Adaptation and mitigation of climate change in vegetable cultivation: a review

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ABSTRACT

Climate change is an unavoidable phenomenon of natural and anthropogenic origin against which mitigation and adaptation are required to reduce the magnitude of impact and vulnerability, to avoid risk in vegetable farming and to ensure sustainable livelihoods of the agricultural community. Genetic improvement of vegetable crops is an appropriate adaptation strategy to cope with climate change adversities. A combination study of genomics and phenomics provides a clear understanding of the environment's effect on the transformation of a genotype into phenotype. Grafting of a susceptible scion cultivar onto a resistant rootstock is another way of utilising plant biodiversity against climate change. Agronomic practices such as resource conservation technologies, mulching, organic farming, carbon sequestration by cropping systems and agroforestry provide a suite of possible strategies for addressing the impacts of climate change on vegetable production. Protected cultivation and post-harvest technology can be significant practices in facing the challenges of climate change. Weather forecasting models and growth simulation models can be used to predict the possible impact of climate change on vegetable crop production and they also help in framing necessary adaptation measures.

Key words | adaptation, climate change, mitigation, vegetables

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INTRODUCTION

It is crystal clear that our climate is changing on either regional or global scales, and its effects are evident. Cultivation is playing a dual role. On the one hand, being a climate-dependent activity, it is adversely affected by the consequences of climate change and, on the other hand, it is an important contributor to climate change (Ahmad *et al.* 2011; Koundinya *et al.* 2014). The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) discussed the causes due to agriculture and the necessary adaptation and mitigation practices in farming. Farming is contributing to climate change in many ways, through tillage, use of chemical fertilisers, pesticides, fungicides and herbicides, and methane emissions from paddy fields and livestock. Annual green house gas (GHG) emissions from agricultural production in 2000–10 are estimated globally as 5.0–5.8 Gt CO_2-equivalent/yr (IPCC 2014). In India, agriculture, including livestock, is one of the largest contributors of GHGs with a share of 17.6% of contributions next to energy and industry, whose share is 57.8% and 21.77%, respectively (INCCA 2010; Planning Commission 2014). Figures 1 and 2 explain the GHG emissions from different sectors and activities of agriculture in India in 2007.

The per cent global share of the five major CO_2 emitting countries and the European Union in 2015 is presented in Figure 3 (Olivier *et al.* 2016). China (29%) is the largest CO_2 emitting country followed by the USA (14%). India

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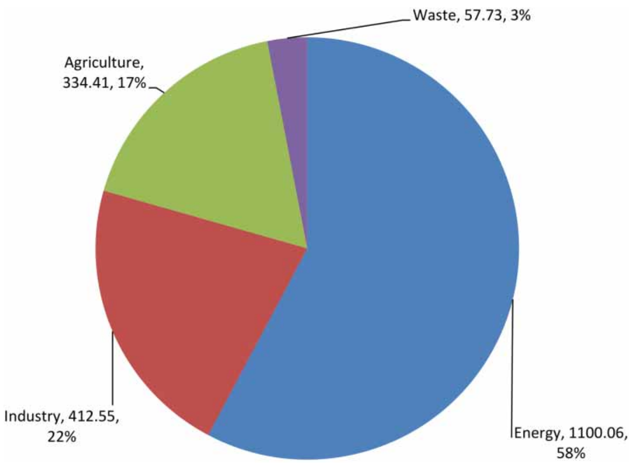

Figure 1 | GHG emissions (Mt CO_2-equivalent) from different sectors in India for the year 2007.

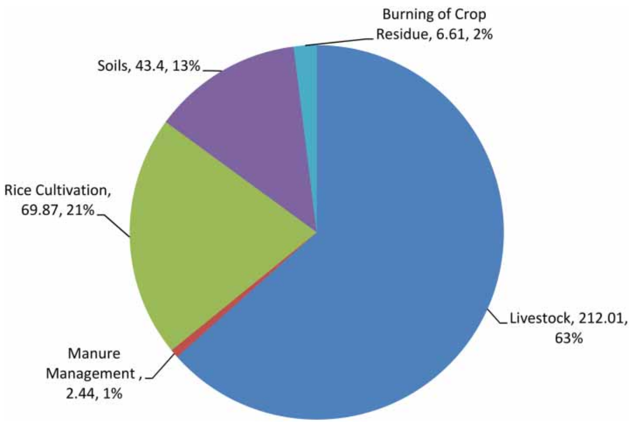

Figure 2 | GHG emissions (Mt CO_2-equivalent) from different activities of agriculture in India for the year 2007 (source of data: INCCA 2010).

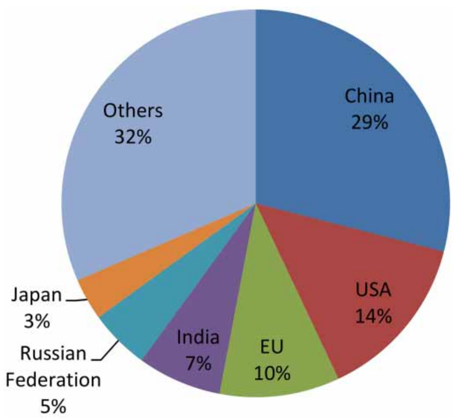

Figure 3 | Per cent share of the five major CO_2 emitting countries and the European Union in 2015 (source of data: Olivier *et al.* 2016).

stands in fourth position (7%) after the European Union (10%). The Indian GHG emissions are projected to increase by three times with respect to the 1990 (988 million tonnes) emissions in 2020 (3,000 million tonnes) as per Sharma *et al.* (2006). Assuming that there is no further increase in CO_2 emissions rate, it is predicted that India's CO_2 emissions will increase from below 2 $GtCO_2$ in 2010 to almost 8 $GtCO_2$ in 2050 (Gambhir *et al.* 2013). The mean annual temperature of India is projected to increase between 2.9°C and 4.3°C from the 1961–90 baseline by the end of 2080 (Mallet 2012).

Farming is the source of methane, nitrous oxide and carbon dioxide. It includes the use of chemical fertilisers, pesticides and herbicides produced by burning of fossil fuels. India's average consumption of fertilisers increased from 69.84 kg/ha in 1991–92 to 128.8 kg/ha in 2014–15 (Anonymous 2016). Fertilised soils release more than two billion tonnes of CO_2 equivalent GHGs every year worldwide (Smith *et al.* 2007). When nitrogenous fertilisers are applied, it is expected that, in general, 1–2% of all the applied nitrogen is emitted as N_2O (Muller 2009; Niggli *et al.* 2009; Sartaj *et al.* 2013). The consumption of nitrogenous fertilisers in India for the year 2014–15 was 16.9 million tonne (Anonymous 2016), so, for that year, at 2% rate, 0.33 million tonne N_2O would have been released into the atmosphere. Tillage accelerates the oxidation of soil organic carbon, thereby releasing high amounts of CO_2 into the air (Prior *et al.* 2000; La Scala *et al.* 2006). The opening of soil crust through tillage further makes the soil prone to soil erosion. Annually, in India, 5.3 billion tonnes of soil gets eroded, and annual soil loss is about 16.4 t/ha (Anonymous 2016). Mislay of organic carbon either through oxidation or erosion leads to a reduction in fertility of soils, depletion of microbial activity and lower fertiliser use efficiency (FUE), which further necessitates a requirement for more fertiliser.

