so that more oxygen can diffuse internally and reach the root tip. Setter et al. (2009) have demonstrated that waterlogging tolerance of wheat is not exclusively associated with difference in anaerobic conditions of the soil; rather it is also associated with micro-elemental toxicities (or deficiencies) which are often affected during waterlogging. The details of these processes are not in the purview of this chapter.

The crop improvement programme in saline, waterlogged and inundation environments through conventional breeding has been a challenging pursuit and slow, as the physiological components of plant response to these stresses are complex and the genetic basis for these responses is largely unknown (Flowers 2004). Flowers and Yeo (1995) and Mullan and Bannett-Lennard (2010) listed three possible solutions to the development of crops for these stresses: (i) seek improvement within existing crop genomes, (ii) incorporate genetic information from halophytes into crop species and (iii) domesticate halophytes (Table 3). These

Table 3 Generalized breeding scheme showing the assessment and incorporation of new genetic variation for salinity, waterlogging and inundation tolerance and bringing out improved genetic population/cultivar

Breeding approach	Crop(s)	Reference(s)
If sufficient genetic variation exists within germplasm		
Conventional breeding	Lucerne	Al-Doss and Smith (1998)
	Rice	Gregorio et al. (2002)
	Wheat	Munns et al. (2006)
When insufficient genetic variation exists, new diversity can be introduced through		
Domestication of halophytes	*Distichlis* spp.	Yensen and Bedell (1993)
Recombinant line introgression	Wheat	Wang et al. (2003)
Amphiploid production	Wheat	King et al. (1997)
Use of transgenics	Wheat	Xue et al. (2004)
Use of landraces	Maize	Day (1987)
	Wheat	Munns et al. (2000)
Synthetic hexaploids		
Other approaches which may increase efficiency of conventional breeding approach		
Physiological trait selection and screening	Rice	Gregorio et al. (2002)
Marker-assisted selection	Rice	Xu and Mackill (1996)
	Wheat	Lindsay et al. (2004)

Source: Modified from Mullan and Bannett-Lennard (2010) approaches may help to genetically improve the tolerance of crops to salinity and waterlogging.

Variations within existing germplasm pools of crops have been limited under salinity stress. Flowers and Yeo (1995) reported that from records that began until 1993, they were only able to identify 25 cultivars from 12 plant species that had been released for their improved salt tolerance. Flowers (2004) further reported that between 1993 and 2000, there had been only three (one for lucerne, *Medicago sativa*, and two for rice) additional registrations. During recent years, however, some encouraging results have been obtained regarding the release of varieties with improved salt-tolerance. For example, Kharchia 65 in wheat and Pokkali and Nona Bokra in rice have given good results. Central Soil Salinity Research Institute (CSSRI) in India has developed high-productive and salt-tolerant varieties of rice (CSR 10, CSR 13, CSR 23, CSR 27, Basmati CSR 30, CSR 36 and CSR 43), wheat (KRL 1–4, KRL 19, KRL 210 and KRL 213), Indian mustard (CS 52, CS 54 and CS 56) and Chickpea (Karnal Chana 1). Further, three salt-tolerant varieties of rice (*Sumati*, *Bhootnath* and *Amalmana*) have also been released for coastal agroecosystem by the CSSRI Regional Center at Canning Town (West Bengal). In another ACIAR (Australian Council of International Agricultural Research) collaborative project with CSSRI, sources of tolerance have been identified in wheat for waterlogging (Westonia, KRL 19) and elemental toxicities (KRL 35).

Despite the low number of released cultivars for salt and waterlogging tolerance, there exists a large resource of potential germplasm for increasing the genetic base of crop plants. Colmer et al. (2006) listed 38 species as possible source of salt-tolerance in *Triticale*, with examples from the *Aegilops*, *Elytrigia*, *Elymus*, *Hordium*, *Leymus*, *Thinopyrum* and *Triticum* species. When Munns et al. (2000) screened 54 *Triticum turgidum* tetraploids comprising the subspecies *T. durum*, *T. turgidum*, *T. polonicum*, *T. turanicum* and *T. carthlicum*, they identified large and useful genetic variation for improving the salt tolerance in durum wheat. From this study, Line 149 derived from a cross between *T. monococcum* (accession C 68–101) and a durum cultivar, Marrocos, was selected with a very low Na^+ uptake which later led to the mapping of two quantitative trait loci (QTLs), designated as *Nax*1 and *Nax*2. These are used in selection of low Na^+ progeny in a durum and bread wheat breeding programme (Byrt et al. 2007). Another interesting example is the successful introduction of landrace Kharchia. The salt tolerance from Kharchia 65 was hybridized with a high-yielding wheat variety (WL 711) to develop salt-tolerant wheat cultivar (KRL 1–4) by Singh and Chatrath (2001). Legumes are usually salt sensitive, but the salt tolerance of *Vigna marina* along beaches of Andamans has encouraged scientists to inculcate salt-tolerant genes in green gram (*Vigna radiata*).

Mackill et al. (1996) described the adaptive mechanism in rice under different hydrological environments. Over time, rice farmers have developed germplasm and management techniques adapted to different eco-hydrological environments. In unbunded fields at the top topo-sequence, farmers grow short-duration, drought-tolerant upland rice varieties established via direct seeding. These varieties are usually tall and unimproved and of the *aus* varietal group (in South Asia) or tropical *japonica* (in Southeast Asia). In upper bunded fields, farmers tend to grow short-duration, photoperiod-insensitive, modern early flowering varieties, escaping late season drought stress. In well-drained mid-topo-sequence fields, farmers usually grow semidwarf high-yield potential varieties developed for irrigated conditions and established by transplanting. In lower and flood-prone fields, farmers usually direct sow tall, photoperiod-sensitive varieties that flower as the rains cease and stagnant water begins to decrease. An important example of specific adaptation to a hydrological stress is submergence-tolerance in rice grown on millions of hectares in eastern India and Bangladesh where rice fields are subject to flash flooding that completely submerges plants. Several landraces tolerate up to 2 weeks of complete flooding and the key trait associated with this tolerance is growth inhibition during submergence (Braun et al. 2010). A highly tolerant Indian landrace FR13A was used as a donor for the trait in genetic analysis that identified a single major quantitative trait locus, designated *sub*1, which controlled 60–70 % of phenotypic variations for the trait in the screening system (Xu and Mckill, 1996). Through marker-assisted selection, the *sub*1 locus has been introgressed into mega-varieties. *Sub 1* locus has been introgressed in many rice varieties and five such varieties have already been released in different countries of Asia (Ismail et al. 2013). One such line has been released in India, Bangladesh, Nepal and Myanmar as *Swarna-Sub1* that can survive full submergence of more than two weeks. Other lines with submergence tolerance have been released as Samba Mahsuri-Sub1 in Nepal, IR 64-Sub1 in the Philippines and Indonesia, BR-11-Sub1 in Bangladesh and Ciherang-Sub1 in Indonesia. Many other lines are in pipeline. These varieties have made perennially flooded area flourish with rice, which were otherwise kept fallow. Recently, Singh et al. (2014) explained physiological basis of tolerance to complete submergence in rice which involves genetic factors in addition to the *Sub1* gene and suggested the possibility of further improvements in submergence tolerance by incorporating additional traits present in FR13A or other similar landraces. Further, *Hordeum marinum* has been identified as a source of genes for salt and waterlogging tolerance that could be transferred into bread wheat (Colmer et al. 2005).

National Bureau of Plant Genetic Resources (NBPGR), India, screened the entire germplasm of wheat (about 22,000 accessions) comprising *Triticum aestivum*, *T. durum* and *T. dicoccum* conserved in National Gene Bank against a biotic stress under National Initiative on Climate Resilient Agriculture (NICRA) project. Besides this, protocols have been standardized for in vitro callus transformation in variety F1D 2967 for developing transgenic wheat with enhanced heat tolerance. Proteome analysis of nitrogen-efficient cultivars at elevated CO_2 conditions was also carried out and final results will be available shortly.

Table 4 Rice cultivars for tolerance to different stresses

Stress	Cultivars
Waterlogging	AC 1125-A, AC 1781, AC 1996, AC 813, AC85, AC 39416A
Anaerobic germination	AC 34245, AC 34280, AC 40331-A, AC 40346, AC 416222-A,
	AC 41647, AC 41644-A, AC 41644-B, AC 39397, AC 394418, AC 39416-A
Complete submergence for 20 days better than Swarna-Sub1	AC 38575, AC, 37887. IC 258990
	IC 258830, AC 42087, AC 20431-B
Vegetative stage drought	IC 568083, IC 568112, IC 568065, IC 568016, IC 568030, IC568083, IC 568112, IC 568065, Mahulata, IR77298-14-1-2-10-3
Reproductive stage drought	CR 143-2-2, IR 55419–04, IR 80461-B-7-1
Seedling stage salinity	Pokkali (AC 41485), Chettivivippu (AC 39389), AC 39394
Tolerant to both anaerobic germination and salinity	Kamini, Ravana, Talmunga, Paloi, Longmutha, Murisal, Rashpanjor, AC 39416 (A)
Tolerant to anaerobic germination, salinity and waterlogging	AC 39416 (A)

Source: Venkateswarlu et al. (2012)

In another project, around 3000 key rice germplasm has been evaluated for tolerance to submergence, drought and salinity, and the tolerant cultivars were identified (Table 4).

Popular rice varieties (six short duration and seven medium and long duration) of Cauvery basin (India) were grown during summer to assess the performance under higher temperature as summer season experienced 3–4 °C higher than the growing season. Among the varieties tested (Geethalakshmi et al. 2011), ADT 38, ADT 48, CO 43, ADT 36, ADT 37 and BPT 5204 withstood higher temperature and gave higher yields compared to others. This indicates that these varieties can be recommended for the further warmer climate.

