THE INSTITUTE OF BIOLOGY SRI LANKA

Adapting to Climate Change: A Sri Lankan perspective

Adapting to Climate Change: A Sri Lankan Perspective

Published by
The Institute of Biology, Sri Lanka
25th September, 2020

Disclaimer: The materials in this book have been provided by the authors and compiled by the Institute of Biology, Sri Lanka (IOBSL). The contents and views expressed therein remain the responsibility of the named authors and do not necessarily reflect those of the copyright holder (The Institute of Biology, Sri Lanka) and its members.

Citation: Name/s of chapter author/s (2020). 'Title of chapter', In: Adapting to Climate Change: A Sri Lankan perspective. H.I.U. Caldera and S.A.C.N. Perera (Eds.), Institute of Biology Sri Lanka, Colombo. pp. x-y

Text by: M.R. Wijesinghe, K.D.K.P. Kumari, G.D.K. Kumara, D.H.B.R. Dassanayake, S.P. Nissanka, C.K. Beneragama, K.W.L.K. Weerasinghe, N. Geekiyanage, M.D.P. Kumarathunge, H.I.U. Caldera, W.M.T.P. Ariyaratne, D.M.S.B. Dissanayaka, B. Marambe, A.J. Mohotti, K.M. Mohotti, R. Wimalasekera, K.P. Waidyarathne, S.A.C.N. Perera, N.W.B.A.L. Udayanga, M.M.M. Najim, N. Gunathilaka

Technical Editing: Dr. H.I.U. Caldera, Dr. S.A.C.N. Perera,

Design: Ms. B. T. Weththasinghe, Department of Plant Sciences, University of Colombo

Printing & Binding: Sanduni Printers, Peradeniya

ISBN: 978-955-8476-09-3

Institute of Biology Sri Lanka (IOBSL)
'Vidya Mandiraya',
120/10, Wijerama Road, Colombo 07.
Email: iobslcouncil@gmail.com
Web: http://www.iobsl.org/

Adapting to Climate Change: A Sri Lankan Perspective

<u>Authors</u>

PREFACE

Institute of Biology of Sri Lanka (IOBSL) formulated in 1981, is the premier organization for biologists in Sri Lanka, bringing together professionals from academia, research and industry. Incorporated by the Act of Parliament No. 22 in 1984, the IOBSL is mandated to promote and advance the science of biology and its applications in Sri Lanka. Adhering to this mandate, the Institute periodically publishes books under salient themes in order to encourage discussion amongst stakeholders whilst furthering appropriate action.

Climate change is a current issue which is discussed both locally and globally. Identified as one of the greatest threats faced by both man-made and natural ecosystems, its impact will be felt by all species including humans. It will affect humans worldwide due to its far-reaching effects on basic needs such as; access to water, food production, health, and the overall environment. While all countries would be affected, the vulnerability of lesser developed nations is predicted to be more. In dealing with climate change, both mitigation and adaptation mechanisms are important. Mitigation mainly refers to the reduction or prevention of emission of greenhouse gases and stabilizing their levels in the atmosphere. Its effects are therefore felt mostly in the long-term. Adaptation on the other hand includes actions taken to moderate, cope or take advantage of actual or anticipated changes in climate and the effects are generally more short-term and local based. It is often regarded as the key strategy available for facing the impacts of climate change and reducing the associated vulnerability. Thus, adaptation to climate change is the focus of this book and it is also in line with IOBSL theme for 2019/2020 which is 'Using the Resilience of Nature to Face the Reality of Climate Change'.

This book, 'Adapting to climate change: A Sri Lankan perspective', discusses current trends and provides recommendations for diverse sectors such as agriculture, health, food security and local policy. The Sri Lankan context presented in the publication attempts to fill a lacuna in this field and thereby provide pertinent information to local stakeholders.

We sincerely hope that this book satisfies the information needs of stakeholders and would also be instrumental in both creating dialogue and encouraging further work in this area.

Dr S.A.C.N. Perera
Dr H.I.U. Caldera
(Technical Editors)
25th September, 2020

REVIEWERS

Prof. H.P.M. Gunasena, Department of Crop Science, Faculty of Agriculture, University of Peradeniya. Peradeniya.

Prof. W. Abeyewickreme, Department of Paraclinical Sciences,Faculty of Medicine, Kotelawala Defence University, Ratmalana.

Prof. M.I.M. Mowjood, Department of Agriculture Engineering, Faculty of Agriculture, University of Peradeniya, Peradeniya.

Prof. (Ms.) N. Dassanayaka, Department of Botany, Faculty of Science, University of Sri Jayawardenepura, Nugegoda.

Prof (Ms.) A.S. Karunaratne, Department of Export Agriculture, Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya.

Dr. RMCS Rathnayake, Department of Botany, Faculty of Science, University of Kelaniya.

Dr. (Ms.) W. Wijesuriya, Principal Research Officer, Biometry Section, Rubber Research Institute of Sri Lanka, Dartonfield, Agalawatta.

Dr. P. K. Dissanayake, Department of Export Agriculture, Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya.

Dr. L. Weerasinghe, Department of Chemistry, Faculty of Applied Sciences, University of Sri Jayewardenepura, Gangodawila, Nugegoda.

Dr. L. Rankoth, Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya.

Dr. S. Seneviratne, Department of Zoology and Environment Sciences, Faculty of Science, University of Colombo, Colombo.

Ms. D. Perera - Climate Change Secretariat, Colombo.

Acknowledgements

The Institute of Biology Sri Lanka would like to acknowledge the contribution from all those who have been involved in the publishing of this book. This book would not have become a reality without the generous support of them.

- We sincerely appreciate the contribution from chapter authors for their willingness to share the expertise by writing a chapter in this publication.

- We gratefully acknowledge the efforts of chapter reviewers for spending their valuable time in reviewing the chapters and improving the content included in the chapters.

- We are thankful to Ms. B.T. Weththasinghe, Department of Plant Sciences, University of Colombo for the cover page designing and Ms. Janani Chathurya for the cover page photograph.

- We are grateful to Dr. H.D.D. Bandupriya for assistance in finalizing the publication.

- We are grateful to Dr. Keerthi Mohotti (Chairman) and the members of the National Steering Committee of Global Environment Facility- Small Grants Programme (GEF-SGP, UNDP), Mrs. Dinali Jayasinghe, National Coordinator (GEF-SGP, UNDP), Mr Nuwan Perera, Programme Assistant (GEF-SGP, UNDP) and Mr Ruwan Weerasooriya, Coordinator, Knowledge Management Team, Sri Lanka Environment Exploration Society (SLEES) UNDP for providing sponsorship to publish this book through United Nations Development Programme, Sri Lanka.

- We also acknowledge the service of Mr. Thusitha Wijekoon, of Sanduni Printers, Peradeniya for printing the book.

CONTENTS

CHAPTER
01

© Malin Ranwala

Impacts of Climate Change on Biological Diversity: A Sri Lankan Perspective on Vulnerability and Resilience

Mayuri. R. Wijesinghe*

Department of Zoology and
Environment Sciences, University of Colombo, Colombo, Sri Lanka.
*mayuri@sci.cmb.ac.lk

Impacts of Climate Change on Biological Diversity: A Sri Lankan Perspective on Vulnerability and Resilience

Abstract

There is now a growing body of evidence that climate change is likely to cause adverse impacts on biodiversity worldwide. Sri Lanka, a tropical island supporting exceptionally high levels of biodiversity and endemism, would be particularly vulnerable, with varying impacts on species and habitats. There is a dearth of information locally on direct impacts of climate change on species. But circumstantial evidence from Sri Lanka and elsewhere suggests that a rise in global temperature is likely to alter life history traits, retard growth, alter rates of development, and cause physiological malfunctioning in both plants and animals leading to range reductions and shifts in distribution. Global warming would also hinder processes such as nutrient cycling which are critical for functioning of many natural ecosystems. Climate change will also bring about numerous other biophysical changes affecting Sri Lanka such as increased frequency of flooding and prolonged drought, which will be especially detrimental to species inhabiting ephemeral aquatic habitats and those in the dry and arid zones where water is limiting. Global warming and sea level rise combined will affect intertidal habitats (e.g. mangroves) and marine ecosystems (e.g. coral reefs) which are important in the context of the island's biodiversity. The depletion and fragmentation of the country's natural forest cover coupled with over-exploitation has already placed many of the country's species at the brink of extinction. Climate change would exacerbate the situation. This paper deals with the potential impacts of climate change on components of biodiversity in Sri Lanka, citing local examples. Activities that could build resilience of species and habitats, facilitating adaptation and tolerance, are also discussed.

Keywords: *Global warming, resilience, restricted range species, thermal sensitivity, tropics*

Sri Lanka's biological diversity

Sri Lanka, despite its small size, supports an exceptionally high diversity of biotic species, many of which are endemic to the island. Among the flora, the highest species diversity is in flowering plants (3771 species), followed in decreasing order by fungi (over 2200 species), bryophytes, freshwater algae, and ferns (Gunatilleke *et al.,* 2008). Faunal diversity is also impressive. Among the vertebrates – 91 species of land mammals, 482 birds, 171 reptiles, more than 106 amphibians, and 82 freshwater fishes have thus far been documented. Invertebrate diversity is expected to be much higher (Gunatilleke *et al.,* 2008). It is the wide range of climatic and topographical variations in Sri Lanka that has led to the emergence of many different ecosystems and habitats with an extraordinarily high diversity of species. What is particularly noteworthy is that the majority of the species, including many endemics, are confined to the fragmented rainforests in the lowland and montane wet zone, in the southwest quarter of the island. Owing to the high species diversity and the exceptional threats facing the biota, Southwest Sri Lanka together with the Western Ghats of India was identified as a biodiversity hotpot way back in 1990 (Myers, 1990); this was later expanded to cover the whole of Sri Lanka (Myers *et al*., 2000). Remarkably, in a small patch of the planet's land surface (i.e. Southwest Sri Lanka), two forest areas with a rich complement of biological diversity and endemic species have been inscribed as Natural World Heritage Sites under UNESCO's World Heritage Convention – the lowland rainforest Sinharaja was inscribed as a World Heritage in 1988, and a group of montane rainforests (the Central Highlands of Sri Lanka) was similarly inscribed in 2010.