Burning of crop residue in the field itself is a common practice in several Indian states such as Uttar Pradesh, Punjab and Haryana and leads to the production of CO, CH_4, NO, N_2O, SO_2 and many other gases. The emitted CH_4 and N_2O from burning crop residue in India in 2007 were estimated as 0.23 and 0.006 Mt, respectively (INCCA 2010; Planning Commission 2014). As well, farm mechanisation contributes to the atmospheric CO_2 in significant quantities. Agriculture consumes 20.95% of total electricity consumption in the country (Anonymous 2015) while power generation is contributing 37.8% to the total GHG produced in the country (INCCA 2010; Planning Commission 2014).

ADAPTATION AND MITIGATION

Adaptation and mitigation are two essential components of addressing climate change. Adaptation is defined as 'Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploit beneficial opportunities' whereas mitigation is defined as 'An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases' (IPCC 2001). Although there are differences between adaptation and mitigation (IPCC 2007; Muller 2009; Locatelli 2011) (Table 1), they are complementary in nature. If mitigation strategies are effective, the lesser will be the impact to adapt and vice versa (Anonymous 2014).

In agriculture, mitigation is necessary as it is contributing to climate change and adaptation is also required because even with strong mitigation efforts the climate would continue changing in the coming years. Moreover, adaptation will not be able to eliminate all negative impacts (Locatelli 2011), and it eventually leads to a magnitude of climate change to which effective adaptation is possible only at very high social, environmental and economic costs (Anonymous 2014). Therefore, both adaptation and mitigation are crucial to face future changes in the climate.

It is a well-known fact that the reduction in GHG emissions requires a decrease in a country's gross domestic product (GDP), with the decrease being greater in the case of developed countries. In India, it is estimated that the pursuit of low carbon strategies will decrease the per capita CO_2 emissions in India, in 2030, to 2.6 t/head at the cost of average GDP growth rate decline by 0.15% (Planning Commission 2014).

STRATEGIES TO COMBAT CLIMATE CHANGE IN VEGETABLE GROWING

In the developing countries of the world, nearly 70% of people live in rural areas where agriculture is the largest supporter of livelihoods (Easterling *et al.* 2007). The majority of

Table 1 | Differences between climate change adaptation and mitigation

S. no.	Adaptation	Mitigation
1	Adjustment or preparedness to changing climatic conditions	Preventing or limiting the climate change (reducing GHG emissions)
2	Includes strategies that aim at coping with climate change and reducing the vulnerability to it	Includes strategies that reduce the climate change
3	Adaptation takes the advantage of positive impacts and reduces the negative impacts	Mitigation reduces both the positive and negative impacts
4	Adaptation entered the agenda more prominently only recently	Mitigation has been a topic for a long time
5	Acts locally	Acts globally
6	Does not consider the causes of climate change	Deals with causes of climate change, i.e., sources of greenhouse gases
7	Strategies provide short-term benefits and must be updated with changing climatic conditions	Strategies provide long-term benefits and are almost permanent
8	Benefits can be visible immediately	Benefits take a long time to become visible
9	Different adaptation practices cannot be valued in a single metric unit	Various mitigation efforts can be assessed in a single unit (CO_2 equivalent), and their cost-effectiveness can be determined
10	In agriculture, the examples of adaptation are the genetic alteration of crop plants to tolerate adverse climatic conditions, and water and soil moisture conservation technologies	In agriculture, the examples of mitigation are carbon sequestration through increasing carbon sinks, avoiding fossil fuel-based fertilisers and chemicals, and zero tillage

India's population is in the countryside and its livelihood is agriculture. The service sector's contribution to the Indian GDP has overtaken that of agriculture, but the number of families that depends on farming for survival remains almost the same. Hence, one can say that climate change poses a grave threat to the livelihoods of the rural farming community. In this perspective, the adaptation and mitigation strategies should be planned in such a way that they reduce the risk and uncertainty in Indian agriculture and ensure sustainable livelihoods in rural communities. UNFCCC (2007) also stated that 'risk management and reduction strategies and economic diversification to build resilience are also important aspects of adaptation to climate change'. In this paper, attempts have been made to discuss necessary adaptation and mitigation strategies (Figure 4) in vegetable crops to combat climate change.

GENETIC IMPROVEMENT OF VEGETABLE CROPS

Genetic improvement of crops mainly forms an adaptation strategy as it is a preparation for crop plants to adapt to future predicted climate. Genetic improvement of crop plants to make them able to withstand the adverse effects of climate change is an important means for their sustainable production and for food security. The complexity arises due to the polygenic nature of abiotic stress tolerance, lack of selection criteria and inadequate knowledge about the genetics of stress tolerance, making breeding for abiotic stress tolerance difficult (Ong 2002).

Characterisation is known as the description of qualities or peculiarities. It helps not only in the identification of useful traits present but also in the estimation of inbuilt variation and diversity among the available germplasm. This information further helps in the possible utilisation of such germplasm in crop improvement programmes. Genetic improvement mainly depends on the amount of genetic variability present in the population. The first and foremost prerequisite for effective selection to occur is genetic variability. In any crop, for any trait, the germplasm serves as an invaluable source of base population and offers a primary source of genetic variability (Koundinya *et al.* 2013a; Sidhya *et al.* 2014). Selection of resistant plants from the existing populations and further development of varieties from their progeny is a primitive and fruitful method of breeding of crop plants.

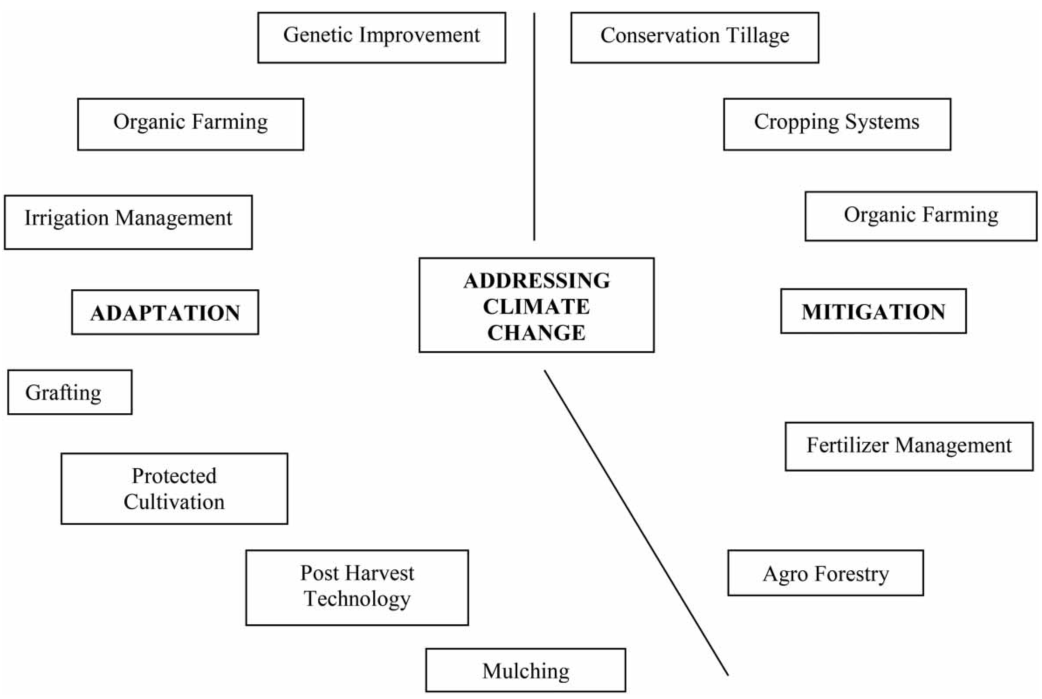

Figure 4 | Different adaptation and mitigation practices to address climate change.

