Bioversity International

Tropical Fruit Tree Species and Climate Change

Bhuwon Sthapit, V. Ramanatha Rao and Sajal Sthapit, editors




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This publication presents part of the findings of the regional UNEP/GEF project "Conservation and Sustainable Use of Cultivated and Wild Tropical Fruit Diversity: Promoting Sustainable Livelihoods, Food Security and Ecosystem Services" implemented in India, Indonesia, Malaysia and Thailand. The project is coordinated by Bioversity International (IPGRI) with financing from the Global Environmental Facility (GEF) and implementation support from the United Nations Environment Programme (UNEP).

Bioversity International is a world leading research-for-development non-profit organization, working towards a world in which smallholder farming communities in developing countries are thriving and sustainable. Bioversity International's purpose is to investigate the use and conservation of agricultural biodiversity in order to achieve better nutrition, improve smallholders' livelihoods and enhance agricultural sustainability. Bioversity International works with a global range of partners to maximize impact, to develop capacity and to ensure that all stakeholders have an effective voice.

Bioversity International is a member of the CGIAR Consortium. CGIAR is a global research partnership that unites organizations engaged in research for sustainable development. CGIAR research is dedicated to reducing rural poverty, increasing food security, improving human health and nutrition, and ensuring more sustainable management of natural resources. It is carried out by the 15 centres who are members of the CGIAR Consortium in close collaboration with hundreds of partner organizations, including national and regional research institutes, civil society organizations, academia, and the private sector.

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Tropical Fruit Tree Species and Climate Change

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The **CGIAR Research Programme on Climate Change, Agriculture and Food Security (CCAFS)** is a strategic partnership of the Consortium of International Agricultural Research Centers (CGIAR) and the Earth System Science Partnership (ESSP), led by the International Center for Tropical Agriculture (CIAT).

EcoAgriculture Partners strives for a world where agricultural communities manage their landscapes as ecoagriculture to enable them simultaneously to enhance rural livelihoods, conserve biodiversity and ecosystem services, and sustainably produce crops, livestock, fish, and fibre.

The **Indian Council of Agricultural Research (ICAR)** is an autonomous organisation under the Department of Agricultural Research and Education (DARE), Ministry of Agriculture, Government of India. With 97 ICAR institutes and 47 agricultural universities spread across the country this is one of the largest national agricultural systems in the world.

The **Rural Development Administration (RDA)** is the central government organization responsible for extensive agricultural research and services in Korea.

The **United Nations Environment Programme (UNEP)** is an international institution that coordinates United Nations environmental activities, assisting developing countries in implementing environmentally sound policies and practices. UNEP's mission is to provide leadership and encourage partnership in caring for the environment by inspiring, informing, and enabling nations and peoples to improve their quality of life without compromising that of future generations. UNEP is one of the Implementing Agencies of the GEF and is the only GEF Agency whose core business is the environment.

The **Global Environment Facility (GEF)** unites 182 member governments — in partnership with international institutions, nongovernmental organizations, and the private sector — to address global environmental issues. GEF is the largest public funder of projects to improve the global environment. An independently operating financial organization, the GEF provides grants for projects related to biodiversity, climate change, international waters, land degradation, the ozone layer, and persistent organic pollutants

Foreword

Bioversity International is the only global non-profit research organization that places the use and conservation of agricultural biodiversity in smallholder production systems at the centre of its work. We generate the knowledge to help our partners implement practical changes on the ground to improve nutrition, livelihoods and to enhance sustainability. The two billion smallholder farmers who live in developing countries rely on agricultural biodiversity to provide food, income and other livelihood resources. However, land degradation, loss of biodiversity and climate change are making this increasingly challenging. Agriculture will need to adapt much faster in the next 50 years than it has ever had to in its entire 12,000 years of history.

Climate change is a major threat to biodiversity, ecosystem services, and human well-being. The global climate is predicted to change radically. This might result in both positive and negative impacts on horticultural crops.

Tropical fruits – full of rich nutrients and health properties – are adapted to hot and humid environments. Many tropical fruit species might spread beyond their current geographical limit whereas some species might exhibit irregular bearing of fruit. In this context, there are some important questions that need answers: What are the key characteristics that allow farmers to choose a new crop that they are not used to growing? Are farmers already experiencing impacts of climate change? If so, what are their adaptation strategies? Are there new opportunities for capitalizing tropical fruit tree genetic resources that benefit human kind?

Phenological patterns are most diverse and least understood in the tropics. Changes in plant phenology are one of the earliest responses to rapid global climate change and could potentially have serious consequences for trees that depend on periodically available rain. There is no evidence for photoperiod control of phenology in the Asian tropics, and seasonal changes in temperature are a likely factor only near the northern margins. An opportunistic response to water availability is the simplest explanation for most observed patterns where water is seasonally limiting. Limited research has been carried out on whether perennial fruit tree species will be seriously affected

by the phenological consequences of climate change or whether these species have sufficient genetic variation to elicit appropriate phenological patterns to cope with climate change. Moreover, how can farmers exploit the latter?

The Consultative Group on International Agricultural Research (CGIAR) Research Programme on Climate Change, Agriculture and Food Security (CCAFS), EcoAgriculture Partners, the Rural Development Administration (RDA, Korea), the United Nations Environment Programme, Global Environment Facility (UNEP/GEF) and the Indian Council of Agricultural Research (ICAR) came together with Bioversity to take stock of the current knowledge on tropical fruits and climate change. The study provides a state of knowledge to overcome threats to agriculture and food security, exploring new ways of helping vulnerable rural communities adjust to global changes in climate.

Stephan Weise, PhD
Deputy Director General - Research
Bioversity International, Rome

Few Words

The Rural Development Administration (RDA) is a government organization undertaking agricultural research and extension service in Korea. RDA assisted Korea in achieving self-sufficiency in rice and other staple food through the dissemination and promotion of high-yielding cultivars and improved cropping technologies. It has also made fresh vegetables always available through year-round cropping technology using greenhouses. RDA has contributed to improving rural environment and nurturing new farmers.

Currently, one of the most critical research topics at RDA is climate change. This inevitable phenomenon affects millions of livelihoods, especially in poor and marginalized communities. Also it has directly impacted the biodiversity within the agricultural production system. Research efforts have been heightened in the wake of irrevocable damages done to agriculture and production systems across the world.

In particular, research on tropical fruits, a vital income source for many Asian households, has been highlighted. Due to the perennial nature of many tropical fruit tree species, they inherently possess adaptive traits leading to their increased resilience to climate change.

This publication reviews status, potential threats and new opportunities in tropical fruit production and diversity conservation. It also helps both researchers and farmers identify and fill key underlying knowledge gaps in tropical fruit tree research. This publication therefore benefits both our local and global research communities.

RDA commends this conscientious effort in gathering the expertise and knowledge of esteemed researchers on various relevant topics from around the world.

June 2012

Hyun Chool Park
Administrator
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Preface

While the reality of climate change has finally penetrated the popular psyche, another environmental crisis – the dramatic loss of agricultural biodiversity – silently threatens the world's food supply. It has been noted by several authorities on the topic that changes in the world's climate will result in major shifts in food production. It may increase in some places due to increases in rainfall and temperature while in others, food production may fall steeply due to a decrease in rainfall. Climate change is predicted to have major impacts on small-scale farmers whose livelihoods depend on rainfed agriculture. In addition, coastal flooding can reduce the amount of land available for agriculture.

In general, food crops are sensitive to climate change. Global yield losses due to global warming have amounted to 40 million tonnes or five billion US dollars yearly for wheat, maize and barley since 1981. Furthermore, crop modeling shows that climate change will continue to reduce agricultural production, thus reducing food availability and thereby affecting food security and farm incomes. For example, models suggest that at least 50% of plant species could be vulnerable or threatened by 2080.

Although perennial fruit tree species may be less affected by climate change than annual grain crops, global warming has the potential to reduce available winter chill and thus greatly impact crop yields of temperate fruits and nuts. On the other hand, tropical fruit tree species might have the opportunity to spread beyond their current latitudinal belts and/or to much higher elevations in the tropics. Changes in climate could therefore rapidly shift plant distributions because some species will expand into newly favourable areas whilst others will decline in increasingly adverse locations. Outcomes of such changes will have both positive and negative impacts on the lives of local people. Information on their plant characteristics combined with the physiology on growth and phenology will be helpful for farmers to choose new crops for their region when they need to substitute the range of crops.

There is very limited information available on perennial tropical fruit trees species in the context of climate change. In practice the

integration of trees into cultivated land, or home gardens, is one traditional practice to agricultural diversification that has been shown to provide a range of potential benefits. Tropical fruits are naturally adapted to warmer climates and many varieties of fruit tree species are resilient to various forms of climate-related stresses. This book takes stock on current knowledge on tropical fruits in the wake of climate change and aims to fill this knowledge gap. It provides important information needed to evaluate the future suitability of tropical fruits beyond the limit of current geographical adaptation and assesses the scope of using genetic resources as new crops in new situations. An attempt is also made to identify serious gaps in our knowledge and areas that need researcher attention.

The views expressed in this bulletin reflect differences in the author's backgrounds, experiences, and interests.

B. Sthapit, V. Ramanatha Rao and S. Sthapit, eds.

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Prem Narain Mathur completed his PhD and MSc in Plant Breeding and Genetics from University of Udaipur, Rajasthan. He was a Post-Doctoral Fellow at Oxford Forestry Institute, University of Oxford, Oxford, UK. He has been working with Bioversity International for over 16 years and presently is the South Asia Coordinator. Prior to joining Bioversity, he served the Indian Council of Agriculture Research (ICAR) for 18 years from 1977 to 1995. Some of his activities include promoting use of plant genetic resources, PGR information management and documentation, use of GIS tools for assessing and locating diversity, and use of crop diversity for climate change adaptation. He has over 95 scientific publications.

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Sajal Sthapit has an MSc in Sustainable Development and Conservation Biology from the University of Maryland and a BA in biology and philosophy from the College of Wooster. He has worked for EcoAgriculture Partners in Washington, DC and is currently the programme coordinator of the Biodiversity and Ecosystem Services for Sustainable Livelihoods programme at Local Initiatives for Biodiversity, Research and Development (LI-BIRD) in Nepal.

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Abbreviations

ACC	Agrobiodiversity Conservation Credits
CAM	Crassulacean Acid Metabolism
CBD	Convention on Biological Diversity
CBOs	Community Based Organizations
CBR	Community Biodiversity Register
CIAT	International Center for Tropical Agriculture
CCAFS	CGIAR Research Programme on Climate Change, Agriculture and Food Security
CGIAR	The Consultative Group on International Agricultural Research
EHU	Effective Heat Unit
FAO	Food and Agriculture Organisation of the United Nations
FGB	Field Genebank
GIS	Geographical Information System
GCM	Global Climate Model
GHG	Greenhouse Gas
IGP	Indo Gangetic Plains
IPCC	Intergovernmental Panel on Climate Change
NGO	Non Governmental Organization
PGR	Plant Genetic Resources
PRA	Participatory Rural Appraisal
TFT	Tropical Fruit Tree
TSS	Total Soluble Solids
WUE	Water Use Efficiency

Tropical Fruit Trees and Climate Change

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Introduction

All tropical continents have great diversity of tropical fruit trees, with about 1000 fruit species described in America, 1200 in Africa and 500 in Asia, including 300 in the Indian subcontinent (Paull and Duarte 2011). Although only a small fraction of this diversity is marketed and even less is exported, this diversity is valuable for the livelihoods of local people throughout the tropical region as potential sources of food, nutrition and income.

In contrast to the diversity of fruits, just 10 annual cereal grains, legumes and oilseeds dominate 80% of the world's cropland (Glover et al. 2007). Currently, wheat, rice and maize cover half of the world's cropland, while adding other annual grains accounts for two-thirds of all arable land in the world (ibid.).

This is starkly reflected in the diets we consume. About 60% of the world's population is currently malnourished because they are either not getting enough calories or they are getting too much of the wrong kinds of calories (Pimentel 2011). Global supply of cereals for consumption as food (excluding alcoholic beverages) is 1290 kcal/capita/day, while the supply of fruits (excluding wine) is 87 kcal/capita/day (FAOStat 2011). The U.S. Department of Agriculture and the U.S. Department of Health and Human Services (2010) recommend between 217 to 332 kcal per person per day of fruit consumption for a healthy lifestyle[2]. The average per capita

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1 Author was affiliated with Local Initiatives for Biodiversity, Research and Development (LI-BIRD) for the majority of the time it took to complete this book.

2 Author's calculations based on data on serving sizes and calories of various fruits provided in USDA 2010.

food consumption in the USA needs to be trimmed by over 1,200 kcal per day. But a reduction in consumption of fruits is still not recommended (Pimentel 2011).

While, globally, more than 90% of fresh fruits are consumed locally, the import demand for tropical fruits has been steadily increasing in the past decade (Paull and Duarte 2011, Tropical Fruit – Global Information System). Global fruit imports have steadily increased from 24 million dollars in 1999-2001 to 56 million dollars in 2008 (FAO 2010)[3]. Developing countries account for most of the production at 98% while developed countries are the major importers at 80% of imports (Paull and Duarte 2011). There is great potential for growth in these fruit markets to take advantage of the increasingly health conscious nutritional trends based on consumption of more fruits and vegetables, and as rural people migrate to cities and have to buy what they previously could gather from wild-grown fruit trees.

At the nexus of climate change and growing demand for fruits, there are both opportunities to seek and challenges to deal with. Current producers who rely on fruits want to know how they can adapt to impending changes and continue producing. New opportunity seekers want to know what fruits are now becoming suitable for production in their countries. However, very little work has been done so far to examine the effects of climate change on fruits in terms of threats, adaptation options and opportunities in new locations. This book attempts to bring together the current state of knowledge on these issues, especially around tropical fruit trees.

Concurrently, climate change is shifting the habitat ranges of plants and animals (Pereira et al. 2010), including agricultural crops. For example, as average global temperatures increase, plant and animal populations may move to new latitudes with more favourable climates. It is, therefore, possible that crops that used to be productive in one area may no longer be so or the other way around.

The rest of this chapter provides a primer on greenhouse gases (GHGs), carbon cycle and land-based adaptation and mitigation strategies and provides an overview of the chapters in this book.

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[3] http://www.fao.org/fileadmin/templates/ess/ess_test_folder/Publications/yearbook_2010 / c11.xls - Accessed 2 January 2012.

Climate Change

Greenhouse gases

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the three main GHGs responsible for climate change. Net carbon dioxide emissions come from energy consumption, i.e. burning of fossil fuels. After fossil fuel use, land use change and forestry, especially deforestation and degradation, are the next largest emitters of carbon dioxide (Baumert et al. 2009). Carbon dioxide is responsible for 77% of global warming over a 100 year period and hence the most important GHG (Climate Analysis Indicators Tool 2011)[4].

The global warming potential of other GHGs are expressed in terms of carbon dioxide equivalence or CO_{2eq}. One CO_{2eq} is the warming effect caused by one molecule of carbon dioxide over a given period of time, usually chosen as 20 or 100 years.

Methane's global warming potential over a 100 year period is about 23 CO_{2eq}. It is released from the enteric fermentation in ruminant livestock (belching and flatulence), from manure, flooded rice cultivation as well as landfills, waste water and other wastes (Baumert et al. 2009).

Nitrous oxide is released primarily from agricultural soil management as a consequence of soil fertilization using chemical fertilizers or farmyard manure. Some nitrous oxide also comes from waste and biomass burning (Baumert et al. 2009). Nitrous oxide's global warming potential over a 100 year period is about 298 CO_{2eq}.

Together, these 3 GHGs are responsible for 99% of the global warming over a 100 year period. The other GHGs (perfluorocarbons, hydroflourocarbons, and sulphur hexaflouride), as of now, make a small contribution to global warming. However, due to very high carbon dioxide equivalence compared to nitrous oxide, even small increases in emissions of these minor GHGs can result in significant warming effect.

4 http://cait.wri.org – Accessed 23 May 2011.

The global carbon cycle

Every year, the atmosphere and oceans exchange 330 billion tons of CO_{2eq} each, while the atmosphere and terrestrial vegetation exchange about 220 billion tons of CO_{2eq} each (Figure 1). In a natural state, these exchanges are in dynamic equilibrium, with the emissions from land and ocean balancing out the removal from the atmosphere. These exchanges, also called the global carbon cycle (Figure 1), are also what drive the engine of almost all life and ecosystems in the world.

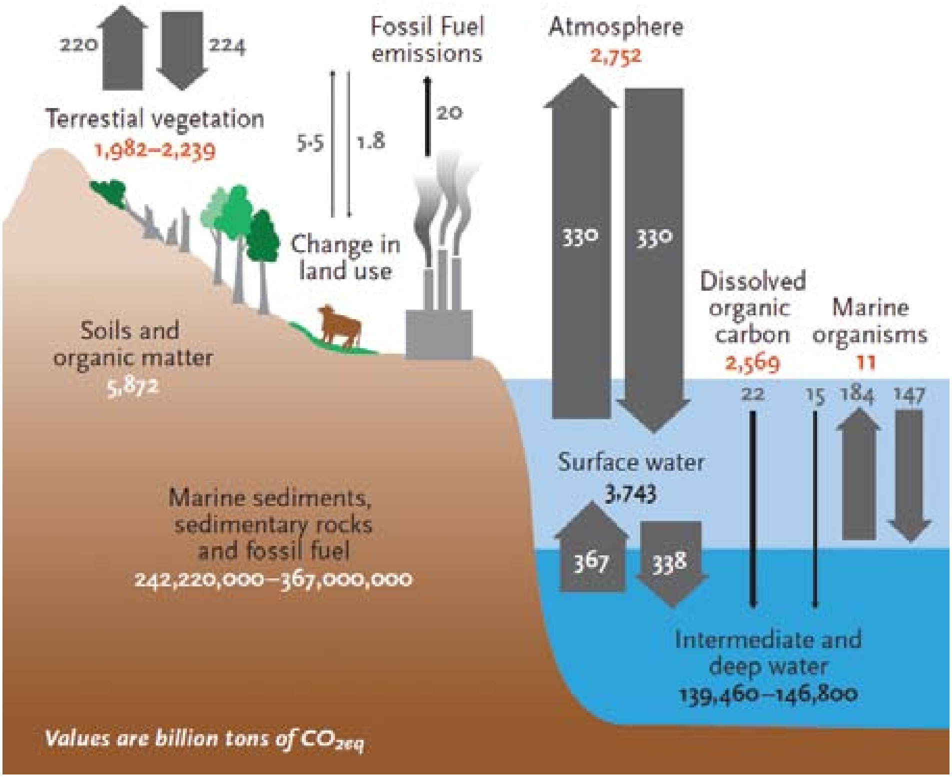

Figure 1. The global carbon cycle. Source: Scherr and Sthapit 2009a, illustrated by Joan A. Wolbier.

The annual anthropogenic GHG emissions of about 50 billion tons of CO_{2eq} pales in comparison to how much carbon is exchanged naturally between the three reservoirs of carbon: the atmosphere, land (including soil and vegetation) and the oceans. However, it is the anthropogenic GHG emissions that are ultimately responsible for current climate change. Anthropogenic GHG emissions are different in that they are unidirectional. These emissions are not being balanced, in the near term, by an equal amount of removal from the atmosphere. Therefore, every year the amount of GHGs in the atmosphere goes up and the globe also warms up.

Emissions by sector and region

Globally, the energy sector is the largest source of anthropogenic GHG emissions, accounting for 66% of the annual emissions. Land use based emissions are the next most important source. Among land use based emissions, agriculture is responsible for 14% and land use change and forestry for 13% of annual emissions (Climate Analysis Indicators Tool 2011).

Global averages, however, tend to hide key regional differences. The energy sector accounts for 86% of annual GHG emissions in North America. It is also the most important source in Central America and the Caribbean, Asia, and Oceania, contributing to around two-thirds of the regions' emissions. However, in South America, land use change and forestry is responsible for 53% of GHG emissions, while agriculture is second at 23% and the energy sector third at 21% (Climate Analysis Indicators Tool 2011). Furthermore, agricultural expansion is the direct cause for 66% of forest area change in South America (FAO 2009).

Regional differences show that emission reduction actions need to prioritize different sectors in different places. However, global negotiations have mostly prioritized energy sector based mitigation, while ignoring agriculture and land use based emissions (Scherr and Sthapit 2009b).

Adaptation and mitigation should go hand in hand

A review of evidence from the last 1000 years indicates that average global temperatures have risen sharply in the last century. There is a lot of variation in estimation of temperatures before the 20th century as they are based on proxy indicators for temperatures. Still, the basic conclusion is the same – the temperature is rising and it will continue to rise in the near future (Mann et al. 2009; Le Page 2009[5]).

These changes will have lasting impacts on the planet. Even if we stop all emissions today, the temperature will continue to rise for many decades or even a century and then stabilize. Lobell et al (2008) find that South Asia and Africa will face severe pressure on food security. As such adaptation is something we need to do.

One might ask then why should we mitigate or reduce emissions if the impacts of climate change are unavoidable now? Why not apply all efforts into adaptation and continue development?

Although adaptation is clearly important, it is dangerous to avoid mitigation. The atmospheric GHG concentration is nearing 400ppm and at this rate it will pass many dangerous tipping points that will further accelerate climate change to the extent that adaptation may become unfeasible for most of the world's population, biodiversity and ecosystems. For example, the Arctic summer ice is responsible for reflecting a lot of sun light and helps in lowering the world temperature average. But the Arctic ice is receding, which reduces the planet's albedo. As a consequence, more of the sun's heat energy is going to be absorbed (NASA 2005)[6]. Likewise, permafrost, soil that is frozen for more than 2-3 years continuously, at higher latitudes is also starting to melt. These permafrosts are vegetation locked in time. When they melt and the decaying vegetation is exposed to air, huge quantities of carbon dioxide and methane will be released (Trumper et al. 2009). Hence, without mitigation, the extent and impacts of climate change will be much more severe and future adaptation will incur very heavy environmental, economic and social costs (IPCC 2007).

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5 http://www.newscientist.com/article/dn11646-climate-myths-the-hockey-stick-graph-has-been-proven-wrong.html - Accessed 30 June 2012.

6 http://www.nasa.gov/centers/goddard/news/topstory/2005/arcticice_decline.html - Accessed 29 May 2011.

Mixing adaptation and mitigation strategies can reduce risks to climate change impacts and dovetail with each other to achieve greater levels of both adaptation and mitigation (IPCC 2007). Luckily, especially for agriculture, land use and forestry sector, adaptation and mitigation tend to go hand in hand. One provides opportunities for the other and vice versa along with many developmental co-benefits. Scherr and Sthapit (2009b) have compiled and described five key farming and land use strategies available to mitigate GHG emissions that also contribute to adaptation.

The first strategy is to enrich carbon content in soil, which has the biggest agriculture based mitigation potential. Agricultural soils managed to build soil organic carbon by minimizing tillage, erosion and chemical use also improve crop production and profitability.

Another strategy is to use more perennial crops, grasses, palms and trees for farming, as they constantly maintain more year round carbon in their biomass and soil compared to annual crops. There is large potential to substitute annual tilled crops with perennials, particularly for animal feed and vegetable oils, as well as to incorporate woody perennials into annual cropping systems in agroforestry or home garden systems.

The third strategy is to make livestock production more climate friendly as livestock related emissions now account for about 15% of annual anthropogenic GHG emissions, eclipsing the entire transportation sector. A reduction in livestock numbers may be needed but production innovations, including rotational grazing systems, manure management, methane capture for biogas, and improved feeds and feed additives, can help.

The fourth strategy is to maintain the planet's 4 billion hectares of forests and 5 billion hectares of natural grasslands that are a massive reservoir of carbon—both in vegetation above ground and in root systems below ground. Conservation of natural habitats will also benefit biodiversity in the face of climate change.

The fifth land-use based strategy is to rehabilitate and revegetate the extensive areas of the world that have been denuded of vegetation through land clearing for crops or grazing and from overuse and poor management. Degradation releases a huge amount of GHG while local people lose valuable livelihood assets and essential

watershed services. Restoring vegetative cover on degraded lands can be a win-win-win strategy for addressing climate change, rural poverty and water scarcity.

The above mentioned mitigation actions can be used to promote sustainable development, which is also synonymous with activities that build adaptive capacity. Adaptive capacity can be built by ensuring access to or building up i) economic resources, ii) technological solutions, iii) information and skills, iv) infrastructure, v) institutions and vi) equity (IPCC 2001).

Overview of the book

Fruit trees provide important adaptive values and tend to be more resilient to climate change due to their perennial nature. But they too are affected by climate change in idiosyncratic ways. Climate change especially poses important difficulties for commercial production of fruit trees. This book aims to review the status and document the potential threats and new opportunities in tropical fruit production and diversity maintenance.

Mathur et al. (chapter two) find that a lot of research has been done to study the impacts of climate change on crops globally, but most of it is focussed on studying major crops such as maize, wheat and rice. Horticultural crops including fruits have mostly been ignored, partly due to lack of data and approaches for modelling. Still, agricultural systems need to cope with the negatives and take advantage of the positives of climate change. Cereal production is predicted to decrease at low latitudes. It is important to explore if and what horticultural crops can play a role in substitution, in addition to developing appropriate cereal varieties and management practices.

Mathur et al. examine the change in climate suitability of various horticultural crops and find that suitable areas may decrease for some (such as onion, cabbage and banana) and increase for others (such as mango and coconut). They also provide perspective on the different adaptation needs and roles in building resilience of short duration versus long lived horticultural crops. If a variety of short duration horticultural crop does not perform well, then it can be replaced by another variety in the next growing cycle. As with annual grains and legumes, having diversity of varietal options is

crucial for this kind of adaptation. This shows the important roles that farmer seed systems and community seed banks can play as sources of diversity of varieties and associated knowledge for short duration crops. On the other hand, fruit trees have long growing cycles in the order of five to 10 years. There is less room for trial and error based changes in varieties. Therefore using climate projections, with an understanding of their limitations, to match existing varieties with suitable areas will be crucial for adaptation of long lived horticultural crops.

Dinesh and Reddy (chapter three) describe how fruit yield depends on a narrow range temperature and rainfall in magnitude and timing, even though the plant itself can live through greater extremes. Fruit yield is a function of light interception, variety's photosynthetic efficiency and cost of respiration. Therefore, pruning is commonly used to increase light interception. Temperature determines quantity and quality of fruits produced. Higher temperature at the fruit development stage speeds up maturity, fruit size and quality. Temperature also determines the number and quality of flowers, and thus directly influences the fruiting potential for the season. Rains during fruiting periods may blacken fruits (in mango) or prevent desirable fruit coloration (in guava), making the produce less appealing for the consumers. Increase in humidity can initiate unseasonal flowering. Various quality traits such as fruit coloration, spottiness, fruit texture and taste can be altered by change in temperature, humidity and rainfall (also see chapter four by Rajan).

Rajan (chapter four) documents the impacts of climate change on different phenological stages of tropical fruits (such as flowering, growth flushes, etc.), using mango as an example. The transitions between different phenological stages, which depend on various environmental cues of temperature and rainfall, have implications on the eventual fruit production, both in terms of quality and quantity. With this in mind, Rajan has made a projection of mango production potential and risks in various vegetation zones of the world. As adapted varieties may no longer be found in commercial orchards, there will also be a need to match varieties with the projected suitable production locations in the future. This might require long distance germplasm exchange between field genebanks. Geographical

information system (GIS) can be a useful tool for such matching. Using GIS, Rajan has identified potential areas for the production of the popular Alphonso variety of mango.

Ramanatha Rao and Sthapit (chapter five) discuss the status of tropical fruit tree genetic resources with respect of climate change impacts and options for conservation. For *ex situ* conservation, fruit trees present a unique challenge because, unlike cereals and legumes, fruit trees may not have seeds or seeds may be recalcitrant or the varieties may need to be vegetatively propagated. Hence a feasible method for conserving fruit trees *ex situ* is in field genebanks. However, field genebanks require large space, especially for large trees. Field genebanks can incur significant establishment, management and maintenance costs. Another approach is *in situ* or on farm conservation in protected areas or with community participation through integration in home gardens and agroforestry systems. Using fruit trees in on farm conservation approaches also provides options for improving the food security of participating communities. Additionally, these approaches leverage on social customs and relations for exchange and regeneration of germplasm over an area or landscape that is larger than a field genebank or an orchard. Hence, genetic resources are less susceptible to being wiped out by localized climatic hazards. However, there need to be incentives and awareness for successful on farm conservation.

Sthapit and Scherr (chapter six) provide a conclusion to the book with a discussion on what all this implies for tropical fruit trees as options for adaptation to climate change as well as mitigation to GHGs from land use.