Domestication of Halophytes

Halophytes are naturally evolved salt-tolerant plants having the ability to complete their life cycle in salt-rich environment where almost 99 % of salt-sensitive species die because of NaCl toxicity and thus may be regarded as a source of potential new crops (NAS 1990; Glenn et al. 1991; Jaradat 2003; Dagar 2003) particularly for coastal areas where, if necessary, these may be irrigated with seawater. The naturally growing halophytes have more resilience to climate change compared to cultivated plants. While since long these have been in the diet of the people and are utilized in variety of ways in routine life, their scientific exploration as crops developed only in the latter half of the twentieth century (Rozema et al. 2013; Panta et al. 2014; Dagar 2014).

Many halophytes have been evaluated for their potential use as crop plants and also for remedial measures (Dagar 1995b; Miyamoto et al. 1996; Barrett-Lennard 2003; Reddy et al. 2008; Ruan et al. 2008; Qadir et al. 2008; Yensen 2008; Flowers et al. 2010; Tomar et al. 2010; Rozema et al. 2013; Hasannuzzaman et al. 2014; Dagar et al. 2009, 2013, 2015c). Species such as *Distichlis palmeri*, *Chenopodium quinoa*, *C. album*, *Pennisetum typhoides*, *Salicornia bigelovii*, *Diplotaxis tenuifolia* and many others have been established as food crops, are being explored commercially and can be cultivated using sea water for irrigation. Similarly species of *Atriplex* and *Maireana*; grasses *Leptochloa fusca*, *Chloris gayana*, *C. barbata*, *Aeluropus lagopoides*, *Brachiaria mutica*, *Paspalum conjugatum*, *Panicum laevifolium*, *P. maximum*; and many others are constituents of silvopastoral systems developed on waterlogged saltlands in different agroclimatic regions of the world. At least 50 species of seed-bearing halophytes are potential sources of edible oil and proteins. *Salicornia bigelovii*, *Terminalia catappa*, *Suaeda moquinii*, *Kosteletzkya virginica*, *Batis maritima*, *Chenopodium glaucum*, *Crithmum maritimum* and *Zygophyllum album* are a few examples. A number of species including the halophytes *Tamarix chinensis*, *Phragmites australis*, *Spartina alterniflora* and species of *Miscanthus* have been evaluated as biofuel crops for ethanol production in the coastal zone of China (Liu et al. 2012), while many others such as *Halopyrum mucronatum*, *Desmostachya bipinnata*, *Phragmites karka*, *Typha domingensis* and *Panicum turgidum* are grown in coastal regions of Pakistan as source of bioethanol (Abideen et al. 2011).

In addition, sugar beet (*Beta vulgaris*), mangrove palm (*Nypa fruticans*) and Kallar grass (*Leptochloa fusca*) are identified as a source of liquid and gaseous fuel (Jaradat 2003). Screw pine (*Pandanus fascicularis*), quite predominant along Indian coast, is rich in methyl ether of beta-phenylethyl alcohol and is used as a perfume and flavouring ingredient (Dutta et al. 1987). *Simmondsia chinensis* yields oil like sperm whale oil from its seeds and is a viable salt-tolerant commercial plant for dry regions. Similarly *Salvadora persica*, *Ricinus communis* and *Pongamia pinnata* yield commercial oils and can be explored economically. *Euphorbia antisyphilitica* has been found as a potential petro-crop producing huge biomass on sandy soils irrigating with saline water of EC 10 dS m^{-1} (Dagar et al. 2014). It produced 23 Mg ha^{-1} dry biomass from degraded calcareous soil and requires very low dose of nutrients. Many medicinal and aromatic plants such as *Aloe vera*, *Asparagus racemosus*, *Adhatoda vasica*, *Cassia angustifolia*, *Catharanthus roseus*, *Citrullus colocynthis*, *Lepidium sativum*, *Ocimum sanctum*, *Plantago ovata*, *Glycyrrhiza glabra*, *Matricaria chamomilla*, *Cymbopogon flexuosus*, *C. martini* and *Vetiveria zizanioides* are successfully cultivated irrigating with saline water of EC up to 10 dS m^{-1} (Tomar and Minhas 2004a, b; Tomar et al. 2005, 2010; Dagar et al. 2004a, b, 2006b, 2008, 2013). More details will follow under agroforestry section of this chapter. Many woody and succulent halophytes are used for turf production for golf and landscape development, paper industry, medicinal use and other commercial purposes. Therefore, more efforts are needed to domesticate these useful resources, particularly in coastal areas in agroforestry mode.

Development of New Land Use Systems

Salinity and inundation are inherited problems in coastal areas of West Bengal and Bangladesh. Farmers struggle in utilizing these lands for crop production. Recently some efforts have been done in reshaping these lands for improving the agricultural production. Different land-shaping techniques for improving drainage facility, rainwater harvesting, salinity reduction and cultivation of plantation crops and fish (freshwater and brackish water fish) for livelihood and environmental security were tested on about 400 ha degraded and low-productive land in disadvantaged areas in Sundarbans region of Ganges Delta (West Bengal) and *tsunami*-affected areas in Andaman and Nicobar Islands covering 32 villages in four districts (South 24 Parganas and North 24 Parganas districts in West Bengal and South Andaman and North and Middle Andaman districts in Andaman and Nicobar Islands) during 2010–2014. The soil in the study area was affected by high level of soil salinity (ECe up to 18 dS m^{-1}) and water salinity (EC up to 22 dS m^{-1}) that limits the choice and options of growing crops in the area. The following land-shaping technologies were tried on farmers' fields in coastal and islands areas (Burman et al. 2013):

- *Land shaping for deep furrow and high-ridge cultivation*: The 50 % of farm land was sloped into alternate furrows (3 m top width × 1.5 m bottom width × 1.0 m depth) and ridges (1.5 m top width × 3 m bottom width × 1 m height). The ridges remained relatively free from drainage congestion and low in soil salinity build-up. These could be successfully used for raising plantations (fruits) or vegetables during both *rabi* and *kharif*; and furrows are used for rainwater harvesting (to be used as life-saving irrigation in *rabi* season) and cultivation of rice and fish along with the remaining original field. During dry season, the remaining field was also used for cultivation of low-water-requiring crops.
- *Land shaping for shallow furrow and medium ridge cultivation*: About 75 % of the farm land was shaped into furrows (2 m top width × 1 m bottom width × 0.75 m depth) and medium ridges (1 m top width × 2 m bottom width × 0.75 m height) with a gap of 3.5 m between two consecutive ridges and furrows. In wet (monsoon) season the furrows could be used for rice and fish culture with rest of the field for rainwater harvesting. In dry season, these could be used for rice cultivation. The ridges are planted with fruit trees or cultivated with vegetables or pulses throughout the year. The remaining original land could be used for low-water-requiring crops.
- *Land shaping for farm ponds*: The 20 % of farm land was converted into on-farm reservoir (OFR) for in situ conservation of excess rainwater used during dry season, supplemental irrigation in *kharif* and fresh water aquaculture. The dugout soil was used to raise land to be used for crop cultivation. The dykes of the pond may also be planted with fruit trees.
- *Land shaping for paddy-cum-fish culture*: Trenches of about 3 m width × 1.5 m depth were dug around the field with a ditch of 6 m × 6 m × 3 m (depth) at one corner. The excavated soil was used for making dykes of about 3 m width and 1.5 m height to protect the fish cultivated with paddy. During wet season, paddy and fish were grown on original land and vegetables/fruits on dykes. During summer, low-water-requiring crops and vegetables were grown on dykes (in case fruits are not grown) and low-water-requiring crops on original land and life-saving irrigation was given from water harvested in furrows. The original land in some cases was used for brackish fish culture. In that case, at the end of summer season, brackish water was drained out along with monsoon rains and the land was again used for paddy-cum-fish culture. Due to the creation of different land situations and following cultivation of crops round the year, organic C; available N, P and K; and biological activities (microbial biomass C) in surface soil improved under land-shaping techniques compared to land without land shaping.

Table 5 Enhancement in cropping intensity, employment generation and net income under different land-shaping techniques in Sundarbans and Andaman and Nicobar Islands

Land-shaping technologies	Cropping intensity (%)		Employment generation (man-days hh^{-1*} $year^{-1}$)		Net return (000 INR $ha^{-1}yr^{-1}$)	
	Before	After	Before	After	Before	After
Farm pond	114[a], 100[b]	193[a], 200[b]	87[a], 8[b]	227[a], 22[b]	22[a], 10[b]	140[a], 148[b]
Deep furrow and high ridge	114[a]	186	87	218	22[a]	102[a]
Paddy cum fish	114[a], 100[b]	166[a], 200[b]	87[a], 8[b]	223[a], 35[b]	22[a], 24[b]	127[a], 148[b]
Broad bed and furrow	100[b]	240[b]	9[b]	48[b]	24[b]	212[b]
Three tier	100[b]	220[b]	10[b]	42[b]	30[b]	221[b]
Paired bed	100[b]	240[b]	9[b]	54[b]	24[b]	216[b]
Brackish water aquaculture	0/100	–	25[a]	100[a]		146[a]

Source: Burman et al. (2015)
Note: Costs and returns at current price of 2012–2013 *hh^{-1}: per household
[a]av. holding was 0.35 ha in Sundarbans
[b]av. holding of implementation was 0.20 ha in Andaman and Nicobar Islands

About 1950 water storage structures were created under different land-shaping techniques and 1,305,000 m^3 rainwater was harvested annually in these structures in the study area, and with this harvested rainwater, about 260 ha areas which were earlier under mono-cropping with rice due to shortage of irrigation water were brought under irrigation for growing multiple crops round the year. The cropping intensity increased up to 240 % from a base level value of 100 % due to the implementation of the land-shaping techniques (Table 5). These land-shaping techniques are very popular among the farmers of both Sundarbans and Andaman and Nicobar Islands as these have increased the employment and income of the farm family by manifolds compared to baseline value. Average net income per ha of farm land has been increased from INR 22,000 to INR 1,23,000 in Sundarbans and INR 22,400 to INR 1,90,000 in Andaman and Nicobar Islands.