Despite the heightened focus on biodiversity conservation worldwide, threats to biodiversity continue to aggravate (Buchart *et al.,* 2010). The latest national assessment in Sri Lanka reveals that around 44% of the flowering plants are under threat of extinction; the situation is as grave with respect to the fauna – one in every six species of inland indigenous vertebrates is currently facing high risks of extinction in the wild (MoE 2012). In common with most other tropical regions, habitat loss and fragmentation have been implicated as the major threat leading to the depletion of biodiversity.

Global warming and its implications to biodiversity

The occurrence of global warming and climate change came into prominence with the adoption of the United Nations Framework Convention on Climate Change at the Earth Summit in Rio de Janeiro in June 1992. Initially, the international community focused attention on the societal and economic consequences of the possible direct impacts of sea level rise and disruption of existing weather patterns that would be caused by climate change. With increasing evidence of global warming and its consequences, it is now recognized that one of the greatest climate-change driven global crises is related to its impact on biological diversity. Stresses imposed by climate change have been implicated as potential causes of population declines, range reductions and local extinction of species, leading to loss of biological diversity worldwide.

Tropical biota more at risk from global warming

Climate, and hence climate change shows spatial variation and so does biological diversity. The tropical regions, though covering less than 10% of the earth's land surface, contain an overwhelming majority of the Earth's biological diversity (Bradshaw *et al.,* 2009). The disproportionately large proportion of species in tropical regions would mean that the overall impact of climate change on biodiversity would be greatest here than elsewhere on the planet. Hence in Sri Lanka, a tropical island and biological hotspot, the overall magnitude of the adverse effects of climate change are likely to be particularly high.

The most pronounced climate-change related direct threat to biological diversity is the rise in ambient temperature. Globally, it is predicted that 20 to 30 percent of species will be facing increasingly high risks of extinction by the year 2100 as global mean temperatures rise to 2-3^{o}C above pre-industrial levels (Fischlin *et al*., 2007). Temperature rise in tropical regions is reported to be of a lesser magnitude than in temperate and polar regions (Rosenzweig and Liverman, 1992), but the deleterious impacts on the biota are expected to be more pronounced in the tropics. Species that have evolved in areas where high temperature variations occur in the course of the year (as in temperate regions) are thermal generalists with broad thermal tolerance (Sunday *et al.,* 2012). In contrast, tropical species usually experience smaller annual variations in temperature and are thermal specialists (Ghalambor *et al.,* 2006), making them more sensitive to even a small overall rise in ambient temperature. Moreover, tropical species are already experiencing ambient temperatures that are close to their thermal maximum i.e. the temperature at which optimal physiological performance is shown (Algiriyage *et al*., 2020). This means that even a small rise in ambient temperature would place these species under physiological stress, endangering their survival. Long term meteorological data from Sri Lanka provide evidence of global warming: e.g. the annual minimum temperature in Nuwara Eliya has increased by 2.36°C during the past 130 years (Sujeeva, 2011), and recent years have seen increasingly frequent extreme temperatures in more parts of the island than before (e.g. Naveendrakumar *et al*., 2018). Given the susceptibility of tropical species to a rise in environmental temperature, climate change could be expected to have deleterious effects on the biotic assemblages in Sri Lanka. Although it is widely recognized that climate change is capable of inflicting negative consequences on biota, direct evidence on individual species is lacking at present. Circumstantial evidence from Sri Lanka and elsewhere, nonetheless, suggests that continuing climate change would exacerbate the existing pressures on biodiversity, both at ecosystem and species levels.

A few studies have attempted to characterize the possible impacts of global warming on species in Sri Lanka. An empirical study by Weerathunga *et al*. (2018) using two native freshwater fishes *Rasbora daniconius* and *Dawkinsia filementosa* demonstrated that the former had reduced operculum movement (indicating lowering of the respiration rate) at temperatures above 30°C, although the latter species was not significantly affected. Another study has shown that tadpoles of the endemic *Polypedates cruciger* (Hourglass frog) exhibited delayed development and growth impairment when exposed to temperatures of 32°C (Weerathunga *et al*., 2020). Although such studies have limited applicability as to the impacts of climate change, they signal the possibility that many species would be vulnerable if exposed to increases in ambient temperature beyond their current ranges.

Would all species and habitats across the island be equally impacted?

There is evidence to suggest that climate change would have differential impacts on species and habitats. Among animal species, in ectotherms, since their body temperature varies with the temperature of the environment, but within limits, they would be more vulnerable to global warming than endotherms (species that are able to maintain a near constant body temperature independent of the ambient temperature) (Deutsch *et al*., 2008). With respect to ectotherms, it must be noted that our rainforests support the second highest density of amphibians in the world (Pethiyagoda and Manamendra-Arachchi 1998) and together with the reptiles make up over 65% of the endemic vertebrate species in the island (MoE, 2012). With respect to other ectothermal species, although relatively little is known of the complement of invertebrates, the diversity in two taxa – spiders (501 species) and land snails (246 species) (Gunatilleke *et al.,* 2008), gives us a premonition of the scale of impacts global warming can have on the country's biotic resources.

Within the country, species inhabiting hot areas (dry and arid zones), unless they possess special adaptations (e.g. ability to undergo torpor), would be particularly vulnerable since these organisms function at or near the upper critical temperature above which physiological dysfunction and death would occur (Araujo *et al*., 2013). A study by Algiriyage *et al*. (2020) which examined interpopulation thermal sensitivity in the Asian common toad (*Duttaphyrnus melanostictus*) from two regions in Sri Lanka has shown that the population in the hot low country dry zone has a narrower thermal safety margin than the population in the cool high altitudinal area. This would make the dry zone population more vulnerable to climate change. In both plants and animals, the potential of physiological functioning to evolve in response to climate change will be a key indicator of the extent of resilience.

Species are known to overcome adverse effects of global warming by shifting their distribution ranges – those in the lowlands will gradually shift to cooler high altitudinal areas (Menéndez, 2007; Chen *et al*., 2011; Pucko *et al*., 2011), and such alterations in distribution are likely to be accompanied by evolutionary changes in genotypes, as predicted for insects by Haag *et al.* (2005). However, in Sri Lanka, which has experienced high rates of deforestation and forest fragmentation with the conversion of natural habitats to anthropogenic land uses, there would be limited opportunities for most species to shift to other suitable areas.

Rise in global temperature induces numerous biophysical changes. In tropical regions changes have been noted to occur in the intensity and timing of rainfall. In Sri Lanka apart from the overall decline in annual rainfall predicted for many parts of the island, rainfall regimes are becoming erratic – there are spells of unusually heavy rainfall giving rise to more frequent flooding events, while periods of drought have got extended. These altered hydrological regimes would adversely affect biota in a variety of ways – breeding in tropical amphibians is triggered by the onset of rains and it is predicted that climate change will result in shifts in breeding seasons (Ulloa *et al.,* 2019); increases in ambient temperature causes insect larvae to mature quicker (McCauley *et al*., 2018); birds would lay eggs earlier (Jàrvinen, 2006) and would suffer lower fecundity (Jayasinghe *et al*., 2016); rise in ambient temperature would negatively affect vertebrates with temperature-dependent sex determination (Valenzuela *et al*., 2019). Furthermore, it is reported that insect larvae experience increased mortality rates at higher temperatures, and those that complete their development have smaller wings compared to body size; these individuals would have a higher wing load that would in turn hamper flight and their ability to disperse (Hassal and Thompson, 2008). Long distance migrants such as some birds and insects would also be affected by climate-driven changes in food availability at overwintering locations. To navigate between their temperate breeding grounds and tropical wintering grounds these species use a network of climatic and geographic cues. Thus, any disruption of climatic cues would pose serious threats to annual migration events (Carey, 2009).

For rainforest dominant tree species such as the dipterocarps, the cue for flowering is the temporary decline in the minimum night temperature (Ashton *et al.,* 1988), which implies that these species would be impacted by changes in ambient temperature regimes. Alterations in timing might cause a mismatch between the presence of pollinators and flowering, lowering regeneration capacity of the plant species (Visser *et al.,* 2004). In the case of plants, research is lacking on the direct effects of climate change on native wild species of Sri Lanka. However, with respect to commercial crops, increased grain sterility has been recorded in rice (Weerakoon *et al.,* 2008) and the reduction in the formation of young shoots in tea (Watson, 1986), both caused by the rise in ambient temperature. These observations suggest that native flora may be affected in a similar manner. Studies on crop plants elsewhere have also shown that higher concentrations of atmospheric CO_2 (associated with climate change) boosts yields by increasing the rate of photosynthesis and reducing water loss through transpiration, both being beneficial effects. However, as to what extent these mechanisms operate under different climatic regimes is yet unknown (Kimball *et al.,* 1990). On an ecosystem scale, drought and temperature stress imposed by climate change is reported to trigger forest die back (Allen, 2009); this has been considered as one of the possible causes for the die back observed in the montane forest in Horton Plains (Kottawa-arachchi and Wijerathne, 2017).

Apart from physiological stresses directly induced by a rise in global temperature, species will be also affected through the impacts of climate change on habitats. For instance, flooding or prolonged drought would be detrimental to many species associated with wetlands, particularly those inhabiting ephemeral habitats. An example is the montane-specific and critically endangered smoky-winged thread tail dragonfly (*Elattoneura leucostigma*) which is found in riparian habitats with temporary pools (Sumanapala, 2020). An elevation in water temperature in floodplains would alter the frequency and duration of hypoxic and anoxic episodes, leading to reduction in both growth rates and reproductive success of species (Hamilton, 2010). Restricted range species, especially point endemics, are typically habitat specialists, and climate change would be expected to affect such species more than others. A case in point is the relict endemic amphibian Nannophrys *marmorata*. This rock dweller restricted to the Knuckles region in Sri Lanka breeds during a relatively short wet season and produces semi-terrestrial tadpoles which attach themselves to moist rock surfaces. Lower rainfall and longer dry periods would limit the window during which breeding can occur and wipe out habitats of the tadpoles (Senanayake *et al.,* 2018). The negative impacts manifested in species could ramify throughout the different levels of an ecosystem.