Genetic diversity delineation helps in the grouping of available germplasm into distinct clusters. It helps in identification of diverse parents for hybridisation. The greater the diversity between the parents the greater will be the heterosis and gain of superior recombinants in segregating generations (Koundinya *et al.* 2013a, 2016). Hybridisation or heterosis breeding helps in the transfer of abiotic stress tolerant genes from the tolerant cultivars to agronomically superior cultivars.

With the changing climatic conditions, crop durations are becoming small and the favourable environment is available for a limited period. In this perception, breeding for short duration and early varieties is gaining importance as a measure to adapt to climate change. Germplasm for maximum nutrient use efficiency is also being screened and identified in all vegetable crops. These traits result in decreased use of chemical fertilisers. At NBPGR, out of 45 accessions of *Brassica juncea* evaluated, ten accessions, namely, IC267693, IC275106, IC277700, IC296501, IC3396605, IC339671, IC338494, IC571625, IC571654 and IC538719 were found with high nitrogen use efficiency (NBPGR 2013). ICAR-CTCRI identified and released a cassava variety Sree Pavithra, which is tolerant to low potassium (K) content in the soil (CTCRI 2015).

Heat tolerant hybrids in Chinese cabbage and breeding lines in tomato (CL5915) were developed at the Asian Vegetable Research and Development Centre, Taiwan (Pena & Hughes 2007). In India, heat and drought tolerant tomato cultivars were developed at the Indian Agricultural Research Institute, New Delhi and Indian Institute of Horticultural Research, Bangalore. Frost, heat and drought tolerant potato cultivars were developed at the Central Potato Research Institute, Shimla. Table 2 shows a list of such cultivars released for cultivation in India in various vegetable crops. In tomato, gene *Pat-2* governs parthenocarpic fruit development at high temperatures. This trait will be helpful in increasing fruit set in tomato at high temperatures where normal fruit set is impaired (George *et al.* 1984).

There are many genes from wild relatives that can be used to modify vegetable crops to become more resilient to harsh environmental conditions. These genes can be transferred to the cultivated types either by conventional

Table 2 | Vegetable varieties with various stress tolerance released in India for cultivation

Crop	Variety	Abiotic stress tolerance
Tomato	Pusa Sheetal	Fruit set up to 8°C (low) night temperature
	Pusa Hybrid 1	Fruit set up to 28°C (high) night temperature
	Pusa Sadabahar	Fruit set at both low (6°C) and high (30°C) night temperature
	Sabour Suphala	Salt tolerant at seed germination stage
	Arka Vikas	Tolerant to moisture stress
Eggplant	SM-1, SM-19 and SM-30	Drought
	Pragati and Pusa Bindu	Salt tolerance
Okra	Pusa Sawani	Tolerant to salinity
Musk melon	Jobner 96-2	High soil pH
Spinach beet	Jobner Green	High soil pH (up to 10.5) tolerant
Cucumber	Pusa Barkha	Tolerant to high temperature
	Pusa Uday	Suitable for throughout the year
Bottlegourd	Pusa Santusthi	Hot and cold set variety
Onion	Hisar-2	Tolerant to salinity
Carrot	Pusa Kesar	Tolerant to high temperature
Radish	Pusa Himani	Grown throughout the year
Sweet potato	Sree Nandini	Drought tolerant
Potato	Kufri Surya	Heat tolerant up to 25°C night temperature
	Kufri Sheetman, Kufri Dewa	Frost tolerant
Cassava	H-97, Sree Sahya	Drought tolerant

breeding or with the aid of biotechnological tools or biotechnology alone (Koundinya *et al.* 2013b). The transfer of beneficial traits from wild varieties to cultivated types has been practised. In India, wild genes have already been successfully introgressed into the cultivated types in vegetable crops like tomato and okra for disease resistance and quality. Wild relatives' utility was recognised in breeding programmes of major crops in the 1940s and 1950s (Plucknett *et al.* 1987), and wild gene use in crop improvement gained prominence by the 1970s and 1980s with their use being investigated in a broad range of crops (Hoyt 1988). Several workers have extensively studied and identified various desirable attributes such as resistance to biotic and abiotic stresses present in different wild species. However, only a few of them have been successfully transferred to cultivated species. A few wild relatives of tomato are tolerant to environmental stresses. *Solanum cheesmani* is tolerant to salt (Epstein *et al.* 1980) and *S. pimpinellifolium* is tolerant to heat (Coons 1989). *S. chilence* is tolerant to drought due to a longer primary root and an extensive secondary root system; *S. pennellii* is tolerant to drought due to the thick cuticle, waxy leaves which allow conserving leaf water in dry soils (O'Connell *et al.* 2007). *S. lycopersicon var. cerasiformae* cultivar Nagarkarlan from the Philippines is tolerant to waterlogging (Rebigan *et al.* 1977). *Phaseolous filiformis,* a wild relative of common bean has tolerance to salinity (Jimenez *et al.* 2002) and extreme temperatures (Buhrow 1983). *P. acutifolius* is tolerant to heat (Lin & Markhart 1996), drought (Mikla *et al.* 1994) and salinity (Jimenez *et al.* 2002). Eggplant wild relatives *Solanum linneaeanum* and *S. macrocarpon* are tolerant to salinity and drought, respectively, as reviewed by Collonnier *et al.* (2001).

Biotechnology also offers scope for the improvement of vegetables to make them suitable for altering climatic situations. Biotechnological tools like tissue culture and genetic engineering of crop plants are useful to screen and develop resistant varieties that can cope with stress factors. Embryo rescue helps in preventing embryo abortion, a post-fertilisation barrier in distant crosses (Koundinya *et al.* 2012), whereas somatic hybridisation by fusing of protoplasts of two different species helps in elimination of pre-fertilisation barriers in distant hybridisation (Collonnier *et al.* 2001; Koundinya *et al.* 2012). Low-temperature tolerance is transferred successfully to *Phaseolus vulgaris* (French bean) from *P. retensis* by hybridisation followed by embryo rescue as mentioned by Jakhar & Sastry (2005). Smillie *et al.* (1979) found that chilling resistance of tomato + potato somatic hybrids was intermediate between the chilling resistances of tomato and potato. They proposed that these somatic hybrids might be useful for transferring genes for chilling resistance into the domestic tomato. Generation of heritable variation during tissue culture is known as a somaclonal variation (SCV). Variations can be created for stress tolerance, disease tolerance and herbicide tolerance (Rai & Rai 2006). A salt-resistant SCV line in eggplant was obtained from cell culture in a medium containing 1% sodium chloride by Jain *et al.* (1988). Genetic engineering or recombinant DNA technology involves moving of genes beyond the species and genus barriers. Cisgenics and transgenics are capable of introducing new genes into the target species from closely related to even completely unrelated organisms. Frost tolerance gene *AFP 1* (anti-freezing protein) was introduced into a tomato cultivar from winter flounder fish (Hightower *et al.* 1991). A heat shock protein gene (*HSP17.7*), which confers high-temperature tolerance, was isolated from carrot (Malik 1989). This gene can be transferred to other vegetable crops for improvement against high temperature. *AVP1* (Park *et al.* 2005) and *AtNHX1* (Zhang & Blumwald 2001) genes, which govern drought and salt tolerance, respectively, were transferred to tomato from *Arabidopsis thaliana*. Collonnier *et al.* (2001) reported that increased tolerance to salt (200 mM NaCl) and polyethylene glycol (PEG)-mediated drought tolerance have been obtained in eggplant genotypes by the introduction of the bacterial mannitol-1-phosphodehydrogenase (*mtlD*) gene responsible for the synthesis of mannitol.