Agroforestry-Based Agricultural Systems

The research efforts in the recent past have greatly enhanced the understanding of biology and management of forestry plantations on salt-affected lands with the use of saline waters (Aronson 1989; Singh et al. 1988, 1993, 1995, 1997; Leith and Al Masoom 1993; Lieth and Lieth 1993; Dagar et al. 2001a, b; Dagar 2003; Tomar et al. 1998, 2003a, b, 2005, 2010; Singh and Dagar 1998, 2005; Dagar and Singh 2007; Dagar 2014; Dagar and Minhas 2016). Evidences are that subject to some of the obligatory changes in reclamation technologies, the salty lands can successfully be put to alternate land uses through agroforestry programmes. In addition to meeting ameliorative and long-term ecological goals on these landscapes, the alternate land use systems can be as economical as some cropping alternatives. Worldwide experiences show that human-induced salinity problems can develop rapidly, while the hydrological, agronomic and biological solutions put forward for reclamation are very expensive and time-consuming. Moreover, implementation of these solutions is constrained due to socio-economic and political considerations. Thus, despite the availability of technical know-how, the rehabilitation of the salty and waterlogged lands is progressing at a very slow pace. The use of agroforestry systems is now being put forward as a viable alternative. Though the salinity and waterlogging stresses can be as hostile for the woody tree species, these are known to tolerate these stresses better than the annual crop species. Therefore, an attempt is made here to collate the existing information on afforestation technologies for the varied agroclimatic situations demanding site-specific solutions and agroforestry systems/

practices evolved for saline and waterlogged environments and utilizing saline waters.

Agroforestry is a dynamic, ecologically sound, natural resource management practice that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production from increased social, economic and environmental benefits. Agroforestry is a better adaptation for land use system to mitigate climate-related risks. Approximately 1.2 billion people (20 % of the world's population) depend to a large extent on agroforestry products and services for their survival (ICRAF 2000). Incorporating trees into farming systems leads to greater prosperity at the farm level. Trees provide farmers with marketable products, such as lumber, building poles, firewood, animal fodder, fruits, medicines, etc., on which farmers can earn extra income. They improve soil fertility by fixing nitrogen from the air and recycling nutrients from the soil, thereby helping to increase crop yields and ensuring stability of future production. Trees on farms also help hold moisture where it is needed, reduce soil erosion and keep valuable topsoil in place, reduce intensity of downstream flooding and maintain watershed building materials. They serve as live fence in semiarid regions, protecting vegetable and cereal crops that would otherwise be over-run by livestock. Trees increase ecosystem biodiversity above and below ground, and they can help ameliorate global climate change by sequestrating carbon – in their live biomass as well as in the soil – that otherwise would be added to the earth's atmosphere. Several studies have shown that inclusion of trees in the agricultural landscapes often improves the productivity of systems while providing opportunities to create carbon sinks (Maikhuri et al. 2000; Pandey 2002, 2007; Albrecht and Kandji 2003; Jeet Ram et al. 2011; Dagar et al. 2015a, b). An average carbon storage by agroforestry land use system has been estimated to be around 9, 21, 50 and 63 Mg C ha^{-1} in semiarid, subhumid, humid and temperate regions, respectively (Schroeder 1994).

It has been estimated that globally approximately 38 Gt (1 Gt = 1 billion tons) of carbon could be sequestered over the next 50 years, i.e. 30.6 Gt by afforestation/reforestation and 7 Gt through the increased adoption of agroforestry practices. The prominent role of forestry and agroforestry systems in carbon sequestration has increased global interest in these land use options to stabilize greenhouse gas emission. Throughout the world, the area under agroforestry is of the order of 400 Mha. It is estimated that an additional 630 Mha of current cropland and grasslands could be converted into agroforestry (IPCC 2000). Agroforestry system especially agri-silvicultural/horti-silvicultural system can be carbon sinks and temporarily store carbon. It plays a significant role in rehabilitation of salt-affected and waterlogged areas by increasing their productivity, amelioration of these lands, carbon sequestration and providing other environmental services including improvement in biodiversity.

Agroforestry in Sodic Lands

Though the records of plantations on alkali soils in India and elsewhere are available from 1874 (Oliver 1881; Leather 1897; Moreland 1901), no systematic experiments were conducted to raise plantation until the recent past (Sandhu and Abrol 1981; Singh and Gill 1992; Dagar et al. 2001a, b; Singh and Dagar 2005). Singh (1994) extended site suitability studies to 20 alkali soil sites in Ganga–Yamuna Doab. Barren alkali soils, represented by Natric Camborthids and Calciorthids, had pH of 10–10.5, ESP of 60–95 and ECe between 1 and 43 dS m^{-1} and constituted mainly by carbonates and bicarbonates of sodium. *Prosopis juliflora* was found to grow in typic Natrustalfs with a maximum pH of 10, ESP up to 60 and ECe less than 3 dS m^{-1} in the rooting zone, even though the top 44 cm of soil had pH 10.3, ESP 70 and ECe 12 dS m^{-1}. Other planted species failed to grow in this soil. Along with some natural growth, *P. juliflora* and *A. nilotica* established on typic Natrustalfs with an average pH of 9.5, ESP 50 and ECe 10 dS m^{-1}. Other species like *Dalbergia sissoo*, *Pongamia pinnata*, *Albizia lebbeck*, *Terminalia arjuna*, *Butea monosperma*, *Capparis decidua* and *Salvadora persica* did well on soil with a pH less than 9.1, ESP up to 44 and ECe up to 7.5 dS m^{-1}. The growth of most of these species except *P. juliflora* was arrested with a *kankar* pan within 80 cm soil depth. *Casuarina equisetifolia* and *Acacia nilotica* could grow well in soil with ESP 30.6, whereas *Pongamia pinnata* and *Dalbergia sissoo* survived only up to ESP of 15.2 (Yadav and Singh 1986). In India, based on the performance of tree saplings planted in soils of different pH (7–12), relative tolerance was reported (Singh et al. 1987) in the order *Prosopis juliflora*>*A. nilotica*> *Haplophragma adenophyllum*> *Albizia lebbeck*> *Syzygium cuminii*. Chaturvedi (1984) reported that a 30 % reduction in biomass was observed at pH 10 as compared to pH 7 in tree species like *A. nilotica*, *Terminalia arjuna* and *Pongamia pinnata*, while at pH 9.5 in *Eucalyptus tereticornis*. Out of 30 tree species planted on highly alkali soil (pH of profile 10.1–10.6), only three species *Prosopis juliflora*, *Acacia nilotica* and *Tamarix articulata* were found economically suitable (Dagar et al. 2001b) by having good biomass, producing 51, 70 and 93 Mg ha^{-1} air-dried biomass, respectively, after 7 years of plantation. From a long-term experiment, Singh et al. (2008) reported a total biomass ranging from 19.2 to 56.5 Mg ha^{-1} from different species after 10 years of plantation in high sodic soil of pH 10.6 in Uttar Pradesh. *Prosopis juliflora* produced the highest biomass (57 Mg ha^{-1}), followed by *A. nilotica* (51 Mg ha^{-1}), *Casuarina equisetifolia* and *Terminalia arjuna* (42 Mg ha^{-1} each), *Pithecellobium dulce* and *Eucalyptus tereticornis* (32 Mg ha^{-1} each), *Prosopis alba* (28), *Pongamia pinnata* (27 Mg ha^{-1}), *Cassia siamea* (22 Mg ha $^{-1}$) and *Azadirachta indica* (19 Mg ha^{-1}). These tree species improved soil in terms of reduction of pH and exchangeable sodium percentage (ESP), and increase in organic carbon significantly. When these trees were harvested after 14 years of plantation, maximum biomass production was achieved in *Eucalyptus tereticornis*, *A. nilotica*, *Prosopis juliflora* and *Casuarina equisetifolia* giving 231, 217, 208 and 197 kg bole weight per plant, respectively, whereas *Prosopis alba*, *Pithecellobium dulce*, *Terminalia arjuna*, *Pongamia pinnata*, *Azadirachta indica* and *Cassia siamea* provided relatively lower bole weight of 133, 100, 97, 84, 83 and 52 kg per plant, respectively. These plants reduced soil pH and increased soil organic carbon ranging from 2.4 g kg^{-1} in *Eucalyptus* to 4.3 g kg^{-1} in *P. juliflora* from initial 0.8 g kg^{-1}.