Temperature and moisture dependent processes such as nutrient cycling would also be altered with concurrent impacts on primary productivity and leaf fall (Chakravarty *et al.,* 2019). It is predicted that there would be a decline in net primary production in areas where water is a limiting resource (Wang *et al*., 2016). In Sri Lanka, where the dry and arid zones characterized by a prolonged dry season make up 4/5th of the land area, this is a matter of considerable concern.

The rise in global temperature and sea level rise could have devastating effects on Sri Lanka's coastal and marine biodiversity. About 2-3 % of the coastline contains near-shore fringing reefs (Swan, 1983) which support over 400 species of reef and reef-associated species, many of which are commercially harvested. Dolphins and sea turtles have been sighted among the near-shore, shore, and offshore reefs (Rajasuriya, 1997). Ocean warming has a direct impact on reef-building corals, decreasing their growth rates and enhancing coral bleaching. Hoegh-Guldberg (1999) documents that 50 – 70 % of coral reefs worldwide are being directly affected by anthropogenic global climate change. The increase in CO_2 (a heat trapping gas) in the atmosphere which is largely responsible for global warming also causes ocean acidification, with negative consequences on biota.

Intertidal habitats are vulnerable to sea level rise. Mangroves, for instance, with their rich complement of plant and animal species, which rely heavily on an intricate mix of salt and freshwater, would be detrimentally affected by permanent inundation with sea water. What was reported for small South Pacific islands that, with little or no geographic space for inward terrestrial migration, the extent of mangroves is likely to decline (Ellison, 2000) would also be applicable to Sri Lanka. Another adverse impact on some coastal habitats is that prolonged drought conditions lead to increased salinity and conversion of upper tidal zones to hypersaline flats.

Some thermal generalist species may be positively affected by climate change. Iqbal *et al.* (2015) has reported that increased diurnal temperatures have led to the wider spread of locally identified invasive alien plants. Extended drought periods would increase the mortality of many native species leaving ecological niches vacant for colonization by the more adaptable invasive species, leading to further erosion of indigenous biodiversity. Extinction and replacement of species through the differential impacts of climate change would result in considerable alterations in biotic assemblages of natural ecosystems. Climate change is also reported to increase the frequency of pests and disease-causing organisms (Petzoldt and Seaman, 2010).

Importance of improving resilience

Climate change is one of the drivers that are pushing species beyond their limits of survival. While it is inevitable that climate change would take a heavy toll on biodiversity, particularly in the tropics, strengthening resilience of species and ecosystems might contribute towards mitigating these adverse impacts. Two of the Sustainable Development Goals outlined by the United Nations – SDG 13 which warrants urgent action to combat climate change and its impacts, and SDG 15 addressing the need to promote conservation by adopting strategies to mitigate biodiversity loss – must be considered top national priorities. These two are inevitably linked. Although itself adversely affected by climate change, biological diversity could, through the provision of ecosystem services, contribute towards mitigating the impacts and promoting adaptation. Consequently, conserving and sustainably managing components of biodiversity are important in addressing the adverse impacts of climate change. Achieving these objectives would entail formulating and implementing a suite of national strategies (Dela, 2009).

It is reported that in order to limit global warming to 1.5^{0}C, the global net CO_2 emissions must drop to 45% between 2010 and 2030 (UN, 2019). Increasing tree cover worldwide could make a significant contribution towards achieving this objective. In this context, there is considerable national focus on increasing tree cover aimed at contributing towards mitigating climate change. It should be noted, however, that a mere collection of trees would not match the structure or function of a natural forest. It would not contribute towards conservation of biological diversity or provide a range of ecosystem services as would a self-regulating ecosystem comprising a heterogeneous complement of flora and fauna. For instance, though a rubber plantation would contribute towards carbon sequestration it would not otherwise be a substitute for a natural forest. Owing to large scale deforestation in the past, Sri Lanka's biodiversity rich rainforests in the wet zone are now heavily fragmented, and many of the small isolated patches are unable to sustain minimum viable populations of most species. In the dry zone, deforestation and forest degradation continues to take place. Given this bleak scenario, it is necessary to focus on the conservation of our natural forests. Strengthening conservation of the natural forests will have a twofold benefit – boosting the survival of many species and increasing carbon sequestration. Increased emphasis must be paid to ensuring the protection of natural habitats, preferably by expanding the protected area network across all zones so as to incorporate all the remnant patches of forests and linking habitats where possible by establishing corridors. This would allow species to extend their range. Such corridors would also facilitate the altitudinal shifts of species. Watersheds are also important both for protecting biodiversity and enhancing ecosystem services. Augmenting populations of endangered species through *ex-situ* means and restoring degraded habitats would increase the resilience of species and ecosystems. Controlling the spread of invasive species and reducing reliance on non-native species for commercial purposes are also important. Potential impacts of climate change on genetic diversity are little understood, though it is thought that increased genetic diversity would add to the resilience of species to climate change. Traditional varieties that have pre-adapted gene pools for responding to climate change must be preserved and used to a greater extent.

While adopting measures to address the impact of climate change on biological diversity, it is of utmost importance to ensure that steps are taken to mitigate the effects of other stressors, notably environmental pollution and over-harvesting. Enhancing legal provision, regular monitoring, and more stringent law enforcement would help in eliminating these threats.

Research relating to global warming has generally focused on assessing long term changes of temperature, sea level rise, and frequency of inclement weather events. There is a severe dearth of information on impacts of climate change on species and ecosystems. This is partly because examining trends on biotic systems requires long term data sets which are not available in many countries including Sri Lanka. It is important to note here that the permanent 25 ha plot which was established in the Sinharaja rainforest in 1993 for monitoring forest dynamics (Gunatilleke *et al.,* 2006) can be used to generate long-term data for discerning effects of global warming on the rainforest plant community. Since many confounding factors contribute towards species losses, isolating impacts of climate change would be difficult, if not impossible. Studies have therefore resorted to predicting impacts of climate change using data derived from empirical trials.

That climate change is occurring as a result of anthropogenic activities is now an indisputable fact. Sri Lanka should in common with other countries carry out measures aimed at contributing towards addressing the problem of climate change. But it must be understood that Sri Lanka, being a small country, with a low carbon footprint, its contribution towards mitigating climate change could only be minimal in the global context. Of paramount importance for Sri Lanka are the biophysical impacts of global warming, and the effects on the island's rich biological diversity are foremost among these.

References

Algiriyage, D.P.H., Jayaweera, H. and Wijesinghe, M.R. (2020). Inter-population variation in thermal sensitivity of the tropical toad *Duttaphrynus melanostictus*, across a small spatial scale in Sri Lanka. *Journal of Thermal Biology*. https://doi.org/10.1016/j.jtherbio.2020.102568

Allen, C.D (2009). Climate-induced forest dieback: an escalating global phenomenon? *Unasylva*. 60: 43-49.

Araujo, M.B., Ferri-Yanez, F., Bozinovic, F., Marquet, P.A., Valladares, F. and Chown, S.L. (2013). Heat freezes niche evolution. *Ecology Letters*, 16: 1206-1219.

Ashton, P.S., Givnish, T.J. and Appanah, S. (1988). Staggered flowering in the Dipterocarpaceae: new insights into floral induction and the evolution of mast fruiting in the aseasonal tropics. *American Naturalist,* 132: 44-66.

Bradshaw, C.J.A., Sodhi, N.S. and Brook, B.W. (2009). Tropical turmoil: A biodiversity tragedy in progress. *Frontiers in Ecology and the Environment*, 7: 79-87.

Butchart, S.H., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P., Almond, R.E., Baillie, J.E., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Hernandez-Morcillo, M., Oldfield, T.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vie, J.C. and Watson, R. (2010). Global biodiversity: indicators of recent declines. *Science*, 328: 1164-1168.

Carey, C. (2009). The impacts of climate change on the annual cycles of birds. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 364: 3321-3330.

Chakravarty, S., Rai, P., Pala, N.A. and Vineeta, V. (2019). Litter production and decomposition in tropical forests. DOI: 10.4018/978-1-7998-0014-9.ch010.

Chen, I-C, Hill, J., Ohlemüller, R., Roy, D.B. and Thomas, C. (2011). Rapid range shifts of species associated with high levels of climate warming. *Science,* 33: 1024-1126.

Dela, J.D.S. (2009). *Fourth Country Report from Sri Lanka to the United Nations Convention on Biological Diversity*. Battaramulla, Sri Lanka: Ministry of Environment, Sri Lanka. 150 p.

Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C. and Martin, P.R. (2008). Impacts of climate warming on terrestrial ectotherms across latitude. *Proceedings of the National*

Academy of Sciences of the United States of America, 105: 6668-6672.

Ellison, J. (2000). How South Pacific mangroves may respond to predicted climate change and sea level rise. pp. 289-301. Chapter 15. *In*: A Gillespie and W.C.G. Burns (eds.) *Climate change in the South Pacific: Impacts and responses in Australia, New Zealand and small island states*. ISBN 978-0-306-47981-6.

Fischlin, A., Midgley, G.F., Price, J., Leemans, R., Gpal, B, Turley, C., Rounsevell, M., Dube, Tarazona, J. and Velichko, A. (2007). Ecosystems, their properties, goods and services. *In*: M.L. Parry, O.F. Canziani, J.P. Palutikof, C.E. Hanson and P.J.V. Linden (eds.) *Climate change: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel of climate change (IPCC).* Cambridge University Press, Cambridge. pp. 211-272.