References

Baumert KA, Herzog T, Pershing J. 2009. Navigating the Numbers: Greenhouse Gas Data and International Climate Policy. World Resources Institute, Washington, DC, USA.

Climate Analysis Indicators Tool. 2011. CAIT version 8.0 [online]. Available from: http://cait.wri.org. Date accessed: 23 May 2011.

FAO. 2009. State of the World's Forests 2009. FAO, Rome, Italy.

FAO. 2010. Statistical Yearbook 2010 [online]. Available from: http://www.fao.org/fileadmin/templates/ess/ess_test_folder/Publications/yearbook_2010/c11.xls. Date accessed: 2 January 2012.

FAOSTAT [online]. 2011. Available from: http://faostat.fao.org. Date accessed: 18 May 2011.

Glover JD, Cox CM, Reganold JP. 2007. Future farming: a return to roots? Scientific American August 82-89.

IPCC. 2001. Climate Change: The Scientific Basis. Cambridge University Press.

IPCC. 2007. Climate Change 2007, Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Le Page M. 2009 [online]. Climate myths: the 'hockey stick' graph has been proven wrong. New Scientist. Available from: http://www.newscientist.com/article/dn11646-climate-myths-the-hockey-stick-graph-has-been-proven-wrong.html. Date accessed: 30 June 2012.

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL. 2008. Prioritizing climate change adaptation needs for food security in 2030. Science 319:607-610.

Mann M, Zhang Z, Rutherford S, Bradley R, Hughes M, Shindell D, et al. 2009. Global signatures and dynamical origins of the little Ice Age and medieval climate anomaly. Science 326:1256-1260.

NASA. 2005. Arctic sea ice continues to decline, Arctic temperatures continue to rise in 2005 [online]. Available from: URL: http://www.nasa.gov/centers/goddard/news/topstory/2005/arcticice_decline.html. Date accessed: 29 May 2011.

Paull RE, Duarte O. 2011. Introduction. In: Paull RE, Duarte O, editors. Tropical Fruits (2nd ed.). CAB International, London, UK. pp. 1-10.

Pereira HM, Leadley PW, Proença V, Alkemade R, Scharlemann JPW, Fernandez-Manjarrés JF, et al. 2010. Scenarios for global biodiversity in the 21st century. Science 330:1496-1501.

Pimentel D. 2011. Food for thought: a review of the role of energy in current and evolving agriculture. Critical Reviews in Plant Sciences 30:35-44.

Scherr SJ, Sthapit S. 2009a. Mitigating climate change through food and land use. Worldwatch Report No. 179. Worldwatch Institute and EcoAgriculture Partners, Washington DC, USA.

Scherr SJ, Sthapit S. 2009b. Farming and land use to cool the planet. In: Starke L, editor. State of the World 2009: Into a Warming World. W.W. Norton & Co, New York, USA. pp. 30-49.

Tropical Fruit - Global Information System [online]. Available from: http://www.itfnet.org/gfruit/Templates%20English/fruits.htm. Date accessed: 21 May 2011.

Trumper K, Bertzky M, Dickson B, van der Heijden G, Jenkins M, Manning P. 2009. The Natural Fix? The Role of Ecosystems in Climate Mitigation. A UNEP rapid response assessment. United Nations Environment Programme, UNEP-WCMC, Cambridge, UK.

U.S. Department of Agriculture and U.S. Department of Health and Human Services. 2010. Dietary Guidelines for Americans, 2010 (7th ed.). U.S. Government Printing Office, Washington, DC, USA.

The Impacts of Climate Change on Tropical and Sub-tropical Horticultural Production

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Introduction

Global warming and climate change is now perceived to be the greatest threat to agriculture production and food security in the 21st century. Nobel Prize winner, the Intergovernmental Panel on Climate Change (IPCC) by means of the four assessment reports that have been released to date (IPCC 1990, 1995, 2001, 2007), has shown scientific evidence that i) temperatures have been increasing during the second half of the 20th century, and that ii) these changes are driven to a considerable extent by increases in the concentration of greenhouse gases (GHGs) in the atmosphere. Agriculture contributes to a considerable extent to increases of GHGs (~12% contribution globally), and therefore to climate change (IPCC 2007), but it is also one of the most (if not the most) sensitive human activities to changes in climates. An increase of 2°C in temperatures will pose a strong pressure on existing crop varieties (temperature thresholds could be exceeded in highly niche-specific and/or temperature-sensitive crops), whilst shifts in rainfall patterns could significantly alter harvests by altering fruit filling periods and delaying vegetative growth, to not speak about the effects of increased CO2 concentrations, the effects on agricultural pests and diseases, and on soil quality, most of which are still highly uncertain and remain under- or unexplored.

By the end of the 21st century and under the GHGs emission scenario SRES-A2 (IPCC 2000) increases in temperatures could range between 1.8-6°C for Asia (IPCC 2007), with most of the variability being accounted to the different global climate models (GCMs) used in the IPCC Fourth Assessment Report (AR4), and with warm periods showing greater increases as compared with cold periods. South Asia is predicted to have the least increase (except for the Himalayas), but even these could be in the order of 1.8-5°C (IPCC 2007). Rainfall is predicted to change between -5 to 20% during the cold season and between -40 to 15% in the warm season (IPCC 2007). Yet there is no certainty as per the extent of the changes (particularly for rainfall) and these changes will affect agricultural production, given its reliance on favourable climatic conditions (Jarvis et al. 2010).

However, agricultural scientists, practitioners and policy makers need to have an idea of what the expected changes are. Therefore, strong, reliable and accurate climate models and predictions need to be provided. Existing climate models, however, are still not able to accurately and consistently predict the climate system, partly because of our still limited understanding of the climate system, and partly because these models are computationally very expensive. Processes such as cloud dynamics (Wagner and Graf 2010), deep moist convection (Lin et al. 2008; Mitra and Das 2001), radiative transfer, turbulent mixing, boundary layer processes, precipitation and gravity wave drag (Govindan et al. 2002) cannot be analysed at coarse spatial resolutions (~100 km), thus are expressed as parameterisation schemes. These parameterisation schemes yield different responses, as they are based on different assumptions. Differences in predictions done by means of the different IPCC AR4 climate models are accounted to these processes (Figure 1).

Uncertainty in climate predictions, therefore, plays an important role whenever future climate projections are to be used. Policy making, agricultural development and research need to base their processes on the fact that there is an inevitable uncertainty level on any prediction of future climate and therefore on any prediction of expected effects. Even short time weather forecasts still fail. Both the assessment of impacts of climate change on agriculture and the development and implementation of adaptation strategies depend upon the availability of climate predictions. Thus, uncertainties have to be properly managed, reported and assessed whenever

predictions of impacts of future climates are to be done. Further, regardless of the uncertainty level, agricultural systems need to be resilient enough to cope with the expected negative effects or capitalise on the positive effects. Cereal production in low latitudes (tropical and partly sub-tropical) is predicted to decrease mostly due to increases in temperature (Parry et al. 2008), with wheat, maize and rice being the most affected crops in regions where they are intensively and extensively produced, i.e. China and India (Parry et al. 2008; IPCC 2007).

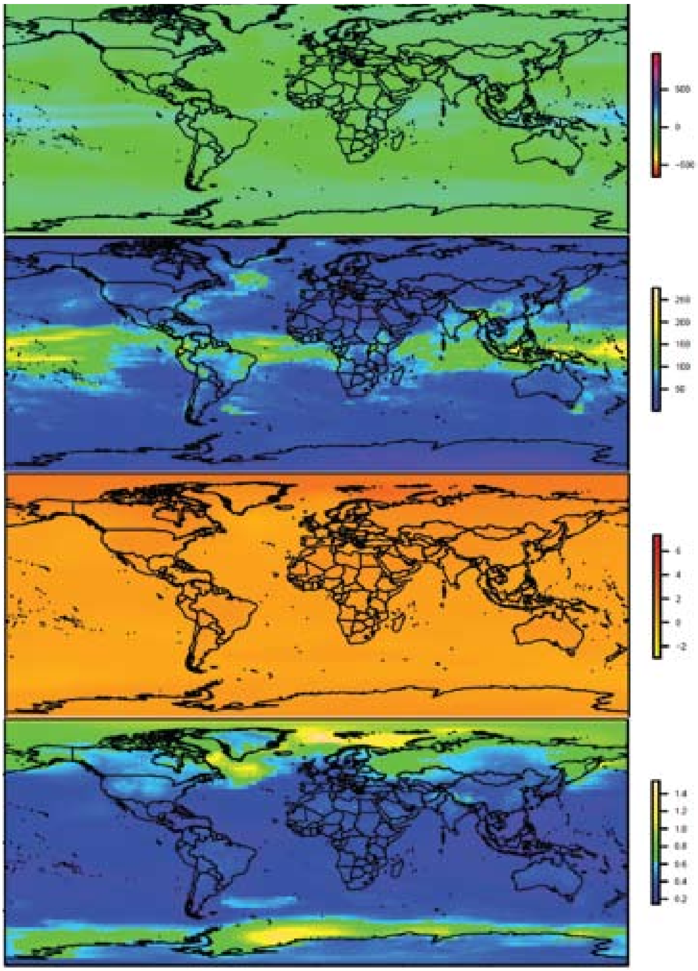

Figure 1. Changes in (A) total annual rainfall and (C) annual mean temperature (0°C) and corresponding expressed as averages of 24 GCMs and uncertainties expressed as the standard deviation of (B) total annual rainfall and (D) annual mean temperature (0°C).

Despite a considerable amount of research in terms of agricultural science under the context of climate change (Jarvis et al. 2010; Lobell et al. 2008; Challinor et al. 2007; Challinor and Wheeler 2008; Challinor et al. 2010), it has been certainly biased towards particular crops (i.e. maize, wheat, rice). Impacts on under-utilised or neglected, horticultural and fruit crops have been barely (if) explored, partly due to the lack of input data and modelling approaches for such crops. Thus, there is no consensus as to whether these crops could provide a supplementary income and dietary base for low-income farmers in the context of adaptation to climate change. In this chapter we explore the likely impacts of climate change on fruit crop production by using a simplistic approach (FAO 2000; Hijmans et al. 2001; Ramirez-Villegas et al. 2011) and selecting relevant literature on the topic. We emphasise the best-bet adaptation strategies to cope with negative impacts; we also analyse the possible trade-offs with mitigation and carbon sequestration that might appear with improved fruit crop production. Finally, we point out specific directions for research in order to deliver meaningful information for adaptation to the expected changes.

Expected impact of climate change on horticulture crops

Given the considerable reliance of agriculture on favourable climate, it is expected that any change in the climate system will drive unexpected responses from agricultural systems. Not only will crops be responding to changes in different climate variables, but also farmers and local agricultural researchers will be generating short and mid-term responses to cope with the likely losses in yields. In order to better manage these processes, impacts need to be properly assessed and improved adaptation strategies need to be tested, targeted and implemented. In order to assess impacts of future climate on crop production, researchers have developed so-called "crop models". Crop models use available information regarding the ecology, growth and physiological development of a crop, the local weather, the management practices, the soil characteristics, among others, to simulate part of the processes that are carried out in the field at different levels in order to predict the attainable yield of a particular growing season for a particular crop in a particular place.

Currently, more than two dozen crop models exist and all of them allow in one way or the other to assess the responses of crops to climate change, all of them mostly agreeing in the direction but not in the extent of the changes. However, as stated before, most of these approaches are developed for annual crops or have only been extensively applied and tested on a limited number of crops (Hoogenboom et al. 2010; Challinor et al. 2004; Aggarwal et al. 2006; Steduto et al. 2009; Williams et al. 1989; Diepen et al. 1989), and in most cases these do not include any horticultural crop. However, horticultural crops might be highly sensitive to changes in climate and climatic variability as they heavily rely on adequate water supply and on a proper amount of daily energy (temperature, solar radiation) in order properly grow. Therefore, even slight variations (temperature increases of the order of 1°C or water shortage or excess during a short period) can cause crop failures.

We harvested ecological data for the most important horticultural crops (Table 1) from the Ecocrop database of the Food and Agriculture Organisation of the United Nations (FAO 2000; available at http://www.ecocrop.fao.org) and used the Ecocrop model implemented in DIVA-GIS (Hijmans et al. 2005) to predict the impacts of climate change. The Ecocrop model calculates a suitability index based on monthly climate data and a set of basic crop-specific ecological parameters. We used the model as implemented by Beebe et al. (2011).

For each of the crops, we first applied the model over spatially explicit datasets representing the 20th century average climatology (representative of the years 1961-1999) (New et al. 2000) (baseline hereafter). We then applied the model over future downscaled datasets (Mitchell and Osborn 2005; Mitchell et al. 2004), from the SRES-A1B emission scenario (IPCC 2000). We used results from 7 GCMs (Table 2), representative of the whole set of GCMs used in the IPCC AR4 (2007) by the 2010-2029 ("2020s") period.

Table 1. Crops analysed, including major producers and total harvested area globally

Crop	Major Producer	Scientific name	AH*	AIS*	ADS*	CHG*	STD*
Alfalfa	USA	*Medicago sativa* L.	15,214	30.5	69.5	-0.8	4.79
Apple	China	Malus sylvestris Mill.	4,786	42.4	57.6	0.5	7.37
Banana	India	*Musa acuminata* Colla	4,180	33.1	66.9	-3.2	9.50
Coconut	Indonesia	*Cocos nucifera* L.	10,616	59.7	40.3	1.2	6.86
Mango	India	*Mangifera indica* L.	4,155	73.5	26.5	1.6	4.93
Onion	China	*Allium cepa* L. v *cepa*	3,341	20.4	79.6	-5.1	15.84
Orange	Brazil	*Citrus sinensis* (L.) Osbeck	3,618	54.0	46.0	0.3	6.05
Sugar beet	France	*Beta vulgaris* L. v *vulgaris*	5,447	18.1	81.9	-4.9	9.88
Tomato	China	*Lycopersicon esculentum* M.	4,597	25.7	74.3	-1.9	7.29
Watermelon	China	*Citrullus lanatus* (T) Mansf	3,785	40.6	59.4	0.2	7.37
Cabbage	China	*Brassica oleracea* L.v capi.	3,138	16.8	83.2	-5.3	8.51

***AH**: Area harvested from FAOSTAT (2008) in thousands of hectares; **AIS**: Percent of global suitable area with increases in climatic suitability; **ADS**: Percent of global suitable area with decreases in climatic suitability; **CHG**: change in climatic suitability as average of all suitable gridcells and 7 GCMs; **STD**: standard deviation of the change in climatic suitability given by all suitable gridcells and 7 GCMs.

For each of the crops and GCMs, we then calculated the change in suitability (future – baseline) and then both the average and standard deviation of the change. We found that there is a considerable variability accounted to the usage of different GCMs, and also accounted to the different geographies of the crops: in a particular place some crops might gain whilst others might lose climatic suitability. In average, amongst the most negatively impacted crops there is sugar beet, onion, cabbage, and alfalfa (Table 1, Figure 2).

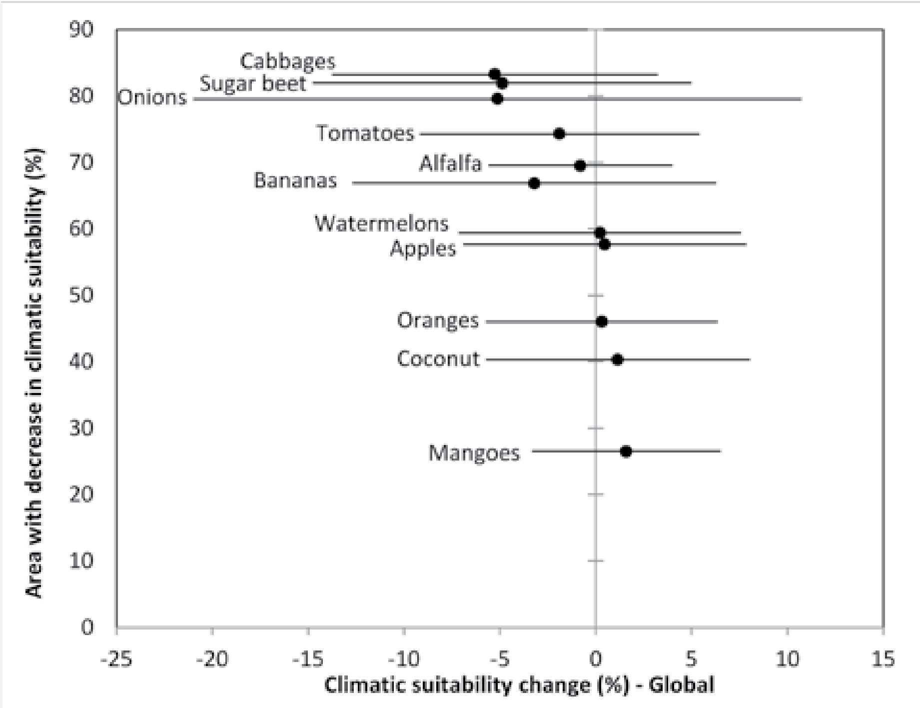

Figure 2. Percent of areas in relation to global suitable area for each crop vs. global change in climatic suitability as average of 7 GCMs for the whole globe. Error bars represent both variability across the globe and variability among GCMs.

Table 2. List of Global Circulation Models (GCMs) used in the analysis.

Model	Country	Atmosphere*	Ocean*	Reference
CCCMA-CGCM3.1 (T47)	Canada	T47, L31	1.85x1.85, L29	Scinocca et al. (2008)
CSIRO-Mk3.0	Australia	T63, L18	1.875x0.84, L31	Gordon et al. (2002)
MPI-ECHAM5	Germany	T63, L32	1x1, L41	Jungclaus et al. (2005)
IPSL-CM4	France	2.5x3.75, L19	2x(1-2), L30	Marti et al. (2005)
NCAR-CCSM3.0	USA	T85, L26	1x(0.27-1), L40	Collins et al. (2005)
UKMO-HadCM3	UK	3.75x2.5, L19	1.25x1.25, L20	Gordon et al. (2002)
UKMO-HadGEM1	UK	1.875x1.25, L38	1.25x1.25, L20	Johns et al. (2006)

*Horizontal (T) resolution indicates number of cells in which the globe was divided, i.e. T47 refers to 47 horizontal cells. Vertical (L) resolution indicates the number of layers in which the atmosphere was divided. When a model is developed with different latitudinal and longitudinal resolutions, the respective cell sizes (Lon. x Lat.) in degrees are provided instead of a unique value.

Sugar beet, onions and cabbages are decreasing their climatic suitability in at least 60% of the areas where they can be grown in Sub-Saharan Africa and India, and in more than 80% of their currently global suitable areas. Oppositely, mangoes are showing an average increase of 1.6% globally, with only 26% of the global suitable areas for mango production being negatively impacted. In the case of coconut, some 40% of the global suitable areas seem to be decreasing their climatic suitability. Although, impacts are widespread across the globe, they are not always predicted negative. Adaptation needs to focus in climatically vulnerable areas where several crops lose their climatic suitability, and therefore reduce their yielding potential.

As stated before, changes are considerably dependent on the geographies of the crops (X axis error bars, Figure 2). In the Indo Gangetic Plains (IGP), for example, only sugar beet (-4%) and alfalfa (-0.5%) are predicted to decrease their climatic suitability, whilst onion (+0.2%), tomato (+0.68%), apple (+1.1%), sweet orange (+1.3%), watermelon (+1.4%), mango (+1.5%), cabbage (+1.7%), banana (+2.6%) and coconut (+5.7%) are predicted to increase their climatic suitability (although such increases are not particularly high). Outside the IGP, more negative impacts are predicted: onion (-6%), sugar beet (-4.7%), cabbage (-4.5%), banana (-2.2%), alfalfa (-0.5%), apple (-0.2%), and again watermelon (0.4%), mangoes (+2.3%) and coconuts (+4.9%) are predicted to increase their suitability.

Changes in climatic suitability suggest that there is no single “loser” or “winner” from climate change. Impacts are highly dependent on both the crop analysed and the environmental conditions in a particular place. Some crops might become less suitable under increased temperature and changed rainfall conditions (i.e. onion, cabbage, banana), but others might enhance their production (i.e. coconuts, mangoes). Here we have analysed the impacts on changes over the whole growing season (i.e. total precipitation, mean, minimum and maximum temperatures), but the effects of climate on physiological aspects during particular periods of the crop’s growing season remain under or unexplored. For short season crops such as cabbage, onions and sugar beet this might be easier, but most models cannot yet assess these effects.

Banana production is highly suitable to both tropical and sub-tropical environments and it is most limited by high temperatures and drought. Decreases in global banana production are expected in most banana growing areas below 500 masl. These changes might be especially caused by the sensitivity of the crop to high temperatures and drought during the flowering and the fruit filling periods. However, this might bring opportunities for cropping in areas currently limited by low temperatures, although these positive impacts could be reduced by changes in rainfall seasonality, a key driver of banana production. Changes are far less drastic by the 2020s, but these trends are very likely to continue towards the second half and the end of the 21st century (Ramirez et al. 2011).

Under the influence of climate shift, early and delayed flowering will be a characteristic feature of mango. An early flowering under the sub-tropics may result in low fruit set because of several abnormalities caused due to low night temperatures. Late flowering also reduces the fruit set because of pseudo-setting leading to clustering disorder. In addition, high temperatures during panicle development cause quick growth and reduce the number of days when hermaphrodite flowers are available for effective pollination, which may lead to a satisfactory crop. Rising temperatures cause desiccation of pollen and poor pollinator activity resulting into low fruit set (Bhriguvanshi 2010).

The most limiting factor restricting citrus geographical distribution is low temperatures: frost and freezing damages the fruits and if it persists long enough may kill the tree. Even at mild, non-damaging range, temperatures present major limitations for vegetative growth as well as fruit development and maturation, and temperatures below 13°C during cold periods delay initiation of flowering. In contrast, temperatures above 37°C may cause serious damage to tender fruitlets, and between 44-45°C can slow down fruit growth and cause excessive fruit abscission (Huchche et al. 2010).

For apple production, the most serious problem is the scab disease and the outbreak of premature leaf fall and infestation of red spider mite. Changes in climate can cause poor harvests or even crop failures. Excess of water and decreased snowfall during winter causes low chilling hours in cropping areas, and this could pose serious threats to apple production worldwide, particularly in India (Singh et al. 2010). In India and Nepal, traditional apple cultivation area is moving further up in elevation because of the warmer climate (see chapter of Dinesh et al in this volume). In addition, climate change and CO_2 are likely to alter important interactions between horticultural plants and pollinators, insects, diseases, and weeds (IPCC 2007).

Adapting horticulture to changing climates

Adaptation to climate change is not only a matter of changing current management practices, changing varieties or crops, or changing cropping zones under a particular future scenario. Adaptation to climate change starts from building resilient systems

under present conditions. Current agricultural production needs to be both environmentally and economically sustainable and provide the basis for meeting local and national food security needs in the present. On top of that, progressive adaptation needs to be addressed if the production is to be maintained and/or enhanced towards the future.

Fruit tree production is a mid- to long-term investment in which only few adjustments can be done once the crop has become established. Growing cycles of fruit trees are commonly in the order of 5 to 10 years, and optimum production is only reached several years after planting. Therefore, varieties used and cropping areas cannot be changed once the crop has been established as this would result in massive economic losses for farmers. Targeting of existing varieties in appropriate and suitable production environments is therefore critical for any fruit tree farmer under current as well as future conditions. Fruit trees have, however, the advantage of being more resilient to variations in weather conditions, except for some critical periods such as flowering or fruit filling.

On the other hand, short term horticultural crops such as cabbage, tomatoes, and onions are easier to adjust to different environmental conditions. Growing cycles of these crops are commonly in the order of 4 to 5 months, and right after the harvest varieties and even the crop can be changed if the response was not adequate. However, once established, these crops are very sensitive to water shortages, during all stages of the growing cycle. Even brief periods of water shortage can cause crop failures. In addition, they are also sensitive to frost and excessive evaporation. Optimal irrigation systems need to be used for these crops if enough water is to be supplied so that the risk of crop failure can be reduced in the present. These practices need to be targeted also in the future in order to sustain production and meet global food security needs.

One of the adaptation measures to mitigate the impact of climate change will be to use more suitable and/or resilient crop varieties (IPCC 2007). However, the adoption of new varieties, a commonly cited option for climate change adaption, occurs much more slowly in perennial fruit crops than for annual crops. The long time horizon of perennial agriculture creates special challenges in a changing climate. Favourable areas may become unfavourable during the life

of a single orchard. The choice of a variety is complicated by the risk that the best variety for the current climate may be poorly suited for future climates. Thus, while adaptations such as planting new cultivars and shifting to new areas may reduce impacts in long-term, short-term losses could be experienced. In this context, farmers will need crop varieties with greater tolerance to stresses such as heat, as well as photo-and thermal-insensitive varieties. The genetic diversity collected from various agro-climatic conditions and conserved *ex situ* and on farm can enable fruit breeders, researchers and other users in improving yields in the context of climate change.

The IPCC AR4 (2007) outlined a set of general recommendations for adaptation to climate change, however, these need to be explored on a crop-specific basis. Genetic improvement is commonly easier for annual crops with fertile seeds, but might not be that easy for other crops such as banana, unless additional and novel technologies (other than normal breeding) are explored in order to incorporate specific desirable traits into current varieties (Hajjar and Hodgkin 2007). In addition, probably equally or more important than developing novel strategies to cope with impacts is the fact that technologies (existing, new and/or adjusted) need to be properly targeted and tested in order to assess their potential for climate change impacts mitigation.

Geographies of crops are likely to change under future conditions and very likely a place where onions can be grown currently, might be suitable for mango production in the future. Thus, not only the targeting of varieties is required but also the cost-benefit analysis of whether it is worthwhile to develop a new variety to withstand the future climates or if crop swapping can be easily done. In the worst case scenario, when a particular environment becomes unsuitable, migration of lands can be considered.

Conclusion

Based on the available information and database for horticultural crop production, it has been established that climate change per se will have impact on horticultural crops, due to erratic rainfall, more demand for water and enhanced biotic and abiotic stresses. However, the changes will not be only harmful, as CO_2 concentration may enhance faster photosynthesis and increased temperature may hasten the process of maturity. However, measures to adapt to these climate change-induced changes are critical for sustainable production. Increased temperature will have more effect on reproductive biology and reduced water supply may affect productivity but adaptive mechanisms like time adjustment and productive use of water may reduce the negative impact.

Predicting the impact of climate change on horticultural crops accurately on regional scale is a big problem. Enhancing the adaptation of tropical production system to changing conditions is a great challenge and would require integrated efforts and an efficient and effective strategy to be able to deliver technologies that can mitigate the effect of climate change on diverse crops and production systems. It can be accomplished only by a modelling approach through well-validated robust crop simulation models. Availability and development of good simulation models for horticultural crops is lacking in general. The perennial nature of large-sized fruit trees and shrubs are problematic in the study of the direct effect of various factors of growth, development and yield in a controlled environment. Innovative methods are thus required to develop simulation models for important horticultural crops like mango, citrus, banana, apple, guava, and coconut. Once these simulation models are available, prediction of vulnerability of existing areas under these horticultural crops to climate change scenarios can be examined and new target areas for possible shifting of species and varieties/cultivars can be identified. Possible adaption measures to reduce the impact of climate change are also possible to study through simulation models for suggesting changes in management practices.

Also trees in general have the property of sequestering carbon in the soil. Therefore, knowledge of carbon sequestration, especially through perennial horticulture, needs to be enhanced. This could be utilised for enhancing income through trading of carbon. Expansion of fruit crops might therefore enhance the carbon sequestration contributing to climate change mitigation (reduction of greenhouse gases emissions). Nevertheless, the establishment of a fruit tree cropping system is not an easy task and it requires a substantial investment of resources, and the carbon sequestration potential might also depend on the soil where the crop is grown. Therefore, in order to both manage impacts and mitigate climate change it is required that adequate crops are grown in the areas where they will both have high yield and carbon sequestration potential.

References

Aggarwal PK, Kalra N, Chander S, Pathak H. 2006. InfoCrop: a dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description. Agricultural Systems 89. No. 1 (7): 1-25. Doi:10.1016/j.agsy.2005.08.001.

Beebe S, Ramirez J, Jarvis A, Rao IM, Mosquera G, Blair M, Bueno JM. 2011. Genetic improvement of common beans and the challenges of climate change. In: Yadav SS, Redden B, Hatfield JL, Lotze-Campen H, editors. Crop Adaptation to Climate Change. Wiley-Blackwell Publishing, UK. pp. 356-369.