Genomic studies help in identifying alleles of candidate genes and further facilitate isolation of molecular markers followed by a screening of populations with the aid of molecular markers (Ishitani *et al.* 2004). Expressed sequence tags (ESTs) can be used for the identification of cell type-specific or tissue-specific genes, characterisation of a genome of an organism, discovery of novel genes or the regulatory networks of metabolic pathways. High throughput DNA microarrays help in studying gene expression profiles, i.e., up-regulation or down-regulation under particular stress condition or the 'switching on' and 'turning off', of a vast number of genes under stress, simultaneously, in a single experiment (Ong 2002).

Identification of quantitative trait loci (QTL) for tolerance to various abiotic stresses helps in pyramiding them into one cultivar. Foolad & Jones (1993) identified five QTL for salinity tolerance in an F_2 population in tomato from a cross between *S. lycopersicum* x *S. pennellii*, while Villalta *et al.* (2008) identified 13 and 20 QTL for fruit yield under saline conditions in *S. pimpinellifolium* and *S. cheesmani*, respectively. Twenty-three QTL were identified for recovery after drought stress in potato (Anithakumari *et al.* 2011). Dumont *et al.* (2009) observed colocalisation of two raffinose sugar QTL and one RUBISCO activity QTL with resistance to frost damage in pea. AFLP markers were used for mapping of ten QTL associated with drought tolerance at seedling stage and maturity in cowpea by Muchero *et al.* (2009). Thirteen QTL were detected for taproot length and the ability to extract water from deep in the soil profile in lettuce (*Lactuca sativa*) and the wild *L. serriola* (Johnson *et al.* 2000) by using AFLP markers.

Marker-assisted selection (MAS) assists conventional breeding by reducing the time involved in long generation screening and accurate confirmation of the presence or absence of particular gene(s) as they are not affected by the external environmental conditions unlike morphological markers (Collard & Mackill 2008; Vogel 2009). They facilitate efficient introgression of superior alleles from wild species into the breeding programmes and enable the pyramiding of resistant genes controlling quantitative traits (Pena & Hughes 2007). MAS by using various DNA and isozyme markers, offers an excellent opportunity for effective screening and selection of suitable plants with desirable allelic combinations that can perform well under varying climatic situations. MAS is extensively used in crop improvement in disease resistance (e.g., bacterial blight resistance in rice) followed by nutrition and quality (provitamin A in sweet potato and cassava) (Vogel 2009). Both disease resistance and nutritional quality are important as diseases are aggravated and the quality of vegetables is affected badly by climate change (Koundinya *et al.* 2014). In vegetables, MAS is utilised in developing high yield cultivars (AB2 tomato in Israel), but its use in improving polygenic traits like abiotic stress tolerance in vegetables is still in progress (Pena & Hughes 2007; Vogel 2009). In the words of Jannink *et al.* (2010, p. 166), 'MAS has failed significantly to improve polygenic traits'. MAS ignores genes with small effects in selection for a quantitative trait. Genomic selection effectively facilitates selection for these characters, which uses all genome-wide markers data and their phenotypic data to calculate genome estimated breeding values (Jannink *et al.* 2010), which are used to select candidate parents (Okogbenin *et al.* 2013). Whole-genome models predict all marker effects in all loci across the entire genome and capture the small effects of QTL (Desta & Ortiz 2014). Genome-wide selection is superior to MAS and phenotypic selection regarding gain per unit cost and time (Wong & Bernardo 2008).

Tropical tuber crops like cassava can withstand moisture stress and recover easily after drought. Efforts can be made towards identifying and characterising drought tolerant genes in these crops. Genetic markers, namely, 3,000 restriction fragment length polymorphism (RFLP), 800 simple sequence repeat (SSR), 120 random amplified polymorphic DNA (RAPD) and nine isozyme markers were identified for drought tolerance in cassava (Okogbenin *et al.* 2013). Expression profiling studies revealed that four genes (*MeALDH*, *MeZFP*, *MeMSD* and *MeRD28*) were exclusively up-regulated in the drought tolerant genotype of cassava to comparable levels. These were identified as candidate cassava drought tolerance genes by Turyagyenda *et al.* (2013).

Phenomics study helps in the complete phenotypic characterisation of germplasm under controlled environmental conditions. It facilitates more precise and accurate observations of the phenotypic expression of a gene or whole genome under a given set of environmental conditions, which may be a single stress or combination of stresses. It uses large-scale approaches like conveyor systems, image capturing systems and robotic and computing systems to measure and analyse various plant growth, development, morphological and physiological observations accurately without destructive sampling. High throughput phenomics facilitates the recording of ultramicroscopic observations like stomata closure under stress conditions. These observations help in the selection of plants that perform well under different stress conditions such as drought, high temperature, salinity and elevated atmospheric CO_2. Phenomics are expected to bridge the gap between physiology and plant breeding. The study of genomics in conjunction with phenomics quantifies the environment-driven dynamics in the phenotypic expression of a genotype. Figure 5 illustrates a model breeding scheme that combines both genomics and phenomics for drought tolerance in cassava. This model is applicable for other vegetable crops and/or other stresses with modifications. As tolerance to drought is a polygenic character, a heterogeneous population approach is suggested instead of the pure stand as it is difficult to pyramid all the genes/alleles into a single cultivar.

GRAFTING

Grafting of a susceptible scion cultivar onto a resistant rootstock is another way of utilisation of plant biodiversity to adapt to climate change (Koundinya *et al.* 2013b). It offers an opportunity to overcome several biotic and abiotic stresses (Koundinya & Kumar 2014), which are a major setback to vegetable production and are becoming intensified by climate change. High and low temperature tolerance in tomato was achieved by grafting onto *Solanum melongena* EG203 (Burleigh *et al.* 2005) and *Solanum habrochaites* LA1777