Ghalambor, C.K., Huey, R.B., Martin, P.R., Tewksbury, J.J. and Wang, G. (2006). Are mountain passes higher in the tropics? Janzen's hypothesis revisited. *Integrative and Comparative Biology*, 46: 5-17.

Gunatilleke, C.V.S., Gunatilleke, I.U.A.N., Esufali, S., Harms, K.E., Ashton, P.M.S., Burslem, D.F.R.P. and Ashton, P.S. (2006). Species-habitat associations in Sri Lankan dipterocarp forest. *Journal of Tropical Ecology*, 22: 371-384.

Gunatilleke, N., Pethiyagoda, R. and Gunatilleke, S. (2008). Biodiversity of Sri Lanka. *Journal of the National Science Foundation Sri Lanka*, 36: 25-62.

Haag, C.R., Saastamoinen, M., Marden, J.H. and Hanski, I. (2005). A candidate locus for variation in dispersal rate in a butterfly metapopulation. *Proceedings of the Biological Science,* B 272: 2449-2456.

Hamilton, S. (2010). Biogeochemical implications of climate change for tropical rivers and floodplains. *Hydrobiologia*. 657: 19-35.

Hassall, C. and Thompson, D. (2008). The effects of environmental warming on Odonata: A review. *International Journal of Odonatology*, 11: 131-153.

Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research*, 50: 839-866.

Iqbal, M.C.M., Wijesundara, D.S.A. and Ranwala, S.M.W. (2015). Climate change, invasive alien flora and concerns for their management in Sri Lanka. *Ceylon Journal of Science*, 43: 1-15.

Jàrvinen, A. (2006). Global warming and egg size of birds. *Ecography,* 17: 108-110.

Jayasinghe J.A.N.S., Ranasinghe, R.W. and Seneviratne S.S. (2018). Parents' role on egg temperature homeostasis of a ground-nesting shorebird: oriental pratincole (*Glareola maldivarum*). *WildLanka,* 6: 84-93.

Kimball, B.A., Rosenberg, N.J. and Allen, L.H. (1990). *Impact of carbon dioxide, trace gases, and climate change on global agriculture.* ASA Publications, USA.

Kottawa-Arachchi, J. and Wijeratne, M. (2017). Climate change impacts on biodiversity and ecosystems in Sri Lanka: A Review. *Nature Conservation Research*, 2: 2-22.

McCauley, S.J., Hammond, J.I. and Mabry, K.E. (2018). Simulated climate change increases larval mortality alters phenology and affects flight morphology of a dragonfly. *Ecosphere,* 9: e02151.10.1002/ecs2.2151.

Menéndez, R. (2007). How are insects responding to global warming? *Tijdschrift voor Entomologie*, 150: 355–365.

MOE (2012). *The National Red List 2012 of Sri Lanka; Conservation Status of the Fauna and Flora.* Ministry of Environment, Colombo, Sri Lanka. viii + 476pp.

Myers, N. (1990). The biodiversity challenge: expanded hot-spots analysis. *Environmentalist*, 10: 243-256.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A. and Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, 403: 853-858.

Naveendrakumar, G., Vithanage, M., Kwon, H-H, Iqbal, M.C.M., Pathmarajah, S. and Obeysekera, J. (2018). Five decadal trends in averages and extremes of rainfall and temperature in Sri Lanka. *Advances in Meteorology,* 1687-9309.

Pethiyagoda, R. and Manamendra-Arachchi, K. (1998). Evaluating Sri Lanka's amphibian diversity. *Occasional Papers of the Wildlife Heritage Trust*, 2: 1-12.

Petzoldt, C. and Seaman, A. (2010). Climate change effects on insects and pathogens. Pp 6-16, *In: Climate change and agriculture: Promoting practical and profitable responses. Part III*.

Pucko, C., Beckage, B., Perkins, T. and Keeton, W.S. (2011). Species shifts in response to climate change: Individual or shared responses? *The Journal of the Torrey Botanical Society,* 138: 156-176.

Rajasuriya, A. (1997). Coral reefs of Sri Lanka: Current status and resource management. *Proceedings of the conference hosted by the Swaminadhan Research Foundation*.

Rosenzweig, C. and Liverman, D. (1992). Predicted effects of climate change on agriculture: A comparison of temperate and tropical regions. *In*: SK Majumdar (ed). *Global climate change: Implications, challenges, and mitigation measures*, The Pennsylvania Academy of Sciences. USA. pp. 342-361.

Senanayake, U., Weerakoon, D. and Wijesinghe, M.R. (2018). Morphometry and population dynamics of Kirtisinghe's Rock frog in Pitawala patana, Knuckles. *Wildlanka*, 6 (1): 018-026.

Sujeeva, K.D. (2011). *Empirical analysis of temperature changes in Sri Lanka during the last 140 years* (1871-2010). M.Sc. dissertation, University of the Philippines. P. 120.

Sumanapala, A. (2020). How a changing climate threatens Sri Lanka's dragonflies and damselflies (https://news.mongabay.com/2020/05).

Sunday, J., Bates, A. and Dulvy, N. (2012). Thermal tolerance and the global redistribution of animals. *Nature Climate Change*. 2: 686-690.

Swan, B. (1983). *An introduction to the coastal geomorphology of Sri Lanka*. National Museum of Sri Lanka.

Ulloa, J.S., Aubin, T., Llusia1, D., Courtois, E.A., Fouquet, A., Gaucher, P., Pavoine, S. and Sueur, J. (2019). Explosive breeding in tropical anurans: environmental triggers, community composition and acoustic structure. *BMC Ecology*,19. https://doi.org/10.1186/s12898-019-0243-y.

UN (United Nations) (2019). Report of the secretary general on the 2019 Climate action summit – way forward in 2020. *Proceedings of the Climate action Summit* (https://www.un.org/en/climatechange/).

Valenzuela, N., Literman, R., Neuwald, J.L. (2019). Extreme thermal fluctuations from climate change unexpectedly accelerate demographic collapse of vertebrates with temperature-dependent sex determination. *Science Reports,* 9: 4254. https://doi.org/10.1038/s41598-019-40597-4.

Visser, M.E., Both, C. and Lamberchts, M.M. (2004). Global climate change leads to mistimed avian reproduction. *Advances in Ecological Research*, 35: 89-110.

Wang, H., Liu, G.Z., Li, Ye, X., Wang, M. and Gong, L. (2016). Impacts of climate change on net primary productivity in arid and semiarid regions of China. *Chinese Geographical Science*, 26: 35-47.

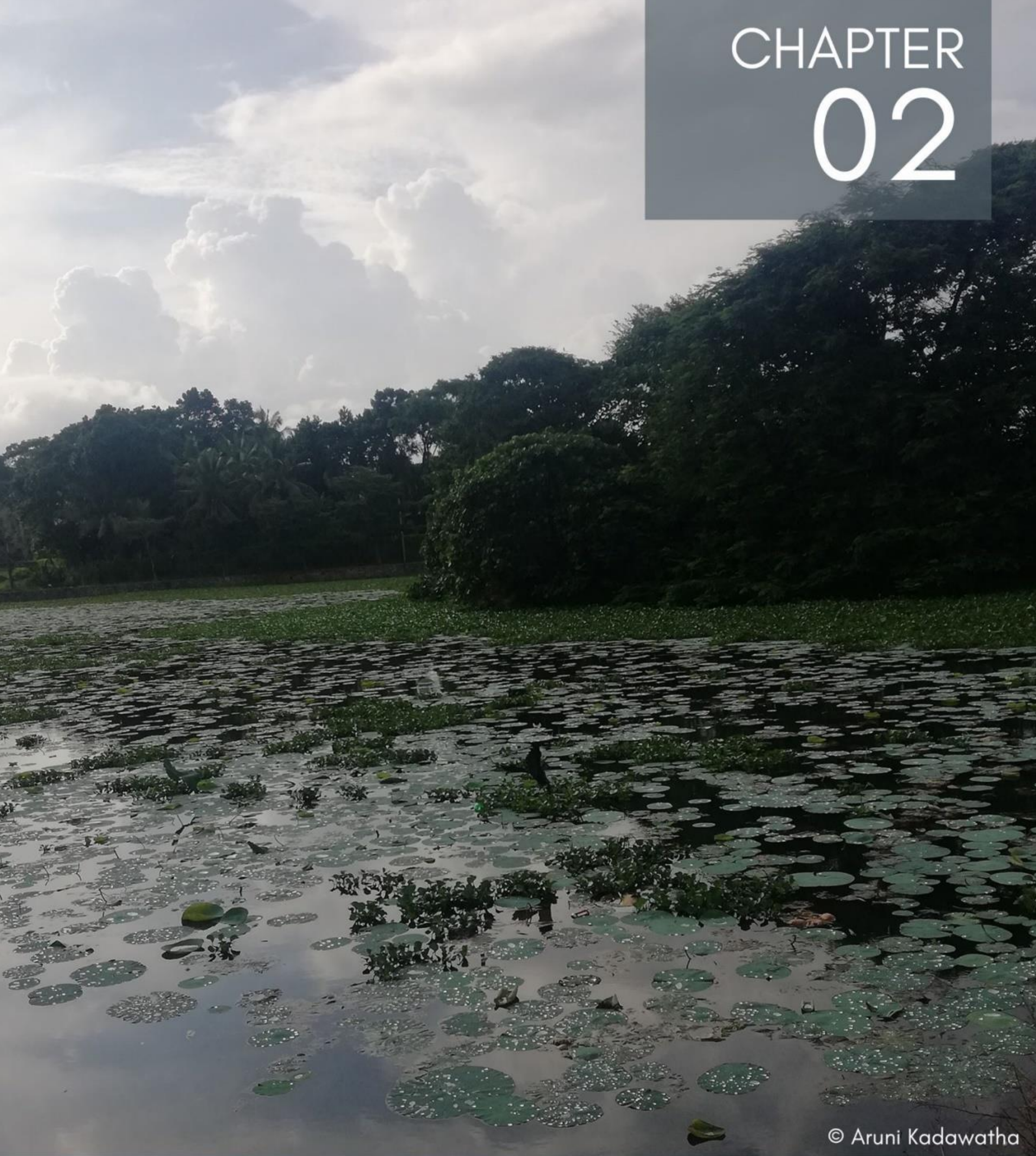
Watson, M. (1986). Soil and climatic requirements. *In*: (eds. P. Sivapalan, S. Kulasegaram and A. Kathiravetpillai) *Handbook on Tea*. Tea Research Institute of Sri Lanka, Talawakelle. pp. 3-5.