Bhriguvanshi SR. 2010. Impact of climate change on mango and tropical fruits. In: Singh HP, Singh JP, Lal SS, editors. Challenges of Climate Change - Indian Horticulture. Westville Publishing House, New Delhi, India. pp. 224.

Challinor AJ, Wheeler TR, Craufurd PQ, Grimes DIF. 2004. Design and optimisation of a large-area process-based model for annual crops. Agricultural and Forest Meteorology 124. No. 1-2 (7): 99-120. Doi:10.1016/j.agrformet.2004.01.002.

Challinor AJ, Wheeler TR, Craufurd PQ, Ferro CAT, Stephenson DB. 2007. Adaptation of crops to climate change through genotypic responses to mean and extreme temperatures. Agriculture, Ecosystems and Environment 119: 190-204.

Challinor AJ, Wheeler TR. 2008. Crop yield reduction in the tropics under climate change: processes and uncertainties. Agricultural and Forest Meteorology 148: 343-356.

Challinor AJ, Simelton ES, Fraser EDG, Hemming D, Collins M. 2010. Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China. Environmental Research Letters 5, 034012. Doi: 10.1088/1748-9326/5/3/034012.

Collins WD, Bitz CM, Blackmon ML, Bonan GB, et al. 2005. The community climate system model (CCSM). Journal of Climate, special issue.

Diepen CA, Wolf J, Keulen H, Rappoldt C. 1989. WOFOST: a simulation model of crop production. Soil Use and Management 5. No. 1 (3): 16-24. Doi:10.1111/j.1475-2743.1989.tb00755.x.

FAOSTAT [online]. 2008. Available from: URL: http://www.faostate.fao.org/

Food and Agriculture Organzation of the United Nations. 2000. The FAO Ecocrop database [online]. Available from: URL: http://www.ecocrop.fao.org/

Gordon HB, Rotstayn LD, McGregor JL, Dix MR, Kowalczyk EA, et al. 2002. The CSIRO Mk3 climate system model [Electronic publication]. Technical paper no. 60. Aspendale: CSIRO Atmospheric Research. p. 130.

Govindan RB, Vyushin D, Bunde A, Brenner S, Havlin S, Schellnhuber HJ. 2002. Global climate models violate scaling of the observed atmospheric variability. Physical Review Letters 89, 028501.

Hajjar R, Hodgkin T. 2007. The use of wild relatives in crop improvement: a survey of developments over the last 20 years. Euphytica 156:1-13.

Hijmans RJ, Guarino L, Cruz M, Rojas E. 2001. Computer tools for spatial analysis of plant genetic resources: 1. DIVA-GIS. Plant Genetic Resources Newsletter 127: 15-19.

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965–1978.

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Boote KJ, et al. 2010. Decision support system for agrotechnology transfer version 4.5 [CD-ROM]. Universityof Hawaii, Honolulu, Hawaii.

Huchche AD, Panigrahi P, Shivankar VJ. 2010. Impact of climate change on citrus in India. In: Singh HP, Singh JP, Lal SS, editors. Challenges of Climate Change – Indian Horticulture. Westville Publishing House, New Delhi, India. p 224.

Intergovernmental Panel on Climate Change. 1990. IPCC First assessment report: climate change 1990. IPCC, Geneva.

Intergovernmental Panel on Climate Change. 1995. IPCC Second assessment report: climate change 1995. IPCC, Geneva.

Intergovernmental Panel on Climate Change. 2000. IPCC Special report on emissions scenarios. IPCC, Geneva.

Intergovernmental Panel on Climate Change. 2001. IPCC Third assessment report: climate change 2001. IPCC, Geneva.

Intergovernmental Panel on Climate Change. 2007. IPCC Fourth assessment report: climate change 2007. IPCC, Geneva.

Jarvis A, Ramirez J, Anderson B, Leibing C, Aggarwal P. 2010. Scenarios of climate change within the context of agriculture. In: Reynolds MP, editor. Climate Change and Crop Production. CAB International. ISBN-13: 978 1 84593 633 4.

Johns TC, Durman CF, Banks HT, Roberts MJ, McLaren AJ, et al. 2006. The new Hadley centre climate model HadGEM1: evaluation of coupled simulations. Journal of Climate 19(7): 1327-1353.

Jugnclaus JH, Botzet M, Haak H, Keenlyside N, Luo J-J, et al. 2005. Ocean circulation and tropical variability in the AOGCM ECHAM5/MPI-OM. Journal of Climate 19:3952-3972. Doi: http://dx.doi.org/10.1175/JCLI3827.1

Lin JL, Lee MI, Kim D, Kang IS, Frierson DMW. 2008. The impacts of convective parameterization and moisture triggering on AGCM-simulated convectively coupled equatorial waves. Journal of Climate 21: 883-909. Doi: 10.1175/2007JCLI1790.1

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, et al. 2008. Prioritizing climate change adaptation needs for food security in 2030. Science 319: 607–610.

Marti O, Braconnot P, Bellier J, Benshila R, Bony S, et al. 2005. The new IPSL climate system model: IPSL-CM4. Technical Report. Institute Pierre Simon Laplace.

Mitchell TD, Carter TR, Jones PD, Hulme M, New M. 2004. A comprehensive September of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100). Working Paper No. 55. Tyndall Center.

Mitchell TD, Osborn TJ. 2005. ClimGen: a flexible tool for generating monthly climate data sets and scenarios. Research Working Paper. Tyndall Centre for Climate Change.

Mitra AK, Das S. 2001. Representation of deep moist convection in NCMRWF global T80 analysis / forecast system: results from different experiments. Megha-Tropiques 2nd Scientific Workshop; 2-6 July 2001, Paris, France.

New M, Hulme M, Jones PD. 2000. Representing twentieth century space-time climate variability. Part 2: development of 1901 --1996 monthly grids of terrestrial surface climate. Journal of Climate 13: 2217-2238.

Parry M, Rosenzweig C, and Livermore, M. 2005: Climate change, global food supply and risk of hunger. Philosophical Transactions of the Royal Society B 360:2125-2138. Doi: 10.1098/rstb.2005.1751.

Parry M, Canziani O, Palutikof J. 2008. Key IPCC conclusions on climate change impacts and adaptations. WMO Bulletin 57 (1):1-8.

Ramirez-Villegas J, Jarvis A, Läderach P. 2011. Empirical approaches for assessing impacts of climate change on agriculture: the EcoCrop model and a case study with grain sorghum. Agricultural and Forest Meteorology. Doi: http://dx.doi.org/10.1016/j.agrformet.2011.09.005..

Ramirez J, Jarvis A, Van den Bergh I, Staver C, Turner D [in press]. Changing climates: effects on growing conditions for banana and plantain (*Musa* spp.) and possible responses. In: Yadav SS, Redden B, Hatfield JL, Lotze-Campen H, editors. Crop Adaptation to Climate Change. Wiley-Blackwell Publishing, UK. pp. 426-438.

Scinocca JF, McFarlane NA, Lazare M, Li J, Plummer D. 2008. The CCCma third generation AGCM and its extension into the middle atmosphere. Atmospheric Chemistry and Physics 8:7055-7074.

Singh HP, Singh JP, Lal SS. 2010. Challenges of Climate Change – Indian Horticulture. Westville Publishing House, New Delhi, India. p. 224.

Steduto P, Hsiao TC, Raes D, Fereres E. 2009. AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and Underlying Principles. Agronomy Journal 101. No. 3: 426. Doi:10.2134/agronj2008.0139s.

Wagner TM, Graf HF. 2010. An ensemble cumulus convection parameterisation with explicit cloud treatment. Journal of Atmospheric Sciences. Doi: 10.1175/2010JAS3485.1

Williams JR, Jones CA, Kiniri JR, Spanel DA. 1989. The EPIC crop growth model. Transactions of the ASAE 32, no. 2: 497-511.

Physiological Basis of Growth and Fruit Yield Characteristics of Tropical and Sub-tropical Fruits to Temperature

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Introduction

The impact of climate change will be felt around the world. Perennial tropical fruit trees species in nature are important mitigation and adaptation strategies for enhancing resilience (Scherr and Sthapit 2009) to adverse impacts of rainfall and temperature variability depending on the place where they grow. Although perennial fruit trees have a number of survival mechanisms that allow them to cope with stressful environments, these come at a considerable energy cost thereby potentially reducing fruit productivity. Knowledge of tropical fruit tree physiology, particularly in relation to the tree's response to varying environmental conditions remains basic, and must be understood in the context of climate change. This chapter reviews the eco-physiological basis of growth and fruit yield of tropical fruit trees as well as temperature limitations to fruit yields and potential expansion beyond the traditional cultivation regions.

Physiological responses of tropical fruits to environmental variables can be related to the evolutionary centre of origin of a specific species and cultivar. For example, there are two distinct mango ecotypes based upon embryony (Mukherjee and Litz 2009). A mango race with a single zygotic seed, which is also known as mono-embryonic type, evolved in dry sub-tropical, monsoonal regions of the Indian subcontinent with very hot summers but cooler winters, whereas polyembryonic type, produced through nucellar embryony, largely evolved in the consistently hot, humid tropics of south-east Asia where the monsoonal pattern still predominates but the dry season is shorter than that of the Indian Sub-continent (Mukherjee

1972). Hybridization occurs freely within and between the two embryonic ecotypes and many unique features of the tree represents evolutionary responses to an indigenous environment that is hostile with sustained extreme heat and high evaporative demand for much of the year.

This chapter provides an overview of the impact of environmental factors on physiology, growth and fruit productivity.

The physiological basis of fruit yield

The biological yield of a fruit orchard is a function of the amount of light intercepted by orchard canopy times the photosynthetic efficiency of the cultivar minus the respiration cost (Montieth et al. 1969; 1977; Lakso 1994). The amount of light available is the function of climate and cannot be manipulated, while the potential net photosynthetic efficiency of a crop is inherent (C3 or C4 or CAM - Crassulacean acid metabolism) and cannot be altered without genetic manipulation. Maximizing light interception by the photosynthetic surface of an orchard is a function of tree spacing, canopy density and tree height. Thus, optimizing biological yield is based upon maximizing the percentage of solar radiation intercepted by the orchard canopy and minimizing stresses so that photosynthetic potential is not compromised.

Agronomic practices, cultivar characteristics and management practices are often manipulated to maximise the light interception and partitioning of higher amounts of assimilates towards fruit yield. For example, light utilization of a mango orchard can be enhanced by pruning. Schaffer and Gaye (1989) increased light interception of mango by removing 25% of the canopy. However, the time of pruning is crucial for mango. In the sub tropics, shoots produced following the harvest generally flower 3-5 months after being exposed to inductive cool temperatures. Therefore, trees should be pruned immediately after picking fruits to improve light penetration. However, in the tropics there is a shorter period between the cessation of summer growth and flowering and summer grown shoots of many cultivars fail to induct that year (Scholefield et al. 1986; Davenport 2009). Therefore, due to the removal of potential flowering buds, summer pruning of mango trees in the tropics generally reduces yield in the following season. For some fruit trees

such as citrus species, the use of low vigour rootstocks and pruning provide opportunities for management practices that farmers can use. However, lack of dwarfing rootstocks and complications in pruning due to floral morphology of the mango limit the efficient harvest of light with respect to the maintenance of fruit productivity.

Temperature and phenology

The range of temperature for growth of most agricultural plants usually ranges between 15°C and 40°C. At temperatures much below or above these limits, growth decreases rapidly. Optimum temperature for plant growth changes with species and varieties, duration of exposure, age of the plant, stage of development, and particular growth criterion used to evaluate performance. Temperature directly affects photosynthesis, respiration, cell wall permeability, absorption of water and nutrients, transpiration, enzymatic activity and protein coagulation.

Perennial fruit trees like mango, guava, jackfruit, grapes are subjected to various climatic changes depending on where they grow. Many tree species bear fruits once in a year. However, among all the factors, temperature plays a vital role in determining the quantity and quality of the produce. Fruit crops have a longer period of flowering so the temperature regime in the soil as well as the outside temperature determine the fruit set. Temperature brings about changes in the level of different hormones necessary for growth and development of the trees.

A fruit crop like mango does well at temperatures as high as 48°C during the period of fruit development and maturity. Higher temperatures during fruit development hasten maturity and improve fruit size and quality, provided that other parameters like available moisture level are maintained. Climate models predict a change in precipitation by 5-25% over India by the end of the century with more reductions in the winter-rainfall than in the summer monsoon, leading to droughts during summer months (Lal et al., 2001). It needs to be understood that apart from the effect of temperature alone, its interaction with other factors like rainfall can affect plant growth at various stages of vegetative or reproductive phases.

In the case of temperate fruit crops, temperature plays a role in breaking the dormancy, while in tropical and sub-tropical fruit species, it plays a very important role in fruit bud differentiation as well as in fruit set. The fruit bud differentiation takes place many a days prior to fruiting in perennial fruit trees.

Identifying suitable varieties for new temperature and rainfall regimes

Temperature is probably the most important environmental variable to consider when selecting tropical fruit cultivars for particular sites. Literature reviews of climatic parameters for major tropical fruits are very basic and drawn from field experiences. The mean temperatures range for optimum growth of most tropical fruits are about 24-30°C (Mukherjee 1953; Whiley et al. 1989).

However, mango trees can tolerate temperatures up to 48°C for short periods (Mukherjee, 1953) and have limited tolerance to cold. Monoembryonic mango cultivars tend to be more cold tolerant than polyembryonic cultivars, probably due to their origin of evolution (Schaffer et al. 2009).

Lychee and longan require a warm sub-tropical to tropical climate that is cool but also frost-free or with only very slight winter frosts not below -4°C, and with high summer heat, rainfall, and humidity. Like the lychee, longan is adapted to a sub-tropical environment with warm, humid summers and cool, dry winters. Nevertheless, it does not tolerate temperatures below 0°C, and temperatures of -2 to -3°C can cause severe damage or death to young trees.

Rambutan is adapted to warm tropical climates, around 22–30°C, and is sensitive to temperatures below 10°C (Tindal 1994). It is grown commercially within 12–15° latitude of the equator.

Citrus species can thrive in a wide range of soil and climatic conditions. Citrus is grown from sea level up to an altitude of 2100 m but for optimal growth a temperature range from 2° to 30°C is ideal. Long periods below 0°C are injurious to the trees and growth diminishes below 13°C. Amongst citrus species, pomelo (*C. grandis* (L.) Osbeck, *C. maxima* Merr.) is a warm climate crop that requires sufficient water throughout the year with well drained sandy clay

loam soils. However, individual species and varieties decrease in susceptibility to low temperatures in the following sequence: grapefruit, sweet orange, mandarin, lemon/lime and trifoliate orange.

Mangosteen requires high rainfall, high humidity and high temperature. It does not tolerate low temperature at all and therefore is limited to humid tropics. Temperatures below 20°C reportedly slow the overall growth of the mangosteen tree whereas high temperatures above 35°C cause some stresses on the trees (Rejab et al. 2008). Table 1 illustrates comparative agro-climatic requirements of major tropical fruit tree species for cultivation.

Growth of tropical fruit trees is not continuous (Davenport 2003). Apical buds spend most of the time in rest. Growth occurs as intermittent flushes of shoots from apical or lateral buds. Stems are resting terminal vegetative structures on branches from which shoot growth occurs. Shoots are elongating vegetative or reproductive structures that emerge from apical or lateral buds of stems. Vegetative shoots develop a prescribed number of nodes during the growth before entering into resting state of a stem. Vegetative growth generally occurs up to 3-4 times a year on individual branches, depending upon the cultivar and environments.

Climate change will have both positive and negative impacts on fruits in tropical regions. In regions where the prevailing temperatures are already high, further increases in temperature will adversely affect the yield and quality of fruits. In regions where cold temperatures are one of the primary factors limiting crop production, temperature increases will be beneficial. The impact of temperature change can be clearly seen from the fact that the northern parts of India are warmer than the southern parts, with a general increase of 3-6°C over the base-period average (Lal et al. 1995; Lonergan et al. 1998). Studies carried out on perennial trees have to be contiguous and long range. Since experiments are carried out for short periods, these studies more often than not have become pointers rather than conclusive.

The increase in temperature has been reported to affect the phenology of perennial trees. In certain regions where prevailing temperatures are already high, there will likely be shifts in growing areas.

The flowering dates in cherry blossoms (*Prunus yedoensis* Matsum.) were analysed in relation to air temperature in March, or as a function of latitude, longitude, coldness / warmth indices. It was shown that mean flowering dates for cherry in Japan and Korea are 3 to 4 days earlier when the mean air temperature in March increases by 1°C (Yoshino and HyeSook 1996).

The general growing season in Europe and Germany has been extended by 10 days (Chmielewski and Rotzer 2001 and 2002). In the peninsular regions of India, it has been noticed that flowering was enhanced by a month in mango, thus affecting the fruit maturity and season of harvest. In the case of crops like guava, which has adapted very well to both tropical and sub-tropical climate environments, changes in temperature have contributed to postponing of fruiting season. Apart from the postponement of fruiting season, it is also true that in several cases fruiting and ultimate set have been badly affected.

Under the influence of climate shift, both early and delayed flowering will be characteristic features in mango. As a result of variations in temperature, unseasonal rains and higher humidity, fruit trees show altered flowering trends. Delays in panicle emergence and fruit set have been noticed. Fruit set and availability of hermaphrodite flowers for pollination have an effect on yield due to pollen and stigmatic sterility. If panicle development coincides with an unusual cold spell, mango production will face several problems.

Early flowering in the sub-tropics may result in a low fruit set because of several abnormalities caused due to low night temperatures coupled with unseasonal rains. It can be generally seen that low day temperatures cause reduced pollinator activity resulting in poor fruit set. Late flowering also reduces the fruit set because of pseudo-fruit setting leading to clustering disorder (Photo 1). High temperatures during panicle development in mango speed up growth and reduce the number of days for effective pollination when hermaphrodite flowers are available, which may lead to unsatisfactory production. It is the authors' experience that unseasonal rains coupled with variation in temperature and humidity can make mango trees flower during off season, but fruit set will be poor because of the showers. Rising temperatures cause

Photo 1: Psuedo-fruit setting in mango.

desiccation of pollen and poor pollinator activity resulting in low fruit set and, ultimately, a poor crop (Bhruguvanshi 2009).

In the sub-topics, low night temperatures (5-10°C) result in synchronous flowering. However, night temperatures of 10-18°C produce asynchronous flowering similar to that in the tropics. Climate changes may cause abrupt changes in night temperatures, which will cause asynchronous flowering in the sub-tropics and result in poor productivity. Flower buds exposed to cold temperature during night may change into vegetative ones under the warm night conditions. In the tropics, cool winters followed by a rise in day temperatures as summer approaches may result in poor flowering.

Table 1. Comparative agro-climatic requirements of tropical fruit tree species.

Species	Climatic Requirements				Agronomic requirement	References
	Elevation (m)	Rainfall (mm)	Opt. Temp. (°C)	Latitudinal limits/ Weather	Soil pH	
Citrus (*Citrus* spp.)[Δ]	0-1400	1500-3000	23-27[§]	44°N-35°S Cool sub-tropical	5.5-8.0	Verjeij and Coronel 1992
Mango (*Mangifera indica* L.)	0-700	1000-2000[◊]	24-27[Ω]	27°N-27°S	5.0-7.5	Mukherjee 1953; Devenport 2009
Mangosteen (*Garcinia mangostana* L.)	0-600	1300-2000	25-35	10°N-10°S Humid tropical	5.5-6.8	Krishnamurthy and Rao 1962; Osman and Milan 2006; Cox 1976
Rambutan (*Nephelium lappaceum* L.)	0-600	1500-2500	25-32[#]	17°N-17°S Humid tropical	4.5-6.5	Tindall 1994; UDPMS 2002; Verjeij and Coronel 1992
Pulasan (*N. ramboutan-ake* L.)	0-1950	2000-5000	20-30	12°N-12°S Humid tropical	4.5-6.5	Idris and Lin 2002
Pomelo (*Citrus maxima* L.)	<400	1900-2400	23-30[§]	35°N-35°S Humid tropical	5.5-6.5	Verjeij and Coronel 1992; Gaffar et al. 2008
Durian (*Durio zibethinus* L.)	0-800	1500-4000	24-30	18°N-18°S Humid tropical	5.0-6.5	Verjeij and Coronel 1992

Table 1. Continued...

Species	Climatic Requirements				Agronomic requirement	References
	Elevation (m)	Rainfall (mm)	Opt. Temp. (°C)	Latitudinal limits/ Weather	Soil pH	
Longan (*Dimocarpus longan* L.)	150-450	1500-2000	20-25Ω	13°N-30°S Humid tropical	4.5-6.0	Verjeij and Coronel 1992
Lychee (*Litchi chinensis* L.)	0-900	>1500	25-35Ω	15°N-29°S Humid tropical	6.0-7.5	Tindall 1994; Menzel et al.1989
Langsat (*Lansium domesticum* L.)	0-700	<1500	25-35	17°N-17°S Humid tropical∂	5.0-6.0	UDPMS 2002
Guava (*Psidium guajava* L.)	0-1500	1000-2000	23-28	25°N-30°S Humid tropical	4.5-9.4	Morton 1987; Verjeij and Coronel 1992
Jackfruit (*Artocarpus heterophyllus* L.)	400-1200	1000-2400	16-28	25°N-30°S Humid sub-tropical	6.0-7.5	Ghosh 2000; Haq 2006

Δ Citrus group includes: mandarin (*C. reticulata* L.); sweet orange (*C. sinensis* L.); acid lime (C. *aurantifolia* L.); jamir (*C. aurantium* L.); sweet lime (*C. limettioides* L.); lemon (*C. limon* L.); rangpur lime (*C. limonia* L.); rough lemon (*C. jambhiri* L.); wild Indian organe (c. indica L); § Dry spell followed by rain promotes flowering; Ω floral induction requires cool temperature (15⁰ C);◊ prolonged rainfall at flowering is detrimental and dry spell promote flowering # warm period promotes flowering.

Cool temperatures during inflorescence development reduce the number of perfect flowers (Naik and Mohan Rao 1943). Inflorescences, which emerge during the middle and end of the flowering season, have been reported to produce between two and seven times more perfect flowers respectively than the early breaking inflorescence. The increase in perfect flowers in the later emerging inflorescence correlates with higher average temperatures during the later part of the flowering season. In controlled environment studies, Whiley et al. (1995) found that low temperatures (15°C day/ 10°C night) during inflorescence morphogenesis reduced the proportion of perfect flowers. The reduction was found to be the greatest in a tropically evolved polyembryonic group of cultivars compared to those from a monoembryonic group. In warm temperatures, vegetative shoots were produced within 17 days of commencing treatments. These results indicate that floral induction is caused by cool temperatures and not by short photoperiods and that flowering is inhibited by warm temperature, not by long photoperiods (Maiti and Sen 1978; Maiti et al. 1978).

In the sub-tropical climate, temperature is important for environmental stimulation of flowering in mango and a number of other fruit tree species. Several studies have shown that low temperatures promote reproductive morphogenesis in mango. Shu and Sheen (1987) noted that there was an increase of 18 to 100% flowering in auxiliary buds of cultivar Haden when trees were transferred to 31/25°C following 1-3 weeks at 19/13°C. Trees of the cultivar Tommy Atkins flowered within 10 weeks when held at day/night temperatures of 18/10°C, whereas trees held at 30/ 25°C produced vegetative growth and did not flower (Nunez-Elisea et al. 1993).

In papaya, higher temperatures have resulted in flower drops in female and hermaphrodite plants as well sex changes in hermaphrodite and male plants. The promotion of stigma and stamen sterility in papaya is mainly because of higher temperatures. It has also been noticed that if flowering takes place under extremely low temperature conditions, flower drop is quite common in most fruit crops like mango, papaya, guava and other fruits.

In grapes, degree-days are important in determining the timing of various phenological events where, a temperature regime of 10°C and temperatures between 28-32°C are most congenial. Variations

in temperature cause alterations in the developmental stages and ultimately the ripening time. Under a higher temperature regime, the number of clusters per shoot was greater and the number of flowers per cluster was reduced (Pouget 1981). In the case of the variety Cabernet Sauvignon, maximum fruit set was observed at 20/15°C with no fruit set at 14/9°C or 38/33°C. Kliewer (1977) demonstrated the loss of ovule viability in the varieties Pinot Noir and Carignane at 35°C and 40°C as compared to 25°C.

The photosynthesis rate was highest in the temperature range of 20-30°C and the evapotranspiration rate increased with temperature and was highest at 30-35°C (Shiraishi et al. 1996). The partitioning of photosynthates within the leaf was affected as temperature increased leading to reduction in concentration of starch within the leaves of Cabernet Sauvignon vines (Buttrose and Hale 1971).

The area for quality production of the mango variety Dussaheri drastically reduced with a 0.7 to 1°C increase in temperature as a result of climate change. However, not many changes were seen with an increase of 0.2°C while the future climate simulation by 2050 exhibited remarkable reduction in the area suitable for the variety. Another example was for Alphonso variety grown mainly in Ratnagiri area of western India with similar results.

Climate based models indicate a shift of suitable area of this variety away from areas where it is presently grown commercially, particularly in the Ratnagiri area. Some of the areas of Maharashtra, Karnataka, Tamil Nadu and Andhra Pradesh where Alphonso is grown may become unsuitable for quality fruit production (Rajan 2008). In the case of fruit crops like pineapple, the impact of temperature variations can be seen from studies where induction of flowering takes place because of reduction in temperature, short day lengths or both (Friend 1981). The coincidence of long days with high temperatures results in irregular flowering, which goes to emphasize the role of temperature.

In longan, over-winter has developmental problems such as small fruit size, severe fruit drop and cracking. Stressful temperatures of <15°C in young fruit stage reduce fruit growth potential and final size. Stressful cold plus abrupt temperature fluctuations induce excessive fruit drop. Severe fruit cracking is related to cold and dry

weather in the young fruit stage (Wai-Hai Young et al. 2010). In the case of mandarins, low temperatures appear to have dual effects, releasing bud dormancy and inducing flowering. Potential flower buds have deeper dormancy than vegetative buds, and the first stages of flower initiation seem to occur before the winter rest period (García-Luís et al. 1992).

Seasonal shifts

Within the last decade of fruit science, the study of phenology has taken on new importance because of its contribution to climate change research. However, availability of phenology data sets spanning many years are rare for mango and guava, making it difficult to evaluate possible responses of these crops to climate change. While remarkable progress has been made in the ability to predict climate variability and extreme events at a local and national scale, especially for a seasonal time frame, challenges still remain. The identified gaps that need to be included are:

- Basic requirements for resources to improve climate and weather observations
- Data collection
- Vulnerability and adaptation assessments
- Higher resolution models for weather prediction and assessment methods suited to specific needs

Most of the fruit crops are highly heterozygous, genotype X environment (GxE) interaction is very high. Hence, the genotypes have to be stable enough to perform under different climatic conditions. The changes in bioclimatic variables extracted from the present and future climate (2030-2050) database were compared for the most suitable "Dashehari" growing area in Malihabad. Major changes were observed in the annual mean temperature (1.9°C) and rainfall (142 mm per year). The data also indicate that precipitation may increase during wet months and wet quarters whereas it will decrease during the cold quarters (Hijmans et al. 2005 and Govindasamy et al. 2003). Increasing frequency of early rains during the fruit maturity period may cause blackening of fruit whereas the reduction in winter rains will increase the irrigation requirement as well as make the conditions prone for poor crops.

Predicted changes in the climate of mango producing regions over the coming decades may alter significantly both the spectrum and the distribution of varieties currently being grown. Changes observed over recent years confirm these predictions. In particular, shifts in precipitation patterns will affect most regions, with increased risk of drought. Given this scenario, the consequences would be dramatic for the mango producing areas. Soil amelioration practices may have to be adapted to account for changes in soil moisture and decay rates of organic matter.

Rising CO_2 concentration alone may increase mango production and water use efficiency, but comprehensive studies predict decreases in yield of mango when increasing temperature and changes in solar radiation are considered simultaneously. Warmer and drier conditions during summer will increase demand for irrigation water. Well-planned efforts for plant adaptation, such as choosing varieties that suit the new climate and allocating water with improved water supply systems, will help minimize the losses and optimize the benefits.

In the sub-tropics, mango tree development is mainly driven by atmospheric temperature. After cessation of growth in winter, phenophases usually appear early in spring with the onset of higher temperatures. Distinct changes in air temperature since the end of the 1980s led to clear responses in mango phenology in many parts of India (Rajan 2008). The strongest shift in development occurs in the very early spring phases. The late spring phases and summer phases also react to the increased temperatures, but they usually show lower trends. The advanced flowering in mango can increase risk due to low temperature at night. Until now the changes in tree development are still moderate and hence strong impacts on yields have not been observed (Rajan 2008). But further climate changes will probably increase the effect on plants, so that in the future, stronger impacts on yields and fruit quality are likely to occur.