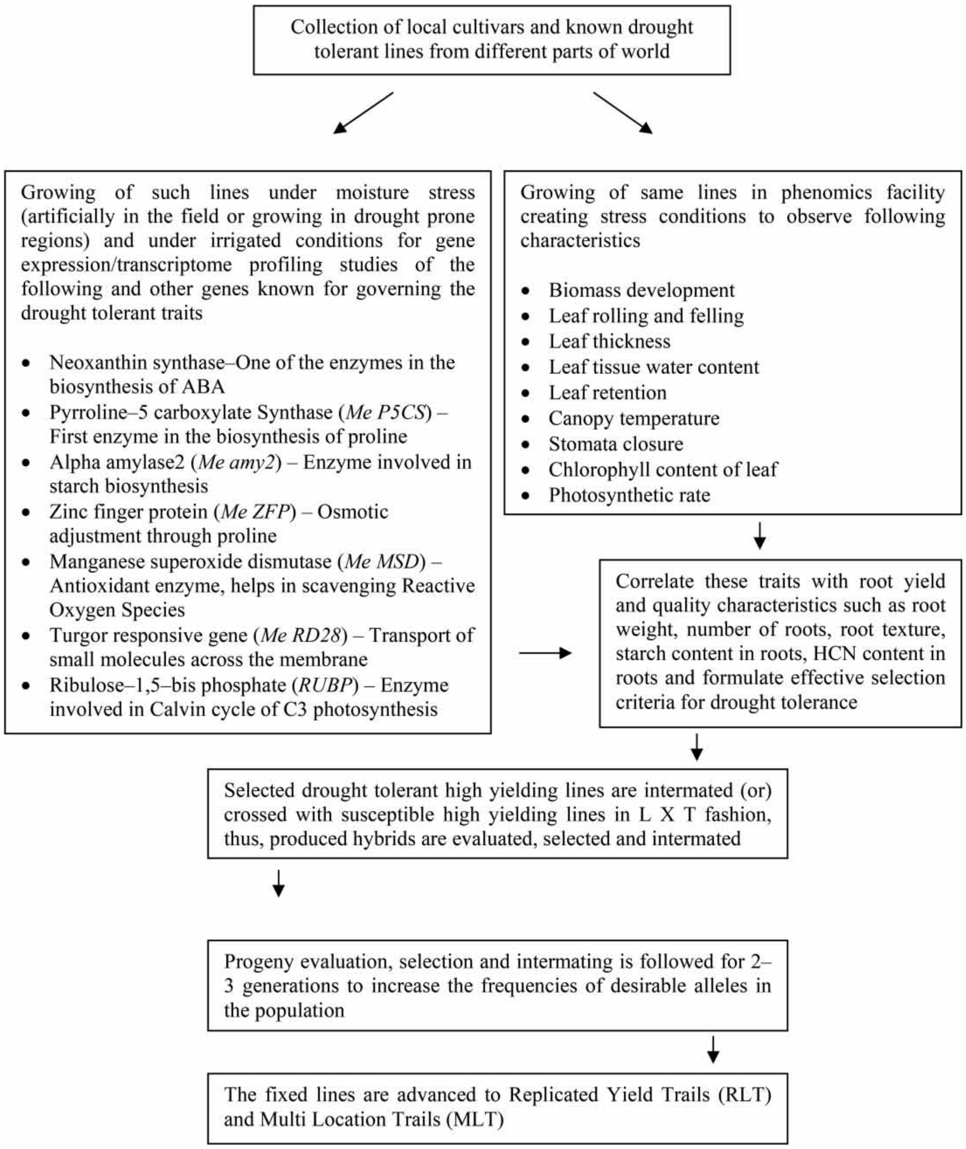

Figure 5 | Model breeding scheme for drought tolerance scheme in cassava.

rootstocks (Venema *et al.* 2008), respectively. Watermelon plants were made drought tolerant by grafting onto ash gourd plants (Sakata *et al.* 2007). Grafting onto *Solanum melongena* rootstock helped in bacterial wilt and flooding tolerance in tomato (Palada & Wu 2007). Rootstocks from *Cucurbita* species were more tolerant to salt than rootstocks from *Lagenaria siceraria* (Matsubara 1989). Interspecific rootstocks like *Solanum lycopersicum* x *S. habrochaites* provided low soil temperature (10 to 13°C) tolerance to their grafted tomato scions and *S. integrifolium* x *S. melongena* rootstocks provided low soil temperature (18 to 21°C) tolerance to eggplant scions, respectively (Okimura *et al.* 1986).

AGRONOMIC PRACTICES

Agronomic practices like resource conservation technologies (RCT), mulching and carbon sequestration by agroforestry and cropping systems may decrease GHGs by increasing their intake and their storage of C in biomass, wood and soil. Agronomic practices globally can mitigate 0.39 t CO_2 equivalent/ha/year under a dry climate, and 0.98 t CO_2 equivalent/ha/year under a moist climate (Smith *et al.* 2007; Milder *et al.* 2011). The main strategies to sequester carbon and to reduce GHG emissions through agricultural practices are enriching soil carbon, minimising the use of inorganic fertilisers, restoring degraded lands and preventing deforestation (Chatterjee 2011). Multiple cropping systems, such as crop rotation, intercropping, cover cropping (Wang *et al.* 2010) and agroforestry systems (Roy *et al.* 2011) play a critical role in optimising carbon sequestration in agriculture by influencing optimal yield, and increasing carbon sequestered with biomass and in the soil. Moreover, it further helps restore degraded soils, enhancing land productivity, improving soil biodiversity and protecting the environment by reducing the enrichment of atmospheric CO_2, which in turn, mitigates climate change (Wang *et al.* 2010).

Resource conservation technologies

Resource conservation practices in cultivation could decrease the net emission of carbon dioxide in many areas (Uri & Bloodworth 2000). It can help to mitigate atmospheric GHG by reducing the existing emission sources and sequestering carbon through minimal soil disturbance by combining no-till, permanent organic soil cover and crop rotation (BIAC 2009; Chatterjee 2011). These techniques result in healthier soil, enhanced carbon sequestration, decreased erosion as well as reduced use of water, energy and labour (Chatterjee 2011).

Zero tillage and reduced tillage help in reduction of oxidation of organic carbon. Jethro Tull, father of tillage, envisaged the importance of tillage in agriculture as it loosens the soil, breaks the soil crust and pebbles and exposes the soil-borne pest and fungal spores to the sun (Reddy & Reddi 2002). However, the present day slogan is '*do not till or little till*' in the light of increasing cost of fuels, labour and climate change problems. Zero tillage prevents the oxidation and escape of soil organic carbon as CO_2 into the atmosphere while cover crops or organic soil cover add carbon to the soil. Moreover, conservation tillage minimises the use of machinery required for tillage, and hence reduces burning of fossil fuels. Conservation tillage and residue management, globally, can reduce emissions by as much as 0.35 t CO_2 equivalent/ha/year under warm dry climate and 0.72 t CO_2 equivalent/ha/year under warm moist climate (Smith *et al.* 2007; Milder *et al.* 2011). Conversion of all croplands to conservation tillage globally could sequester 25 Gt carbon over the next 50 years (Baker *et al.* 2007). Conservation tillage facilitates much slower decomposition of plant residue than conventional tillage (Drury *et al.* 2006). This reduction in decomposition will result in reduced CO_2 emission. Lifeng *et al.* (2008) found lower daily soil carbon dioxide emissions from no tillage when compared to conventional tillage and rotary tillage.

Precision farming, another RCT, includes site-specific nutrient management through the judicious application of fertilisers as per the soil nutrient status, thereby reducing the excess use of fertilisers. In this type of farming, the amount of irrigation water required by the crop is determined based upon the soil moisture status and crop requirement for water at that stage of growth in a site-specific manner. It also makes use of protected structures to safeguard the plants from harsh external environmental conditions (Mondal *et al.* 2011). Also, RCT can play a major role in reducing the cultivation cost, improving soil carbon build-up and reducing the water runoff and soil erosion besides improving irrigation water efficiency, input use efficiency, resource base and environment (Yadav 2012).