Weerakoon, W.M.W., Maruyama, A. and Ohba, K. (2008). Impact of humidity on temperature-induced grain sterility in rice (*Oryza sativa* L). *Journal of Agronomy and Crop Science*, 194: 135-140.

Weerathunga, W.A.M.T., Athapaththu, A.M.G.K. and Shanaka, W.A.K.S. (2018). Physiological response of two freshwater fish species (*Rasbora daniconius* and *Dawkinsia filementosa*) in Sri Lanka to selected factors of climate change. *Proceedings of the 2nd International Conference on Climate Change,* p. 48.

Weerathunga, W.A.M.T. and Rajapaksa, G. (2020). The impact of elevated temperature and CO_2 on growth, physiological and immune responses of *Polypedates cruciger* (common hourglass tree frog). *Frontiers in Zoology,* 17: 3. https://doi.org/10.1186/s12983-019-0348-3

CHAPTER 02



The Role of Nanotechnology in Adapting to Climate Change

K.D.K. Peshala Kumari*

Department of Basic Sciences, Faculty of Allied Health Sciences, General Sir John Kotelawala Defense University, Sri Lanka.
*kripeshala@gmail.com

The Role of Nanotechnology in Adapting to Climate Change

Abstract

Currently, global warming is an international problem which requires immediate attention from all countries. However, there is no single solution identified to overcome the challenge of reducing greenhouse gas emissions and combating climate change. Recently, nanotechnology has been recognized as an emerging field which could make a significant impact on the mitigation of climate change. The impact of nanotechnology on climate change will be exerted through strategies to increase the efficiency of existing energy production and storage systems to reduce the current usage of fossil fuels as well as through the development and improvement of renewable energy generation systems. Sri Lanka is a country which is available abundant solar energy throughout the year. Therefore, the scientists attempt in different ways to introduce cost effective solar cells in order to solve the issues regarding energy supply to the country. Although findings of these research have not been applied for commercial productions yet, they have the potential to be marketed in near future. Therefore, encouragement of Sri Lankan scientists to continue research and development on solar cells will be a worthwhile investment for the future.

Keywords: *Nanotechnology, Automotive, Renewable energy, greenhouse gases*

Introduction

Any change occur in weather patterns of climate system on the earth during an extended period of time, is known as a climate change. It can be seen as different phenomena such as extreme weather events, rising temperatures, shifting wildlife populations and habitats, rising sea levels, etc. As a result of industrial revolution, human activities affected on climate changes significantly, which ultimately led to global warming. Thus, over the last century, there was an unusually rapid increment of average temperature of the earth surface. As the world's population quadrupled during the 20th century, the global energy consumption increased in sixteen fold. Hence, there was a drastic surge in emission of greenhouse gases, which was mainly resulted from automobiles and industries. Greenhouse gases affected on the ozone layer and cause irreparable damage which in turn increase the global warming (Rahman, 2013).

Currently, global warming is an international problem which requires immediate attention from all countries. However, there is no single solution identified to overcome the challenge of reducing greenhouse gas emissions and combating climate change. The identified approaches are to reduce the demand of fossil fuel, improvement of existing energy supplying systems and also discovering novel energy generating systems which use renewable fuels. Recently, nanotechnology has been recognized as an emerging field which could improve existing energy supplying systems as well as to provide alternatives to fossil fuels and thereby contribute for reduction of greenhouse gases emission (Shahzad, 2015).

Nanotechnology allows to manipulate the structure of matter in the nanometer scale which is one-billionth of a meter. The structures in the range of 1 to 100nm scale at least in one dimension are considered as nanometarials and they exhibit superior properties compared to their bulk form. Nanotechnology has the ability to organize matter with atom-by-atom precision to fabricate novel products with supreme properties (Bhushan, 2017).

Nanotechnology will reshape the world through revolutionary breakthroughs in different fields including healthcare, energy storage and production, food and water purification, information technology, instrumentation as well as environment. Hence, the current focus of the attention of scientists has been directed towards nanotechnological applications, in order to find solutions for climate change as well. The impact of nanotechnology on climate change will be exerted through two main strategies, which will lead to reduce the emission of greenhouse gases. The first strategy is to increase the efficiency of existing energy production and storage systems to reduce the current usage of fossil fuels. The second one is the development and improvement of energy generation systems which use renewable energy sources (Mamalis *et al.,* 2011).

Contribution to increase the efficiency of fossil fuel based energy production and storage systems

During past decade, the majority of fossil fuels is utilized for transportation. Therefore, it is reported as the main contributor of greenhouse gas emissions. It was observed that a 10% reduction in weight of a vehicle, reduced the fuel consumption by 10%, leading to a significant fall in gas emissions. Hence the focus of interest of scientists has been directed towards fabricating lighter, stronger and stiffer nanomaterials to replace the metal parts of vehicles, in order to reduce the overall weight. Different types of nanocomposites fabricated using a variety of metals (Fe-

Cr/Al_2O_3, Ni/Al_2O_3), ceramics (Al_2O_3/SiC, Al_2O_3/MoS_2, SiO_2/Ni,), and polymers (polyester/TiO2, polymer/CNT, polymer/layered double hydroxides) which exhibit excellent thermal and mechanical properties are currently under investigations for their application in automotive industry (Mathew *et al.,* 2018). In addition, for the purpose of making aircrafts light weighed, novel nano-coatings which were fabricated using low density metals such as aluminum, magnesium and titanium were applied to replace the conventional bulk metals such as steel. Using carbon nanotube-reinforced polymers in production of aircraft structures is also significantly reduced the airframe weight and thereby the fuel consumption (Verma *et al.,* 2015).

Incorporation of nanocatalysts in the combustion engines of the vehicles, significantly enhances the electricity generation rate and promoted complete combustion of fuel (Khan *et al.,* 2012). This will also help to decrease the fuel consumption and greenhouse gas emission effectively. Enercat is a commercially produced nanocatalyst by oxygen storing cerium oxide nanoparticles, which promoted the complete combustion of fuel in diesel vehicles and reduced fuel consumption by 8%–10% (Khan *et al.,* 2012).

Recently, synthetic nano- based compounds are used as additives in diesel engines in order to increase fuel combustion efficiency. Ultradur® High Speed is a nanotechnology-based engineering plastic developed by the chemical company known as BASF, which improved flowability of the fuel of the engines and thereby saves energy (Khan *et al.,* 2012).

Another suggested method to reduce fuel consumption is the reduction of the friction between moving parts in the engines. Applying nanolubricants and nanocoatings in locomotives of the engines improved wear resistance effectively and thereby reduce the coefficient of friction between them. BORPower is a solid nanocoating produced by the UK-based company, NanoBoron, which contains mono crystal diamond powder and nanoboron as the two main active ingredients. Through minimizing the friction on working metal surfaces by means of a coating and bearing-ball effect, BORPower effectively reduce fuel consumption and greenhouse gas emission by 8-15% (Shafique and Luo, 2019).

The fuel combustion efficiency also can be enhanced by improving the thermal conductivity of the engine (Khan *et al.,* 2012). The addition of nanomaterials to the engine coolant significantly improved the heat transfer rate of the vehicle engines. The investigations revealed that the addition of Al_2O_3–water and SiO2–water nanofluids as the engine coolant improved the efficiency of the fuel utilization (Peyghambarzadeh *et al.,* 2011). Addition of silver and aluminum nanoparticles to pure diesel fuel also greatly reduced the emission rates of hazardous gases such as NOx and CO (Soukh *et al*., 2015).

Tires of the vehicles also can be improved by addition of nanoparticles in rubber composite, which in turn reduce the energy consumption of the vehicle. Investigations revealed that the vehicles equipped with improved tires by application of nano-particles of Al_2O_3 and Si consume less fuel than those with conventional tires (Alkhazraji, 2018).

Developing nanoscale sieves that can filter out toxic agents in fuels and fuel byproducts is another successful approach to reduce greenhouse gas emission to the atmosphere. Recent investigations indicated that nanosieves produced by porous nanoparticles made up of graphene and other inorganic and organic substances are cable of extracting more clean gas from oil by capturing CO_2 before it is released in to the atmosphere. A company known as Oxonica incorporated Envirox™, a fuel borne catalyst and a nanosieve, into commercial diesel which reduces fuel consumption by 10% while reducing CO_2 emissions by up to 15% (Khan *et al.,* 2012).

Contribution for the improvement of fuel cells

Another possible alternative for reducing greenhouse emissions from vehicles is replacing fuel-burning internal combustion engines with fuel cells. Hydrogen fuel cell is an alternative for usage of fossil fuels, which generate power by converting hydrogen into electricity without combustion. However, due to high production cost and the limitations in production and storage of hydrogen prevented them from commercial applications (Khan *et al.,* 2012).

Nanotechnology offers some solutions to these limitations. Utilization of expensive platinum as the catalyst increased the production cost of the hydrogen fuel cells. A team of scientists at the Technical University of Munich recently applied nanoparticles of platinum which doubles the catalytic performance (Garlyyev *et al*., 2019). Researchers at Brown University developed a new nanocatalysts with cobalt-graphene, in which the properties are similar to platinum but the cost is far less (Guo *et al.,* 2012).