The variation in temperature under Bangalore conditions coupled with change in rainfall patterns and humidity (Figure 1) have influenced flowering in mango. Though the temperature variation during the past three years is not very pronounced, marginally higher temperatures during November and December in 2009 coupled with higher moisture caused drastic reduction in flowering in all of South India. The influence of rainfall, with a slight increase

in humidity during 2009 resulted in unseasonal flower initiation. Furthermore, unseasonal showers have resulted in failure to set fruits.

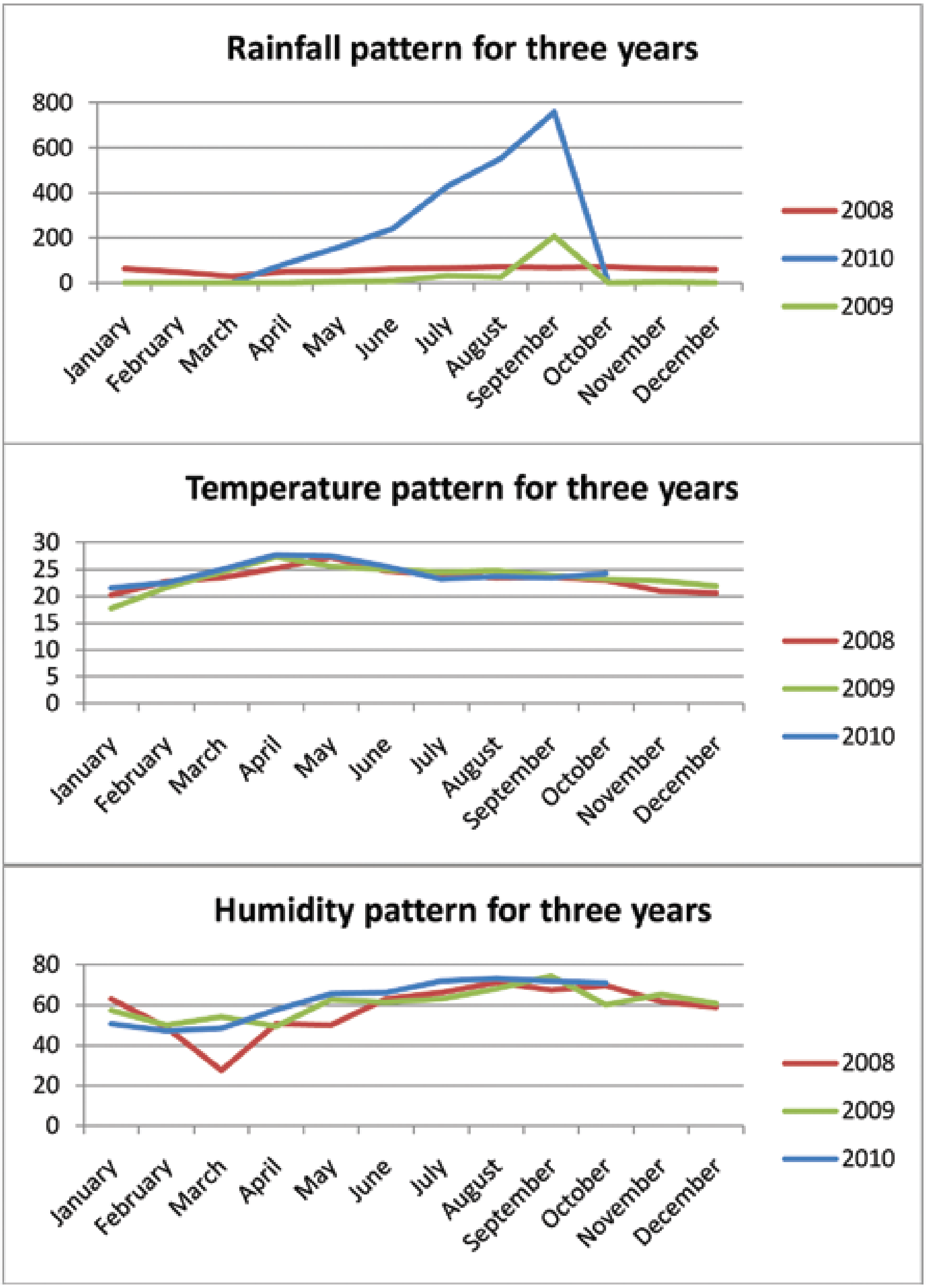

Figure 1. Rainfall, temperature and humidity patter of three years in Bangalore.

Effect of temperature changes on pest and disease scenario

A number of factors affect the pest and disease scenario in fruits. High temperatures coupled with high rainfall and humidity help in building up ideal conditions for the growth of a number of disease pathogens. For example, the powdery mildew disease in mango caused by *Oidium mangiferae* Berthet is a sporadic but serious disease of mango inflorescence that can cause up to 80-90% losses of the crop in extreme cases. Optimal disease development occurs at 10-31°C and 60-90% RH. Chhata et al. (2006) reported that high humidity (85-90%), moderate temperatures (maximum temperature of 25-26°C and minimum of 18-20°C) provided favourable condition for the initiation of disease. Correlations between weather parameters like different maximum temperature regimes and sunshine hours had negative correlations with disease development, while minimum temperature, humidity and wind speed had positive correlations.

Diedhiou et al. (2007) reported that fruits harvested during humid conditions were more heavily infested but a smaller number of fungal agents were involved; *Colletotrichum gloeosporioides* and secondarily *Phoma mangiferae* played the main role. In mango and guava, it has been observed that the incidence of fruit fly is much less at higher temperature regimes. However, a recent study conducted in India by Kumar et al. (2010) has shown that in mango cv. Chausa the rate of development of fruit fly increased with the increase in temperature from 20-35°C. The percent larval survival, adult emergence and growth index also increased with an increase in temperature from 20 to 27°C and thereafter decreased up to 35°C. Thus a temperature of 27°C was found to be ideal for survival and development of the immature stage and reproduction of *Bractocera dorsalis*. Verghese et al. (2002) have observed that post-harvest treatment of fruits at 48°C for 60-75 minutes has given good control of fruit flies.

Downy mildew is found worldwide wherever grapes are grown, occurring primarily where warm, humid conditions exist during the growing season. All common cultivated and wild species of grape as well as a few hosts outside the *Vitis* species, are susceptible to this disease (Pearson and Goheen 1988). Unseasonal rains coupled with higher temperatures during vegetative phases in grapes will result in damage due to this disease.

Thus, climate change is likely to impact growth and development of many fruit crops in the tropics and sub-tropics. To mitigate the damage caused, information on specific climatic conditions and interactions needs to be generated. One of the complications that arises in studies regarding the occurrence of pests and diseases and correlating them with climatic parameters is the presence of alternate hosts for these organisms and different strains of the organism.

Impact on fruit quality

Although, it is true that higher temperature regimes generally result in the best quality fruits, excessively high temperatures for extended periods of time are known to damage fruits. Excessively higher temperatures generally result in delay of fruit maturation and reduction in fruit quality of grapes (Kliewer, 1971; Kliewer and Schultz., 1973). High temperatures also reduce colour development. At 35°C pigment development was completely inhibited in Tokay and reduced in Cardinal and Pinot Noir compared to 20 or 25°C. Higher daily temperatures were also related to a decrease in colour hue values, i.e. more red fruit.

In the case of guava, it has been observed that red colour development on the peel of guava requires cool nights during fruit maturation. Varieties like Apple Colour, which have attractive apple skin colour under sub-tropical conditions of North India, have red spots on the skin under tropical South Indian conditions. The areas suitable for production of red colour guava were studied by Rajan (2008). He observed that when mapped with the present climate database, an increase of 0.2°C in temperature resulted into dramatic reduction in the areas suitable for development of red colour in guava; an increase of 0.5°C in temperature will reduce the areas drastically with the suitability probability of more than 97% to a very low level. Based on a future climate database, predictions show that areas with suitability percentage of less than 70% will be available for red colour guava development. Areas suitable for red coloured guava cultivation will be reduced dramatically because the minimum temperature during the coldest month may increase up to 1.9°C, whereas, the mean temperature of the coldest quarter will be 3.2°C higher than the existing temperature resulting in less red colour development in guava fruits.

High temperatures also appeared to reduce monoterpenes (Muscat flavor) in grapes under Tunisian conditions. Linalool, an important monoterpene was also higher at low temperature grown Tunisian grape cultivars (Zemni et al. 2005). Total soluble solids, fruit firmness and percentage dry mass were negatively correlated with temperature during fruit growth. However, the relationship varied with the cultivar (Hoppula and Karhu 2006). Fruit quality was positively related to warm and dry weather in Western Norway where it is cooler and wetter. However, in Eastern Norway a negative correlation was found between July's mean temperature and soluble solids (Vangdal et al. 2005).

Size and appearance, soluble solids content, total sugar content, total acids content and water content were greater and sugar to acidity ratio and vitamin C content were lower in pear fruits collected from the low temperature regions of China compared to high temperature regions (Chen et al. 1999). In Navel oranges the content of acidity was affected by low temperature leading to low TSS content. Among other climatic factors the rainfall in September and October had an obvious effect on the fruit soluble solids content where less rainfall in this period increased the soluble solids (Peng et al. 2000). Fruit juice quality was assessed in Australia in terms of Brix and percent acid at the time of harvest during a nine year period from 1988 to 1996 for Navel and Valencia oranges. The relationship between quality (Brix and acid content) and temperature sums (effective heat units – EHUs) for the period the fruits were held on the trees was tested. The juice acid relationship with EHUs was stronger than the Brix relationship with EHUs. In addition, the seasonal 'behaviour' of percent acid was more consistent than that of Brix in both Valencia and Navel oranges. A linear reduction in percent acid with increasing EHUs was evident in both varieties, indicating the negative relationship of temperature with acid/ brix ratios (Hutton and Landsberg 2000).

It is the authors' experience that in papaya higher temperature coupled with higher moisture content will bring about higher TSS. This has also been observed in many of the fruit crops like mango and guava. Another notable example is that in passion fruit, sugar content in the juice was highest at 28/23°C and lowest at 33/28°C, sucrose accumulated more at 23/18°C and glucose and fructose contents increased at higher temperatures (Naoki Utsunomiya 1992).

In sub-tropical and tropical fruit crops, there is a direct effect of the temperature on the maturity and ripening of the fruits. When there is sufficient moisture, the TSS of the fruit increases with the temperature. However, in some fruits like passion fruit, increases in temperature do not increase TSS. Hence, the effect of different regimes of temperature can be different on different crops under sub-tropical and tropical environments.

In the case of pomegranate, the aril colour turns from red to pink. However, it is the genotype x environment interaction that ultimately decides the expression of a trait. The stability of the genotype to perform under different environment is the ultimate deciding factor in the expression of any trait.

It is the authors' experience that in fruit crops like guava, which are grown in the tropics as well as the sub-tropics, and in strictly tropical arid crops like pomegranate, certain genes responsible for skin colour or pulp colour are not expressed under certain environmental conditions. In mango under different temperature regimes, fruit size is affected. In the case of the Cavendish banana, development of the golden yellow colour is affected under high temperatures, which is not the case with other cultivars. It has been decisively shown by the above examples that temperature is one of the main factors affecting gene expression for certain traits.

Uniqueness of perennial nature

Very little work has been done on the strategies that perennial trees use to tide over a crises arising out of changes in temperature. The major issues that need to be considered in the case of perennial trees are:

- Responses to climate change during different phases of growth for perennial fruit crops will be different. Hence, only long term experiments covering different growth phases can give reliable results.
- The physiological age at which a tree responds to different temperature regimes is different. The climatic parameters such as temperature will have profound effects on the flowering and fruit set. The climatic parameters during

bud differentiation can result in vegetative or reproductive phases. Hence, detailed studies for different crops may be necessary.

- Usually there are fewer varieties in perennial crops compared to annual crops, but there tends to be a high degree of heterozygosity in these varieties. Because of high heterozygosity, varietal responses may be different in different climates, making even a small set of varieties adaptive in a wide range of environments.
- Many fruit species may in the long run prove to be quite efficient in overcoming such crisis. Perennial fruit trees have the advantage of rootstocks, where in some cases they are resistant to biotic stresses. Hence, the response of climate by fruit crops on rootstocks also varies.

These issues can also be beneficial for some fruit crops, especially in a crop like grapes, where rootstocks like Dogridge have shown remarkable adaptability within a region. Several studies have shown that rootstocks have influenced the scion cultivars. In grapes, Candolfi-Vasconcelos et al. (1994) observed that Pinot Noir or 101 – 14 Mgt had higher CO_2 assimilation, transpiration rates and higher water use efficiency than that on 3309C. Sharad Seedless recorded maximum water use efficiency (WUE) when budded on Dogridge followed by Flame Seedless on Dogridge rootstock at 50% moisture stress (Satisha and Prakash 2005).

Selection of appropriate rootstocks in various fruit crops like mango and guava to suit the changed climatic conditions could be one of the solutions for combating temperature change. Along with such rootstocks, one can consider the use of certain specific species that are better adapted to changed conditions. For instance, several fruit crops have modified physiological and morphological adaptations and withstood these changes well. Fig has adapted to retain high bound water in the tissue, by having sunken stomata, thick cuticle and waxy coating on the leaves. Underutilized fruits like ber (*Ziziphus mauritiana* L.), phalsa (*Grewia asiatica* L.) and tamarind (*Tamarindus indica* L.) also have sunken stomata, thick cuticle and waxy coating of the leaves. Indian gooseberry or Aonla (*Emblica officinalis* L.) have adapted by reducing leaf area, thereby reducing the transpirational area. Pomegranate (*Puncia granata* L.) is fairly

winter hardy and also drought tolerant. Aonla, being a hardy and drought tolerant sub-tropical tree, can be grown well under tropical conditions. Papaya (*Carica papaya* L.) has adapted well to both tropical and sub-tropical conditions, which is also the case with guava.

Through pruning and cultural manipulations, grapes (*Vitis vinifera* L.), which are basically a temperate crop, are able to have their vines adapt well to the tropics. Pineapple (*Ananas comosus* L.), being a CAM (crassulacean acid metabolism) plant, has remarkable adaptability to different climatic regimes and has high water use efficiency. These crops and many other fruit crops viz., custard apple (*Annona cherimola* L.), jamun *(Syzygium* spp.), woodapple, bael (*Aegle marmelos* L.), avocado (*Persa americana* L.), passionfruit (*Passiflora edulis* L.) and karonda (*Carissa carandas* L.) could be considered as candidate crops under climate change conditions.

Future line of work

Conducting a study on most perennial tropical and sub-tropical fruits for a short period and arriving at a conclusion more often than not can be misleading. In many cases the germplasm evaluation has not been carried out to a desirable extent. In the perennial trees, rootstocks play an important role in deciding performance under different soil and climatic conditions. During recent times improved agro-techniques have helped to tide over several crises be it biotic or abiotic. Although climate change has brought out several changes in the behaviour of the plants, perennial fruit trees have performed well. However, a lot of work needs to be carried out and their performance must be correlated with climate change, be it in the juvenile or in the reproductive phase. Future work can be carried out on the lines given below:

- Evaluation of wild species should be probed thoroughly, which could be a source of resistant genes for tying over adversaries of the temperature.
- Evaluation of local types and landraces should be carried out to locate useful genotypes.

- Development of stable genotypes, which can perform across different environments within the region, is needed. There is a need to develop and test the performance of different genotypes across several environments so that their suitability can be judged.
- Development or location of rootstocks that can tolerate biotic stresses induced by temperature regimes is needed. In many crops, rootstocks have helped in combating the biotic stress induced by varying temperature conditions.
- Adoption of improved agro-techniques like mulching and cover crops in orchards will help in bringing down the orchard temperature. It is a feasible proposition to grow cover crops of economic importance, which will also add to the income from the orchard.
- Use of precision farming methods like high density planting and drip irrigation would help in maintaining the ground cover within the orchard thereby reducing the temperature and providing an ideal microclimate.

References

Bhruguvanshi SR. 2009. Implications of climate change in mango. Impact Assessment of Climate Change for Research Priority Planning in Horticultural Crops. Central Potato Research Institute, Shimla. pp. 43-46.

Buttrose MS, Hale CR, Kliewer WM. 1971. Effect of temperature on the composition of 'Cabernet Sauvignon' berries. American Journal of Enology and Viticulture 22: 71-75.

Candolfi-Vasconcelos MC, Koblet W, Howell GS, Zweifel W. 1994. Influence of defoliation, rootstock, training system and leaf position on gas exchange of Pinot Noir grapevines. American Journal of Enology and Viticulture 45:173-180.

Chen Z, Zhao S, Xia H, Ding H. 1999. Effect of ecological factors and cultural systems on pear fruit quality. South-China-Fruits 28(3):41-42.

Chhata LK, Jat ML, Jeeva Ram, Jain LK. 2006. Effect of weather variables on outbreak and spread of leaf spot fruit spot in pomegranate. Current Agriculture 30(1/2):39-44.

Chmielewski FM, Rotzer T. 2001. Response of tree phenology to climate change across Europe. Agricultural and Forest Meteorology 108:101-112.

Chmielewski FM, Rotzer T. 2002. Annual and spatial variability of the beginning of growing season in Europe in relation to air temperature changes. Climate Research 19(1):257-264.

Cox JEK. 1976. Garcinia mangostana-Mangosteen. In: Garner RJ, Ahmed Chaudhari S, editors. The Propagation of Tropical Fruit Trees. Horticultural Review No. 4. Commonwealth Bureau of Horticulture and Plantation Crops, East Malling, UK. pp. 361-375.

Davanport TL. 2003.Management of flowering in three tropical and sub tropical fruit tree species. HortScience 38:1331-1335.

Davanport TL. 2009. Reproductive physiology. In: Litz RE, editor. The Mango (2nd ed.). Botany, Production and Uses. CABI, UK.

Diedhiou PM, Mbaye N, Drame A, Samb PI. 2007. Alteration of post harvest diseases of mango Mangifera indica through production practices and climatic factors. African Journal of Biotechnology 6(9):1087-1094.

FAO [online]. Available from: URL: http://www.fao.org/DOCREP/003/X6908E/x6908e01.htm#TopOfPage

Friend DJC. 1981. Effect of night temperature on flowering and fruit size in pineapple (*Ananas comosus* (L) Merrill). Botanical Gazette. 142(2):188-90.

Gaffar MBA, Osman MS, Omar I. 2008. Pomelo (*Citrus maxima* L.) In: Kwok CY, Lian TS, Jamaluddin SH, editors. Breeding Horticultural Crops. MARDI, Malaysia. pp. 67-82.

García-Luís A, Kanduser M, Santamarina P, Guardiola JL. 1992. Low temperature influence on flowering in *Citrus*. The separation of inductive and bud dormancy releasing effects. Physiologia Plantarum 86(4): 648–652.

Ghosh SP. 2000. Status report on genetic resources of jackfruit in India and SE Asia. IPGRI, New Delhi Office, India.

Govindasamy B, Duffy B, Coquard J. 2003. High resolution simulations of global climate, part2: effects of increased greenhouse cases. Climate Dynamics 21:391-404.

Haq N. 2006. Fruits for the Future 10. Jackfruit (*Artocarpus heterophyllus*) Southampton Centre for Underutilised Crops. p. 192.

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25(15): 1965-78.

Hoppula KB, Karhu ST. 2006. Strawberry fruit quality responses to the production environment. Journal of Food, Agriculture and Environment. 4 (1) : 166-170.

Hutton RJ, Landsberg JJ. 2000. Temperature sums experienced before harvest partially determine the post-maturation juicing quality of oranges grown in the Murrumbidgee Irrigation Areas (MIA) of New South Wales. Journal of the Science of Food and Agriculture 80:275-283.

Idris S, Lin RM. 2002. Status report on genetic resources of Pulsan *(Nepelium ramboutan-ake)* in Southeast Asia. MARDI, Malaysia and IPGRI Office for South Asia.

Kliewer WM. 1971. Effect of temperature on the composition of cabernet sauvignon berries. American Journal of Enology and Viticulture 22:71-75.

Kliewer WM, Schultz HB. 1973. Effect of sprinkler cooling of grapevines on fruit growth and composition. American Journal of Enology and Viticulture 24:17-26.

Kliewer WM. 1977. Effect of high temperature during the bloom-set period on fruit-set, ovule fertility, and berry growth of several grape cultivars. American Journal of Enology and Viticulture 28:215-221.

Krishnamurthy S, Rao NVM. 1962. Mangosteen deserves wider attention. Indian Horticulture 7(1):3-4, 8.

Kumar R, Omkar, Shukla RP. 2010. Effect of temperature on growth, development and reproduction of fruit fly *Bractocera dorsalis* Hendel (Diptera: Tephritidae) in mango. Journal of Eco-friendly Agriculture 5(2): 150-53.

Lasko AN. 1994. Apple. In: Schaffer B, Andersan PC, editors. Handbook of Environmental Physiology of Fruit Crops. Vol I. Temperate Species, CRC Press, Boca Taton, Florida. pp. 3-43.

Lal M, Cubasch U, Voss R, Waszkewitz J. 1995. Effect of transient increase in greenhouse gases and sulphate aerosols on monsoon climate. Current Science 69(9):752-763.

Lal M, Nozawa T, Emori S, Harasawa H, Takahashi K, Kimoto M, Abe-Ourchi A, Nkajima T, Takemura T, Numaguti A. 2001. Future climate change: implications for Indian summer monsoon and its variability. Current Science 81:1196-1207.

Lonergan S. 1998. Climate warming and India. In: Dinar A, Mendelsohn R, Evenson R, editors. Measuring the Impact of Climate Change on Indian Agriculture. World Bank Technical Paper No. 402. Washington DC Mall RK.

Maiti SC, Sen PK. 1978. Studies on biennial bearing in mango III. Cessation of Shoot Growth and Flowering. Orissa Journal of Horticulture 6: 43-51.

Maiti SK, Maity SC, Sen PK. 1978. Effects of short day with and without ringing on growth and flowering of mango *(Mangifera indica L.)*. Indian Agriculturist 22:159-164.

Menzel CM, Rasmussen TS, Simpson DR. 1989. Effects of temperature and leaf water stress on growth and flowering of lychee *(Litchi chinensis* Sonn*.)*. Journal of Horticultural Science 64: 739-752.

Montieth JL. 1969. Light intereception and radiative exchanges in crop stands. In: Eastin et. al. editors. Physiological Aspects of Crop Yield. American Society of Agronomy, Madison. USA. pp. 89-109.

Monteith JL. 1977. Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society of London, Series B 281: 277-294.

Morton JF. 1987. Fruits of Warm Climates. Florida.

Mukherjee SK. 1953. The mango-its botany, cultivation, uses and future improvement, especially observed in India. Economic Botany 7:130-162.

Mukherjee SK. 1972. Origin of mango *(Mangifera indica* L.). Economic Botany 26(3):260-264.

Mukherjee SK, Litz RE. 2009. Introduction: Botany and importance. In: Litz RE, editor. The Mango (2nd ed.). Botany, Production and Uses. CABI, UK.

Naik KC, Rao M. 1943. Studies on blossom biology and pollination in mangoes (M*angifera indica* L.). Indian Journal of Horticulture 1:107-119.

Naoki Utsunomiya.1992. Effect of temperature on shoot growth, flowering and fruit growth of purple passionfruit *(Passiflora edulis Sims var. edulis).* Faculty of Agriculture, Kyoto University, Sakyo-ku, Kyoto 606, Japan.

Nunez-Elisea R, Davenport TL, Caldeira ML. 1993. Bud initiation and morphogenesis in 'Tommy Atkins' mango as affected by temperature and triazole growth retardants. Acta Horticulturae 341:192.

Osman MB, Milan AR. 2006. Mangosteen (*Garcinia mangostana* L.). DFID, FRP, CUC, World Agroforestry Centre and IPGRI.

Pearson RC, Goheen AC, editors. 1988. Compendium of Grape Diseases. APS Press, St. Paul, MN. p. 93.

Peng L, Wang C, He S, Guo C, Yan C. 2000. Effects of elevation and climatic factors on the fruit quality of Navel orange. South-China-Fruits 29(4):3-4.

Pouget R.1981. Action de la temperature sur la differenciaction des inflorescences et dus fleurs durant les phases de pre debourrement et de post debourrement des bourgeons latents de la Vigne. Conn. vigne vin 15:65-79.

Rajan S. 2008. Implications of climate change in mango. Impact Assessment of Climate Change for Research Priority Planning in Horticultural Crops. Central Potato Research Institute, Shimla. pp. 36-42.

Rejab M, Teck CS, Zain KM, Muhamad M. 2008. Mangosteen. In: Kwok CY, Lian TS, Jamaluddin SH, editors. Breeding Horticultural Crops. MARDI, Malaysia. pp. 155-174.

Sathisha J, Prakash GS. 2005. Influence of water and gas exchange parameters on grafted grapevines under conditions of moisture stress. South African Journal of Enology and Viticulture 27(1):2006.

Schaffer B, Gaye GO. 1989. Season effects of pruning on light penetration, specific leaf density, and chlorophyll content of mango. Scientia Horticulturae 41:55-61.

Schaffer B, Urban L, Lu P, Whiley AW. 2009. Ecophysiology. In: Litz RE, editor. The Mango Botany, Production and Uses. CABI, UK.

Scherr SJ, Sthapit S. 2009. Mitigating climate change through food and land use. Worldwatch Report No. 179. Worldwatch Institute and EcoAgriculture Partners, Washington DC, USA.

Scholefield PB, Oag DR, Sedgley M. 1986. The relationship between vegetative and reproductive development in the mango in northern Auystralia. Australian Journal of Agricultural Research 37:425-433.

Shiraishi S, Hisung-Tung Chuan, Shiraishi M, Kitazaki M, Hisung TC. 1996. Effects of temperature on the photosynthetic rate of grape cultivars. Science Bulletin of the Faculty of Agriculture, Kyushu University 51:1-2.

Shu ZH, Sheen TH. 1987. Floral induction in auxillary buds of mango (*Mangifera indica* L) as affected by temperature. Scientia Horticulturae 31:81-87.

Tindall HD. 1994. Rambutan Cultivation. Food and Agriculture Organization of the United Nations. ISBN 9789251033258.

UDPSM. 2002. Plant propagation and planting in uplands. Training Manual for Municipal Extension Staff. Upland Development Programin Southern Mindanaao, Oct 2002, Davao, Philippines.

Vangdal E, Meland M, Måge F, Døving A. 2005. Prediction of fruit quality of plums (*Prunus domestica* L.). Acta Horticulturae 674:613-617.

Verghese A, Madhura HS, Kamala Jayanthi PD, Stonehouse John M. 2002. Fruit flies of economic significance in India, with special reference to Bactrocera dorsalis (Hendel). Proceedings of 6th International Fruit fly Symposium; 6 – 10 May 2002, Stellenbosch, South Africa. pp. 317 – 324.

Verheij EWM, Coronel RE. 1992. Edible fruits and nuts. Plant Resources of South-East Asia No. 2. Prosea Foundation, Bogor, Indonesia. pp. 128-131.

Wai-Hai Yang, Xiao-Chuan Zhu, Si-Cong Wang, Gui –Bing Hu, Hang Hee, Xu-Ming Huang. 2010. Developmental problems in over-winter offseason longan fruit. I: Effect of Temperature. Scientia Horticulturae 126:351-358.

Whiley AW, Rasmussen TS, Saranah JB, Wolstenholme BN. 1989. Effect of temperature on growth, dry matter production and starch accumulation in ten mango *(Mangifera indica L.)* cultivars. Journal of Horticultural Science and Biotechnology 64: 753-765.

Whiley AW, Rasmussen TS, Saranath JB, Wolstenholmv BN. 1995. Effect of temperature on growth, dry matter, production and starch accumulation in ten mango (*Mangifera indica* L) cultivars. Journal of Horticultural Science and Biotechnology 64:753-765.

Yoshino M, Park Ono Hye Sook. 1996. Variations in the plant phenology affected by global warming. In: Omasa K, editor. Climate Change in Plants in East Asia. Springer Verlag, Tokyo, Japan. pp. 93-107.

Zemni H, Souid I, Salem AB, Fathalli N, Mliki A, Ghorbel A, Hammami M, Hellali R. 2005. Aromatic potential of grapevines cultivated in Northern and Southern Tunisia. Acta Horticulturae 689:87-94.