Organic farming

Organic farming integrates both adaptation and mitigation of climate change (IFOAM 2009; Muller 2009; Niggli *et al.* 2009). Mitigation of climate change through organic farming is possible due to the avoidance of chemical fertilisers, herbicides and pesticides, soil carbon build-up, and crop rotations with legumes (IAASTD 2008; IFOAM 2009; Muller 2009). Green and green leaf manuring, animal manure, legume crop rotations are major components of nutrient management in organic agriculture. They add sufficient nitrogen (N) to the soil, and they release N slowly compared to chemical fertilisers, leading to significant reduction in the loss of N from agriculture fields. Organic matter also diversifies soil food webs and helps in cycling more N from biological sources within the soil (Pimentel 2006). Organic farming uses 60–70% less N than chemical agriculture. Therefore, organic farming is estimated to reduce emission of N_2O at the rate of 1.2–1.6 Gt CO_2 equivalent annually (IFOAM 2009). Reduced N_2O emission is due to lower N inputs (Ho & Ching 2008; Muller 2009), less N from organic manure, higher C/N ratios of organic manure and efficient uptake of mobile N in soils by using cover crops (Ho & Ching 2008). It is clear that CO_2 emission in organic farming is lower compared to conventional agriculture as it does not disturb the soil structure, reduces soil erosion and increases plant cover, and also there is minimal use of fertilisers and pesticides produced from fossil fuels (Muller 2009; Sartaj *et al.* 2013). Restoration of organic soils can globally mitigate all GHGs emissions from 33.51 t CO_2-equivalent/ha/yr in a cool climate to 70.18 t CO_2-equivalent/ha/yr in a warm climate (Smith *et al.* 2007). Organic farming facilitates soil carbon sequestration through organic manures, green manures, intercropping, and tree and hedge planting (IFOAM 2009; Muller 2009). Total (100%) conversion of all agricultural lands worldwide to organic agriculture globally could sequester 2.4 Gt CO_2/annum for organic farming with good organic practices and up to 15.50 Gt CO_2/annum for organic farming with high standards of soil fertility build-up and conservation practices (IFOAM 2009).

Organic farming of crops helps in climate change adaptation through preventing and reversing soil erosion, restoring degraded land, improved drought and flooding resilience, increased water use efficiency (WUE), water conservation practices and agro-genetic biodiversity (IAASTD 2008; IFOAM 2009). The addition of organic manures, less tillage and crop rotation improves soil structure, soil organic matter and soil fertility build-up (IFOAM 2009; Sartaj *et al.* 2013). Organic farming produces 20% higher soil carbon than conventional farming, and it could offset 11% of global GHGs for at least the next 20 years (Wright 2010). Organic matter improves water infiltration and thus reduces soil erosion and prevents loss of nutrients through runoff (Pimentel 2006). Conservation of soil moisture through mulching and cover crops in organic farming facilitates drought resilience of the crops. Moreover, soils under organic farming have better water-holding capacity than conventional farming; hence, organic agriculture is more resistant to moisture stress or drought (Muller 2009; Sartaj *et al.* 2013). Organic farming of crops eliminates the risk and decreases the vulnerability of the farmers to climate change as it is low input and less risky farming (Muller 2009; Sartaj *et al.* 2013). The produce obtained through growing crops organically is highly remunerative and fetches a higher price for the farmer. Hence, organic farming is a better alternative for the agricultural community under a climate change situation (Sartaj *et al.* 2013).

At the Central Tuber Crops Research Institute, Thiruvananthapuram, an experiment was conducted on organic farming in elephant foot yam for five years by Suja *et al.* (2012). They found a 20% yield increase and net profit was estimated as 28% higher compared to chemical farming. Organic farming, besides, improved the root quality and physical and chemical properties of the soil. Significantly higher pH and 19% higher organic C, higher exchangeable Mg, available Cu, Mn and Fe contents and 28.4% increased water-holding capacity were observed in the case of organic farming.

Integrated cropping systems

Integrated cropping systems in association with cropping practices have the ability to sequester atmospheric carbon, thereby helping in the formulation of mitigation choices of climate change (Wang *et al.* 2010). Intercropping, mixed cropping, relay cropping and strip cropping helps in increasing the yield and productivity of crops. Under changing climatic situations, crop failures, reduced yields, reduction in crop quality and increasing pest and disease problems are common, and they render vegetable cultivation unprofitable (Koundinya *et al.* 2014). Under such circumstances, multiple cropping systems are more beneficial than monocropping as the loss due to the failure of one crop can be compensated by the yield from another crop. Cropping systems also aim at increasing the farm income by crop diversification, thereby reducing the risk and uncertainty as a result of climate change. Intercropping of vegetables can be a possible and reliable measure to cope with these problems as it is a more productive system and a less risky technology (Kamanga *et al.* 2010). It is productive through judicious utilisation of resources, namely, light, space, water and nutrients in stress-prone areas, especially in South Asia and Africa where environmental stresses are common (Machado 2009). The growing space, as well as the residual moisture after harvesting of a short duration crop, might be utilised by a long duration crop during the reproductive phase, when it normally experiences moisture stress after withdrawal of monsoon rains. Hence, intercropping could be an option to address the detrimental effects of climate change and reduce the vulnerability of crops to climate change. There are few examples of intercropping of vegetables in which the yield of the component crops is higher than the individual crop. Legumes have been the common intercrops in any intercropping system owing to their short duration and N-fixing ability. Intercropping with legumes has been becoming more stable and dependable than sole cropping systems in vegetable cultivation (Patel *et al.* 1998). Although the nonleguminous and no-N-fixing vegetables require longer duration than the legumes, they are also suitable as intercrops because of their high profitability and higher yields. Intercropping of baby corn with cowpea, okra, brinjal and chilli during summer (Adhikary *et al.* 2015a) and with tomato, brinjal, chilli and pea during autumn–winter (Adhikary *et al.* 2015b) is a much more profitable and productive system than sole cropping. Research work in rainfed areas has shown that intercropping with specific planting geometry and selection of compatible crops is a cost-effective practice to make use of available soil moisture and nutrients more efficiently and thus improve the productivity of dryland crops (Goswami *et al.* 2002). Tree-based intercropping (TBI) systems are believed to be effective in mitigating GHGs. Research done at the University of Guelph Agroforestry Research Station (GARS) in Canada indicated that TBI systems are capable of lowering N_2O emissions by 1.2 kg/ha/yr, as assessed by Evers *et al.* (2010). Annual cereals, grain crops and vegetables can also be grown as intercrops in between the rows of perennial tree vegetables such as drumstick and thereby help farmers to gain more income per unit area. The farmers in Tamil Nadu, an Indian state, grow sorghum and other dry land *Poaceae* crops as intercrops in drumstick fields (de Saint Sauveur 2001). Moreover, intercropping prevents the spread of vector-borne diseases, which are becoming aggravated due to climate change (Koundinya *et al.* 2014). Adhikary *et al.* (2015a) found that intercropping of okra plants with baby corn reduces the spreading of yellow vein mosaic virus in okra as the baby corn plants act as a barrier to whitefly, the vector for this virus.

Crop rotation with legumes helps in fixing atmospheric N, thereby, reducing the burning of fossil fuels for the production of chemical fertilisers as reported by Wang *et al.* (2010). Growing cover crops is an effective approach to improve carbon sequestration and soil organic carbon storage (Chatterjee 2011). Moreover, cover crops assist in moisture conservation in soil by preventing the loss of moisture through evaporation, thereby cover cropping forms an important adaptation strategy against drought or moisture stress.