In addition, nanotechnology has also applied to improve fuel cell membranes. A research group at the University of Illinois produced a proton exchange membrane consists of a layer of porous silica applied over a few nanometer thick silicon layer, which performs 100 times better than conventional fuel cell membranes (Raj *et al.,* 2017).

As hydrogen is a highly inflammable gas, storing it safely in the fuel cell is another major challenge. Scientists at Rensselaer Polytechnic Institute used graphene sheets with high surface area for binding hydrogen in the fuel cell, which greatly increased the Hydrogen storage capacity (Xin *et al.,* 2014).

Development and improvement of energy generation systems which use renewable energy sources

Utilization of renewable energy technologies is another strategy which leads to reduction of the foils fuel usage as well as the greenhouse gas emission. Renewable energy is collected from renewable resources such as sunlight, wind, tides, rain, geothermal heat and waves which are naturally replenished. Application of nanotechnology for the improvement of renewable energy resources allows to provide cleaner, more efficient, more affordable and more reliable ways to harness renewable energy resources (Khan *et al.,* 2012).

Photovoltaic (PV) cells are the devices which convert light into electricity using semiconducting materials. Among them, solar cells convert sunlight in to electricity using crystalline silicon as the semiconducting material (Khan *et al.,* 2012). The current drawbacks in the use of solar cells for production of electricity are the high cost of manufacturing due to requirement of pure silicone, low absorption rate of solar energy and low efficiency of converting solar energy in to electricity. Recently, nanotechnology is applied to introduce alternative materials which have the ability to absorb wider spectrum of solar energy and also have a higher energy conversion efficiency (Khan *et al.,* 2012).

The application of nanomaterials such as fullerenes, carbon nanotubes and quantum dots resulted lighter, cheaper and more efficient solar cells. Due to high surface area to volume ratio of nanoparticles, they are capable of collecting higher amount of solar radiation, compared to bulk materials in conventional photovoltaic cells. The application of nanoparticles of lead selenide indicated higher energy conversion efficiency due to release of more electrons when hit by a photon of light. Instead of expensive silicon, usage of organic or plastic thin-films which are based on nanoparticles and polymers leads to manufacture cost effective solar cells. (Khan *et al.,* 2012).

The most recent advance in solar cell development is the application of perovskites instead of silicon. Perovskites are organic–inorganic halide compounds with a special crystal structure, which showed a promising high-performance in solar cell technology. Due to usage of highly abundant raw materials and low cost processing, perovskite solar cells may have the potential to enter the market in near future (Qiu, *et al.,* 2018).

Wind energy is also a free, clean and inexhaustible energy which is recognized as a potential source for electricity generation. Continuous efforts have been made in order to increase the performance of wind power machines or wind turbines, in term of efficiency as well as cost-effectiveness. Recently, application of nanotechnology on wind turbine blade design, offshore deployment and operation, significantly enhanced the efficiency of energy conversion of wind turbines. Through application of nanocoatings and nanopaints, the cycle lifetime of the wind turbine blades is successfully enhanced. It also leads to reduce the weight of the turbine blades significantly, which in turn increases the performance of the turbines. The efficiency of energy conversion is also increased by the use of nano-enabled wires and cables, nanofluids and nanolubricants in wind power machines (Muzammil *et al.,* 2019).

The Sri Lankan perspective

The automobile industry is still in an infant stage in Sri Lanka, therefore application of nanotechnology as a strategy of efficient usage of available fossil fuels in transportation is not practicable. However, considering about the renewable sources of energy, Sri Lanka has a very rich sun energy supply throughout the day as it is a county located near the equator. Therefore, the Sri Lankan scientists' attention has been focused on the development of high efficient solar cells at an affordable cost.

Majority of the research that have been carried out on photovoltaic systems, mainly focused on development of low cost thin film solar cells and the discovery of low cost alterative solar energy conversion materials. Recently, Sri Lankan scientists initiated the application of nanotechnology to create novel concepts, ideas and materials, which will enhance the efficiency of solar cells while reducing the production cost.

During last decade, Sri Lankan scientists who worked on photovoltaic cells, mainly focused on the improvement of dye-sensitized solar cell (DSSC) by applying nanotechnology in order to discover novel electrolytes, dyes, electrodes, etc. They explored the effectiveness of solid-state electrolytes as well gel-polymer electrolytes. The different types of dyes including Indoline D-358 and N719 were tested in the terms of electron transport efficiency. As an attempt to apply nanotechnology to enhance the efficiency of solar cells, they incorporated nanostructures such as titania nanotubes, optically transparent TiO_2 nanocrystalline,

$CaCO_3$ coated SnO_2 nanocrystalline, SnO_2/MgO composite thin Film, ZnO nanostructures and nanocomposites of TiO_2 nanotubes in to different components of the solar cells. Through application of these nanostructures in dye-sensitized solar cell, they observed significant improvements in energy conversion efficiency. In addition, they invented in-house method for spray pyrolysis technique which allowed them to synthesis novel nano-films to apply for the development of novel photovoltaic cells (https://scholar.google.com/ citations?user= q101KUgAAAAJ&hl=en).

During past five years there was a prompt advancement in the research field of photovoltaic cells in Sri Lanka, due to application of novel nanotechnological concepts. Among different types of solar cells, the Sri Lankan scientists continue to pay attention towards mainly on dye-sensitized solar cells due to their low production cost and higher energy conversion efficiency.

A group of scientists developed dye-sensitized solar cells using interconnected nanoparticles of semiconductors such as ZnO and SnO_2. They introduced an ultra-thin layer (~1 nm or less) of a wide band-gap semiconductor or an insulator on the surface of interconnected nanoparticles of SnO_2. Newly developed nano-composite thin film based dye-sensitized solar cells convert the solar energy in higher efficiency compared to solar cells fabricated using conventional semiconductors. For the development of these solar cells they synthesized SnO_2 nanoparticles by acid route which applied tin(ii) chloride as a starting material and also by hydrothermal method using tin(iv) chloride (Wanninayake *et al*., 2016a). Furthermore, they applied an ultrathin covering layer of $CaCO_3$ on the surface of SnO_2 nanoparticles to enhance the efficiency further (Wanninayake *et al*., 2016b).

They also achieved a significant improvement in energy conversion efficiency of these devices through applying a double-dye sensitization, using different members of the indoline dye family. The combination of D149/D131 showed the maximum energy conversion efficiency. They observed the improvement of efficiencies by 5.10% and 4.80% for a liquid electrolyte and a gel electrolyte solar cells respectively. The overall results of their investigations discovered that there is an enhancement in efficiency of about 30% for the D149/D131 combination, compared to their individual performances (Wanninayake *et al.,* 2017).

Another group of scientists from National Institute of Fundamental Studies of Sri Lanka investigated on alternative materials to replace highly expensive platinum which uses as the counter electrodes in solar cells.

They reported that, carbon based nanomaterials can be tailored in order to provide higher efficiency similar to platinum. They developed a novel DSSC applying expanded graphite produced from Sri Lankan natural vein-type graphite which were obtained from Bogala mines. They observed 8% improvement in energy conversion efficiency through applying graphite as the counter electrode (Kumara *et al.,* 2017). The same group of scientists developed a dye-sensitized solar cells applying a dense layer of ZnO on FTO glass plate which is covered by a mesoporous layer of interconnected ZnO nanoparticles, using the spray pyrolysis technique. The results of the study revealed that the newly invented solar cell showed a significant improvement of energy conversion efficiency (Kumar *et al.,* 2018).

Jayaweera and coworkers fabricated a novel solar cell by depositing a mesoporous layer of SnO_2/MgO film, on a thin film of CdS nanostructures using chemical bath deposition method. Through applying another layer of ZnS on the prepared CdS nanosheets, they enhanced the energy conversion efficiency successfully (Jayaweera *et al*., 2018).

Kumarasinghe and coworkers attempted to reduce the production cost of the solar cells considerably by applying naturally abundant carbon sources as the counter electrode catalysts in the place of highly expensive platinum. They invented novel dye-sensitized solar cells using different forms of activated carbon derived from bio-materials as the counter electrode. The maximum energy conversion efficiency was observed in the cells produced using activated charcoal from coconut shells which was deposited on conducting tin oxide glass as a thin film (Kumarasinghe, 2019).

Recently, a team of Sri Lankan scientists fabricated highly efficient perovskite solar cells. They employed solvent-free powder pressed cuprous iodide (CuI) as a hole-transporting material which enhanced the energy conversion efficiency by 8.0%. It is the maximum efficiency reported for perovskite solar cells fabricated in an open environment with CuI using as the hole-transporting material (Uthayaraj *et al.,* 2019).

Conclusion and future directions

Nanotechnology is a promising approach to mitigate the global warming issue through increasing the efficiency of existing technologies in order to minimize the current utilization of fossil fuels and also by improving renewable energy systems. Among the renewable energy sources, solar power is considered the cleanest, inexhaustible, import-independent, and affordable source. The use of the solar energy for electric generation does not cause further pollution or damage to the environment like conventional fossil fuels.

Sri Lanka is a country which is available abundant solar energy throughout the year. Therefore, the scientists attempted in different ways to introduce cost effective solar cells in order to solve the issues regarding energy supply to the country. Although findings of these research have not been applied for commercial productions yet, they have the potential to be marketed in near future. The concepts arise from these researches may leads to introduction of less sophisticated solar energy converting devices which are affordable for a middle income country like Sri Lanka. Therefore, encouragement of Sri Lankan scientists to continue research and development on solar cells will be a worthwhile investment for the future.

References

Alkhazraji, A.N. (2018). Enhancement of mechanical properties and handling characteristic of tire rubber using different percentage of Nano Aluminum Oxide and Carbon Black. *SMR*, 20: 100.

Bhushan, B. (2017). Introduction to nanotechnology. *In*: Bhushan B. (ed.). *Springer handbook of nanotechnology*. Springer handbooks. Springer, Berlin, Heidelberg, 1-19.