Phenological Responses to Temperature and Rainfall: A Case Study of Mango

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Introduction

The geographic distribution of plant species, vegetation types and agricultural cropping patterns demonstrates the strong influence climate has on plant growth. Solar radiation, temperature and precipitation values and seasonal patterns are key determinants of plant growth through a variety of direct and indirect mechanisms (Morison and Morecroft, 2006). This chapter aims to discuss the impact of climate change on tropical fruits with specific examples of mango cultivation in India.

Climate and weather play critical roles in the economic success or failure of tropical fruit tree species including commercial mango production. Air temperature and rainfall influence vegetative and phenological phases in mango and are two of the most important factors determining suitability of an area's climate for mango production. Climate-related changes have already brought widespread changes in flowering and fruiting patterns of mango. This is adversely affecting fruit production in some areas. But rising temperature in areas previously too cold for mango production are making them more suitable for mango production. For instance, an increase in temperature the during coldest month has made mango cultivation possible in the valley areas of Himachal Pradesh and Uttarakhand. In several parts of the globe increasing temperature will offer opportunities for mango production in new areas.

Mango Phenology

The seasonal cyclic changes of growth in shoot, root, flower, fruit and their development depend on cultivars and climatic conditions. Varietal responses to the environment within and between mango cultivars account for their relative performance at different locations.

Thus, phenological patterns are strongly under environmental control in mango. The timing of life-cycle events like flowering and crop maturity have only recently been considered as an area of climate impacts research in several crops. Under the influence of climate shift, early and delayed flowering is a characteristic feature of mango.

Two of the most important factors determining suitability of an area's climate for mango are air temperature and rainfall. The sequence of phenological changes is either advanced or retarded with the rise and fall in temperature and the onset of wet and dry seasons. Therefore, climate change is likely to influence phenological patterns and indirectly vegetative and reproductive processes leading to reduced quality and quantity of production (see also Dinesh and Reddy in this volume for changes in phenology of TFT species).

Impact of Temperature

The distinct increase in air temperature in many parts of the northern hemisphere since the end of the 1980s and the demand for indicators of climate change impacts have caused a growing interest in phenological data of fruit crops. Changes in the timing of phenophases of mango could be of great economic importance, because they could have direct impacts on yield. Unusually low temperature spells may wipe out the crop by influencing the flowering and fruit set.

Temperature has a dominant influence on the growth cycle, time and frequency of flowering, fruit growth, taste and appearance of the mango in almost all production areas. Growth requires comparatively higher temperature regimes while inflorescence emergence starts just after the coldest period of the winter in the region. Flowering progresses as the temperature increases gradually. Vegetative growth on the other hand coincides with a period in which the mean monthly temperature exceeds 15°C. The difference in the apparent temperature requirements for the two processes is quite marked.

The maximum temperature of the warmest month of a location may be a limiting factor for mango cultivation. In most of the areas where the temperature is less than 30°C, mango is not well adapted. Areas with less than 6°C minimum temperature in the coldest month are

not suitable for commercial production. In mango producing areas, minimum temperature of the coldest month ranges from 6-22°C indicating a wide range distributed from the equator to upper latitudes.

Climate projection studies indicate a general increase of 3–6°C with more warming in the northern parts than the southern parts of India (Lonergan 1998; The Energy Resources Institute 2001). Climate change would have negative impact on tropical regions where the prevailing temperature is already high. Although mango is a heat-loving crop – it is well adapted to the hot, semi-arid sub-tropics and monsoonal tropics – if it experiences extremes of heat, drought and evaporative demand, potential production capacity will fall.

Mango, being a perennial fruit crop, would respond to increases in temperature differently as compared to annual crops (Litz 2009). A perennial crop like mango may stay alive under desiccating conditions and this capacity can be highly advantageous for yield in succeeding growth seasons. The capacity to survive is largely irrelevant in an annual crop plant where a stress-induced delay in development can result in a complete loss of yield (Morison and Morecroft 2006).

Mango can withstand a wide range of temperatures from 0°C to 48°C, without being adversely affected. But exposure to low temperature for more than 6 hours can kill the plant. In general, most varieties, if not in active growth at the time cold weather strikes them, will withstand 1-2°C, provided such temperature does not persist for more than a few hours. Young trees in vigorous growth are seriously injured at 0°C.

Cool temperatures below 17°C produce abnormal and non-viable pollen grains. The prevaculate stage of meiosis during microsporogenesis appears to be most sensitive to temperatures below 10°C. Cool temperatures also adversely affect germination and pollen tube growth, which is completely inhibited at temperatures below 15°C (Issarakraisila and Considine, 1994).

Low sex ratio (proportion of hermaphrodite and male flowers) contributes significantly to low yields in some cultivars (Singh et al. 1966, 1965). Cool temperature during inflorescence development reduces the number of perfect flowers and these flowers may

produce aborted, deformed and fused ovaries, which does not happen above 17°C. Polyembryonic cultivars suffer more from low temperature than monoembryonic (Whiley and Schaffer 1997). Occasional low temperature during flowering causes embryo abortion in areas of Brazil, Peru and Chile (Sauco 2000).

At a given latitude, temperature changes with changes in altitude. Thus, low temperatures above 1500 m and the occurrence of frost may limit the cultivation of mango. In India, it thrives well from Kanyakumari in the tropical south to the sub-mountainous regions of north India (30°N) up to 1400 m. Subedi et al. (2008) reported mango orchards at the altitude of 1400-1490 m in far western Nepal. But in general, mango grows from sea-level up to an elevation of 1250 m within the tropics, and commercial production is difficult in areas above 700 m. Although, mango cannot be grown very successfully in the hilly tracts of northern India, it has been found to flourish well in protected sites and at lower elevations of 300 to 700 m in some of the sub-Himalayan valleys. In the Philippines, the mango is successfully grown up to an elevation of 450 m (Singh 1960). Above, or at, a height of 1000 m young trees can be killed by frost, and the growth of older trees is also stifled. Frost occurrence may differ at different altitudes and topography may affect the severity of damage caused by frost. Altitude also affects the time of flowering. It is reported that for each 121 m increase in altitude flowering is delayed by four days (Hopkins 1938).

Impact of Rainfall

Unpredictable rains during pre-flowering and flowering periods may cause poor fruit set and low pollinator activities. In the changing climatic scenario, a major portion of the harvest may be wiped out by storms during later fruit development stage. Changes in rainfall patterns can adversely affect the quality and appearance of ripe mango fruits. Unseasonal rains encourage pests, which also lower fruit yield.

Mangoes grow best in climates which have low rainfall and low relative humidity at flowering, fruit setting and harvesting, and that are warm to hot during fruiting. Although mango tolerates a wide range of climates from warm temperate to tropical, anthracnose can become a serious problem for mango cultivation in humid, high

rainfall environments (Cook 1975; Lim and Khoo 1985; Ploetz 2003). Areas with seasonal rainfall of 100 mm or above are favoured for growing mango because vegetative growth is inhibited during the dry season. Quantity and distribution of rainfall both are important in mango production. Although mango grows naturally in low as well as heavy rainfall (250-3000 mm) areas, rainfall during fruit development and maturity is critical. In high rainfall areas, fruits at the time of maturity are exposed to diseases like anthracnose and these fruits are less attractive because of blackening of the peel. Mango can be grown with little irrigation in areas having annual rainfall above 250 mm.

Mango is grown mostly in areas with a wide range of annual rainfall with no water logging. Rainfall during flowering adversely affects fruit set, fruit development and yield. In certain areas of southern Thailand and India, excessive vegetative growth and drop of flowers occur due to heavy and prolonged rainfall. However, some of the regional cultivars are resistant to this. Mango trees perform well in some arid regions of Thailand and southern India. Therefore, varietal differences exist for their performance in wet and dry conditions and fruits develop better colour and are less affected by diseases where the air is comparatively dry during flowering, fruit set and fruit growth.

Very low rainfall (<40 mm) in the wettest month of the year may be a limiting factor in commercial production. This parameter ultimately increases the irrigation requirement for proper vegetative and fruit growth. Some important mango growing areas like Konkan region in India, experience high annual rainfall but with a dry period, which is necessary for proper floral induction and fruit development. In tropical rainforest areas of Malaysia and Indonesia annual rainfall is quite high with limited or no dry period, encouraging flowering for longer periods and many flushes. These areas may become unsuitable for quality mango production because of high rainfall during fruit development and may promote pre- and post-harvest diseases.

Phenological Responses to Temperature and Rainfall in Mango

Important phenological stages of mango and how they respond to changes in temperature and rainfall are described below.

Vegetative Growth flushes

Emergence of growth and flowering flushes in mango are influenced by weather dynamics. They determine yield in varieties with irregular bearing tendencies. There are different periods of flushing in mango which varies with climatic zones. Three vegetative flushes occur in Northern India from March to April, June to July and September to October. In Western India three growth flushes are recorded from February to March, March to April and October to November. However, two to five flushes occur in South and Eastern India with two growth flushes in the dry parts of South India (February to June and October to November). In Sri Lanka, one to two growth flushes in the dry zone and two to six growth flushes in the wet zone have been observed in various mango cultivars. Pairi mango in Hawaii flushes throughout the year similar to that in tropical climates like West Africa. In the southern hemisphere, Brazilian mango begins flushing in August and lasts until February with a short resting period from November to January. Thus, the number of flushes in a year can vary depending upon the climate in different parts of the world. The number of flushes may increase in tropics, near the equator or in coastal areas with less temperature fluctuation during different months.

Young trees flush continuously while older trees remain quiescent for several weeks at a time in the same environment. Young trees put forth continuous growth, irrespective of their regular and alternate bearing habits, perhaps because of sparse flowering and poor crop load.

Under optimum temperatures for growth with non-limiting nutrients and water, a tree may remain in vegetative growth phase with growth flushes occurring at regular intervals. Cessation of shoot growth favours the flower bud formation and too much growth may result in low yield. The large size and poor cropping of trees in

the humid lowland tropics are well known because there is a direct relationship between temperature and the frequency of vegetative flushes. Trees grown at 20°C days/15°C nights (20/15°C) required 20 weeks (mean of ten cultivars) to complete a growth/dormancy cycle while at 30/25°C the same cycle was completed in six weeks (Whiley et al. 1989). There are marked differences between cultivars with respect to their tendency towards vegetative growth. For instance, in controlled temperature studies, over a 20-week period, at 30/25°C, Irwin mango produced 2.0 growth flushes with approximately 45 days of dormancy between active growth periods while Kensington produced 4.7 growth flushes with only five days of quiescence between flushes (Whiley et al. 1989).

The number and size of leaves, which develop on each growth flush, are also influenced by temperature. Trees growing at 30/25°C produced more leaves per flush compared to trees exposed to 20/15°C (Whiley et al. 1989). Soil temperature, which is influenced by ambient temperature, has a strong effect on the vegetative and reproductive growth of mango (Yusof et al. 1969). These results indicate that environmental control over shoot growth of mango may in part be related to soil temperature. Controlled temperature studies have revealed that the mean daily temperature (mean of the maximum and minimum daily temperature at which shoot growth ceases is approximately 15°C (Whiley et al. 1989; Issarakraisila et al. 1991). Stress-inducing temperature, which prevents shoot growth may promote floral induction in mangoes.

Mango trees can tolerate air temperature up to 48°C for a short period in a day. The trees are adversely affected by frost and long cold spell leading to death of leaves, shoots and their branches, killing the trees from top to thick trunks, which normally occurs at 0°C. Younger trees suffer greater damage due low temperature (Carmichael 1958).

Intermittent rainfall can also increase random flushing. However, when the tree matures, biennial-bearing varieties put forth very little growth during the fruiting period and also after harvest. Mango is a day neutral plant whose flowering is unaffected by photoperiod. Studies revealed that the effect of cool temperature on flowering is independent on photoperiod (Nunez-Elisea and Davenport 1995) and the developmental fate of mango buds is strongly influenced by

cool night temperatures (15°C) followed by <20°C day temperature (Ou 1980 and 1982).

Flowering time

Flowering time is one of the most important features regulated by climatic conditions. Flowering starts at the equator and moves towards the north and south in a similar manner all over the world. Flowering in India is a classic illustration of this phenomenon in mango. Flowering commences in India around the first of December in the southern part of Kerala and Tamil Nadu and by 15th December in coastal Karnataka, Maharashtra and Tamil Nadu and southern Andhra Pradesh. Subsequently flowering proceeds northwards and by the first of January, it occurs in Andhra Pradesh, Southern Maharashtra and all over Orissa, southern Madhya Pradesh, northern Maharashtra and coastal Gujarat. By the first of February mango trees flower all over eastern India, Madhya Pradesh and Gujarat and by the 15th of February flowering occurs in western Uttar Pradesh, Haryana and Punjab. Flowering begins in March in hilly tracts of Assam, Meghalaya, Tripura, southern part of Himachal Pradesh and Jammu and Kashmir particularly in the valleys. Flowering is over in about a month in northern India.

In the Philippines, mango trees flower in December-January and in Java (Indonesia), they flower in June-August and fruits mature during October-November. Mango trees flower throughout the year in some locations of Indonesia, being on both sides of the equator. However, the supply of mango is still seasonal due to concentrated production in Java, and the fruits are available from September to December starting from early August (4-5 months in a year). In Malaysia, mango trees flower during February- March. In Thailand, flowering starts in December near the equator in the southern part and it continues till the end of March in the north. Fruits in the northern region are harvested about one month later than in rest of the country. In southern Myanmar, mango trees flower in December-January, while January-February is the flowering time in the north (Ram and Rajan 2003).

Under the influence of the projected changing climate, the flowering time and duration are likely to be more influenced in the sub-tropics.

Early and late flowering will be the characteristic changes, which are also apparent under present weather dynamics.

High temperature, rainfall and humidity may force a mango tree to grow continuously, without any distinct pause in growth, and flowering may not occur. In most varieties mango flower bud formation takes place in the shoot with cessation of growth.

Growth and flowering responses of mango to environmental variables can be related to the evolutionary centre of origin of a cultivar. They grow well in the tropics and sub-tropics. Dissimilar timings in flowering in different parts of the world are mostly governed by temperature.

Growth chamber studies show that cool night temperatures between 8°C and 15°C in combination with day temperatures below 20°C bring flowering, if shoot initiation occurs (Shu and Sheen 1987). Whiley et al. (1988, 1989, 1991) described vegetative induction at 30°C day and 25°C night temperatures and floral induction at 15°C day and 10°C night temperatures in mono and polyembryonic cultivars.

Flowering time and duration are likely to influence fruit set in the sub-tropics. Under the changing scenario, early and late flowering are apparent in several parts of the world. Delayed or early flowering may lead to pollen desiccation while low temperatures can cause embryo abortion and psuedo-setting of fruits without normal fertilization.

In addition, a prerequisite for successful mango production is the absence of rain during the flowering period. Moist and humid atmosphere washes pollen and encourages insect pests and diseases, and also interferes with the activity of pollinators. Rain, heavy dew or foggy weather during the blooming season stimulate tree growth but interfere with flower production and encourage diseases of the inflorescence.

Plant water stress has been presumed to provide the stimulus for flowering (Singh 1960). In the absence of cool temperatures, mango trees in the tropics may flower in response to irrigation or rain following periods of water stress lasting 6-12 weeks or more (Pongsomboon 1991). Increased flowering is reported following 12 weeks of water deficit in Queensland, Australia.

Fruit set

At fruit set stage mango is very sensitive to unfavourable weather conditions prevailing at anthesis (i.e. period when flowers are fully open and functional), pollination and fertilization resulting in low yield because of pollination failure, poor pollen germination and pollen tube growth, and ovule abortion. Cultivars differ in their propensity to set fruit. Most of the cultivars set fruit poorly at the slightest exposure to unfavourable environmental conditions viz., rain, humidity, temperature, light, wind, drought, water logging, etc. In the sub-tropics, an abrupt rise in day temperatures or low temperatures (less than 10°C) in the night during flowering may increase the number of stenospermocarpic fruit (nubbins). Self pollination in some varieties like Dashehari may be one of the cause of nubbins (clustering), which is further elevated by the reduced pollinator activity due to low or high temperature.

Fruit growth and development

Both increased precipitation and drought are projected as important components of climate change. An increase in precipitation during fruit growth and development may delay the number of days taken to maturity and fruits lose their attractive appearance if exposed to several rains during fruit growth and development periods. Thus, the time taken for maturing and appearance are likely to change under the changing climate scenario. In the Philippines, mango varieties are harvested 100-110 days after flowering during April to June but those picked from January to March are the result of retention on the tree for 120-125 days during the cooler part of the year (Ram and Rajan 2003). In India and Thailand, mangoes grown in the Northern provinces take longer to mature than in central and southern provinces.

A heat unit is an objective measure of the time required for the development of the fruit to maturity after flowering and can be measured by the degree days or heat units in a particular environment. The heat unit required for mango fruit maturity not only differs from cultivar to cultivar but also from place to place based on temperature of the locality. The base temperature fixed for mango was 17.9°C by Oppenheimer (1947) in which heat unit

calculations are based on the sum of the temperature units in excess of the base temperature over the growing period above 17.9°C. The base temperature 15°C was given by Whiley et al. (1991). Several workers used different base temperature (10-17°C) for heat unit calculations. In the Philippines, heat unit requirement for Carabao mango is over 1000 units even though fruit from Quezon took 130 days to mature, while fruits from Nueva Eciza took 123 days. In different geographical regions variability in time of maturity of a variety is well known and thus more variable maturity behaviour of the mango varieties will be apparent.

High temperature induces physiological changes within the mango fruit also. Spongy tissue, a physiological disorder in Alphonso mango, is induced because of build up of high temperatures within the fruits, leading to tissue breakdown. Both artificially and naturally induced spongy tissue showed low rates of transpiration and high rates of respiration. The results have indicated that the rate of transpiration and respiration has an influence on fruit temperature, which in turn has an influence on normal fruit ripening processes. To protect from heat stress, soil is kept moist by irrigation.

Excessive rainfall and high humidity during the period of fruit maturity invites severe attacks of fruit fly, anthracnose and mango stone weevil. Conversely, fruits that are well exposed to the sun become well coloured and are relatively free of disease.

Existing mango distribution in vegetation zones and perceived future adaptation

Presently mango is grown in various vegetation zones viz., sub-tropical humid, tropical desert, tropical dry, tropical moist deciduous, tropical mountain system, tropical rainforest and tropical shrubland. In large countries like Brazil and India, it is grown under several vegetation zones. Climate change is having different impacts on mango production in different vegetation zones. Some areas previously suitable for mango production are no longer suitable and vice-versa (Table 1).

Table 1. Vegetation zone characteristics and perceived climate changes vis-à-vis mango production.

Vegetation zone	Countries	Characteristics	Projections
Tropical rainforest	Bangladesh, Bolivia, Brazil, Cameroon, Columbia, Congo Republic, Côte d'Ivoire, Dominican Republic, Equatorial Guinea, Gabon, Ghana, Guinea, Guyana, Haiti, Honduras, India (Western Ghats and North East), Indonesia, Laos, Liberia, Malaysia, Myanmar, Nicaragua, Nigeria, Peru, Philippines, Sri Lanka, Suriname, Thailand, Uganda, Venezuela, Vietnam, and Zaire	These regions receive high rainfall (more than 2000 mm, annually) distributed throughout the year. The vegetation is evergreen where the summers are warm and very humid. It also rains a lot in the winter. Daily maximum temperature reaches about 32°C while night time temperature averages at 22°C. Monthly temperature variations in this climate are less than 3°C. Because of intense surface heating and high humidity cumulus and cumulonimbus clouds form early in the afternoons almost every day. These regions are excellent for mango production when the annual rainfall is less than 2500mm. The suitability decreases as precipitation goes above 3000 mm.	Under changing climate scenario the decline in precipitation in this zone will increase the possibility of off season production because very little monthly temperature variation can be exploited for induction of flowering at the time when fruits produced through off season flower induction are least affected by diseases and pests.

Table 1. Continued...

Vegetation zone	Countries	Characteristics	Projections
Tropical moist deciduous vegetation	Angola, Bangladesh, Benin, Brazil, Cambodia, Cameroon, Central African Republic, Côte d'Ivoire, Cuba, Ghana, Guinea, Hainan Province of China, India (West Bengal, Laos, Madagascar, Mali, Mexico, Mozambique, Myanmar, Nigeria, Paraguay, part of Orissa, Philippines, South Sudan, Sri Lanka, Thailand, Venezuela, Vietnam, Western Ghats), Zaire, and Zambia	These regions receive high overall rainfall with a warm summer wet season and a cooler winter dry season. Some tree species in these regions drop some or all of their leaves during the winter dry season. This climate is best developed in South East Asia. As warm, moisture-laden air flows from the Indian Ocean in summer, a wet season develops. The dry season is short and is followed by heavy rain so there is rarely a soil moisture deficit. The conditions here are excellent for mango production. The maximum temperature is 30-35°C and minimum temperature is less than 18°C (8-18°C). Annual rainfall ranges from 1000 to 2000 mm.	Changing climate pattern may cause shift in rainfall pattern and induce early or delayed flowering which may result in poor setting.

Table 1. Continued...

Vegetation zone	Countries	Characteristics	Projections
Tropical dry vegetation	Argentina, Australia, Brazil (East), Chad, India (UP, Bihar, MP, AP, parts of Maharashtra, Chhatisgarh and Orissa), Mozambique, Nigeria, Paraguay (North), Sudan, and Zimbabwe	There is an extended dry season during winter. Precipitation is only during the summer season. Here the climate is hot and humid during the long summers and cool during the short winter season. The annual rainfall is 500-1500 mm. The temperature shows high variability affecting the suitability of mango production. The conditions are suitable in the areas where maximum temperatures exceed 38°C and minimum temperature is 8-12°C. The conditions are excellent for mango when the maximum temperature is 32-38°C and minimum temperature is 15-20°C.	Unpredictable rains and temperature fluctuations during winters may be the limiting factors in this zone. Frequent pre-monsoon rains reduce fruit quality and develop black patches on the fruits making them unattractive. Fluctuating temperature during flowering may cause poor fruit set and low pollinator activity.

Table 1. Continued...

Vegetation zone	Countries	Characteristics	Projections
Tropical shrubland	Australia, Botswana, Chad and Niger, Ethiopia, India (southern peninsula, Maharashtra, Gujarat, Rajasthan, Uttar Pradesh, Haryana, Punjab), Kenya, Madagascar, Namibia, Pakistan, Somalia, Sudan, and Tanzania	The climate is temperate and semi-arid to semi-humid. Summers are often warm to hot and the winters are cold to freezing. The maximum temperature can be from 34-42°C and minimum temperature has a range of 8-18°C. Suitability increases as minimum temperature increases. The annual rainfall is 200-800 mm.	Climate change impact may be more pronounced in these zones because of unpredictable rains, temperature fluctuations during pre-flowering and flowering periods and may result in low pollinator activity and poor fruit set
Tropical desert	Egypt, Oman, Sudan, and UAE	The most obvious climatic feature of this climate is possibility of evaporation and transpiration exceeding precipitation. The average maximum temperature can reach greater than 36-38°C and minimum temperature can get below 10°C. The annual rainfall is less than 500 mm with negligible rainfall in the dry winters. These conditions are not very suitable for mango production but become marginally suitable with irrigation facilities.	Increasing temperatures during fruit development, low rainfall and temperature fluctuations are likely to cause low production. Mango production in this zone is highly dependent on irrigation and limited irrigation water may become a constraint.

Table 1. Continued...

Vegetation zone	Countries	Characteristics	Projections
Sub-tropical humid vegetation	Brazil, China, Taiwan, Uruguay, and USA (Florida)	The climate is warm and moist with warm and humid summers and mild winters. Significant amounts of precipitation occur in all seasons in most areas. Winter rainfall is associated with large storms brought by westerlies. Most summer rainfall occurs with thunderstorms and occasional tropical storm, hurricane or cyclone. The maximum temperature is 28-35°C and minimum range is 8-10°C. The annual rainfall is 1000-2000 mm. These conditions are marginally suitable for mango.	Temperature fluctuations in these regions may cause low fruit set and frequent rainfall during fruit development may increase the incidence of postharvest diseases.
Tropical mountain system	Brazil, China (South), Columbia, Ethiopia, India (Manipur), Kenya, Madagascar, and Mexico	These are cooler-climate mountainous areas with a maximum temperature less than 25°C and minimum temperature below 10°C. Rainfall varies with the geographical region.	These regions are likely to experience higher incidence of disease and pest problems in high rainfall areas.

Opportunities for Adaptation

Mango ecotypes, wild relatives and climate change

Mango ecotypes are distinct geographic varieties, which are adapted to specific environmental conditions and thus climate changes are likely to influence their habitat and natural occurrence. Typically, ecotypes exhibit growth and flowering differences stemming from environmental heterogeneity. Although in the tropics mango grows easily everywhere, each and every variety is not fruitful at every place.

Mango cultivars can be classified into two ecotypes based on embryony since physiological responses of mango cultivars to the environment are related to the evolutionary centre of origin of the cultivars. Monoembryonic cultivars evolved in the dry subtropics of the Indian subcontinent with very hot summers and cooler winters produce a single zygotic seed (Ram and Rajan 2003). The polyembryonic types that evolved in the hot humid tropics of south east Asia, where the dry season is shorter than in the Indian subcontinent, are different in their climatic requirements than the monoembryonic ones (Mukherjee 1972). Natural hybridization between the two embryonic ecotypes has led to proliferation of cultivars of varying genetic composition. Therefore, differences in growth and flowering responses to temperature occur in the two embryonic ecotypes (Whiley et al. 1989).

The response differences between cultivars may be the contributing factor to their performance in the tropics where temperature is non-limiting for growth. Under these conditions Irwin mango has more reliable cropping than Kensington, suggesting that the genetically determined low-vigour trait is more sensitive to environmentally precipitated stresses that induce flowering.

In India, mango has adapted to diverse vegetation zones viz., tropical dry, tropical moist deciduous, tropical mountain, tropical rainforest and tropical shrubland. Mango varieties of these zones exhibit specific climatic requirements for adequate vegetative growth,

flowering and development of proper fruit quality. Therefore, the commercial varieties of a region behave differently when grown in other agroclimatic zones of the country. North Indian varieties like Chausa do not flower and fruit in Western Ghats. Alphonso, the most important commercial variety of Western Ghats, fails to perform under North Indian conditions. Certain varieties, however, have a much wider adaptability, e.g. Langra of North India and Banglora and Neelum of South India (Yadava and Rajan 1993).

In contrast to Indian varieties, Floridian varieties like Tommy Atkins have better adaptability and can be grown in a wide range of climatic conditions ranging from sub-tropical humid, tropical dry to tropical moist vegetation areas. Because of wider climatic adaptation, Floridian varieties have become common in new mango growing countries. However, in tropical rainforest vegetation conditions of Asia, their popularity among growers is less as compared to that in Australia, Africa and Latin American countries.

Mangifera species occur mainly in the biome types of tropical humid forests, sub-tropical rainforests/woodlands, and tropical dry forests/woodland of the Indo-Malayan biogeographic realm (Udvardy 1975; Mukherjee 1985). Biomes are defined as "the world's major communities, classified according to the predominant vegetation and characterized by adaptations of organisms to that particular environment" (Campbell 1996). Wild *Mangifera* species have a comparatively narrow range of adaptability as compared with the common mango *M. Indica* L. being grown in various vegetation zones viz., sub-tropical humid, tropical desert, tropical dry, tropical moist deciduous, tropical mountain system, tropical rainforest and tropical shrubland. However, the wild relatives have evolved in sub-tropical humid, tropical mountain system and tropical rainforest.

The genus *Mangifera* is restricted to tropical Asia and the highest concentration of *Mangifera* species is found in the western part of Malaysia (Malay Peninsula, Sumatra, Java, Borneo) (Kostermans and Bompard 1993). *M. gedebe* Miq. is a wetland species distributed from Myanmar to Malaysia and New Guinea. The other species may be divided into two groups, those adapted to the monsoon climate in Myanmar, India, Thailand, Indochina and lesser Sunda island of Indonesia and the larger part of the ever wet tropical rain forest stretching from India east ward to Micronesia

(Kostermans and Bompard 1993). Under the influence of human interference in tropical rain forest and changing climatic conditions, *Mangifera* species adapted to this habitat may disappear or become endangered. Because of specific habitat requirements of wild *Mangifera* species, projected climate changes are likely to affect their distribution in tropical Asia.