In one trial, Singh and Singh (1990) observed that fruit trees like *Emblica officinalis*, *Carissa carandas*, *Ziziphus mauritiana*, *Syzygium cuminii*, *Grewia asiatica*, *Psidium guajava*, *Aegle marmelos* and *Vitis vinifera* when grown on different alkali soils could produce 20.5, 5.2, 15.5, 16.0, 6.0, 12.5, 6.5 and 18.3 Mg ha^{-1} fruits at different pH of 10.1, 10.0, 9.6, 9.5, 9.2, 9.0, 8.5 and 9.0, respectively. Out of ten fruit tree species tested on highly alkali soil (pH ~ 10) using different soil amendments (Singh et al. 1997; Dagar et al. 2001b; Singh and Dagar 2005), *Ziziphus mauritiana*, *Syzygium cuminii*, *Psidium guajava*, *Emblica officinalis* and *Carissa carandas* were found the most successful species showing good growth and also initiated fruit setting after 4–5 years of plantation. After 10 years, these could produce 12–25 Mg ha^{-1} fruits annually. Thus, based on the evaluation of more than 60 species (through series of experimentation on sodic soils in Indian subcontinent), it could be concluded that *Prosopis juliflora* was the best performer for the sodic soils of high pH (>10), followed by *Tamarix articulata* and *Acacia nilotica*. Species such as *Eucalyptus tereticornis*, *Terminalia arjuna*, *Salvadora oleoides* and *Cordia rothii* and fruit trees (with improved management) such as *Carissa carandas*, *Emblica officinalis*, *Syzygium cuminii* and *Psidium guajava* can be grown with great success on moderate alkali soil (pH < 10), preferably at pH around 9.5 or less.

In Pakistan, Hafeez (1993) summarized the results of field experiments on a soil with pH from 8.0 to 9.5 and soluble salt content varying from 0.3 to 2.9 %, in which 26 tree species from Australia and several indigenous species were compared for their salt tolerance. *Eucalyptus camaldulensis* performed the best, followed by *Casuarina cunninghamiana*, *Eucalyptus rudis*, *E. microtheca* and *C. glauca*. Qureshi et al. (1993a, b) reporting the results of a long-term study on saline sodic soil (pH 9.5, ECe 10–15 dS m^{-1}, SAR 116) concluded that *Eucalyptus camaldulensis* was the most successful species under a variety of salinity conditions, while *Leucaena leucocephala* was the most aggressive species especially under moderate salinity conditions. *Tamarix articulata* showed rapid growth under light salinity.

In agroforestry, forest or fruit trees are raised in wider spaces (row to row 4–5 m, plant to plant 4 m) and the arable crops are cultivated in the interspaces. In one trial, Egyptian clover (*Trifolium alexandrinum*), wheat, onion (*Allium sativum*) and garlic (*Allium cepa*) could be grown successfully for 3 years as intercrops with fruit trees *Carissa carandas*, *Punica granatum*, *Emblica officinalis*, *Psidium guajava*, *Syzygium cuminii* and *Ziziphus mauritiana*. These crops yielded 10.6–16.7 Mg ha^{-1} forage from *L. fusca*, 1.6 to 3.0 Mg ha^{-1} grains from wheat, 1.8 to 3.4 Mg ha^{-1} onion bulbs and 2.3 to 4.1 Mg ha^{-1} garlic (Tomar et al. 2004), showing that during establishment of fruit trees, suitable arable crops can be harvested profitably from interspaces of trees. Many forest and fruit tree species can be raised on alkali soils (pH up to 10), but some of these like pomegranate (*Punica granatum*) and bael (*Aegle marmelos*) are unable to tolerate water stagnation during rainy season. To avoid water stagnation problem in alkali soils, Dagar et al. (2001a) raised these trees on bunds and arable and forage crops in sunken beds. The water-loving crops such as Kallar grass (*Leptochloa fusca*) or rice (salt-tolerant varieties like CSR-10, CSR-30 and CSR-36) could be cultivated successfully in interspaces during rainy season. For the winter season, crops such as Egyptian clover (*Trifolium alexandrinum*) or wheat (var. KRL-4, KLR-210) can be grown in sunken beds. Results showed that these crops could be grown successfully when plantations were raised on bunds. On an average, grain yield of 4.3–4.9 Mg ha^{-1} of rice (salt-tolerant var. CSR 10) and 1.2–1.4 Mg ha^{-1} of wheat (KRL 1–4) was obtained in sunken beds. In second rotation, 21.3–36.8 Mg ha^{-1} fresh forage of Kallar grass (*Leptochloa fusca*) and 44.9–47.8 Mg ha^{-1} fresh forage of Egyptian clover (*Trifolium alexandrinum*) were obtained. There was no yield reduction due to plantation. After 2 years, soil amelioration in terms of reduction in soil pH and increase in organic matter and nitrogen contents was significant.

The sodic lands are very poor in forage production under open grazing, but when brought under judicious management, these can be explored successfully for sustainable fodder and fuel wood production. *Leptochloa fusca*, *Brachiaria mutica*, *Chloris gayana*, *Panicum maximum*, *P. antidotale* and *Panicum laevifolium* were found most suitable grasses for these soils and can constitute viable silvopastoral system. *L. fusca* could be rated the most tolerant grass to high sodicity (pH $>$ 10) and waterlogged conditions and produced 45 Mg ha^{-1} green forage without application of any amendment. On an average, this grass produced 16 Mg ha^{-1} dry biomass along with *P. juliflora* and *Acacia nilotica* trees and forage biomass of 17–18 Mg ha^{-1} with *Dalbergia sissoo* and *Casuarina equisetifolia* (Singh and Dagar 2005).

An associative nitrogen-fixing bacterium, *Azoarcus*, occurs as an endophyte in the roots of Kallar grass (*L. fusca*) – a pioneer species of alkali soils which yields 9–12 Mg ha^{-1} of dry biomass without application of any nitrogen fertilizer; nearly half of the plant N of 90–120 kg ha^{-1} is derived from associative fixation (Malik et al. 1986) and helps the plants survive in adverse habitats. As discussed above, sodic soils with moderate pH may be explored for growing arable crops as intercrops with forest and fruit trees both. Singh et al. (1997) proved that poplar (*Populus deltoides*)-based agroforestry approach on moderate alkali soil (pH 9.2) was highly profitable (B:C ratio 3.3) in irrigated rice–wheat crop rotation. This system also helped in soil amelioration by reducing soil pH and improving soil organic carbon. Under tree cover, the bulk density of soils decreased and there was substantial increase in soil porosity and hence infiltration rate, water-holding capacity, field capacity and permeability. In India, using auger hole technique, different state forest departments have reclaimed about 60 thousand ha of highly deteriorated sodic soils through agroforestry plantations on village community lands, adjoining roads, railway lines and canals (CSSRI 2011).

The salt-affected soils of black soil zone (saline/sodic vertisols) are generally either contemporary or of secondary origin. The contemporary salty soils exist in the topographic situation having poor drainage conditions. However, the soils that might have become sodic due to injudicious use of irrigation water can also be encountered in the irrigation command area. These lands can successfully be grown with forest and fruit trees. In 14 years of plantation, it was found that *P. juliflora* and *Azadirachta indica* were the most successful species for these soils. Among fruit trees, gooseberry (*Emblica officinalis*) and *ber* (*Ziziphus mauritiana*) were the most successful on alkaline vertisol (ESP 25–60), followed by sapota (*Achras zapota*). The latter is tolerant to sodicity but sensitive to frost and hence has limitations for northwest India. Through series of experiments conducted on raised and sunken beds, it was concluded that both forest tree species such as *Azadirachta indica* and fruit trees like pomegranate (*Punica granatum*), jamun (*Syzygium cuminii*) and goose berry (*Emblica officinalis*) can successfully be grown on raised bunds and rainfed rice during rainy season in sunken beds, and suitable winter crops can be cultivated in residual moisture in sunken beds (CSSRI 2002–2003 to 2012–2013).

Among grasses, *Aeluropus lagopoides*, *Leptochloa fusca*, *Brachiaria mutica*, *Chloris gayana*, *C. barbata*, *Dichanthium annulatum*, *D. caricosum* and *Bothriochloa pertusa* and species of *Eragrostis*, *Sporobolus* and *Panicum* are the most successful and may form suitable silvopastoral system for sodic vertisols. In another experiment on these soils, it was found that under 7 years of plantations of *P. juliflora* and *Azadirachta indica* with Kallar grass, the soil pH, ECe and ESP reduced from 8.8, 4 dS m^{-1} and 35 to 8.5, 1.29 dS m^{-1} and 10, respectively, under *Prosopis*-based system and 8.5, 1.3 dS m^{-1} and 14, respectively, under *Azadirachta* system. The experiments conducted in sodic vertisols with ESP 40 growing grasses, namely, *Leptochloa fusca*, *Brachiaria mutica* and *Vetiveria zizanioides*, showed that all these grasses performed well and the forage biomass increased during second year because of good establishment and forming clumps. The uptake of sodium by *L. fusca* was highest, followed by *B. mutica* at every stage of cutting. During 3 years, these grasses removed 144.8, 200.0 and 63.5 kg ha^{-1} sodium from soil, respectively (AICRP 2002–2004).

Integrating trees with the grasses in silvopastoral systems has been found to be effective to improve soil fertility and increase soil carbon sequestration. Organic carbon increased by 24–62 % in soils under the silvopastoral systems as compared to that in the grassland system on a sodic soil (Gupta et al. 2015). The microbial carbon, as regulated by litter and root carbon input, was found to be good in bio-amelioration of sodic soils (Table 6). Carbon sequestration also provided associated ecosystem co-benefits such as increased soil water-holding capacity, better soil structure and improved soil quality and nutrient cycling. Implementing appropriate management practices to build up soil carbon stocks in grasslands could lead to considerable mitigation, adaptation and development benefits. The soil microbial biomass carbon and soil carbon at 0–15 cm soil depth in

Table 6 Microbial biomass carbon and soil carbon in surface 0.15 m soil under grassland systems of sodic soils in Northwestern India

Grassland system	Microbial C (kg ha^{-1})	Soil carbon (kg ha^{-1})
Sporobolus marginatus[1]	85	4816
Desmostachya bipinnata[1]	112	5265
Dalbergia sissoo + *D. bipinnata*[1]	325	13,572
Acacia nilotica + *D. bipinnata*[1]	225	10,902
Prosopis juliflora + *D. bipinnata*[1]	348	14,211
Mixed grassland[3]	148	7732
D. bipinnata[3]	408	15,443
Vetiveria zizanioides[3]	475	17,088
D. bipinnata[2]	347	13,949

Sources: Kaur et al. (2002), Neeraj et al. (2004), Gupta et al. (2015); location of sites: Bichhian[1], Karnal[2], Kurukshetra[3] silvopastoral system were positively related to soil carbon (r^2 0.997).