Garlyyev, B., Kratzl, K., Rück M., Michalička, J., Fichtner, J., Macak, J.M., Kratky, T., Günther, S., Cokoja, M., Bandarenka, A.S., Gagliardi, A. and Fischer, R.A. (2019). Optimizing the size of platinum nanoparticles for enhanced mass activity in the electrochemical oxygen reduction reaction. *Angewandte Chemie*, 58(28): 9596-9600.

Guo, S., Zhang, S., Wu, L. and Sun, S. (2012). Co/CoO nanoparticles assembled on graphene for electrochemical reduction of oxygen, *Angewandte Chemie*, 51(47): 11770-11773.

Jayaweera, E.N., Kumara, G.R.A., Kumarage, C. and Ranasinghe, S.K. (2018). CdS nanosheet-sensitized solar cells based on SnO_2/MgO composite films. *Journal of Photochemistry and Photobiology A: Chemistry,* 364: 109-115.

Khan, W.S., Ceylan, M., Asmatulu, E. and Asmatulu, I.R. (2012). Effects of nanotechnology on global warming. *In: Proceedings of the 2012 Midwest Section Conference of the American Society for Engineering Education*.

Kumara, G.R.A., Deshapriya, U., Ranasinghe, C.S.K., Jayaweera, E.N. and Rajapakse R.M.G. (2018). Efficient dye-sensitized solar cells from mesoporous zinc oxide nanostructures sensitized by N719 dye. *Journal of Semiconductors*, 39(3): 033005.

Kumara, G.R.A., Jayaweera, E.N., Itawala, H.M.T.G.A., Malikaramage, A.U., Wickramasinghe, G.K., Senaratne, A., Gunawardhana, N. and Rajapakse R.M.G. (2017). Low-cost dye-sensitized solar cells utilizing expanded graphite in dye-sensitized solar cells for efficient power generation. *In: The 28th International Symposium on Transport Phenomena*. 22-24th September 2017, Peradeniya, Sri Lanka.

Kumarasinghe, K., Kumara, G.R.A. Rajapakse, R.M.G. and Liyanage, D.N. (2019). Activated coconut shell charcoal based counter electrode for dye-sensitized solar cells. *Organic Electronics*, 71: 93-97.

Mamalis, A.G., Ramsden, J.J., Holt, G.C., Vortselas, A.K. and Mamali, A.A. (2011). The effect of nanotechnology on mitigation and adaptation strategies in response to climate change. *Nanotechnology Perceptions*, 7: 159–179.

Mathew, J., Joy, J. and George, S.C. (2019). Potential applications of nanotechnology in transportation: A review. Journal of King Saud University. *Science*, 31(4): 586-594.

Muzammil, W.K., Rahman, M.M., Fazlizan, A., Ismail, M.A., Phang, H.K. and Elias M.A. (2019). Nanotechnology in renewable energy: Critical reviews for wind energy. *In*: S. Siddiquee, G. Melvin, M. Rahman (eds.). *Nanotechnology: Applications in Energy, Drug and Food*. Springer.

Peyghambarzadeh, S.M., Hashemabadi, S.H., Hoseini, S.M. and Seifi Jamnani, M. (2011). Experimental study of heat transfer enhancement using water/ethylene glycol based nanofluids as a new coolant for car radiators. *International Communications in Heat and Mass Transfer*, 38: 1283-1290.

Qiu, L., Ono, L.K. and Qi, T. (2018). Advances and challenges to the commercialization of organic–inorganic halide perovskite solar cell technology. *Materials Today Energy*, 7: 169-189.

Rahman, M.I. (2013). Climate change: A Theoretical Review. *Interdisciplinary Description of Complex Systems*, 11(1): 1-13.

Raj, B., Van de Voorde, M. and Mahajan, Y. (2017). *Nanotechnology for energy sustainability: Applications of nanotechnology*, John Wiley & Sons. doi: 10.1002/9783527696109.

Shafique, M. and Luo, X. (2019). Nanotechnology in transportation vehicles: An overview of its applications, Environmental, health and safety concerns. *Materials*, 12: 2493.

Shahzad, U. (2015). Global Warming: Causes, effects and solutions. *Durreesamin Journal*, 1(4).

Soukht, S.H. Jafarmadar, S. Taghavifar, H. and Ashrafi, S.J. (2015). Reduction of emissions and fuel consumption in a compression ignition engine using nanoparticles. *International Journal of Environmental Science and Technology*, 12: 2245–2252.

Uthayaraj, S., Karunarathne, D.G.B.C., Kumara G.R.A., Murugathas, T., Rasalingam, S., Rajapakse, R.M.G., Ravirajan, P. and Velauthapillai, D. (2019). Powder pressed Cuprous iodide (CuI) as a hole transporting material for Perovskite solar cells. *Materials*, 12: 2037.

Verma, P. Saini, P. and Choudhary, V. (2015). Designing of carbon nanotube/polymer composites using melt recirculation approach: E ect of aspect ratio on mechanical, electrical and EMI shielding response. *Materials and Design*, 88: 269-277.

Wanninayake, W.M.N.M.B., Premaratne, K. and Rajapakse, R.M.G. (2016a). High efficient dye-sensitized solar cells based on synthesized SnO_2 nanoparticles. *Journal of Nanomaterials*, 2016, https://doi.org/10.1155/2016/5203068.

Wanninayake, W., Premaratne, K., Kumara, G.R.A. and Rajapakse, R.M.G. (2016b). A study of the efficiency enhancement of the gel electrolyte-based SnO2 dye-sensitized solar cells through the use of thin insulating layers. *Electrochimica Acta*, 210: 138-146.

Xin, G., Sun, H., Scott, S.M., Yao, T., Lu, F., Shao, D., Hu T., Wang, G., Ran, G. and Lian, J.A. (2014). Advanced phase change composite by thermally annealed defect-free graphene for thermal energy storage. *ACS Applied Materials and Interfaces*, 6(17).

CHAPTER
03

© Aruni Vimukthi

Urban Greening to Mitigate Rising Urban Heat Island (UHI) Effect in Sri Lanka: Challenges and Opportunities

G.D. Kapila Kumara[1], D.H.B.R. Dassanayake[2], S.P. Nissanka[3] and C.K. Beneragama[3*]

[1]Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Sri Lanka.
[2]Wayamba University of Sri Lanka, Kuliyapitiya , Sri Lanka.
[3]Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.
*chalindab@gmail.com

Urban Greening to Mitigate Rising Urban Heat Island (UHI) Effect in Sri Lanka: Challenges and Opportunities

Abstract

Urban Heat Island (UHI) effect is among the challenges faced by urban dwellers, that is created as a result of inevitable rapid urbanization. An increase in UHI effect over the years in Sri Lanka has been reported by previous studies. The current climate change scenarios augment the effect of UHI urging necessity for possible alternatives. Urban greening can be recommended as a viable and sustainable solution to mitigate the UHI effect. Green roofs, green walls, street trees, urban parks, urban forests, vegetation cover on the ground and urban home gardens can play a pivotal role in urban greening. The ways of urban greening together with challenges and opportunities are discussed in this chapter.

Keywords: *Green roof, green wall, urban forest, urban park*

Urban environment and urban planning

A globally accepted definition is not available to describe 'urban' at present. As a result, different countries use different definitions based on the administrative status, population size and density, and the extent of non-agricultural activity (UNESCAP, 2013). On the Sri Lankan definition, it has been estimated that, *c.a.* 18.4% of the total population live in urban environments with an annual growth rate of 1.5% as of 2018 (World Bank, 2020). However, a recent report suggesting an alternative 'urban' definition to Sri Lanka estimates that the urban population in Sri Lanka can be as high as 43.8% (Weeraratne, 2016).

Problems of urbanization

Although urbanization has long been associated with human development and progress creating a number of benefits to people such as employment opportunities, access to safe food and drinking water, and access to goods and services, several problems of urbanization have also been identified. Among the problems of urbanization, nutrition-related major health problems (Kuddus *et al.*, 2020), degradation of environmental quality (Shahbaz *et al.*, 2014), managing urban waste (Vij, 2012) and rising temperature which is often referred to as 'Urban Heat Island (UHI) effect' (Tam *et al*., 2015) are noteworthy. With the climate-change scenarios, it is extremely important to re-visit the ways to mitigate the UHI effect as it impacts the urban dwellers adversely (Akbari *et al*., 2016).

What is urban heat island (UHI) effect?

As shown in the Figure 1, the UHI effect is a phenomenon in which a significant difference in temperature can be observed between a city and its surrounding rural areas, or among different parts of a city (O'Malley *et al*., 2014). In general, a 3-5°C variation can be observed between urban and rural areas in the day time, whereas in the night, a greater variation as high as 12°C can be observed due to the slow release of heat from the urban surface (Kikon *et al.*, 2016). There are two main types of UHI effects: (i) atmospheric UHI effect: the elevated air temperature in urban areas in comparison to that of rural areas and (ii) surface UHI effect: during sunny days, urban surfaces absorb more solar energy and become warmer than the moist and often shaded rural surface (EPA, 2013; Sachindra *et al*., 2016). The UHI phenomenon is recognized as one of the major negative impacts of the rapid urbanization (Tran *et al*., 2006) which transforms a significant amount of natural landscape into built environments leading to an increase in temperature in the environment.