Mulching

Mulching helps to conserve soil moisture, prevents soil degradation and protects vegetables from torrential rains, high temperatures and flooding (Pena & Hughes 2007). Both organic and inorganic mulches are being used in the cultivation of vegetable crops like okra, brinjal, round melon, ridge gourd, bottle gourd and sponge gourd, under stress conditions. Mulching reduces soil moisture evaporation, moderates soil temperature, restricts weed growth and reduces soil runoff and erosion. Moreover, organic mulches like rice straw, fenugreek, cluster bean and grasses help in improving the soil fertility and add organic carbon to the soil as they are allowed to degrade after their use. Mulching with rice straw in summer season benefited tomato production in Taiwan (AVRDC 1981; Pena & Hughes 2007). Rice straw mulching in a tomato crop exhibited maximum B:C ratio due to higher fruit yield and lower initial input requirement during summer (Pandey & Mishra 2012). Inorganic or plastic mulches do not add organic matter to the soil, but conserve soil moisture and reduce weed growth. Some coloured plastic mulches also help in controlling pests and diseases (Table 3), which are being provoked by the climate change.

Irrigation and fertiliser management

Irrigation water management is a critical adaptation strategy under varying climatic conditions. Water is one of the most important requisites for crop production, a vital component in all biological systems, and climate change directly hits its sources and reduces its availability. Climate change affects and delays the monsoons and often causes crop failure. The delay or failure of the monsoons results in water shortage and below average crop yields (Koundinya *et al.* 2014). Timely irrigation and conservation of soil moisture are critical components of irrigation water management under climate change (Pena & Hughes 2007). The role of mulching and cover cropping and how precision farming helps in conserving soil moisture have already been discussed above. Micro irrigation systems such as sprinkler and drip irrigation are already proven technologies of water conservation and increasing WUE, FUE and crop yield. Their performance in the climate change context has been discussed previously by several authors. The maximum WUE in cabbage is found under drip irrigation over furrow irrigation by Kumar *et al.* (2012). In Florida, when need-based irrigation is given to tomato crops by recognising soil moisture content through sensors, it saves 15–51% irrigation water over conventional drip irrigation (Zotarelli *et al.* 2009). It also takes part in the mitigation strategy as micro irrigation avoids soil disturbance and reduces the soil surface runoff, which are common problems with surface irrigation methods.

Fertiliser management, another input management approach in crop production under climate change, mainly forms the mitigation strategy. Integrated nutrient management (INM) makes use of organic manures, inorganic and biofertilisers and thereby reduces the dependence on chemical fertilisers (BIAC 2009). Nutrient management has global GHG emissions mitigating potential up to 0.33 t CO_2-equivalent/ha/yr in a moist climate and 0.62 t CO_2-equivalent/ha/yr in a warm climate (Smith *et al.* 2007). Complex (NPK) and customised fertilisers, fortified micro-nutrient fertilisers, bio-fertilisers (phosphate solubilising bacteria; *Azospirillum, Azotobacter, Rhizobium* and potash mobilising biofertilisers) can supplement up to 20–25% of chemical fertilisers usage in the country (Anonymous 2016). Fertigation helps in the judicious application of nutrients, reduces wastage and increases FUE of crops. Planting

Table 3 | Benefits of coloured mulches (adapted from Chandra 2009)

Mulch colour	Observed benefits	Crops
Transparent	Greater soil warming	Crop raising in colder regions/seasons
Black	Suppress weed growth, reduce soil water loss, increases soil temperature, and can improve vegetable yield	
Silver	Increases yield, repels certain aphid species and whiteflies and reduces or delays the incidence of aphid-borne viruses, reduction in soil temperature	Pepper
Red	Warming the soil, controlling weeds, conserving moisture, increasing the yield, reducing the incidence of early blight, and suppression of nematodes	Tomato
Blue	The colour attracts thrips	Cucumbers, summer squash
Green IRT	Weed control, moderate soil warming	Cantaloupe
Yellow	Attracts certain insects, such as whitefly, cucumber beetle, some aphids and serves as a trap to prevent damage to the main planting	

fast-growing trees in degraded areas, converting them to biochar and subsequent addition to the soil as a source of nutrients provides a way for carbon sequestration (Chatterjee 2011). Application of silicate amendments helps in the conversion of CO_2 into bicarbonates besides reversing the acidification of soils (BIAC 2009; Chatterjee 2011).

Farming with perennials

Perennials improve soil health as they maintain the ground cover, soil structure and biota. They also have a deeper root system than annuals which helps in binding soil particles together and supports microbial and fungal processes that increase water stable aggregates and soil organic matter. Moreover, perennial roots contain more carbon than annuals (FAO 2011; USDA 2015). Growing of perennials also prevents soil erosion (USDA 2015) by binding soil particles together, and their management practices do not disturb the soil much. Moreover, during drier years and in whole drought situations, the deep root system of trees can exploit a large volume of water and nutrients, thereby helping the plants to survive under diminishing soil moisture conditions to some extent (Roy *et al.* 2011). Moreover, growing of perennials with multiple uses of food, fodder and fuel will diversify the income source (FAO 2011). The majority of vegetables are grown as annuals. However, some tree perennial vegetables, such as drumstick, help farmers in gaining more income per unit area. Drumstick (*Moringa oleifera*) is drought tolerant and grows well in arid regions. The farmers in the drought-prone district Ahmednagar of Maharastra of India are cultivating drumstick with a benefit cost ratio of 3:1 (CCKN-IA 2016).

Agroforestry

The adoption of agroforestry practices like windbreaks and riparian forest buffers, which incorporate trees and shrubs into ongoing farm operations, represents a potentially significant sink of greenhouse gases. Agroforestry significantly stores carbon in plant biomass (Smith *et al.* 2007; Chatterjee 2011). Use of some legume and nitrogen-fixing trees in agroforestry systems supports the fixing of atmospheric nitrogen in the soil (Chatterjee 2011), which reduces the need for application of nitrogenous fertilisers to the intercropped crops in case of silvi–pastorial, horti–pastorial systems. Agroforestry globally can mitigate 0.3 t CO_2-equivalent/ha/year under warm dry climate and 0.7 t CO_2-equivalent/ha/year under warm moist climate (Smith *et al.* 2007; Milder *et al.* 2011). Verchot *et al.* (2007) mentioned that carbon sequestration by agroforestry will be 600 Mt by the year 2040. Agroforestry systems avoid long-term vulnerability as trees act as an insurance against drought, insect pest outbreaks and other threats (Rathore 2004). In addition, they provide socio-economic benefits to the farming community, thus helping to minimise the risk and uncertainty in agriculture under a climate change situation.

PROTECTED CULTIVATION

Protection of crops from unfavourable environmental conditions is an age-old agronomic practice. Under varying weather, cultivation of crops under protected structures is becoming compulsory to protect them from high and low temperatures, drought and flooding situations and soil pH stresses. The climate inside the greenhouse can be regulated by using various devices such as heating and cooling systems, CO_2 emission and absorbing systems, automated need-based irrigation and nutrient supplying systems (Jensen & Malter 1995). Soilless cultivation (hydroponics and aeroponics) avoids the problems associated with soil cultivation like weeds, salinity, alkalinity, acidity and soil-borne pests and diseases (Eng 2010). Several researchers and authors have described the role of protected cultivation in protecting crops from extreme environmental conditions such as high and low temperatures. In addition, the harvested produce will fetch a good price in the market (Singh & Sirohi 2006).