Off-season production and markets

Off-season production and extended period of mango availability is likely to be a feature under the projected climate changes. This may be due to an increase in mango cultivation in non traditional areas where the changing climate is responsible for replacement of stone and pome fruits that require sufficient chilling hours by mango. The Philippines and Thailand are commercially producing off-season mangoes on a larger area using specific varieties and chemical manipulation. However these production technologies could not be successfully replicated in other mango producing countries probably because of climatic variations. Temperature is one of the most important factors influencing the growth and off-season flowering phenology. Management of off-season flowering in mango trees is being accomplished in the tropics by successfully synchronizing shoot initiation through tip pruning and use of potassium nitrate sprays coupled with management of the stem age to induce flowering such that it can be accomplished during any desired week of the year. The requirements for mango flowering include mature, quiescent, terminal leaves and buds and simultaneous bud initiation and inductive environmental conditions. Inductive conditions may be exposure to cool non-freezing temperature for monoembryonic mangoes or exposure to drought or stress both of which induce a period of growth cessation. Under natural conditions, flowering of mango depends on climatic conditions and seasonal changes in the environment will trigger changes in endogenous hormonal levels, which influence flowering.

In south India, a shorter maturation period is recorded during the main season (March to August) than those grown in off season (September to February). This behaviour is because of less heat unit accumulation during the off-season fruit growth period. Even in the tropical areas where the temperature is relatively constant year round, mango fruit availability is season bound. During the harvest

season, fruits are available in abundance, but are scarce during off-season.

Using Geographical Information System tools for aiding adaptation

Climate change will also affect phenology and yields, leading to changes in the varieties that can be cultivated in different areas. Therefore, in order to adapt to the changing climate, farmers will need mango varieties with greater tolerance to stresses such as drought and heat, erratic rainfall pattern, and excess moisture and resistance to new races of pest and pathogens. The genetic diversity collected from various agro-climatic zones of the world, conserved *ex situ* and *in situ*/on farm can contribute genetic materials that will enable and assist fruit breeders, researchers and other users in improving yields in spite of climate change. Adapted germplasm may no longer be found in commercial orchards. Therefore interventions must involve long distance germplasm exchange and be facilitated by field genebanks. Systematic evaluation of genetic diversity held in genebanks and on farm and access to climatic information will enable stakeholders to identify genetic stocks, which will be adaptive to changing climatic conditions. Further, development of new scientific tools, techniques and methodologies will help to identify areas in which production of mango is likely to be impacted by climate change and will thus benefit fruit improvement programmes to mitigate the impact of possible climate change.

Matching crop varieties to climate is an important activity for profitable mango production in traditional and newer areas. The availability of detailed environmental data, together with inexpensive and powerful computers, has facilitated predicting process specific environmental requirements and natural geographic distributions of fruit crops. For some mango varieties, detailed occurrence data is available, allowing the use of various standard GIS (Geographical Information System) techniques for modelling their habitat requirements. The analysis based on environmental variables can result in selection of climatic characteristics that allow variety to adapt a wider diversity of habitats. Differences in the environmental characteristics of areas occupied by a variety can be examined by modelling distribution, a technique that integrates locality data,

GIS data and modelling algorithms (Anderson et al. 2002; Anderson and Martinez-Meyer 2004; Elith et al. 2006; Phillips et al. 2006; Rajan 2008).

For mango varieties, climate suitability models were developed using Genetic Algorithm for Rule Set Prediction (GARP), maximum entropy DOMAIN, and BIOCLIM can be used for determining/ mapping the potential areas (Rajan 2009). Predictions for the geographical area suitable for various commercial varieties were generated using two modelling approaches: a method based on the principle of maximum entropy (Maxent) and BIOCLIM based on environmental data layers. Niche modelling has revealed that climatic parameters specific to a mango variety can be worked out and analysis can indicate scope for searching analogous areas for cultivation of a specific mango variety in non-traditional areas.

A climate suitability map for Alphonso was generated using Maxent and BIOCLIM models. Most suitable areas for mango cultivation were located in similar regions by both the methods (Figures 1 and 2). Mapping indicated that in India, northern as well as northeastern parts of the country are not suitable for Alphonso cultivation representing two different ecological zones. Apart from Ratnagiri, an area near Jamnagar in Gujarat, has been mapped as a suitable area for Alphonso cultivation by both the methods. A comparison of Alphonso and Dussaheri based on bioclimatic variables clearly indicates that temperature seasonality is the most important variable for both the cultivars but minimum temperature of the coldest month plays an important role in the successful cultivation of Dussaheri. Between both the varieties, variables like precipitation of the warmest quarter, precipitation of the wettest quarter, precipitation of the driest quarter, precipitation of the coldest quarter, annual temperature range, and mean temperature of the driest quarter have not made much difference. However, differences are striking in the minimum temperature of the coldest month, precipitation of the driest month, mean monthly temperature range, and mean temperature of the warmest quarter.

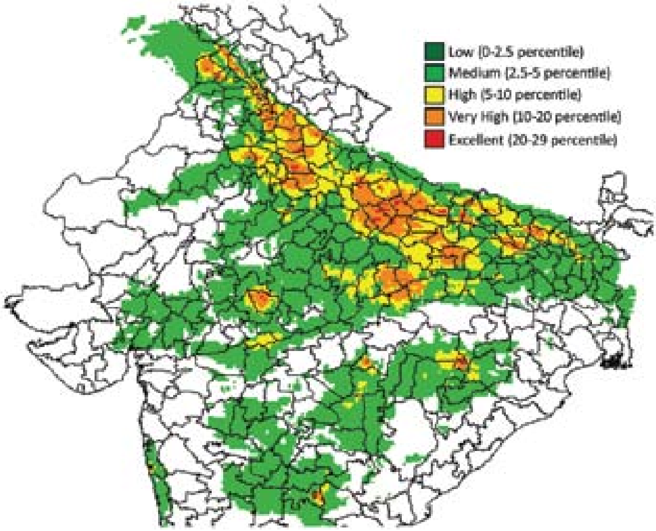

Figure 1. Climate suitability map for Dussaheri mango.

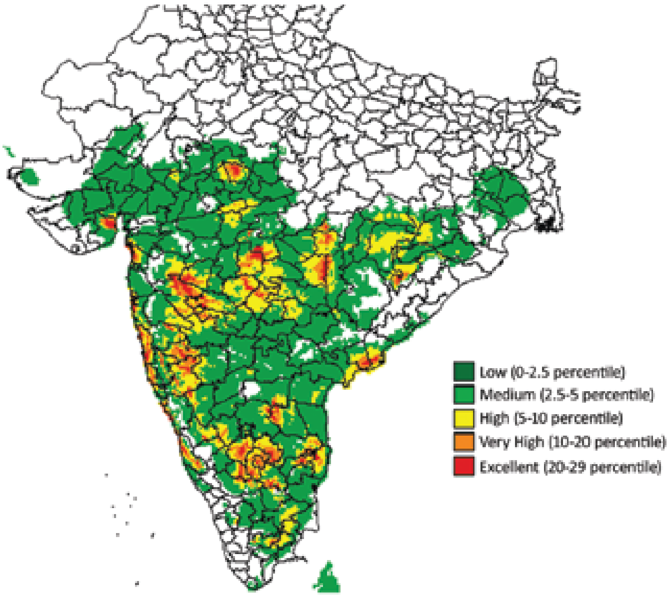

Figure 2. Climate suitability map for Alphonso mango.

Conclusion

In conclusion, projected climate change may have a profound impact on highly climate sensitive crops like mango. Under the influence of climate shifts impacting fruit-bud differentiation, early and delayed flowering are likely to be a characteristic feature of mango production. An early flowering under the sub-tropics may result in low fruit-set because of abnormalities arising from low night temperature. As a result, flowering trends of mango will considerably alter and directly influence panicle growth. Fruit set and availability of hermaphrodite flowers for pollination may be defined as a function of time taken for panicle growth. Evidence of warmer winters and earlier panicle development, paired with the freeze event are likely to pose several problems in mango production. Abrupt temperature rise during the flowering of mango will cause poor fruit set. Predicted changes in the climate of mango producing regions over the coming decades may alter significantly both the spectrum and the distribution of varieties currently being grown. In particular, shifts in precipitation patterns will affect most regions, with increased risk of drought, and given this scenario, the consequences would be dramatic for the mango producing areas.

Depending on geographical location, projected climate change will have beneficial and deleterious effects on mango cultivation. Suitable areas for mango cultivation may increase in regions were low temperature is a limiting factor for growing mango. Conversely, several well known traditional mango growing areas will experience risks of abnormal flowering, fruit set and reduced yield with a risk of untimely rains deteriorating fruit quality and giving rise to disease and pest build-up.

References

Anderson RP, Peterson AT, Gómez-Laverde M. 2002. Using niche-based GIS modeling to test geographic predictions of competitive exclusion and competitive release in South American pocket mice. Oikos 98: 3-16.

Anderson RP, Martínez-Meyer. 2004. Modeling species' geographic distributions for conservation assessments: an implementation with the spiny pocket mice (Heteromys) of Ecuador. Biological Conservation 116:167-179.

Campbell NA. 1996. Biology (4th ed.). The Benjamin/Cummings Publishing Company Inc., Menlo Park, California.

Carmichael WW. 1958. Observations of cold damage to mangos in Dade county and the Lower West Coast. Proceedings of the Florida State Horticultural Society. 71: 333-335.

Cook AA. 1975. Diseases of Tropical and Sub-tropical Fruits and Nuts. Hafner Press New York.

Elith J, Graham CH, Anderson RP, Dudik M, Ferrier S, Guisan A. 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography 29:129-51.

Hopkins AD. 1938. Bioclimatics: A Science of Life and Climate Relations. U.S. Govt. Printing Office, Washington, DC, USA.

Issarakraisila M, Considine JA, Turner DW. 1991. Pattern of vegetative and reproductive growth of mango trees in warm temperature region of Western Australia. Acta Horticulturae 291: 188-197.

Issarakraisila M, Considine JA. 1994. Effects of temperature on pollen viability in mango cv. 'Kensington' annals of botany 73: 231-240.

Kostermans AJGH, Bompard JM. 1993. The Mangoes, their Botany, Nomenclature, Horticulture and Utilization. International Board for Plant Genetic Resources and the Linnean Society of London.

Lim TK, Khoo KC. 1985. Diseases and Disorders of Mango in Malaysia. Tropical Press, Kuala Lumpur.

Litz RE. 2009. The Mango (2nd ed.). Botany, Production and Uses. CABI International, UK.

Lonergan S. 1998. Climate warming and India. In: Dinar A, Mendelsontin R, Evenson R, editors. Measuring the Impacts of Climate Change on Indian Agriculture. World Bank Technical Report No. 402. Washington DC, USA.

Morison IL, Morecroft M. 2006. Pant Growth and Climate Change. Blackwell Publishing Ltd, UK.

Mukherjee SK. 1972. Origin of the mango (*Mangifera indica* L.). Economic Botany 26: 260-266.

Mukherjee SK. 1985. Systematic and ecogeographic studies on crop genepool: I. *(Mangifera L.*). International Board for Plant Genetic Resources, Rome, Italy, pp. 86.

Núñez-Eliséa R, Davenport TL. 1995. Effect of leaf age, duration of cool temperature treatment, and photoperiod on bud dormancy release and floral initiation in mango. Scientia Horticulturae 62:63-73.

Oppenheimer C. 1947. The Acclimatization of New Tropical and Sub-tropical Fruits in Palestine. Bulletin No. 44. Jewish Agency for Palestine. Agricultural Research Station, Rehovot.

Ou SK. 1980. Temperature effect on flowering and fruiting in the 'Irwin' mango (*Mangifera indica* L.). Journal of Agricultural Research in China 29. pp. 301-308.

Ou SK. 1982. Temperature effect on differential shoot development of mango during flowering period. Journal of Agricultural Research in China 31. pp. 209-212.

Phillips SJ, Anderson RP, Schapire RE. 2006. Maximum entropy modeling of species geographic distributions. Ecological Modeling 190: 231-259.

Ploetz R, Ploetz R. 2003. Diseases of Tropical Fruit Crops. CABI Publishing. pp. 327-363.

Pongsomboon W, Stephenson RA, Whiley AW, Subhadrabandu S. 1991. Development of water stress in juvenile mango (*Mangifera indica* L.) trees. Acta Horticulturae 321: 496-503.

Rajan S. 2008. Geographical information system (GIS): role in characterization of climatic requirements for fruit crops. In: Chadha KL, Singh AK, Patel VB, editors. Recent Initiatives in Horticulture. The Horticultural Society of India, New Delhi. pp. 669-677.

Rajan S. 2009. Impact assessment of climate change in mango and guava research. In: Govindakrshnan PM, Singh JP, Lal SS, Dua VK, Shashi Rawat, Pandey SK, editors. Information Technology Applications in Horticultural Crops. Central Potato Research Institute, Shimla, India. pp. 36-42.

Ram S, Rajan S. 2003. Status report on genetic resoruces of mango in Asia-Pacific Region. International Plant Genetic Resource Institute, New Delhi. pp. 196.

Sauco VG. 2000. The mango in Latin America. Acta Horticulturae 509: 123-131

Shu ZH and Sheen TF. 1987. Floral induction in axillary buds of mango *(Mangifera indica* L.) as affected by temperature. Scientia Horticulturae 31: 81-87.

Singh LB. 1960. The Mango: Botany, Cultivation and Utilization. Leonard Hill, London.

Singh RN, Majumdar PK, Sharma DK. 1965. Studies on the bearing behaviour of some south Indian varieties of mango (*Mangifera indica* L.) under north Indian conditions. Tropical Agriculture 42: 171-174.

Singh RN, Majumdar PK, Sharma DK. 1966. Sex-expression in mango (*Mangifera indica* L.) with reference to prevailing temperature. Proceedings of the American Society for Horticultural Science 89. pp. 228-229.

Subedi A, Bajracharya J, Joshi BK, Gupta SR, Regmi HN, Sthapit BR. 2008. Locating and managing the mango (*Mangifera indica* L.) genetic resources in Nepal. PGR Newsletter 155:52-61.

Udvardy MDF. 1975. A classification of the biogeographical provinces of the world. IUCN Occasional Papers No. 18. International Union for Conservation of Nature and Natural Resources, Morges, Switzerland. pp. 28-30.

Whiley AW, Schaffer B. 1997. Stress physiology. In: Litz RE, editor. The Mango: Botany, Production and Uses. CAB International, 198 Madison Avenue, New York. pp. 147-174.

Whiley AW, Saranah JB, Rasmussen TS, Winston EC, Wolstenholme BN. 1988. Effect of temperature on 10 mango cultivars with relevance to production in Australia. Proceedings 4th Australasian Conference on Tree and Nut Crops. ACOTANC, Lismore. pp. 176-185.

Whiley AW, Rasmussen TS, Saranah JB, Wolstenholme BN. 1989. Effect of temperature on growth, dry matter production and starch accumulation in ten mango (*Mangifera indica* L.) cultivars. Journal of Horticultural Science and Biotechnology 64: 753-765.

Whiley AW, Rasmussen TS, Wolstenholme BN, Saranah JB, Cull BW. 1991. Interpretation of growth responses of some mango cultivars grown under controlled temperature. Acta Horticulturae 291: 22-31.

Yadav IS, Rajan S. 1993. Genetic resources of mangifera. In: Chadha KL, Pareek OP, editors. Advances in Horticulture Vol. 1 Part 1. Malhotra Publishing House, New Delhi. pp 77-93.

Yusof IM, Buchanan D W and Gerber JF. 1969. The response of avocado and mango to soil temperature. Journal of the American Society for Horticultural Science 94: 619-612.

Tropical Fruit Tree Genetic Resources: Status and Effect of Climate Change

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Introduction

In spite of what has been written in most recent literature, the implications of climate change for plants in general and agriculture in particular are still a bit vague and mostly based on modelling and estimations. However, even the little that we know indicates that there will be a major reduction in food supply (Rosenzweig and Parry 1994; Hijmans 2003; Hijmans and Graham 2006; Jones and Thornton 2003). This is the main reason for a discussion on the future role of agricultural biodiversity under changing conditions brought about by climate change and its impact on various agricultural and horticultural crops. For example, climate related changes have brought widespread changes in flowering and fruiting patterns of mango that adversely affect fruit production in some areas. Meanwhile some areas that previously could not profitably grow mangoes due to low temperatures are now turning out to be areas suitable for mango production (see Rajan et al. in this volume). Further, the impact of climate change on plant biology *per se* and conservation and use of agricultural biodiversity is still vague and anything we can say on this subject can only be a most probable scenario currently predicted (see Mathur et al. in this volume). However, we believe that we can be guided by this probable scenario for preparatory actions.

There is evidence that climate change is already affecting biodiversity and that it will continue to do so. The Millennium Ecosystem Assessment ranks climate change among the main direct drivers affecting ecosystems. The impacts of climate change can manifest in plant biodiversity in many ways (Box 1).

Box 1. Consequences of climate change on the species component of plant biodiversity include:

- Changes in distribution of genetic diversity
- Changes in reproduction timings
- Changes in length of growing seasons for plants
- Changes in phenology
- Changes in plant community composition
- Changes in pest and pathogen composition and distribution
- Changes in ecosystems
- Increased extinction rates
- Changes in rainfall pattern and distribution
- Changes in temperature regimes
- Changes in available water for plant growth

These changes may require significant adaptations and modifications to agricultural practices and genetic resource management practices that we use now. Klien (2003) provides five generic adaptation responses that can be planned.

One response is to increase the ability of physical infrastructure to withstand climate change impacts. For example, building higher sea walls can be a defence against the rise in sea level. The second response is to increase the flexibility of potentially vulnerable human managed systems. For example, the capacity of a water reservoir might be increased to deal with fluctuations in rainfall. The third response is to enhance the adaptability of vulnerable natural systems. This could involve reducing stresses due to non-climatic effects, or removing barriers to the migration of plants or animals (for example, by enabling mangrove ecosystems to migrate towards land in order to adapt to rising sea levels). The fourth response is to reverse the trends that increase vulnerability. This includes reducing human activities in vulnerable areas such as floodplains and coastal zones. The fifth response is to improve public awareness and preparedness. This can include informing the public about the risks and possible consequences of climate change, as well as setting up early-warning systems for extreme weather events.

Although the available evidence is still being debated, many agree that there will be drastic changes in available water supply in different regions of the globe. This will have a major effect on current agricultural systems as well as on total productivity. Currently available information indicates that sub-tropical regions recently received less precipitation and were subjected to more frequent droughts and the northern hemisphere received higher rainfall than they had in the recent past. Nevertheless, research to date suggests that this trend is less predictable and the degree of variation will be more pronounced (IPCC 2001; 2002). All of these will have serious consequences on how we do agriculture, maintain agricultural biodiversity and develop crop improvement. However, we will focus here on its impact on *in situ* conservation of tropical fruit biodiversity.

Given the scarce data on the actual impact of climate change on specific areas and specific plant species/crops, it is difficult to firmly say how one can modify conservation protocols and actions. Nevertheless, it is possible to visualize its major effects and be prepared to make modifications to conservation methods and management practices so that we are not caught off guard. Here we focus on what can be done for better management of conservation practices of tropical fruits genetic resources in the event of drastic impact of climate change on the environment in which they can be grown and on their biology.

Ex situ conservation

The two basic approaches to conservation of plant genetic resources (PGR) are termed *ex situ* and *in situ*. *Ex situ* approach involves conserving the genetic resources outside their original habitat in the form of seed, embryos, tissues or plants. Methods of *ex situ* conservation can include cold storage of seeds, *in vitro* storage or field genebanks, depending on the propagules used. In contrast, *in situ* conservation involves the maintenance of genetic diversity of a species or genepool in the habitat in which the diversity evolved. As defined in the Convention on Biological Diversity, it includes the maintenance of diversity in farmers' fields and orchards. Generally, the term on-farm conservation is applied to *in situ* conservation of cultivated species, landraces and wild species (including crop wild relatives).

It is now well recognised that for any given genepool, a number of different approaches and methods will be necessary for efficient and cost-effective conservation. Such a strategy is termed as a complementary conservation strategy.

Conservation of tropical fruit tree genetic resources in field genebanks

With current level of developments in conservation options for tropical fruit tree genetic resources, field genebanks play major roles in their conservation and use. They are presently the most feasible *ex situ* conservation method used for tropical fruit tree genetic resources.

Many important varieties of field, horticultural and forestry species are either difficult or impossible to conserve as seeds (either no seeds are formed or if formed, the seeds are recalcitrant) or reproduce vegetatively. Tropical fruit species belong to this group of plants and hence they are conserved in field genebanks (FGBs).

FGBs provide easy and ready access to conserved material for research as well as for use. For a number of plant species, including many tropical fruit tree species, alternative methods of conservation have not been fully developed. It is one of the options of a complementary strategy for the conservation of germplasm of many plant species. At the same time, efforts to develop and refine other methods such as *in vitro* conservation and cryopreservation for some fruit species are continuing.

Even if technology for conserving recalcitrant seeds is developed, there is still a problem with long regeneration cycle that will pose problems for utilization. FGBs may also run a greater risk of being damaged by natural calamities, infection, neglect or abuse. Thus, *ex situ* conservation of tree species using FGB requires a substantial number of individual genotypes to be an effective conservation measure. Hence, FGB requires more space, especially for large plants such as mango. They may also be relatively expensive to maintain, depending upon the location and the complexity of alternative techniques available. However, FGBs provide easy and ready access to conserved material for research as well as for use. The advantages and drawbacks of FGBs are well debated (Engelmann and Engels

2002; Ramanatha Rao 2005) and hence we will not go into it here. It is clear that establishment of FGBs will play a major role in any conservation strategy for PGR, especially where tropical fruit genetic resources are concerned.

There are many field collections of tropical fruit tree genetic resources in various countries that are usually connected with fruit research institutes. For example, 52 field genebanks were established for different crops, including 21 for mango, 13 for citrus, 8 for rambutan, 4 for jackfruit, 4 for lychee and 2 for mangosteen, in 10 Asian countries between 1999-2002 (Ramanatha Rao et al. 2005).

Tropical fruit trees may respond to climate change through phenotypic plasticity, adaptive evolution, migration to suitable sites or extinction (Bawa and Dayanandan 2010). However, the potential to respond is limited by a rapid pace of change and the non-availability of alternate habitats due to past and present trends of deforestation. Thus climate change may result in extinction of many populations and species. Human ability to estimate the precise response of tropical fruits and forest ecosystems to climate change is limited by lack of long-term data on parameters that might be affected by climate change. However, farmers have used homegardens as a refuge for some domesticated fruits from wild and continue to select through sapling or scion selection.

FGBs are a common methodology of conservation and management of tropical fruit trees with recalcitrant seeds (see Box 2 for the major steps for successfully establishing and managing FGBs). This is an immediate option to consider for the conservation and utilization of tropical fruit genetic resources. However, insufficient population size of reproductive trees in research stations, new emerging diseases and pests and a lack of associated biodiversity in natural ecosystems are a few biological constraints of field genebank management.

Climate proofing genebank maintenance and management

We are now fairly sure that the main impacts of climate change are going to be in terms of changes in distribution of plant materials, rate of extinction of some species, change in reproduction timings, and length of growing seasons, plant community composition and ecosystems. These impacts have implications on the management and maintenance of FGBs.

Box 2. Series of steps for establishing and managing a FGB (Rao 1998).

- Agreement on precise functions of the collection
- Selection of site, based on the criteria established
- Agreement on obligations and responsibilities of host countries; countries participating in the Network (i.e. COGENT) and international institutions, including funding
- Establishment of infrastructure and facilities
- Legal aspects and exchange protocols (ownership, conditions of release, intellectual property rights issues, benefit sharing, use of material transfer agreements and other mechanisms) as agreed by all partners
- Establishment of a tropical fruit tree FGB
    - Assure comprehensiveness of collection by including as much genetic diversity as appropriate from the sub-region
    - Consider carefully the sampling techniques (random vs. non-random, and the need for deviation)
    - Assure that there is no duplication of accessions as this directly increases cost of FGB
    - Determine the need for having replications, the number, etc., based on the objectives of FGB
    - Determine through discussions and by actual visitations the\ accessions and the number of accessions to be included in FGB, and number of plants per plot.
    - Establish nursery of vigorous and healthy seedlings raised from nuts produced through hand pollination, determine planting conditions etc., depending on the location of FGB
    - Lay out square blocks of equal size
    - Plan space for present and future accessions (as much as possible) to be randomized in the FGB
    - Follow all protocols for safe movement of germplasm
    - Ensure that embryo culture/tissue culture facilities can be put in place for exchange of material
    - Accept more material into FGB as they become available by going through all the steps discussed

Box 2. Continued...

- Maintenance of a tropical fruit tree FGB
  - Take all the necessary agronomic and plant protection measures to maintain a healthy stand of tropical fruit trees
  - Take all the measures feasible to protect FGB from adverse environmental conditions, physical stresses, etc.
  - Make sure that a safety duplication is established and all the needs of health care are fulfilled
  - Document all accessions as well as activities carried out in FGB by establishing and running an appropriate information management system
  - Provide linkages to other methods of conservation, if any, such as *in vitro* conservation of zygotic embryos, pollen preservation, etc.
- Ensuring access to material in FGB
  - Ensure physical availability of the material
  - Keep the plants in healthy condition
  - Facilitate propagule (seedlings, scions, grafted plants, etc.) production through hand pollination for distributing germplasm as agreed at the time of establishment of the genebank
  - Characterise/evaluate the material in FGB according to agreed principles.
  - Provide for production of propagules through hand pollination, rather than harvesting from the centre of plot to be certain of purity of the material
  - Make available the information on the material conserved in the FGB to all users

Selection of site for a field genebank

It will be important to select the site for a field genebank that will be affected minimally by climate change for its long term viability. Although it is not currently possible to establish such sites in a very precise manner, some level of site stability in a region that is known to be less affected by climate change will be useful.

Maintenance

The effect of climate change on *ex situ* conservation mainly depends on the location of the genebank and the conditions of rejuvenation and regeneration of PGR stocks. Rapid changes in the climate can prevent conservation activity by making it difficult to raise crops and provide appropriate conditions for regeneration. Sending germplasm to regions of its origin for seed multiplication may no longer be feasible if the climate in the area of origin or collection has changed. Alternative procedures will have to be devised. In addition, this may not be an option for tree crops due to their perennial nature.

Infrastructure and facilities needed

Climate change is expected to have an impact on pest and pathogen attacks, water availability, temperature, etc. This will require field genebanks to be prepared to deal with different pests and pathogens (identification and control). Facilities for irrigation and for raising nurseries under controlled temperature conditions will be required.

Assembling a comprehensive collection

It is expected that climate change will impact species distribution and plant composition in a community. Comprehensive collection will require identification of geographical regions where untapped TFT diversity is located for the purpose of being collected and maintained in a field genebank using geographic information tools. However, changes in plant composition, increases in extinction rates, etc. may take a long time to materialize and hence they may not have an immediate impact on field genebank management.

It is well recognized that there is continuous erosion of agricultural genetic resources even in the absence of climate change. Climate change appears to further exacerbate genetic erosion (IPCC 2002) by changing both agroecosystems (important consideration in the case of landraces) and wild landscapes (important in the case of crop wild relatives and useful plants in the wild). Thus exploration, mapping and predictive modelling become important to identify which species are the most at risk and what mechanisms (*ex situ* or *in situ*) of conservation could be put in place (Jarvis et al. 2008). Thus exploration and collecting have important roles to play in *in situ* conservation.

Characterization and evaluation

The impacts on pest and disease regimes are largely unknown and could offset any benefits arising from climate change. For instance, the Eastern spruce budworm is a serious pest defoliating North American forests. Changing climate is shifting the geographic range of the warblers that feed on the budworms, increasing the odds for budworm outbreak (IPCC 2001). Utilization of available agricultural biodiversity entirely depends on the level of characterization and evaluation of conserved material. Historically, looking for desired traits, genes or gene sequences either in the same species or any other species has been done only when the problem (such as a pest or disease) becomes serious either in specific locations or in many locations. This paradigm of looking for cures may still work in some cases (for example, drought, flooding, etc.). However, our thinking in this area needs to change dramatically.

As noted earlier, the changes that can occur due to climate change are not entirely predictable. Hence there is a need to anticipate the problem based on available information and plan for it. For example, it can be predicted under given conditions some very minor pest can become a major one in the near future (for example, there is now evidence that the leaf eating insects will become a major threat with increases in temperature). Enhanced evaluation of available genetic resources to identify promising accessions for such pests is an option for mitigating damage by such changes in intensity of specific pests.