Many of the medicinal and aromatic underexplored crops are in great demand for both internal requirements and export. But since these crops are nonconventional in nature, it is not always feasible to produce these on fertile lands, which can be used for arable crops. The marginal lands, specifically the saltlands where profitable returns are not possible from conventional crops, can successfully be utilized for the cultivation of these high-value crops with marginal inputs. Results of several experiments conducted by Dagar et al. (2004b) clearly indicated that aromatic grasses such as palmarosa (*Cymbopogon martini*) and lemon grass (*C. flexuosus*) could successfully be grown on moderate alkali soils up to pH 9.2, while vetiver (*Vetiveria zizanioides*), which withstands both high pH and stagnation of water, could successfully be grown without significant yield reduction (as compared to normal soil) on highly alkali soils. Medicinal isabgol (*Plantago ovata*) produced 1.47–1.58 Mg ha^{-1} grain (including husk) at pH 9.2 and 1.03–1.12 Mg ha^{-1} at pH 9.6 showing its potential at moderate alkali soil (Dagar et al. 2006a). *Matricaria chamomilla*, *Catharanthus roseus* and *Chrysanthemum indicum* were other interesting medicinal and flower-yielding plants, which could be grown on moderate alkali soil (Dagar et al. 2009). All these crops can be blended suitably as intercrops in agroforestry systems. Mulhatti (*Glycyrrhiza glabra*), a leguminous medicinal crop, was found to perform better in moderate alkali soil (up to pH 9.6) than normal soil and is quite remunerative. Besides 2.4–6.2 Mg ha^{-1} forage per annum, a root biomass (medicinal and commercial) of 6.0–7.9 Mg ha^{-1} could be obtained after 3 years of growth (Dagar et al. 2015c) fetching Rs 6–8 lakhs ha^{-1}, i.e. 2.0–2.6 lakhs ha^{-1} per annum, and the soil was ameliorated in terms of reduction in pH and ESP and increase in organic carbon substantially. Thus, moderate alkali soils can be explored for remunerative alternate agroforestry crops.

Agroforestry in Waterlogged Saline Soils

On the basis of performance of trees for 6–9 years after planting in saline waterlogged soils (Tomar and Patil 1998; Tomar and Minhas 1998; Tomar et al. 1998), it was found that species like *P. juliflora*, *Tamarix articulata*, *T. traupii*, *Acacia farnesiana*, *Parkinsonia aculeata* and *Salvadora persica* are most tolerant to waterlogged saline soil and could be raised successfully up to salinity levels of ECe 30–40 dS m^{-1}. Species like *A. nilotica*, *A. tortilis*, *A. pennatula*, *Casuarina glauca*, *C. obesa*, *C. equisetifolia*, *Callistemon lanceolatus*, *Eucalyptus camaldulensis*, *Feronia limonia*, *Leucaena leucocephala* and *Ziziphus mauritiana* could be grown on sites with ECe 10–20 dS m^{-1}. Other species including *Casuarina cunninghamiana*, *Eucalyptus tereticornis*, *Terminalia arjuna*, *Albizia caribaea*, *Dalbergia sissoo*, *Emblica officinalis*, *Guazuma ulmifolia*, *Punica granatum*, *Pongamia pinnata*, *Samanea saman*, *Acacia catechu*, *Syzygium cuminii* and *Tamarindus indica* could be grown satisfactorily only at ECe < 10 dS m^{-1}. Based on the salinity level at which satisfactory growth of species occurred, salt-tolerant agroforestry species have been grouped into highly tolerant, tolerant and moderately tolerant categories (Table 7).

Qureshi et al. (1993a, b) reported that the *Atriplex amnicola* and *A. lentiformis* were the most successful species on saltlands in Pakistan, producing forage dry biomass up to 8 Mg ha^{-1}. The feeding trials showed that these species could be used effectively to supplement normal requirements of fodder for goats and buffaloes to the extent of 25 % by weight. These bushes could be grown as intercrop with *Eucalyptus camaldulensis*. *Leptochloa fusca* grass was found to have special advantages in terms of forage production having no ill effects on animal health and playing role in soil amelioration. *Aeluropus lagopoides*, *Sporobolus helvolus*, *Cynodon dactylon*, *Brachiaria ramosa*, *Dactyloctenium aegyptium*, *Dichanthium annulatum*, *D. varicosum*, *Panicum maximum*, *Digitaria*

Table 7 Important species for saline soils

Tolerance (Soil ECe dS m^{-1})	Trees and shrubs	Grasses and forbs
Highly tolerant (30–40)	*Prosopis juliflora*, *Tamarix articulata*, *T. traupii*, *Acacia farnesiana*, *Parkinsonia aculeata*, *Salvadora persica*, *S. oleoides*	*Leptochloa fusca*, *Aeluropus lagopoides*, *Cressa cretica*, *Heliotropium curassavicum*, species of *Sporobolus*, *Atriplex*, *Haloxylon*, *Suaeda*, *Salsola*, *Salicornia*, *Kochia*, *Cyprus*, *Portulaca*, etc.
Tolerant (20–30)	*Acacia nilotica*, *A. tortilis*, *A. pennatula*, *A. ampliceps*, *Casuarina glauca*, *C. obesa*, *C. equisetifolia*, *Callistemon lanceolatus*, *Eucalyptus camaldulensis*, *Feronia limonia*, *Leucaena leucocephala*, *Ziziphus mauritiana*, *Z. nummularia*, *Prosopis cineraria*	Species of *Panicum*, *Chloris*, *Bothriochloa*, *Cynodon*, *Digitaria*, *Dactyloctenium*, *Dichanthium*, *Eragrostis*, *Brachiaria*, *Chenopodium*, *Echinochloa*, *Fagonia*
Moderately tolerant (10–20)	*Casuarina cunninghamiana*, *Eucalyptus tereticornis*, *E. rudis*, *E. microtheca*, *Acacia catechu*, *A. eburnea*, *A. leucophloea*, *Terminalia arjuna*, *Samanea saman*, *Cassia siamea*, *Albizia procera*, *Borassus flabellifer*, *Prosopis cineraria*, *Azadirachta indica*, *Dendrocalamus strictus*, *Butea monosperma*, *Cassia siamea*, *Feronia limonia*, *Leucaena leucocephala*, *Tamarindus indica*, *Guazuma ulmifolia*, *Ailanthus excelsa*, *Dichrostachys cinerea*, *Balanites roxburghii*, *Maytenus emarginata*, *Dalbergia sissoo*, *Salix babylonica*, *Cordia rothii*, *Kigelia pinnata*, many others	*Andropogon annulatus*, *Anthistria prostrata*, *Chrysopogon fulvus*, *Paspalum notatum*, *Urochloa mosambicensis*, *Glycine javanica*, *Phaseolus lunata*, *Cenchrus pennisetiformis*, *C. ciliaris*, *C. setigerus*, *Lasiurus sindicus*, *Echinochloa colonum*, etc.

ciliaris and *Eragrostis* sp. are other grasses, which are salt tolerant and can be grown in silvopastoral systems on saline conditions.

Ahmad (1988) reported tolerance of different tree and forage species studied at the Nuclear Institute for Agriculture and Biology in Pakistan. Species such as *Atriplex amnicola*, *A. lentiformis*, *A. undulata*, *Acacia cambagei*, and *Leptochloa fusca* could tolerate salinity of 20–30 dS m^{-1} (yield reduction up to 50 %), while many others such as *Sesbania aculeata*, *Leucaena leucocephala*, *Medicago sativa*, *Lolium multiflorum*, *Echinochloa colonum* and *Panicum maximum* could tolerate up to EC 10–12 dS m^{-1}. Among woody plants, *Cornus stolonifera*, *Celtis occidentalis*, *Cephalanthus occidentalis*, *Salix* sp., *Alnus* sp., *Populus deltoides*, *Acer saccharinum* and *Quercus* sp. and, among herbaceous species, *Phragmites australis*, *Schoenoplectus lacustris*, *Phalaris arundinacea*, *Iris pseudacorus*, *Panicum virgatum* and species of *Scirpus*, *Typha* and *Eleocharis* are the prominent species reported to be found in Australia (Mitchell and Wilcox 1994) and can be explored elsewhere under similar conditions. Samphires (*Halosarcia pergranulata*, *H. lepidosperma* and *H. indica* subsp. *bideris*) and blue bush (*Maireana brevifolia*) are a group of highly salt-tolerant succulent perennial shrubs, which could be grown on waterlogged saltland pastures in Australia. *H. pergranulata* contains about 14 % crude protein on oven-dry basis and is better suited to sheep grazing.