POST-HARVEST TECHNOLOGY

Cotty & Jamie-Garcia (2007) and Costello *et al.* (2009) discussed the effect of climate change on post-harvest quality of produce. Climate change is adversely affecting agricultural productivity. Moreover, an ever-increasing population coupled with decreasing land under cultivation enhances the demand for food for human consumption. In this context, minimising post-harvest losses and increasing the shelf life of the harvested produce are required to meet the ever-increasing food requirement. About 2% of horticultural produce is processed in India, and the post-harvest losses of fruits and vegetables in India are 50%; this compares to developed countries whose losses are 2–25% (Sudheer & Indira 2007). These losses could be minimised to a great extent through appropriate commodity and location-specific post-harvest technology, preferably in the production catchment. The food processing industry is growing rapidly in India due to its low base, the increased availability of surpluses, changing lifestyles, tastes and higher disposable income of consumers. For the year 2014–15, in India, the growth rate of the food processing industry was 4.7%, outperforming the manufacturing sector whose growth rate was 2.3% (Anonymous 2016). Furthermore, investment in technologies that minimise wastage of food, food storage and safe transport, and in developing small-scale industries like low-cost drying, packing, bottling and canning is clearly needed (BIAC 2009). Such primary processing industries enhance byproduct utilisation and quality of food products, facilitate employment and income generation for rural youth, and guarantee sustainable livelihoods in the countryside.

Preservation through processing is followed only in some vegetables like tomato, onion, potato and tropical tuber crops in India. The Central Tuber Crops Research Institute, Thiruvananthapuram, Kerala, India has developed several types of starch-based value-added products: gluten-free spaghetti from sweet potato, noodles from cassava and sweet potato, and pickles from yam and elephant foot yam (CTCRI 2015). Tropical tuber crops' capacity to thrive, to some extent, under adverse climatic conditions and the potential for the preparation of various value-added products from them have made them the most suitable for changing weather conditions.

FORECASTING

Technology to improve the quality and accessibility of data on crop production under climate change has been developed. Forecasting is the prediction of future value based on past data. Weather forecasting models (WFM) provide the advantage of daily forecasting of weather information through remote sensing, validation of different land-use products and dissemination of information (Vermeulen et al. 2010). The crop growth simulating models (GSM) (Table 4) predict crop growth and yield under future climatic conditions using various parameters which include future weather scenarios predicted by weather forecasting or global circulating models. These can be used to predict the possible impact of climate change on crop production and also help in framing necessary adaptation measures. Different pest and disease forecasting models have also been developed to predict the appearance of pest and diseases in advance to allow preventive actions to be taken. Luck et al. (2010) used three global climate models (EH5OM, HadCM3Q and CCAM-Mark 3.5) and two regional climate models (RegCM3 and PRECIS) for prediction of potato yields in India, Bangladesh and Australia. They also used the Hyre model, Smith model, Wallin model, Blitecast, Fry model, Hartil and Young models for the prediction of late blight disease incidence in potato under changing climatic conditions.

Another way of assessing the possible impact of climate change on crop production is by conducting the experiment in a modified environment condition (Table 4) that includes high temperature, and high CO_2 and other GHG concentrations. For example, growing crops in a CO_2 enriched environment helps attain a better understanding of crop growth and yield under elevated CO_2 conditions. These types of environments can be created in a closed environment like greenhouses and growth chambers or an open environment like FACE, FATE. Most of such studies are performed in closed environments, but the experiments conducted in an open environment are more representative of field conditions as a closed environment misses several other factors such as plant competition.

From the huge amount of literature on crop production under the influence of climate change, it is understood that climate change threatens crop production and its impacts will continue in the future, causing global food security to worsen. It necessitates the framing up of needs-based sustainable adaptation and mitigation strategies that can effectively combat climate change, avoid risk and uncertainty in agriculture, and also ensure sustainable livelihood. The review suggests that cropping systems, conservation tillage, fertiliser management and agroforestry form important mitigation strategies whereas genetic

Table 4 | Examples of crop growth simulation models and experiments under modified environment

S. no.	Crop growth simulation models	Application	Case study examples
1	DSSAT: Decision Support System For Agrotechnology Transfer	A software application that includes crop simulation models for 42 crops	Potato DSSAT-SUBSTOR (Raymundo *et al.* 2014)
2	WOFOST; World Food Studies	A mechanistic model which explains crop growth based on the underlying physiological processes, such as photosynthesis, respiration and the influence of environmental conditions on these processes	Potato SWAP-WOFOST (Yan 2015)
3	INFOCROP	A generic crop model that simulates the effects on crop growth, yield, soil carbon, nitrogen and water, and greenhouse gas emissions by weather, soils, agronomic practices (crop husbandry) and major pests	INFOCROPPOTATO (Singh *et al.* 2005)
4	APSIM: Agricultural Production Systems Simulator	A simulation of systems which deals with a range of plant, animal, soil, climate and management interactions	APSIM-Potato (Brown *et al.* 2011; Lisson & Cotching 2011)
5	CropSyst: Cropping Systems Simulation Model	An analytical tool to study the influence of climate, soils, and crop management on cropping systems productivity and the environment	Greater yam, CROPSYSTVB-yam, (Marcos *et al.* 2011); CROPSYSTVB-CSPOTATO (Alva *et al.* 2010)
6	Madhuram	A sweet potato specific model to predict crop phenology based on vegetative developmental days and reproductive developmental days	Sweet potato (Somasundaram & Santhosh Mithra 2008)
	Experiments under modified environment		
1	MLT: Multi Location Trial	To find out the genotypes or varieties with high adaptability to different locations	
2	FACE: Free Atmospheric Carbon dioxide Enrichment	To study the crop growth and yield in response to high atmospheric CO_2	Chinese yam (Thinh *et al.* 2017); Potato (Miglietta *et al.* 1998)
3	FATE: Free Atmospheric Temperature Elevation	To study the crop growth and yield in response to high atmospheric temperatures	
4	T-FACE: Temperature + FACE	A combination of FACE and FATE	
5	OTC: Open Top Chamber	To study the effects of elevated CO_2 and other atmospheric gases on vegetation	Potato (Finnan *et al.* 2005)

improvement, grafting, irrigation management, protected cultivation, post-harvest technology and forecasting models are the adaptation strategies. Organic farming acts as an adaptation and mitigation strategy. A holistic approach based on all these strategies is required to combat climate change. Questions remain such as is organic farming efficient enough to feed sufficiently? How is protected cultivation possible for a small or marginal farmer with limited capital and resources? These questions need to be taken into serious consideration while framing strategies. The time has come to initiate intensive research on climate change specific to agriculture at national and international levels. Establishment of a strong cooperation between public sector institutions and private NGOs, which are working on climate change, is much needed. Financial incentives that encourage farmers to take up efficient carbon storage and improved WUE and FUE practices are needed. Afforestation and reforestation under clean development mechanisms can be taken up at farmer level. A well-organised extension system should be developed to help farmers become aware and to keep them well informed regarding climate change and its effects on crop production, to prepare them to face uncertainty, and to provide information about new regulatory structures and government priorities and policies. Training programmes should be conducted to motivate and to train farmers to follow mitigation and adaptation practices.

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