Research on the effects of climate change on plant disease continues to be limited, but some striking progress has been made. At the genomic level, advances in technologies for the high-throughput analysis of gene expression have made it possible to begin discriminating responses to different biotic and abiotic stresses and potential trade-offs in responses. At the scale of the individual plant, enough experiments have been performed to begin synthesizing the effects of climate variables on infection rates. However, pathosystem-specific characteristics makes synthesis challenging. Models of plant disease have now been developed to incorporate more sophisticated climate predictions. At the population level, the adaptive potential of plant and pathogen populations may prove to be one of the most important predictors of the magnitude of climate change effects. Ecosystem ecologists are now addressing the role of plant disease in

ecosystem processes and the challenge of scaling up from individual infection probabilities to epidemics and broader impacts (Garret et al. 2006).

Thus, scientists will have to be prepared with the necessary resources to counter the problem as soon as it arises. Although, looking for resistances/tolerances for biotic and abiotic stresses that are not currently predominant may seem to be a waste of time and effort, we believe this strategy will pay for itself in the end. It pays to be prepared.

Safety duplication

Proper site selection is important for safety duplication as well. In addition, it will be useful to speed up research on alternate conservation technologies like *in vitro* and cryopreservation for many TFT species that can assist in establishing proper safety duplication of material held in FGB.

Agronomic and plant protection measures

There is a need to keep in focus agronomic practices such as irrigation, flooding control, etc. and standardize such practices for use in case of changed climatic conditions. Similarly, pest identification, control – both chemical and biological methods - of currently less serious pests should be available for ready use in case of changed conditions of their infestation and infection. Facilities for speedy research on any new pests should be thought of. This is important for ensuring access to material in FGBs by keeping the plants in healthy condition.

In situ/on-farm conservation

It is now well recognized that the *in situ*/on-farm conservation of agrobiodiversity helps not only to conserve the genetic diversity in target crop species, but also the evolutionary processes and the ecosystems that host the genetic diversity. Although it has been alluded to, it may be appropriate to define *in situ* and on-farm conservation. *In situ* conservation means the conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings. *In*

situ conservation also means the conservation of domesticated and cultivated species in the surroundings where they have developed their distinctive properties (CBD Article 2). It is the sustainable management of genetic diversity of locally developed crop varieties (landraces), along with its associated wild and weedy species or forms by farmers within traditional agricultural, horticultural or agri-silvicultural systems (Maxted et al. 1997). As the habitat for domesticated and cultivated species is on farm, *in situ* conservation of agricultural biodiversity is also on-farm conservation. It refers to the maintenance of traditional crop varieties (landraces) or cropping systems by farmers within the natural habitats where they occur – in farmers' fields and uncultivated plant communities (Altieri and Merrick 1987; Brush 1991).

Despite implementation of various *ex situ* and *in situ* conservation of agrobiodiversity projects, the efforts to improve farmers' access to germplasm and associated information within communities have been limited. Interventions such as seed/biodiversity fairs could improve access to information and germplasm within and between communities (Grum et al. 2003; Adhikari et al. 2005). Community seed banks can improve the access to traditional crop varieties by communities (Adhikari et al. 2005). Small but significant effects of efforts such as distribution of small quantities of germplasm seed (diversity kits) can lead the concept of informal research and development and could be effective in both remote and accessible areas in terms of adoption of varieties (Joshi et al. 1997). Lessons learned from various informal research activities is that there must be hundreds of unique and useful local crop diversity that could be assessed, multiplied and distributed to farmers and communities and provide direct benefits. Such efforts with community seed banks to characterise germplasm, multiply healthy seed, sell these seeds to support community seed banks, participatory variety selection, and plant breeding could be practical community adaptation strategies (Shrestha et al. 2006). However, these methodologies have been evolving over time. This is the kind of basic plant breeding that farmers were doing in the past and could be done by grassroots institutions today. All these efforts can improve the access to materials by farmers as well as improve the germplasm on-farm and climate change can be factored into the equation.

In situ conservation of wild relatives of TFT species depends mainly on their geographic distribution and how this may change over time due to changes in climate; mainly rainfall (pattern and total precipitation) and temperature (range). For example, mango and its relatives presently occur in various vegetation zones viz., sub-tropical humid, tropical desert, tropical dry, tropical moist deciduous, tropical mountain system, tropical rainforest and tropical shrubland. Climate changes occurring in different vegetation zones have different impacts on the mango distribution and on its reproductive success. These changes may convert some of these areas from suitable to unsuitable and vice-versa. This should be understood while proposing sites for conservation of wild relatives of mango and other TFT species (for details see Rajan in this volume).

Since the adaptation of fruit species (as well as others) mostly depends on the centre of their origin, changes in climate in those places can threaten future survival and distribution. This is especially true for the wild relatives. The cultivated ones may have developed different patterns of adaptation as well as wide adaptability due to genetic mixing through hybridization and continuous cultivation. For example, Mangifera species occur mainly in the biome types of tropical humid forests, sub-tropical rainforests/woodlands, and tropical dry forests/woodlands of the Indo-Malayan biogeographic realm (Udvardy 1975; Mukherjee 1985). Wild Mangifera species are much narrower in their adaptation than the common mango, M. Indica, and are grown in various vegetation zones viz., sub-tropical humid, tropical desert, tropical dry, tropical moist deciduous, tropical mountain system, tropical rainforest and tropical shrubland. The wild relatives have evolved in sub-tropical humid, tropical mountain system and tropical rainforest. The genus Mangifera is restricted to tropical Asia and its highest concentration is found in the western part of Malaysia (Malay Peninsula, Sumatra, Java, Borneo) (Kostermans and Bompard 1993). M. gedebe is a wetland species and is thus distributed from Myanmar to Malaysia and New Guinea. The other species may be divided into two groups, those adapted to monsoon climate in Myanmar, India, Thailand, Indo-China and the lesser Sunda Island of Indonesia and the other adapted to larger part of the ever wet tropical rain forest stretching from India east wards to Micronesia (Kostermans and Bompard 1993). (also see Rajan in this volume). So while predicting the impact

of climate change on TFT species, one should understand precisely what could be the changes in the centres of origin of particular TFT species/genus. For doing so we need to understand the change in climate in these areas and see if there are obvious changes in mango phenology and other adaptive traits.

On-farm conservation can also play a role in other aspects of the ecosystem, such as ecosystem health, services and functions (see Box 3), and in socioeconomics of the communities that are involved in such conservation efforts.

Box 3. Some areas in which on-farm conservation may play a role (Ramanatha Rao et al. 2000):

- Conservation of the processes of evolution and adaptation
- Conservation of diversity at all levels (ecosystems, species, intra-specific)
- Integrating farmers/communities into national plant genetic resources conservation systems
- Contribution to ecosystem services and ecosystem health
- Maintaining the process of local crop development by strengthening capacity of farming communities in landrace assessment, selection and exchange of crop germplasm
- Improving the livelihoods and quality of life of farmers
- Empowering farmers and communities over their crop genetic resources and improving access to them
- Providing information for national seed policy decisions regarding the importance of traditional seed supply system
- A component of complementary conservation strategy-linking farmers to genebank

Once understanding between institutions, collaborators and farming communities has been reached and most of the researchers and other partners understand the nuances of participatory approaches to conservation, the actual on-farm conservation work could start. This would include preparation, site selection, sampling and developing, and putting in place the mechanisms for on-farm management of agrobiodiversity. Ahead of site selection, the existing data such as descriptor lists, databases of e*x situ* germplasm collections, herbarium collections, published literature in the natural and social

sciences and other unpublished information should be collected and used for eliminating inappropriate sites. Personal knowledge of experts, including personnel from NGOs, CBOs, and others existing local institutions would be most valuable. Simultaneously, the criteria for site and farmer selection have to be well defined. Broadly speaking, the criteria would be based on the genetic diversity, accessibility and interest of the farmers to continue to grow the varieties that are being targeted and these will have to be evaluated through a survey. Some generalized criteria that could be used for developing an on-farm conservation programme could include (Ramanatha Rao et al. 2000):

- **Ecosystems:** It will be important to select sites in diverse agroecosystems preferably with different ecotypes. This will increase the chances of conserving genetic diversity, as this may be associated with agroecosystem diversity.

- **Intra-specific diversity within target species:** It is important that the areas selected are grown to different landraces.

- **Specific adaptations:** Efforts should be made while selecting different agroecosystems (see 1 above) to select sites with extreme environmental conditions (high soil salinity, cold temperatures, etc.) and variation in pests. This will help to include types with specific adaptations.

- **Genetic erosion:** For obvious reasons, it is better to select sites with less threat of genetic erosion to increase the life of conservation efforts.

- **Diverse use values:** It is possible to ensure conservation of hidden genetic diversity by selecting sites with diverse use values of crops for food and other uses. It is important to note that for many farming communities, a crop is not just a matter of food production but also an investment and is important in maintaining social relations and religious rituals.

- **Farmers and communities:** Farmers' interest and willingness to participate are keys in site selection. This may require preliminary work in community sensitization on the benefits to farmers of conserving crop varieties. Site selection should

also include sites with: socio-cultural and economic diversity, diversity of livelihoods, importance of target crops for various ways of life, farmers' knowledge and skills in seed selection and exchange, and market opportunities.

- **Partners:** Partners with interest in community and cooperation, as well as experience in conservation interventions will be beneficial to the programme. Partners with distinct community participation expertise will have a comparative advantage in dealing with communities.

- **Logistics:** These would include mainly the accessibility of the site throughout the year (essential to *in situ* conservation monitoring) and availability of resources.

The existing data should be combined with an exploratory survey, using a Participatory Rural Appraisal (PRA), or a similar approach such as four cell analysis specifically designed to understand the amount and distribution of genetic diversity (Sthapit et al. 2006). Communities need to be sensitised to issues on hand and for this use, participatory approach is recommended (Ramanatha Rao et al. 2000; Brush 2000).

Thus, essential elements of an *in situ* conservation programme for any crop genetic resource, including its wild relatives, would be (Ramanatha Rao 2009):

- Identification of sites with typical ecotypes/landraces of the country concerned based on traditional knowledge and historical information and any available information on genetic diversity;

- Identification of crop wild relatives in natural habitats, forested areas, protected areas, etc. and mapping the located areas;

- Identification of organizations that are stakeholders in such an effort, including community based organizations and users' groups of the natural forest;

- Identification of threats to continued maintenance of farms and forested areas with unique and diverse crop cultivars and wild relatives;

- Identification of means to remove threats in the short term (to gain time to put in place longer term efforts);
- Ensuring continued management of such farms and forested areas by enhancing benefits to farmers or user groups (in case of those depending on wild species/relatives);
- Identification of means to remove the threats in the long term (e.g. study to understand the basis for *in situ* conservation of crops and wild relatives, adding value, market incentives, improving the current cultivar for specific traits, ecotourism, sustainable harvesting, etc.);
- Identification of sustainable ways to monitor genetic erosion of crop genetic diversity using the help of local institutions or organizing participatory approaches such as diversity fairs, community biodiversity register (CBR), community seed bank.

Followed by

- Creating (or using existing) institutional framework and management;
- Site selection (Training in participatory approaches may be needed);
- Sensitizing and strengthening local community and institutions;
- Locating diversity (e.g. *in situ* evaluation, questionnaire, crop diversity fair);
- Measuring and assessing diversity (establish diversity rich sites and baseline);
- Understanding the value of genetic diversity;
- Understanding and validating the processes that maintain diversity;
- Monitoring diversity (e.g. community biodiversity register);
- Developing strategies for on-farm conservation;

- Linking problems with new opportunities (capacity of local farming community enhanced using CBR and diversity fair, adding value, etc.);
- Institutionalizing on-farm strategies for integrating farmers into national PGR system.

Effect of climate change on in situ/on-farm conservation

Earlier we have seen that *in situ* conservation of agricultural biodiversity is defined as the management of a diverse set of crop populations by the farmers in the ecosystem where the crop evolved. It allows for the maintenance of the processes of evolution and adaptation of crops to their environment. We also use this term for managing useful plants and crop relatives in the wild.

Various climate change predictions make it clear that many regions around the globe are going to change in various ways. Thus, a good question to ask is how these various changes will affect different *in situ* conservation efforts of landraces and wild species. Although ecosystems have adapted to changing conditions in the past, current changes are occurring at rates not seen historically. In general, the faster the climate changes, the greater the impact on people and ecosystems.

Reductions in greenhouse gas emissions can lessen these pressures, giving these systems more time to adapt (CBD 2007). In addition to mitigation, however, there is an urgent need to develop and implement climate change adaptation plans. There is a significant research gap in understanding the genetic capacity to adapt to climate change. Examination of available literature indicates that while a broad range of studies examine the generic impacts of climate change on crop productivity, few studies examine varietal level changes in adaptation (Jarvis et al. 2008). There is an indication that traditional food crops, such as aroids and fruit trees, are an important source of community resilience in Asia—including resilience to climate change and economic turbulence. Unlike traditional crops, the majority of commercial crops that have been introduced to the region "are not adapted to local conditions and require high agrochemical inputs such as fertilizers, mechanization, and water supply," according to the study. These crops tend to be more

vulnerable to climatic changes, such as drought and subsequent flooding (Kindt and Lengkeek 1999).

Changes in range and size of species distribution

Climate is one of the major factors governing the distribution of wild plant species and cultivation of crops. It impacts physiological and reproductive processes and influences ecological factors such as competition for resources (Shao and Halpin 1995). There have been many cases where climatic change over the past century has had significant impacts on the distribution, abundance, phenology and physiology of a wide range of species. It is now possible to apply species distribution models, predict range shifts and assess extinction risks due to climate change (Walther et al. 2002; Parmesan and Yohe 2003; Root et al. 2003; Parmesan 2006; Thomas et al. 2004; IPCC 2007; Araújo and Rahbek 2006; Hijmans and Graham 2006; Howden et al. 2007; Lawler et al. 2006; Lobell et al. 2011). Here an attempt is made to review some of the basic information available on the expected impact of climate change on *in situ* conservation.

Jarvis et al. (2008) used current and projected future climate data for ~2055, and a climate envelope species distribution model to predict the impact of climate change on the wild relatives of groundnut (*Arachis*), potato (*Solanum*) and cowpea (*Vigna*). They report that wild groundnut were the most affected group with 24 to 31 (depending on the migration scenario) of 51 species projected to go extinct and their distribution area on average reduced by 85 to 94% over the next 50 years. In terms of species extinction, *Vigna* was the least affected of the three groups studied.

Their results suggest that there is an urgent need to identify and effectively conserve wild relatives that are at risk from climate change. While increased habitat conservation will be important to conserve most species, those that are predicted to undergo strong range size reductions should be a priority for collecting and inclusion in genebanks (Jarvis et al. 2008).

It will be challenging to carry out such studies for tropical fruit trees. An additional factor that may have to be used for such studies is to take into consideration the capacity to adapt to changed conditions. Can the species that are shown to be at risk adapt fast

enough to changing climatic conditions or have they really run out of time? Diversity conserved in the *in situ* areas will be interesting to monitor as rich biodiversity can better buffer against unpredictable temperature and precipitation change than areas with increased uniform farming system (Ramanatha Rao 2009).

Changes in phenology

Changes in plant phenology will be one of the earliest responses to rapid global climate change and could potentially have serious consequences for both plants and animals that depend on periodically available plant resources. Phenological patterns are most diverse and least understood in the tropics. In those parts of tropical Asia where low temperature or drought impose a seasonal rest period, regular annual cycles of growth and reproduction predominate at the individual, population, and community level. There is no evidence for photoperiod control of phenology in the Asian tropics, and seasonal changes in temperature are a likely factor only near the northern margins. The nature of current phenological patterns- high interannual and spatial variability - suggests that most plant species will not be seriously affected by phenological consequences from climate change alone. However, some individual plant species may suffer, and the consequences of changes in plant phenology for flower- and fruit-dependent animals in fragmented forests could be serious (Corlett and Lafrankie 2010). Since TFT species are perennial crops, much of their phenological phases (vegetative and reproductive growth stages) are highly dependent on temperature (range) and rain fall (quantity and distribution).

Protected areas

While considering the *in situ* conservation of useful wild plants and crop wild relatives it is important to consider the effects of climate change on protected areas. Even though there is precious little empirical data, it can safely be assumed that a significant amount of tropical fruit species genetic resources occur in protected areas and this needs to be substantiated through survey and determination of distribution. Thus, the mitigation of the negative effects of climate change on protected areas will indirectly help to conserve valuable agricultural biodiversity. Hannah et al. (2007) studied the range shifts due to climate change and species range dynamics

that reduce the relevance of current fixed protected areas in future conservation strategies. They applied species distribution modelling and conservation planning tools in three regions (Mexico, the Cape Floristic Region of South Africa, and Western Europe) to examine the need for additional protected areas in light of anticipated species range shifts caused by climate change. Their findings indicate that protected areas can be an important conservation strategy in such a scenario and that early actions are both more effective and less costly than inaction or delayed action. According to their projections, costs may vary among regions and none of the three areas studied will fully meet all conservation targets, even under a moderate climate change scenario. This suggests that limiting climate change is an essential complement to adding protected areas for the conservation of biodiversity. We need more studies on these lines for making appropriate conservation decisions for tropical fruit tree species occurring in and out of protected areas.

Evolutionary response

Generally speaking, landraces cultivated in the centres of tropical fruit diversity are the result of past and contemporary patterns of natural and farmer-mediated evolutionary forces. Unlike in annual crops, these forces take a longer time for perennial fruit tree species due to the longer generation cycle. Successful *in situ* conservation of tropical fruit tree genetic resources depends on continuity of these evolutionary processes. However, due to a longer generation cycle, much of what might happen is only an estimate. Climate change is projected to affect agricultural production, yet analyses of impacts on *in situ* conservation of crop genetic diversity and farmers who conserve it have been absent (Mercer and Perales 2010) even in crops with shorter generation cycles. Hence, in the case of tropical fruit tree genetic resources, it may be difficult, if not impossible, to answer the question: how do tree fruit landraces respond to alterations in climate?

Mercer and Perales (2010) reviewed the roles that phenotypic plasticity, evolution, and gene flow might play in sustaining production, although one might expect erosion of genetic diversity if landrace populations or entire races lose productivity. For example, highland maize landraces in southern Mexico do not express the plasticity necessary to sustain productivity under climate change,

but may evolve in response to altered conditions. The outcome for any given crop in a given region will depend on the distribution of genetic variation that affects fitness and patterns of climate change. Understanding patterns of neutral and adaptive diversity from the population to the landscape scale is essential to clarify how landraces conserved *in situ* will continue to evolve and how to minimize genetic erosion of this essential natural resource (Mercer and Perales 2010). No one has attempted to clarify this in the case of perennial crops species like tropical fruit trees.

More work is needed

At the same time, it is important to note that key risks associated with projected climate trends for the 21st century include the prospects of future climate states unlike the current states (novel states) and the disappearance of some extant climates. Williams et al. (2007) conclude that there is a close correspondence between regions with globally disappearing climates and previously identified biodiversity hotspots. For these regions, standard conservation solutions (e.g. assisted migration and networked reserves) may be insufficient to preserve biodiversity. By extrapolation, we can assume that this applies to agricultural biodiversity found in areas affected by climate change. This further strengthens the earlier statement that there is a large gap in research to make correct conservation decisions.

Conservation in homegardens

Most rural areas have always experienced climate variability, and farmers have had to constantly cope with a degree of uncertainty in relation to the local weather. They maximize the wide range of ecosystems available in the landscapes in which they live. Their production systems are integrated with crops, animals, fisheries, perennial fruits and trees around homesteads or in the vicinity of rivers, lakes and forests. They maintain portfolios of varieties of staple crops for managing adversity. There is interdependence within the system that is designed to spread risk and vulnerability to stochastic events. In the past, the systems with greater diversity or that have successfully integrated livestock or orchards were often less vulnerable to sudden changes and showed higher levels of resilience (Gurung et al. 2009). Farming with perennial fruit trees such as

coconut, mango, mangosteen, durian, jackfruits, guava, rambutan, etc., not only provides options for household food supply but also allows for maintenance and development of their roots, biomass and associated carbon (Scherr and Sthapit 2009). It also provides vegetative cover for soils while maintaining livestock on the side provides a form of income in case of emergency.

Homegardens are characterized by the deliberate management of intimate association with annual and perennial agricultural crops, fishery and livestock within homesteads. The whole tree-crop is intensively managed by family labour as an agroforestry system. Integrated homegardens of crops, fruits, livestock and trees are common strategies used by farmers to cope with climate change. This is a practical homestead level strategy to deal with adversity (Sthapit et al. 2010). Networks of such small homegardens in the larger ecosystem or landscape provide a wide range of options for food security and source of planting materials for further migration (seed flow) and colonization (spread of genetic resources). Sthapit et al. (2008) documented a range of examples in Nepal and Vietnam. In homegardens of East Java a portfolio of emergency root crops (e.g. *Amorphophallus campanulatus*, *Colocessia* spp., *Discorea* spp., *Manihot* spp. etc) are found to the buffer food supply chain during climatic adversity. Aryal et al. (2009) also reported many such examples in the Chepang indigenous community of Nepal.

As has been noted, a community of homegardens provides a unique opportunity for TFT and crop species conservation as well as selection/domestication opportunities for the farmer/grower. Nevertheless, it is not yet clear how the climate change impact on conservation through homegardens is going to pan out. Since different individuals of diverse fruit tree species are planted in homegardens, distance between individual trees of a particular species generally tends be more (e.g. mango) when compared to a FGB or orchard. This network of homegardens can cover a larger area than a FGB when it is considered at a landscape level. Hence any local climatic impact is unlikely to wipe out all the mango genetic resources in the landscape that spread across many homegardens. The trees stand still but their genes do not as pollen and seeds disperse by various mechanisms. Ennos (1994) provided a testable model relating the estimated levels of geneflow for the different types of markers to the levels of interpopulation pollen

and seed dispersal. All the above conceptual and methodological approaches that assess the contribution of pollen and seed movements and the overall geneflow levels in natural populations hold great promise for the preservation of natural levels of genetic diversity and for cohesiveness of plant metapopulations at the landscape level (Jordano 2010). We may need such information on climate change on a landscape scale and on processes that are already in place to counter much of the variation created by it at homegarden level.

Cultivated commercial and semi commercial orchards

We can expect changes in productivity and incidence of pests as well as shifts and changes in varieties that are presently grown in commercial orchards. However, specific changes can only be predicted on continued studies in these areas.

Commercial and semi commercial tropical fruit orchards present us with an opportunity in the climate change context. Plantations of diverse species of tropical fruit trees on degraded lands can also sequester carbon by the process of photosynthesis. Incentives such as carbon credits to these fruits orchards and plantation crops are not yet viable under the Kyoto Protocol's CDM credits.

Similar to carbon credits, Agrobiodiversity Conservation Credits (ACC) could be awarded to farmers who nurture wild and cultivate agrobiodiversity in their fields, adopt agrobiodiversity or carbon friendly farming practices such as no-till, use higher residue cover crops and rotations, decrease use of fossil based fertilizer or pesticides, convert marginal crop land to trees or grass residue management, rotate high-biomass crops, cover crops and integrate homegarden systems or perennial grasses for pastures, rotational grazing, etc. In order to meet the restrictions on greenhouse gas emissions, industries need to buy carbon credits, essentially paying one another for storing carbon to offset the excess it is releasing to the air. Strong policy support is required to implement such incentives.

Tropical fruits biology

All crops and plants have base temperatures for germination and time to onset of flowering. Warming trends at lower latitudes are associated with movements of tropical species into more temperate areas. There is ample evidence that ecological responses are already occurring because of climate change drivers (Montoya and Raffaelli 2010). First, data on many taxa in the Northern Hemisphere show a consistent trend of northward or westward expansion of species ranges and altitudinal shifts (Parmesan et al. 1999; Walther 2010). Second, globally rising temperatures trigger spring advancement of phenology (Parmesan, 2006). Third, changes in the chilling requirement of crops like apple are causing a shift in altitudinal adaptation and reduction in onset of timely flowering in the mountain belt of the Hindu-Kush Himalayas (see Dinesh and Reddy in this volume). Therefore, there is increasing interest to understand the physiological basis of growth and development in this changing context.

Most of the empirical evidence for rapid adaptation to climate change comes from examples of evolution in the interiors of species' ranges toward higher frequencies of already existing heat-tolerant genotypes. It is expected that a warming climate strengthens climate stress at equatorial range (i.e. tropical fruit species as well) boundaries and reduces at poleward boundaries. Tropical fruit populations are often under natural selection for increased tolerance to extreme climate in the absence of climate change, but may be unable to respond due to lack of necessary genetic variance (Parmesan 2006). Associated biodiversity such as pollinators are needed at the landscape level to facilitate pollen and gene dispersal to take place and often these pollinators connect fragmented habitat patches (Jordano 2010). Understanding the fundamentals of pollen and gene dispersal and its genetic bases in natural populations represents a challenge from both a theoretical and methodological perspective in the context of climate change.

As noted earlier, adaptation of fruit species mostly depends on the centre of their origin. This is especially true for the wild relatives since the cultivated ones might have developed different patterns of adaptation as well as wide adaptability due to genetic mixing through hybridization and continuous cultivation. Hence, changes

in climate in these centres of origin are important for future survival and distribution. Tropical Asian countries are the centre of origin for many globally important tropical fruit tree species and their wild relatives. These tropical fruit tree genetic resources include more than 400 species of edible tropical fruits (Arora and Ramanatha Rao 1995). Over 70 cultivated species of major and minor fruits are presently grown that largely represent native diversity. However, only about 20 species are well known under cultivation and these include banana, citrus, mango, pineapple, papaya, durian, rambutan, jackfruit, lychee, longan, tamarind, chempedak, carambola, langsat, guava, soursop, custard apple, salak, passion fruit and jujube (Verheij and Coronel 1991; Arora and Ramanatha Rao 1995). The predominant fruit tree species are citrus, mango, jack fruits, guava, lychee, mangosteen, rambutan, durian, longan, custard apple and carambola. This diversity is very valuable for the livelihoods of local people throughout tropical Asia, both as a source of nutrition and income as well as for better nutrition for urban consumers at the local, regional and even global levels. Additionally, fruit tree diversity in farms, orchards, homegardens and natural forests contributes to the provision of valuable ecosystem services and may provide buffers against the effects of climate change.

Further research is required in order to better understand the potential impacts of climate change on tropical fruit tree species in the wild as well as in cultivated homegardens and orchards. In addition, regional and location specific information on changes in climate are required to better strategise conservation efforts.

Information needs in dealing with challenges posed by climate change

Impact on growth, development and flowering

The impacts of climate change on trees in general remain poorly understood. Some studies have noted that increased carbon dioxide concentration in the atmosphere could increase plant growth rate in a phenomenon called carbon fertilization. However, Feely et al. (2007) examined changes in tree growth rates over the past two decades for all species occurring in large (50-ha) forest dynamics plots in Panama and Malaysia. They have reported that the stem

growth rates declined significantly at both forests regardless of initial size or organizational level (species, community or stand). While the underlying cause(s) of decelerating growth is still unresolved, these patterns strongly contradict the hypothesized pantropical increase in tree growth rates caused by carbon fertilization. Decelerating tree growth will have important economic and environmental implications. One can expect that cooling and warming in different zones can either benefit TFT species negative or positively. The degree of negativity would have great impact on how humanity will deal with the change. However, it is to be admitted that most studies on climate change are conducted with certain limitations as it is extremely difficult to imitate natural conditions. Studies on the responses of tree species to changing environmental conditions are of short duration and are conducted with seedlings or juvenile plant materials. Hence, there is need for generating more information on the impact of climate change on TFT species growth.

Impact on reproductive biology

As noted by Dinesh and Reddy (in this volume), temperature is one of the most important factors that affect pollen fertility, sterility and ultimately fruit set. Fertilization success in plants is the result of a sequence of processes that take place during the pregametic phase. It has been shown that temperature has a clear effect on pollen tube kinetics. While temperature affects pollen tube kinetics, information on the effect of temperature on pollen tube dynamics is missing. However, specific information for individual TFT species or group of species of the same genera is required to effectively predict the impact of climate change on the reproductive behaviour of these species. This information must be obtained in order to understand and develop changes to currently available conservation options.

Shift in seasons

It has been well established that perennial TFT species vary greatly in various phonological responses from season to season (Dinesh and Reddy, this volume). However, phenology data sets spanning many years in combination with bacteriological data are almost non-existent for TFT species, making it impossible to evaluate possible responses of these communities to climate change. There is a need to assemble such information to be used along with high resolution

weather prediction models to assess specific impacts on TFT species communities. This is necessary in order to draw up conservation options.

Shifts in pests and their effect

It has been fairly well established that with climate change there would be a change in prevalence of certain plant pests. Parameters such as temperature rainfall create ideal conditions for most pests and diseases (see Dinesh and Reddy in this volume for details). Using this general principle, there is a need to develop regional and conservation area specific information that can be of great use in combating devastating pests. Plants conserved *ex situ* or *in situ* must also be saved.