In India, species of *Phragmites*, *Rumex*, *Polygonum*, *Typha*, *Coix*, *Brachiaria*, *Pasalum*, *Echinochloa*, *Scirpus*, *Cyperus*, *Saccharum* and *Vetiveria* are among the predominant herbaceous/grass species, and species of *Salicornia*, *Suaeda*, *Haloxylon*, *Salsola*, *Tamarix* and *Ipomoea* are prominent shrubs or undershrubs found in waterlogged saline situations. *Paspalum vaginatum* has an amazing ability to thrive in wet salty areas. *Leptochloa fusca*, *Brachiaria mutica* and species of *Paspalum* are excellent fodder grasses, which can be cultivated under waterlogged situations in Indian subcontinent. *Juncus rigidus* and *J. acutus* can successfully be explored for paper and fibre making (Zaharan and Abdel Wahid 1982). *Vetiveria zizanioides*, a tall aromatic grass of waterlogged areas, may be propagated from rootstocks.

Nearly 20 years of work with varieties of *Distichlis* grass, from around the world, could result in a number of useful cultivars, most notably a grain crop trademarked ‘Wild Wheat Grain’, a forage grass called ‘NyPa Forage’, a turf grass called ‘NyPa Turf’ and a reclamation grass called ‘NyPa Reclamation Saltgrass’ (Yensen and Bedell 1993). Species of *Atriplex*, *Kochia*, *Suaeda*, *Salsola*, *Haloxylon* and *Salvadora* are prominent forage shrubs of saline regions and relished by camel, sheep and goats. Today, in search for potential halophytic crops, work is in progress in a number of countries including Australia, Bahrain, Bangladesh, Belgium, Brazil, Canada, China, Egypt, France, Germany, India, Iran, Israel, Italy, Japan, Kenya, Kuwait, Mexico, Morocco, Pakistan, Puerto Rico, Russia, Saudi Arabia, Senegal, Sri Lanka, Switzerland, the United Kingdom, the United States and Venezuela. The efforts in these countries have resulted to identify a number of potential halophytic genera such as *Acacia*, *Anacardium*, *Arthrocnemum*, *Atriplex*, *Avicennia*, *Batis*, *Brachiaria*, *Bruguera*, *Calophyllum*, *Capparis*, *Carandas*, *Cassia*, *Casuarina*, *Ceriops*, *Chloris*, *Coccoloba*, *Cressa*, *Crithmum*, *Distichlis*, *Eucalyptus*, *Grindelia*, *Juncus*, *Kochia*, *Kosteletzkya*, *Leptochloa*, *Limonium*, *Lumnitzera*, *Maireana*, *Nypa*, *Pandanus*, *Pongamia*, *Panicum*, *Plantago*, *Porteresia*, *Prosopis*, *Rhizophora*, *Salicornia*, *Salvadora*, *Simmondsia*, *Sonneratia*, *Spergularia*, *Sporobolus*, *Suaeda*, *Tamarix*, *Taxodium Thinopyrum*, *Vetiveria*, *Xylocarpus*, *Ziziphus* and *Zostera* to name a few. There may exist as many as 250 potential staple halophytic crops (Yensen et al. 1988). The question then is not if there are potential halophyte crops, but, which will meet the needs of particular area and which can be grown with an economic worth. The distribution and adaptability of a species to saline habitats of different regions along with its economical utilization will make a species more acceptable.

In tidal zones along the coast, mangroves such as *Acanthus ilicifolius*, *A. volubilis*, *Aegialitis rotundifolia*, *Aegiceras corniculatum*, *Avicennia marina*, *A. officinalis*, *Bruguiera gymnorrhiza*, *B. parviflora*, *B. cylindrica*, *Ceriops tagal*, *C. decandra*, *Cynometra ramiflora*, *C. iripa*, *Excoecaria agallocha*, *Heritiera fomes*, *H. littoralis*, *Kandelia candel*, *Lumnitzera racemosa* (*L. littoris* in Andamans only), *Nypa fruticans*, *Phoenix paludosa*, *Rhizophora apiculata*, *R. mucronata*, *R. stylosa*, *Scyphiphora hydrophyllacea*, *Sonneratia alba*, *S. apetala*, *S. caseolaris*, *S. ovata*, *Xylocarpus gangeticus* and *X. granatum* and associated species such as *Acrostichum aureum*, *Barringtonia asiatica*, *B. racemosa*, *Caesalpinia bonduc*, *C. crista*, *Calophyllum inophyllum*, *Casuarina equisetifolia*, *Cerbera floribunda*, *Erythrina indica*, *E. variegata*, *Hernandia peltata*, *Hibiscus tiliaceus*, *Intsia bijuga*, *Licuala spinosa*, *Manilkara littoralis*, *Morinda citrifolia*, *Ochrosia oppositifolia*, *Pongamia pinnata*, *Pandanus* spp., *Scaevola taccada*, *Tabernaemontana crispa*, *Terminalia catappa*, *Thespesia populnea*, *Tournefortia ovata*, *Vitex negundo* and many others are common. Many of these are highly potential and can be explored commercially. Mangroves bear a net of aerial roots protecting the entire coastal area from cyclonic tidal waves. These also provide an important habitat for young stages of commercially important fish and prawns and also as breeding grounds for fish and shellfish and also turtles and home for a variety of wild life (Dagar et al. 1991, 1993; Dagar 1995a, 1996, 2003; Dam Roy 2003; Goutham-Bharathi et al. 2014; Dagar et al. 2014; Dagar and Minhas 2016). In scenario of climate change and sea level rise rehabilitation of mangrove areas, planting mangrove and associate species will not only save the coastal areas from disasters like cyclones and *tsunamis*, but it will sequester huge amount of carbon and protect wild coastal marine life.

Introduction of canal irrigation in arid and semiarid regions without provision of adequate drainage causes rise in groundwater table leading to waterlogging and secondary salinization. As subsurface drainage is costly and disposal of effluents has inherited environmental problems, a viable alternative is tree plantation (biodrainage), which is 'pumping of excess soil water by deep rooted plants using bioenergy'. There are evidences to show that trees help in reducing salinity, lowering water table and checking seepage depending upon their salt tolerance (Tomar and Patil 1998; Jeet Ram et al. 2008, 2011). Reliance on capability of vegetation to lower down the water table has been reported promising both in India as well as other countries. Trees have two major beneficial effects: (i) interception and evaporation of rainfall and (ii) transpiration of soil water. Several plant species are used for this purpose from saltbush (*Atriplex*) to tall trees like species of *Eucalyptus*, *Casuarina equisetifolia*, *C. glauca*, *Pongamia pinnata* and *Syzygium cuminii*. The main physiological feature of such vegetation is profuse transpiration whenever the root system comes in contact with groundwater. Several tree species have been shown to survive and grow in waterlogged and saline soils and are being used increasingly to utilize and rehabilitate salt-affected and waterlogged land (Chhabra and Thakur 1998; Tomar et al. 1998; Benyon et al. 1999; Cramer et al. 1999; Angrish et al. 2006; Jeet Ram et al. 2008, 2011).

One of the most promising species used for biodrainage is *Eucalyptus tereticornis* (Mysore gum) which is one of the most widely distributed and fast growing under a wide range of climatic conditions, grows straight and thus has low shading effect and luxurious water consumption where excess soil moisture conditions exist. In waterlogged non-saline areas, it can be successfully grown by ridge planting. In saline waterlogged areas, subsurface or furrow planting is more successful as compared to ridge method (Tomar et al. 1998). The world's *Eucalyptus* plantation area has increased to 20 Mha because of its fast growth rate, favourable wood properties and carbon sequestration and thus seems to be a good option for biodrainage (Hubbard et al. 2010; Jeet Ram et al. 2011; Dagar et al. 2015a).

The impact of block plantations of *Eucalyptus tereticornis* was tested and found effective in Indira Gandhi Nahar Pariyojana (IGNP) area, where groundwater under the block plantation was reported to fall by 15.7 m over a period of 6 years (Kapoor 2014). In another experiment, it was observed that the groundwater table underneath the strip plantations (1 m × 1 m space on acre-line) was 0.85 m during a period of 3 years and it reached below 2 m after 5 years (Jeet Ram et al. 2011). The average above-ground oven-dry biomass of 5 ½-year-old strip plantation was recorded to be 24 Mg ha^{-1} based on 240 surviving trees. The average below-ground oven-dry biomass of roots was 8.6 Mg ha^{-1}. The carbon sequestered was 15.5 Mg ha^{-1} (Jeet Ram et al. 2011). At the same location, the results of 6-year-old cloned *Eucalyptus* plantation when raised in different spaces on acre-line and also as block plantations along canal produced 193 Mg ha^{-1} biomass and when planted in 1 m × 1 m space on acre-line produced 49.5 Mg ha^{-1} biomass, showing its potential in waterlogged areas. These could keep the water table below 2 m depth throughout the growing season and farmers could cultivate both rice and wheat

Table 8 Carbon sequestration (Mg ha^{-1}) in different parts of clonal *Eucalyptus* after 6 years of growth when grown on bunds with different spacing and as block plantation along canal

Plant part	1 m × 1 m (300)[a]	1 m × 2 m (150)[a]	1 m × 3 m (100)[a]	Block (2 m × 4 m) (1250)[a]
Timber (main bole)	15.2	8.9	6.4	66.5
Twigs and leaves	1.1	0.7	0.5	4.2
Roots	6.5	3.9	2.6	19.9
Total	22.8	13.5	9.5	90.6

Source: Dagar et al. (2015a)

[a]Number of trees planted per ha (most of the trees survived after gap filling)

crop in time. The plantations could sequester 9.5 to 22.8 Mg ha^{-1} carbon in different spaces and 90.6 Mg ha^{-1} in block plantation after 6 years of plantation (Table 8).

The effect of trees on seepage on saline vertisols revealed that higher seepage from canal was observed in control (without trees and grasses) as compared to when planted with different species. Among six species, *Acacia nilotica* (with 4.22 m canopy width) effectively intercepted (86 %) incoming seepage from canal as compared to control. It was followed by *Dalbergia sissoo* (84% interception), *Sesbania grandiflora* and *Casuarina equisetifolia* each with 72 % interception. When planted with grass Hybrid Napier (*Pennisetum purpureum*), the interception was more as grass also plays a role in transpiring water. Most of the trees were found effective in reducing soil salinity and increasing organic carbon and available N, P and K. The impact of block plantations of *Eucalyptus tereticornis* on reclamation of waterlogged areas was tested and found effective at the Indira Gandhi Nahar Pariyojana (IGNP) site in Rajasthan and Dhob-Bhali research plot in Haryana (Heuperman et al. 2002; Kapoor 2001, 2014; Jeet Ram et al. 2007, 2008). On these sites, it was established that the transect of trees such as *Eucalyptus tereticornis*, *E. camaldulensis*, *Acacia nilotica*, *Populus deltoides*, *Prosopis juliflora*, *Casuarina equisetifolia*, *Pongamia pinnata*, *Terminalia arjuna*, *Dalbergia sissoo* and *Syzygium cuminii* when planted along canals successfully checked seepage and helped in controlling the waterlogging. During the studies conducted in IGNP area (Heuperman et al. 2002), groundwater under the block tree plantation was reported to fall by 15.7 m over a period of 6 years. At 100 m from the edge of the plantation, the level of the groundwater was about 9 m higher than at the edge, with a drawdown of 6.7 m. The higher groundwater level further away from the plantation edge is apparently the result of recharge from irrigation of areas under cultivation. Through these observations, Heuperman et al. (2002) concluded that the plantations act like groundwater pumps (tube wells) pumping out water at the rate of 34,460 m^3 yr^{-1} or 3.93 m^3 hr^{-1} ha^{-1} of plantation and the water used by plantations in the IGNP command was 3446 mm $year^{-1}$, which was about 1.4 class A pan. No abnormal increase in salinity levels of soils and groundwater was observed under these plantations.

Jena et al. (2011) planted *Acacia mangium* and *Casuarina equisetifolia* with intercropping of pineapple (*Ananas comosus*), turmeric (*Curcuma domestica*) and arrowroot (*Maranta arundinacea*) in Khurda district of Orissa coast. The depth to pre-monsoon water table changed from 0.50 to 1.67 m after 1 year of plantation and to 2.20 m in the next year and to 3.20 m during third year due to biodrainage. *Acacia* was better performer than *Casuarina*. Roy Chowdhury et al. (2011, 2012) also summarized the role of plantations (*Eucalyptus tereticornis* and *Casuarina equisetifolia*) for reclamation of waterlogged situations in Deltaic Orissa. Toky et al. (2011) observed the water table drawdown in ten tree species grown as strip plantations in semiarid regions with water table at 95 cm from ground without plantation. In 6-year-old plantations, they found maximum water table depression of 9.7, 9.5 and 8.4 cm in *Eucalyptus tereticornis* hybrid, clone C-10 and clone C-130, respectively, followed by *Prosopis juliflora* (8.2 cm) and *E. tereticornis* clone C-3 (8.0 cm). Other trees showed depression of 7.9 cm in *Tamarix articulata*, 6.5 cm in *Callistemon lanceolate*, 5.0 cm in *Melia azedarach*, 4.4 cm in *Terminalia arjuna* and 3.3 cm in *Pongamia pinnata*. The drawdown of water table was in correspondence with growth of trees particularly the leaf area index.

Use of Saline Underground Water in Agroforestry

Tomar and Minhas (2002, 2004a, b), Tomar et al. (2003a, b, 2005), Dagar et al. (2006a, 2008, 2013, 2015b) and Dagar (2014) developed technologies of establishing and growing forest and fruit trees, grasses, arable and nonconventional crops in agroforestry mode and medicinal and aromatic plants utilizing judiciously the saline underground water for irrigation. Several tree species could be established using

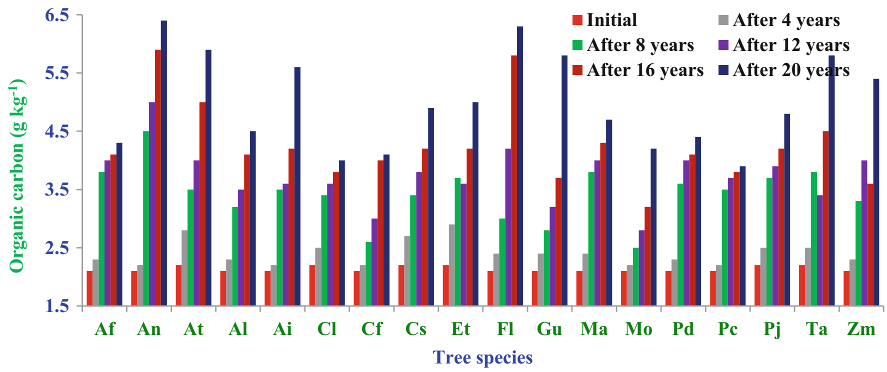

Fig. 11 Development of organic carbon by different tree species at different stages of their growth when established with saline groundwater. Depictions: Af = *Acacia farnesiana*, An = *Acacia nilotica*, At = *A. tortilis*, Al = *Albizia lebbeck*, Ai = *Azadirachta indica*, Cl = *Callistemon lanceolatus*, Cf = *C. fistula*, Cs = *Cassia siamea*, Et = *Eucalyptus tereticornis*, Fl = *Feronia limonia*, Gu = *Guazuma ulmifolia*, *Ma* = *Melia azedarach*, *Pd* = *Pithecellobium dulce*, *Pc* = *Prosopis cineraria*, *Pj* =*Prosopis juliflora*, *Ta* = *Tamarix articulata*, *Zm* = *Ziziphus mauritiana* (Source: Based on Dagar et al., personal communication)

subsurface planting and furrow irrigation technique on degraded calcareous soil using saline water up to EC of 10 dS m^{-1}. Tree species such as *Tamarix articulata*, *Azadirachta indica*, *Acacia nilotica*, *A. tortilis*, *A. farnesiana*, *Cassia siamea*, *Eucalyptus tereticornis*, *Feronia limonia*, *Prosopis juliflora*, *Pithecellobium dulce*, *Salvadora persica*, *S. oleoides* and *Ziziphus mauritiana* were found promising (Tomar et al. 2003b; Dagar et al. 2008). After 8 years of growth, alternate rows were harvested for fuel wood creating sufficient space for tree growth. After 20 years of growth, many of these trees could produce good biomass. *T. articulate*, *A. nilotica*, *A. tortilis*, *P. juliflora*, *E. tereticornis*, *A. indica* and *C. siamea* produced 392, 230, 185, 154, 145, 123 and 122 Mg ha^{-1} aboveground biomass, respectively (Dagar et al. unpublished). Most of these trees improved soil organic carbon to ameliorate the soil to greater extent (Fig. 11). *A. nilotica*, *Feronia limonia*, *A. tortilis*, *G. ulmifolia*, *T. articulata* and *A. indica* were among the most efficient and developed more than 5.5 g kg^{-1} organic carbon in soil (Dagar et al. unpublished).

One of the tested forage grasses (Tomar et al. 2003a) which can also be grown with trees includes *Panicum laevifolium* which produced maximum annual forage dry biomass (16.9 Mg ha^{-1}), followed by *P. maximum* (13.7 Mg ha^{-1}). Among other species (which also grow natural at site), *Cenchrus ciliaris*, *C. setigerus*, *Sporobolus* spp., *Panicum antidotale*, *Dichanthium annulatum*, *D. caricosum*, *Cynodon dactylon*, *Digitaria ciliaris*, *D. decumbense*, *Dactyloctenium aegyptium* and *D. sindicum* are prominent. Even in the lean period (when people are forced to lead nomadic life along with their herds of cattle), sufficient forage was available from all these perennial grasses. When irrigation with saline water was applied during summer, reasonably good green forage was obtained to feed cattle during this lean period. This is applicable for large grazing areas in dry ecologies which otherwise remain barren.

Among fruit trees, *Carissa carandas*, *Emblica officinalis*, *Feronia limonia*, *Ziziphus mauritiana* and *Aegle marmelos*) were found promising. In the interspaces, crops such as pearl millet (*Pennisetum typhoides*), cluster bean (*Cyamopsis tetragonoloba*) and sesame (*Sesamum indicum*) during *kharif* and barley (*Hordeum vulgare*) and mustard (*Brassica juncea*) during *rabi* were found highly profitable. Medicinal crops such as psyllium (*Plantago ovata*), *Aloe vera* and *Withania somnifera* may find place as intercrops as these are found doing well in partial shade. Among other nonconventional crops, castor (*Ricinus communis*), dill (*Anethum graveolens*), taramira (*Eruca sativa*), periwinkle

(*Catharanthus roseus*) and lemon grass (*Cymbopogon flexuosus*) could be cultivated successfully. Their agronomic practices irrigating with saline water have been developed (Tomar et al. 2010; Dagar et al. 2008, 2013, 2015c). *Cassia senna* and *Lepidium sativum* can also be cultivated successfully irrigating with saline water of EC 8 dS m^{-1}. All these high-value crops can successfully be grown as inter-crops with forest or fruit trees at least during initial years of establishment.