Concluding Remarks

Climate changes have always occurred. However, the rate at which the changes are occurring is faster than in the past and are human induced. TFT conservation may have a role in adapting to the effects of climate changes, and this needs to be explored. The question remains as to whether plants, especially perennial species like tropical fruit tree species, will have time to adapt and withstand the newer demands placed on their efforts to survive. We do not know enough about the impact of climate change on plant biology *per se.* Anything we say on this subject can only be the most probable scenario at this stage of climate change science development. However, we believe that we can be guided by probable scenarios for preparatory actions. With available information we have tried to visualize its major effects and developed some suggestions so that we are not caught unaware and are able to make any modifications to conservation methods and management practices as necessary.

Here we focused on what could be done for better management of tropical fruit genetic resource conservation practices in the event that climate change drastically impacts the environment. Although it is not exhaustive, we have provided some assessment of available information and have indicated future needs of information on some specific aspects of impacts of climate change. This information is necessary in order to successfully strategise conservation efforts, be them in *ex situ* or *in situ*.

References

Adhikari A, Rana RB, Sthapit BR, Subedi A, Shrestha PK, Upadhayay MP, Baral KP, Rijal DK, Gyawali S. 2005. Effectiveness of diversity fair in raising awareness on agrobiodiversity management. In: Sthapit BR, Upadhyay MP, Shrestha PK, Jarvis D, editors. On-farm Conservation of Agricultural Biodiversity in Nepal. Vol II. Managing Diversity and Promoting its Benefits. Proceedings of the Second National Workshop; 25-27 August, Nagarkot, Nepal.

Altieri MA, Merrick LC. 1987. *In situ* conservation of crop genetic resources through maintenance of traditional farming systems. Economic Botany 41: 86-96.

Araújo MB, Rahbek C. 2006. How does climate change affect biodiversity? Science 313: 1396-1397.

Arora RK, Ramanatha Rao V, editors. 1995. Expert Consultation on Tropical Fruit Species of Asia. Proceedings of Expert Consultation on Tropical Fruit Species of Asia; 17-19 May 1994, MARDI, Kuala Lumpur, Malaysia.

Aryal K, Berg Åke, Ogle Britta. 2009. Uncultivated plants and livelihood support –a case study from the Chepang people of Nepal. Ethnobotany Research & Applications 7: 409-422.

Bawa KS, Dayanandan S. 2010. Global climate change and tropical forest genetic resources. Climatic Change 39(2-3):473-485.

Brush SB. 1991. A farmer-based approach to conserving crop germplasm. Journal Economic Botany 45(2):153-165.

Brush SB, editor. 2000. Genes in the Field: On-Farm Conservation of Crop Diversity. IDRC, IPGRI, Lewis Publishers, Boca Raton, Ottawa, Rome.

CBD. 2007. Biodiversity and Climate Change. Book produced on the occasion of International Day for Biological Diversity.

Corlett RT, Lafrankie JV. 2010. Potential impacts of climate change on tropical Asian forests through an influence on phenology. Climatic Change 39(2-3): 439-453.

Engelmann F, Engels JMM. 2002. Technologies and strategies for *ex situ* conservation. In: Brown A, Jackson M, editors. Managing Plant Genetic Diversity. CAB International in conjunction with IPGRI, Wallingford. pp. 89-104.

Ennos RA. 1994. Estimating the relative rates of pollen and seed migration among plant populations. Heredity 72:250-259.

Feeley KJ, Wright SJ, Nur Supardi MN, Kassim AR, Davies SJ. 2007. Decelerating growth in tropical forest trees. Ecology Letters 10(6): 461 – 469.

Garrett KA, Dendy SP, Frank EE, Rouse MN, Travers SA. 2006. Climate change effects on plant disease. Genomes to Ecosystems Annual Review of Phytopathology 44: 489-509

Grum M, Gyasi EA, Osei C, Berisavljevic K. 2003. Evaluation of best practices for landrace conservation: farmer evaluation. Unpublished donor report, IPGRI, Nairobi.

Gurung GB, Bhandari DN. 2009. An integrated approach to climate change adaptation. LEISA Magazine 24, 4 December 2008.

Hannah L, Midgley G, Andelman S, Araújo M, Hughes G, Martinez-Meyer E, Pearson R, Williams P. 2007. Protected area needs in a changing climate. Frontiers in Ecology and the Environment 5(3): 131–138.

Hijmans RJ. 2003. The effect of climate change on global potato production. American Journal of Potato Research 80: 271-280.

Hijmans RJ, Graham CH. 2006. The ability of climate envelope models to predict the effect of climate change on species distributions. Global Change Biology 12: 2272-2281.

Howden SM, Soussana JF, Tubiello FN, Chhetri N, Dunlop M, Meinke H. 2007. Climate Change and Food Security Special Feature: Adapting Agriculture to Climate Change. PNAS 104: 19691-19696.

IPCC (Intergovernmental Panel on Climate Change). 2001. Climate Change: The Scientific Basis. Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Change). 2002. Climate change and biodiversity. Technical Paper V. Geneva.

IPCC (Intergovernmental Panel on Climate Change). 2007. IPCC Fourth Assessment Report: Climate Change 2007 (AR4).

Jarvis A, Upadhyaya H, Gowda CL, Aggerwal PK, Fujisaka S. 2008. Climate change and its effect on conservation and use of plant genetic resources for food and agriculture and associated biodiversity for food security. Thematic study for the State of the World Report on PGRFA, FAO, Rome, Italy.

Jarvis D, Lane J, Hijmans RJ. 2008. The effect of climate change on crop wild relatives. Agriculture, Ecosystems and Environment 126: 13-23.

Jones PG, Thornton PK. 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. Global Environmental Change 13: 51-59.

Jordano P. 2010. Pollen, seeds and genes: the movement ecology of plants. Heredity 105: 329-330.

Joshi KD, Subedi M, Rana R, Kadayat KB, Sthapit BR. 1997. Enhancing on-farm varietal diversity through participatory varietal selection: A case study for *Chaite* rice in Nepal. Experimental Agriculture 33: 335-344.

Kindt R and Lengkeek, AG. 1999. Tree diversity on farm – use it or lose it. National Workshop on Agricultural Biodiversity Conservation; 27–29 January 1999. Intermediate Technology Development Group (ITDG), Nairobi. pp. 75–85.

Klein RJT. 2003. Adaptation to climate variability and change: what is optimal and appropriate? In: Giupponi C, Schechter M, editors. Climate Change and the Mediterranean: Socio-Economics of Impacts, Vulnerability and Adaptation. Edward Elgar, Cheltenham, UK. pp 32–50.

Kostermans AJGH, Bompard JM. 1993. The Mangoes, their Botany, Nomenclature, Horticulture and Utilization. International Board for Plant Genetic Resources and the Linnean Society of London.

Lawler J, Whit D, Nelson R, Blaustein AR. 2006. Predicting climate-induced range shifts: model differences and model reliability. Global Change Biology 12:1568-1584.

Lobell DB, Schlenker W, Costa-Roberts J. 2011. Climate trends and global crop production Since 1980. Science 333:616-620.

Maxted N, Ford-Lloyd B, Hawkes JG. 1997. Plant Genetic Conservation: The *in situ* Approach. Chapman and Hall, London.

Mercer KL, Perales HR. 2010. Evolutionary response of landraces to climate change in centers of crop diversity. Evolutionary Applications. Published Online; 10 Jun 2010. doi:10.1111/j.1752-4571.2010.00137.x

Montoya JM, Raffaelli D. 2010. Climate change, biotic interactions and ecosystem services. Philosophical Transactions Royal Society 365: 2013–2018.

Mukherjee SK. 1985. Systematic and Ecogeographic studies on crop genepool: I. *(Mangifera L.)*. International Board for Plant Genetic Resources. Rome, Italy. p. 86.

Parmesan C, Ryholm N, Stefanescu C, Hill JK, Thomas CD, Descimon H, Huntely B, Kaila L, Kullberg J, Tammaru T, Tennent WJ, Thomas JA, Warren M. 1999. Poleward shifts in geographical ranges of butterfly species associated with regional warming. Nature 399: 579-583.

Parmesan C, Yohe G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature 421(6918): 37–42.

Parmesan C. 2006. Ecological and evolutionary responses to recent climate change. Annual Review of Ecology and Systematics 37: 637-669.

Ramanatha Rao V. 1998. Complementary conservation strategy. Tropical Fruits in Asia: Diversity, Maintenance, Conservation and Use. Proceedings of the IPGRI-ICAR-UTFANET Regional Training Course on the Conservation and Use of Germplasm of Tropical Fruit Species in Asia held at Indian Institute of Horticultural Research; 18-31 May 1997 Bangalore, India. IPGRI Office for South Asia, New Delhi. pp. 142-151.

Ramanatha Rao V. 2005. Coconut field genebank. In: Batugal PA, Ramanatha Rao V, Jeffrey O, editors. Coconut Genetic Resources. IPGRI-APO, Serdang, Malaysia. pp. 91-105.

Ramanatha Rao V. 2009. *In situ*/on-farm conservation of crop biodiversity. The Indian Journal of Genetics and Plant Breeding 69(4): 284-293.

Ramanatha Rao V, Jarvis D, Sthapit B. 2000. Towards *in situ* conservation of coconut genetic resources. Paper presented at the 9th COGENT Steering Committee Meeting; 20-12 July 2000, Chennai, India

Ramanatha Rao V, Mal B, Zongwen Z. 2005. Exploitation of native tropical and sub tropical fruit species diversity: Asian perspective. Crop Improvement and Production Technology of Horticultural Crops Vol. 1. Proceedings of First Indian Horticulture Congress; 6-9 November 2004, Horticulture Society of India, New Delhi, India. pp. 36-56.

Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA. 2003. Fingerprints of global warming on wild animals and plants. Nature 421(6918): 57–60.

Rosenzweig C, Parry ML. 1994. Potential impact of climate change on world food supply. Nature 367: 133-138.

Scherr S J, Sthapit S. 2009. Mitigating climate change through food and land use. Worldwatch Report No. 179. Washington, DC.

Shao G, Halpin PN. 1995. Climatic controls of eastern North American coastal tree and shrub distributions. Journal of Biogeography 22:1083-1089.

Shrestha P, Sthapit BR, Subedi A, Paudel D, Shrestha PK, Upadhyay MP, Joshi BK. 2006. Community seed bank: a good practice for on-farm conservation of agricultural biodiversity. Paper presented at the "Incentives for Supporting On-Farm Conservation, and Augmentation of Agro-biodiversity through Farmers' Innovations and Community Participation: An International Policy Consultation for Learning from Grassroots Initiatives and Institutional Interventions"; 27 – 29 May 2006 in Indian Institute of Management, Ahmadabad, India.

Sthapit B, Rana RB, Subedi A, Gyawali S, Bajracharya J, Chaudhary P, Joshi BK, Sthapit S, Joshi KD, Upadhyay MP. 2006. Participatory four cell analysis (FCA) for local crop diversity. In: Sthapit, BR, Shrestha PK, Upadhyay MP, editors. Good Practices: On-Farm Management of Agricultural Biodiversity in Nepal. NARC, LI-BIRD, IPGRI and IDRC.

Sthapit BR, Eyzaguirre P, Jarvis D, Rana R. 2008.The value of genetic diversity to resource–poor farmers in Nepal and Vietnam. International Journal of Agricultural Sustainability 6(2): 148-166. Doi: 10.3763/ijas.2007.0291

Sthapit BR, Padulosi S, Bhag Mal. 2010. Role of *in situ* conservation and underutilized crops in the wake of climate change. Indian Journal of Plant Genetic Resources 23(2): 2010

Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham Y C, Erasmus BFN, Ferreira De Siqeira M, Grainger A, Hannah L, Hughes L, Huntley B, Van Jaarsveld AS, Midgley GF, Miles L, Ortega-Huertas MA, Peterson AT, Phillips OL, Williams SE. 2004. Extinction risk from climate change. Nature 427: 145-148.

Udvardy MDF. 1975. A classification of the biogeographical provinces of the world. IUCN Occasional Papers No. 18. International Union for Conservation of Nature and Natural Resources, Morges, Switzerland. pp. 28-30.

Verheij, Coronel, editors. 1992 Plant Resources of. South-East Asia. No. 2. Edible Fruits and Nuts. Prosea, Bogor, Indonesia.

Walther GR. 2010. Community and ecosystem responses to recent climate change. Philosophical Transactions of Royal Society 365(1549): 2019-2024.

Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Jean- Fromentin M, Hoegh-Guldbergand O, Bairlein F. 2002. Ecological responses to recent climate change. Nature 416: 389-395.

Williams JW, Jackson ST, Kutzbach JE. 2007. Projected distributions of novel and disappearing climates by 2100 AD. PNAS 104(14): 5738-5742.

Tropical Fruit Trees and Opportunities for Adaptation and Mitigation

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Introduction

The agriculture and land use sector is a major contributor to global GHG emissions, and it is also a sector that has great potential to remove carbon from the atmosphere and contribute to climate mitigation (Scherr and Sthapit 2009). The perennial trees found in forests and agricultural lands, in the form of agroforests, home gardens and orchards are important sources of mitigation from this sector. Trees, especially tropical fruit trees, also have the additional benefit of augmenting rural income sources, providing physical materials, and adding to ecosystem services and resilience.

The chapters in this book have documented the idiosyncratic ways in which climate change is likely to affect tropical fruit trees. In this concluding chapter, we take stock of these impacts of climate change on tropical fruit trees and highlight the unique role they can play in adaptation as well as discuss opportunities for mitigation.

Tropical fruit trees for adaptation

Diversification is a strategy used to minimize risk and build resilience, be it in investments or in farming systems. While monocultures may deliver bumper harvests during favourable weather and market conditions, they also expose producers to the risk of absolute failure. On the other hand, production systems with high agricultural biodiversity can bring stability in yield, limit pest

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and disease outbreaks and increase resilience to disturbances (Frison et al. 2011). Consequently, farming communities across the world, from Sub-Saharan African to Himalayan high mountain ecosystems maintain diversity of species and income sources to deal with variation and uncertainty in their production. Farming communities rely on the diversity of emergency root crops, animal breeds and farm trees to buffer their food supply during lean periods. For these communities, it is important to have options that take advantage of various niches and the extreme growing conditions they face from year to year (Sthapit et al. 2009). Tropical fruit trees provide one important option in diversifying a household's or a community's livelihood strategies.

Fruit trees add resilience to farming systems as they can withstand climate adversity better than annual crops. Depending on the species, they also provide multiple use values in addition to fruits, such as timber, firewood, fodder, nitrogen fixation and windbreaks.

For instance, during the Indian Ocean tsunami of 2004, agricultural crops and many trees were destroyed, topsoil was swept away and the land became too saline for cultivation. However, coconut trees did much better at surviving the winds and the waves due to their flexible trunks. Being adapted to saline conditions they also continued to bear fruits during this period of need. Coconuts in Sri Lanka have multiple uses for food, raw materials and construction materials. Therefore, farmers growing coconuts were able to continue making up to half of their pre-tsunami income (Harvey undated)[2].

Likewise, indigenous fruits from the miombo woodlands in southern Africa contribute to food as well as income needs in rural households. They are especially critical for cash income during periods of famine, when income from other sources is low (Akinnifesi et al. 2006). The Chepang community of the sloping lands of the hills of Nepal also rely on wild fruits and root crops because their practices of shifting cultivation are perennially vulnerable to climate threats (Sthapit et al. 2008). A regional project is now promoting integrated hedgerows with nitrogen fixing trees as well as banana and citrus to reduce soil erosion, improve soil fertility and increase fruit consumption.

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2 http://www.grif.umontreal.ca/pages/HARVEY_Melissa.pdf - Accessed 10 May 2011.

Reproductive stages of fruit trees are most susceptible to climate change with implications on quantity and quality for fruits produced (Ramos et al. 2011). Winter chilling temperature requirements (Leudeling et al. 2011) and timing of water stress and rainfall (see Dinesh and Reddy, and Rajan in this book) have repercussions on flowering and fruiting. One way to deal with this risk is to use fruit trees that provide multiple benefits or uses or to devise multiple uses for the existing trees. For example, *Garcinia* spp. fats can be used for high quality facial soaps. In Thailand, *Garcinia* twigs, which have resin, are used to provide distinct flavour to local chicken recipes. In Sirsi of Western Ghats in India, the rind from *Garcinia* is used as an active ingredient in anti-obesity medicine, which fetches lucrative prices in the western markets (Sthapit pers. comm.).

For farmers to reap benefits from novel tree crops or from new products made from existing crops, they need to improve production and in parallel develop post-harvest, processing technologies and develop market linkages (Leakey 2007). For example, in Ghanteshwor village of Doti district of Nepal, fresh lime and lemon fetch very low prices because, unlike mandarin and sweet lime, they are not eaten as fresh citrus fruits. As such, the community invested in a small processing plant for juicing lime and lemon into squash (a juice concentrate that is mixed with cold water for a refreshing drink) and chuk (a thick dark form of traditional vinegar used both for food and medicine). The leftover rind and pulp from the juicing process is used to make pickles. These three products are now flying off the shelves in the local markets. As a result, in one season the farmers have recognized the potential for these new fruit products and planted over a thousand new saplings each of lime and lemon (Sthapit et al. 2010).

However, changing or adapting varieties of longer lived fruit trees to rapidly occurring climate change is an emerging challenge. Fruit trees have long productive lives ranging from over two to four decades. Hence, any change in variety happens over this long period (Lobell et al. 2006). Short duration crops such as cereals and vegetables are attractive to farmers as they give income in the first season. And if change in variety is needed, it can be done quickly with annual crops compared to fruit trees.

There are, however, techniques to speed up varietal change in fruit trees such as grafting. Selection of strong rootstocks in fruit trees can provide the necessary resilience to climate change. By grafting desirable varieties to these resilient rootstocks farmers can try new varieties without replanting. Side grafting on existing rootstocks can help speed up the process of changing varieties. In fact, a farmer near Lucknow in India, the place of origin of the famous Dussaheri variety of mango, has grafted over 150 varieties onto a single rootstock (Sthapit pers. comm.). Practiced to showcase rich diversity, this innovation also allows farmers to assess and compare which varieties do well in a given climate and to maintain a large amount of diversity in a relatively small area. However, without replication, there is a risk of putting all eggs in one basket. From a production perspective, selecting a resilient rootstock and grafting on it a couple of varieties that bear at complementary times may ensure production even in seasons with erratic climate patterns.

In conjunction with the above farmer innovation, there are also computational innovations taking place. Bioversity International's Climate Change, Agriculture and Food Security programme is using climate modelling to match analogous climate areas around the world across time periods. Hypothetically, if the prevailing climate in South America is found to be similar to the projected climate in Sub-Saharan Africa in 30 years time, then the agrobiodiversity and associated knowledge from South America will be a good starting point for adapting agriculture in Sub-Saharan Africa in the future. Some matching of existing fruit trees with future climates is already being explored by Mathur et al. and Rajan in this book.

Tropical fruit trees for mitigation

In addition to their role in adaptation, fruit trees are also an important part of the perennial based solutions for climate change mitigation. In a year, perennial crops can sequester between 320 to 1,100 kg of soil carbon per hectare, as compared to 0 to 450 kg of annual crops, and are more likely to get better yields than annual crops at higher temperatures (Glover et al. 2007). Breeding for perennial cereals, especially for use in fodder and feed is one promising path, and the Land Institute has been working towards that aim. Transitioning to more perennial trees, such as fruit trees, is an existing solution.

However, certain barriers preclude expansion or new adoption of perennial trees in general and fruit trees in particular. A primary barrier to expansion of fruit trees is the minimum two to four years of establishment period that farmers need to wait to get a return on their investment. Despite farmers' interest in fruit trees, establishing new trees in homegardens of poor Nepalese households has been a challenge. In the short term tree saplings are likely to be neglected in favour of vegetables because the vegetables will feed the family in a matter of weeks (Pudasaini pers. comm.). However, in Kenya intercropping with crops such as maize, sorghum, cassava, legumes, and other fruits in the initial stages of mango orchard establishment have been practiced to ease the transition (Bekele-Tesemma 2007).

For existing orchards, the challenge is in changing to an appropriate variety in the context of changing climate. While annual crops and vegetables can be replaced every season to match variety with the changing climate, the same process can take at least a few years during which production is foregone. However, farmers in India as well as Thailand have started carrying out top working and grafting with scions of suitable varieties to speed up the transition of varieties.

Without access to a market outlet, the increase of fruit trees in agroforestry systems also seems to have limited scope. For example, in Africa fodder and fuel trees tend to outnumber fruit trees in agroforests by more than 10 times. This is simply due to the fact that a household's need for fuel and fodder are greater in terms of volume than the household's capacity to consume fruits (Place pers. comm.). As such, without an ability to sell the surplus fruits produced, there is no need to have more fruit trees on farm.

Several initiatives around the world are now looking at carbon finance as a way to achieve climate mitigation whilst generating co-benefits for rural communities. In the compliance markets of the Kyoto Protocol's Clean Development Mechanism, forestry based credits play a very limited role (only 1% in 2008). Most of the innovations in land use based carbon credits are taking place in the voluntary carbon markets (Ecosystem Marketplace 2012). Standards such as Voluntary Carbon Standard, CCB (Climate, Community and Biodiversity) project design Standard and Plan Vivo allow for carbon credits to be generated from agroforestry and perennial trees because of their focus on co-benefits.

For the traditional *ex situ* conservation of field genebanks, the current carbon prices might be too low to make a difference. For example, the annual maintenance cost of CATIE's nine hectare coffee field genebank in Costa Rica with 1992 accessions is US$ 30,343 per year on top of the initial establishment cost of US$ 138, 681 (Dullo et al. 2009). The potential carbon sequestration of agroforestry systems in the tropics is between 1.5 to 3.5 tons of carbon per hectare per year, i.e. 5.5 to 13 tons of CO2eq. per hectare per year (Trumper et al. 2009). With average credit prices of US$ 5.2 per ton of CO_{2eq} for agroforestry or US$ 7.3 per ton of CO_{2eq} for forest management (Hamilton et al. 2010), carbon finance is unlikely to make these field genebanks more economically viable. However, devolving the management of field genebanks to communities and integrating it with homegardens in the community can significantly increase the carbon sequestration in the landscape. Farmers in the community-based biodiversity management programme in Nepal are maintaining small field genebanks of banana and citrus. Due to low labour costs and basic management practices, even the modest carbon credit prices could make a difference for these farmer managed field genebanks, especially if the financing is paid to the farmers' group's core funds rather than to individuals.

For on-farm conservation with community participation, carbon finance under these standards can play a stronger role in increasing tree density on-farm. In this case too, carbon finance is unlikely to be the main benefit due to low price of carbon. But they can financially help the farmers achieve transition in their land management practices (Shames et al. 2011). Carbon finance can play a strategic role in helping establish more fruit tree saplings in the farming system. Once the transition to a more fruit tree based farming system is achieved, the productivity and resilience of the new system itself is likely to be the principle benefit for the farmers.

From the above discussion, we can conclude that carbon financing can meet the additionality criterion (i.e. without carbon financing the activities would not have been undertaken) by helping address the barriers to the establishment for fruit orchards, field genebanks and promotion of fruit trees in homegardens. For commercial fruit orchards, additionality of carbon payments will continue even after the period of initial establishment. This is because without appropriate adaptation measures, changing climate will make the

year to year production highly variable subject to the temperature and timing of rainfall. However, despite losses in productivity, the standing trees in the orchard*s* will continue to provide carbon sequestration services. If commercial orchards are established in previously degraded and abandoned lands, the sequestration benefits can be really significant. To really take advantage of this opportunity, a higher and stable carbon price, and research on fruit tree systems with high carbon sequestration will be necessary.

Conclusion

Despite the importance of tropical fruits in terms of nutrition and food security, very little work has been done on it compared to cereal crops. Many studies so far have focussed on the impact of climate change on cereals and major crops only. This book tries to bring together the current status of knowledge regarding tropical fruit trees and climate change.

As woody perennials, tropical fruits trees are perceived to be less susceptible to the changing climate. But this book finds that there are idiosyncratic ways in which tropical fruit trees are affected. Although the tree might itself be left standing, there are risks of production losses. Being long lived trees, adapting to climate change through varietal change is also a challenge. However, climate modelling and GIS can help match fruit trees to probable future climate scenarios and open up avenues for production in new areas.

Being a perennial crop that can stay productive for decades and in the process sequester carbon, commercial fruit tree orchards, field genebanks and fruit trees in homegardens, can be options for using both agricultural and degraded lands for carbon sequestration. Since the trees continue to provide mitigation services, even while suffering production losses, they also fulfill the additionality criterion of carbon financing. However, for the carbon financing to really have an impact, the global carbon pricing needs to go up.

Finally, knowledge gaps in terms of tropical fruit trees and climate change need to be urgently addressed to strengthen humanity's toolkit for building climate resilient agriculture systems that also mitigate climate change.

References

Akinnifesi FK, Kwesiga F, Mhango T, Mkonda A, Kadu CAC, Kadzere I et al. 2006. Towards the development of miombo fruit trees as commercial tree crops in southern Africa. Forests, Trees and Livelihoods 16:103-121.

Bekele-Tesemma A. 2007. Profitable agroforestry innovations for Eastern Africa: experience from 10 agroclimatic zones of Ethiopia, India, Kenya, Tanzania and Uganda. World Agroforestry Centre, Nairboi, Kenya.

Dullo ME, Ebert AW, Dussert S, Gotor E, Astorga C, Vasquez N et al. 2009. Cost efficiency of cryopreservation as a long-term conservation method for coffee genetic resources. Crop Science 49:2123-2138.

Ecosystem Marketplace [online]. 2012. Available from: http://www.ecosystemmarketplace.com. Date accessed: 26 February 2012.

Frison EA, Cherfas J, Hodgkin T. 2011. Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. Sustainability 3:238-253.

Glover JD, Cox CM, Reganold JP. 2007. Future farming: a return to roots? Scientific American August 82-89.

Hamilton K, Sjardin M, Peters-Stanley M, Marcello T. 2010. Building Bridges: State of the Voluntary Carbon Markets 2010. Ecosystem Marketplace and Bloomberg New Energy Finance, Washington, DC, USA.

Harvey M. Undated. Cultivating resilience: the rehabilitation of homestead gardens in post-tsunami Sri Lanka [online]. Available from URL: http://www.grif.umontreal.ca/pages/HARVEY_Melissa.pdf. Date accessed: 10 May 2011.

Leakey RRB. 2007. Domesticating and marketing novel crops. In: Scherr SJ, McNeely JA, editors. Farming with Nature: The Science and Practice of Ecoagriculture. Island Press, Washington, DC, USA. pp. 83-102.

Luedeling E, Girvetz EH, Semenov MA, Brown PH .2011. Climate change affects winter chill for temperate fruit and nut trees. PLoS ONE 6(5):1-13.

Lobell DB, Field CB, Cahill KN, Bonfils C. 2006. Impacts of future climate change on California perennial crop yields: model projections with climate and crop uncertainties. Agricultural and Forest Meteorology 141:208-218.

Ramos C, Intrigliolo DS, Thompson RB. 2011. Global change challenges for horticultural systems. In: Araus JL, Slafer GA, editors. Crop Stress Management and Global Climate Change. CAB International.

Scherr SJ, Sthapit S. 2009. Mitigating climate change through food and land use. Worldwatch Report No. 179. Worldwatch Institute and EcoAgriculture Partners, Washington DC, USA.

Shames S, Buck LE, Wollenberg E, Krisjanson P. 2011. Institutional innovations for engaging smallholder farmers in agriculture carbon projects. [draft]

Sthapit B, Rana R, Eyzaguirre E, and Jarvis D. 2008. The value of plant genetic diversity to resource-poor faremrs in Nepal and Vietnam. International Journal of Agricultural Sustainability 6(2):148-166.

Sthapit B, Padulosi S, Mal B. 2009. Role of on-farm/*in situ* conservation and underutilized crops in the wake for climate change. Indian Journal of Plant Genetic Resources 23(2):145-156.

Sthapit S, Bhandari B, Devkota BR. 2010. Sweet and Sour Delight: Value Addition in Citrus. LI-BIRD, Pokhara, Nepal.

Trumper K, Bertzky M, Dickson B, van der Heijden G, Jenkins M, Manning P. 2009. The Natural Fix? The Role of Ecosystems in Climate Mitigation. A UNEP Rapid Response Assessment. United Nations Environment Programme, UNEP-WCMC, Cambridge, UK.

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