Conservation Agriculture (CA) Vis-a-vis SMART Agriculture

The 'Green Revolution' paradigm for production intensification in India has been guided by (a) the improvement of genetic potentials of crop and animal genotypes, (b) greater application of external inputs of agrochemicals for plant nutrition and pest (weeds, pathogens, insects, parasites) control and (c) increased mechanical disturbance of exposed soil and terrain with tillage for crop establishment and other farming operations. In agricultural production systems, the implicit assumption with this approach is that if more output is required, then more inputs must be applied. This approach is now known to be ecologically intrusive and economically and environmentally unsustainable and leads to soil and environmental degradation and suboptimal factor productivities and yield levels that are difficult and expensive to maintain over time. Conservation agriculture (CA) is a farming approach that fosters natural ecological processes to increase agricultural yields and sustainability by minimizing soil disturbance, maintaining permanent soil cover and diversifying crop rotations. Construed more broadly, CA also encompasses natural resource management at the farm, village and landscape scales to increase synergies between food production and ecosystem conservation. CA is a knowledge-intensive management approach to manage agro-ecosystems for improved and sustained productivity and increased profits and food security while preserving and enhancing the resource base and the environment. As such, its implementation varies considerably depending on the context, and it can include diverse practices such as agriculture and livestock management. SMART (sustainable management of agricultural resources and techniques) agriculture is an approach of crop production that deals with the management of available agricultural resources with latest management practices and farm machinery under a particular set of edaphic and environmental conditions. Thus, SMART, if CA implemented at right time with required resources in a particular typological domain, will lead towards food security while using adaptive and mitigating techniques/strategies for sustainable agricultural production.

Crop production techniques may be as important as other resilient strategies in climate change adaptation and mitigation. In the projected scenario of climate change, CA holds good as adapting strategy to build up organic matter in soils (including salt-affected soils) and create a healthy soil ecosystem by retaining the crop residues and not tilling the soil before each planting. CA fits within the sustainable intensification paradigm of producing more from less purchased inputs and enhancing the resource base and its productivity and ecosystem service provision capacity over time. Thus, it is not intensification in the classical sense of greater use of inputs to obtain greater output but rather of the intensification of knowledge, skills and management practices and the complementary judicial and precise use of other inputs. In CA systems, outputs of desired products and ecosystem services are built on three interlocked principles of no or minimum mechanical soil disturbance, maintenance of soil mulch cover and diversified cropping system. Practices based on these principles and supported by other "good agricultural practices" provide a robust and sustainable ecological underpinning to any rainfed or irrigated production system including arable, horticulture, agroforestry, plantation, pasture, crop–livestock and mixed systems, thereby predisposing them to respond efficiently to any applied production inputs to achieve *intensification*. Zero tillage (ZT) is widely adopted by farmers in the Northwestern India, particularly in areas where rice is harvested late. It has been well documented that ZT can save 13–33 % water use and 75 % fuel consumption (Malik et al. 2002), whereas bed planting has the potential to save water by 30–50 % in wheat (Kukal et al. 2005). Both the technologies have also been shown beneficial in terms of improving soil health, water use, crop productivity and farmers' income (Gupta and Seth 2007).

CA practices have been widely adopted in tropical, subtropical and temperate regions of the world for rainfed and irrigated systems and sometimes referred to as win–win agricultural systems. These are now practised globally on about 125 Mha in all continents and all agricultural ecologies (Friedrich et al. 2012). At present, adoption has been low (4.72 Mha) in Asia, particularly in South Asia where the awareness and adoption of CA is on the increase (Friedrich et al. 2012). Largest area with 49.6 Mha (46.6 % of total global area) under CA is in South America, followed by North America (40 Mha, 37.5 %), Australia and New Zealand (12.2 Mha, 11.4 %), Asia (2.6 Mha, 2.3 %), Europe (1.5 Mha, 1.4 %) and Africa with 0.5 Mha, 0.4 % (Kassam et al. 2009). In salt-affected soils, also CA can play a significant role in soil amelioration and crop production. Permanent ground cover is a critical aspect of CA and it is important for several reasons. The presence of residue over the soil surface prevents aggregate breakdown by direct raindrop impacts as well as by rapid wetting and drying of soil (LeBissonnais 1996). CA increases water-stable aggregates, enhances water-holding capacity and infiltration rate, hence reduces run-off resulting in lower soil erosion, increases soil penetrability of roots, increases biological porosity and increases microbial population including earthworms (Li et al. 2007; Kladivko 2001; Govaerts et al. 2007a,b, 2009a; Hobbs and Govaerts 2010). Soil sodicity and salinity can be ameliorated by CA practices. Under permanent raised bed planting with residue retentions, sodicity was reduced significantly, reducing Na concentration by 2.64 and 1.80 times in 0–5 cm and 5–20 cm layer, respectively, compared to conventional tilled raised beds (Govaerts et al. 2007c). Compared to conventional tillage, values of exchangeable Na, exchangeable Na percentage and dispersion index were lower in an irrigated vertisol after 9 years of minimum tillage (Hulugalle and Entwistle 1997). A simple CA technique laser-levelling could increase crop yield and save water significantly (Table 9). Effects of CA-based technologies are presented in Table 10.

Table 9 Effect of laser-levelling on crop productivity and water saving

Crop	Grain yield ($Mg\ ha^{-1}$) in un-levelled field	Grain yield ($Mg\ ha^{-1}$) in laser-levelled field	Water saving (%)
Paddy	6.50	6.79	38
Wheat	4.55	4.75	20
Sugarcane[a]	98.75	112.00	24
Summer green gram	0.37	0.50	20
Potato	9.00	10.00	25
Onion	9.00	10.00	20
Sunflower	2.00	2.25	20

[a]Cane biomass
Source: Personal communication (AK Singh)

Table 10 Effect of CA-based technologies on yield gain, water saving and increase in WP over conventional practice in IGP of South Asia

Technologies	Cropping system	Yield gain ($kg\ ha^{-1}$)	Water saving (cm)	Increase in WP_I ($kg\ m^{-3}$)	References
Laser levelling	Rice–wheat	750–810	24.5–26.5	0.06	Jat et al. (2009a)
ZT	Wheat	610	2.2	0.28	Saharawat et al. (2010)
ZT	Maize	150	8	0.21	Parihar et al. (2011)
ZT + mulch	Rice–wheat	500	61	0.24	Gathala et al. (2011)
ZT + mulch	Wheat	410	10	0.13	Jat et al. (2009b)
DSR	Rice	112	25	0.08	Jat et al. (2006)
RB planting	Wheat	310	16	0.58	Jat et al. (2011)

ZT, *DSR*, *RB* and *WP* denote zero tillage, direct-seeded rice, raised bed and water productivity, respectively

In RW system, conventional establishment of wheat after rice involves removal of the rice residues (predominantly by burning in NW India), followed by intensive tillage. The adoption of ZT with and without residue in the IGP has been rapid since the mid-1990s, and the major driver for adoption is increased profitability as a result of lower establishment costs (INR ~4000 ha^{-1}). There are considerable evidence from farmers adoption studies that ZT wheat gives irrigation water saving of at least 10 % (at least 20–30 mm) in comparison with conventional practice, while yields are generally slightly higher (<5 %), leading to higher net income and benefit to the practitioners (Table 11).

CA is as an approach to farming that seeks to increase food security, alleviate poverty, conserve biodiversity and safeguard ecosystem services. Conservation agriculture practices can contribute to making agricultural systems more resilient to climate change. In many cases, conservation agriculture has been proven to reduce the farming systems' greenhouse gas emissions and enhance its role as carbon sinks. Climate change presents a profound challenge to food security and development. Negative impacts from climate change are likely to be greatest in regions that are currently food insecure and may even be significant in those regions that have made large gains in reducing food insecurity over the past half-century. Adaptation in the agricultural sector is being given a high priority within this effort because of the inherent sensitivity of food production to climate and the strong interlinkages that exist between climate, agriculture and economic growth and development. The purpose is to identify and summarize potential climate change impacts on agriculture in regions, examine the causes of vulnerability, provide information on where investments are needed to better climate-proof agriculture and describe the relevance of current efforts to achieve more sustainable agriculture to that of managing climate risks for adaptation.

In northwest India, system intensification through resilient cropping system and management scenarios was compared using a wide range of indicators (crop rotation, tillage, crop

Table 11 Effect of establishment techniques on productivity and economics of wheat in Haryana

Establishment techniques	Yield (Mg ha^{-1})	Cultivation cost (INR ha^{-1})	Gross returns (INR ha^{-1})	Net income (INR ha^{-1})	B:C ratio
Conventional tillage (CT)	6.31	54,321	73,323	19,002	1.35
ZT without residue	6.40	50,179	74,389	24,210	1.48
ZT with anchored residue	6.57	50,631	76,276	25,645	1.51

Source: Jat et al. (2013)

Table 12 System yield, irrigation water saving and energy saving in different scenarios (3 years average; 2009–2012)

Scenario	Systems	Residue management	System yield (rice equiv) Mg ha^{-1}	Irrigation water (mm)	Energy use (MJ ha^{-1})	SOC (%)
I – farmers practice	Rice–wheat (CT/TPR)	No residue	13.0	2687	73,832	0.46
II – partial CA-based	Rice-Wheat-Green gram (TPR-ZT-ZT)	Rice residue removed; green gram residue incorporated; anchored wheat residue	15.8	2073	56,543	0.52
III – full CA-based	Rice–wheat–green gram (ZT-ZT-ZT)	Retention of full (100 %) rice and green gram; anchored wheat residue	14.8	1793	51,582	0.56
IV – full CA-based	Maize–wheat–green gram (ZT-ZT-ZT)	Retention of maize (65 %) and full green gram; anchored wheat residue	14.5	766	36,457	0.58