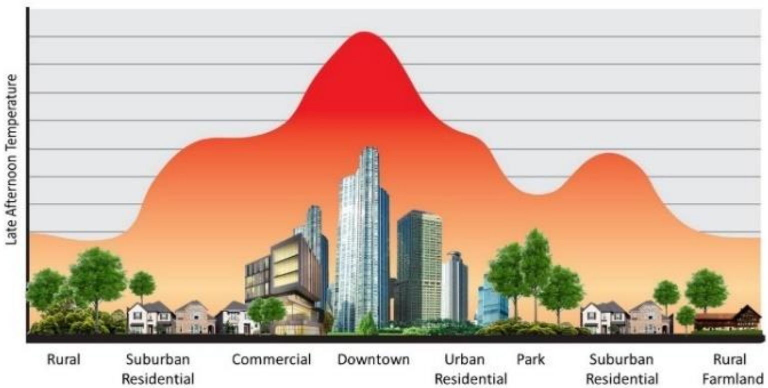


Figure 1: Urban Heat Island Effect

As revealed in some previous investigations, the Colombo District (Ranalage *et al*., 2018a) and the Kandy city (Ranalage *et al*., 2018b) have undergone rapid infrastructural and landscape transformation due to various development projects over the past decade, resulting UHI formation. Ranalage *et al*. (2017) showed that there is a strong positive correlation between Land Surface Temperature (LST) and Normalized Difference Built-up Index (NDBI: an index for identifying and classifying built-up areas or impervious surfaces) across three time points (1997, 2007 and 2017) investigated in the Colombo Metropolitan Area (CMA). Figures 2 and 3 clearly indicate the mirrored effect of built-up areas and impervious surfaces on LST specifically during the 2007–2017 period when urbanization was more rapid.

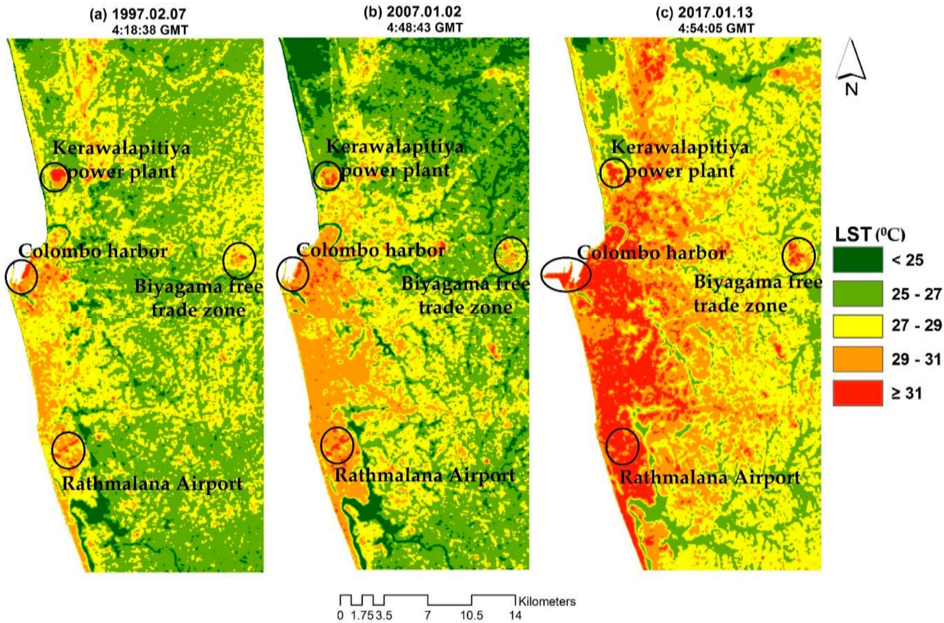


Figure 2: Land Surface Temperature (LST) maps of the Colombo Metropolitan Area in (**a**) 1997; (**b**) 2007; and (**c**) 2017 (Source: Ranalage *et al*., 2017).

As reported by Ranalage *et al*., (2018a), the mean surface temperature in the Colombo Metropolitan area (within 5 km from the city center) was

30.1 and 31.2 °C in 2007 and 2017 respectively, whereas the mean air temperature of Colombo city during the years 1901-2001 remained around 27 °C (Ukwattage and Dayawansa, 2012), depicting a rise in UHI effect in the recent past.

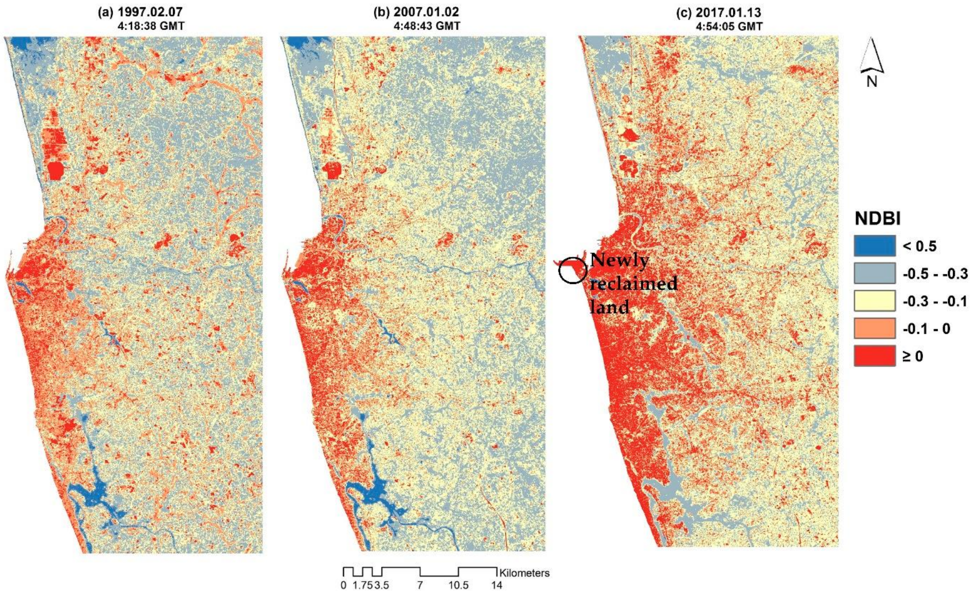


Figure 3: Normalized Difference Built-up Index (NDBI) maps of the Colombo Metropolitan Area in (**a**) 1997; (**b**) 2007; and (**c**) 2017 (Source: Ranalage *et al*., 2017).

Causes of UHI

There is plenty of evidence that urban geometry, thermal properties of surface material and anthropogenic activities in urban areas are the major causes of UHIs (Emmanuel and Fernando, 2007; Lee and Levermore, 2019; Le *et al.*, 2019; Sen and Roesler, 2019; Raj *et al.,* 2020). More specifically, (i) vast amount of densely situated buildings with bulky thermal mass and heat retaining properties, (ii) anthropogenic heat emissions, pollution and energy consumption, (iii) nature of the activities performed (e.g. industrial cities have high UHI intensities), (iv) lack of green areas and intense land coverage with less permeability, (v) use of low-albedo materials for rooftops, walls, parking lots, roads and pavements (e.g. asphalt and concrete), (vi) reduced speed of wind caused by design and layout of the built environment, and (vii) urban 'greenhouse' effect (increased incoming long-wave radiation from polluted urban atmosphere) can be identified as the main causes for UHI effect. Consequently, accumulation of excess amounts of heat energy causes urban areas to have elevated temperatures compared to the surrounding rural areas.

Effects of UHI on people and environment

Effects of UHI can be classified under two major categories: on people and on microclimates, which are not mutually exclusive (O'Malley *et al.*, 2014). Elevated temperatures caused by UHIs directly influence the health and comfort of the population in cities (Sachindra *et al*., 2016). The optimum temperature for human body functions is 37±1°C (NIOSH, 1986). A simple change of 1°C outside this range can initiate symptoms of hypothermia or heat stress. According to the NIOSH (1986), heat exposure can have both acute and chronic effects. Exposure to short-term heat events can cause fainting, heat stroke, heat rash, heat exhaustion, heat cramps, and death. Repeated exposure to high heat can result in chronic problems such as reduced heat tolerance and kidney stones (Keim *et al*., 2002). Emmanuel and Fernando (2007) showed that, Colombo has already been subjected to some outmigration toward cooler areas such as Kandy, due to the increasing trend of thermal discomfort.

Elevation of ground-level ozone, increased energy consumption for cooling, elevated emissions of air pollutants and greenhouse gases, impaired water quality (Ranalage *et al*., 2017), increased use of water, reduced working performance, heat stress resulting death of the bird population, heat stress in plants, alteration of local climates (i.e. wind patterns, humidity changes, storms, floods) and change in local ecosystems are regarded as other consequences of the UHI effect (Emmanuel and Fernando, 2007).

Strategies to reduce UHI effect

The urban heat island effect could be mitigated basically in three ways: (a) by increasing the albedo of the urban surface, (b) by increasing evaporation/ evapotranspiration (Sailor, 2006) and (c) by harnessing natural wind pattern (O'Malley *et al*., 2014) as elaborated bellow.

- High albedo materials can reflect much of the solar radiation and reduce heat absorption. Using high albedo materials for roofing, walls, roads and paving can minimize surface temperature. However, multiple reflections of light and heat throughout urban canyons may further amplify the warming process.

- Increased amount of water bodies may reduce temperature due to their evaporative action and enhanced wind speed. However, the high thermal inertia limits of water may delay nocturnal cooling once water bodies are warmed
- Pervious pavements allow water to infiltrate and create cooling effect by evapotranspiration. For instance, inter-locking pavings are more pervious than concrete or asphalt pavings.
- Vegetation cover prevents direct exposure of land surfaces to solar radiation and leads to lower surface temperatures through evapotranspiration. Hence, the urban greening, that is, incorporation of trees, shrubs and grass to urban landscape is highly recommended as an UHI mitigation strategy with multiple benefits.

Urban greening and its benefits

Most of the urban planning and sustainable development projects begin by emphasizing the multiple benefits of urban green spaces (Li and Pussella, 2017). The European Commission (2013) defined urban green spaces as a strategically planned network of high quality natural and semi natural areas with other environmental features, which are designed and managed to deliver a wide range of ecosystem services and protect biodiversity in urban settings. This includes smaller green space features (such as street trees and roadside vegetation), green spaces not available for public access or recreational use (such as green roofs and facades, or green space on private gardens), and larger green spaces (such as parks, playgrounds or greenways) that provide various social and recreational functions (Li and Pussella, 2017).

Current high rate of urbanization and its impacts reduce green spaces gradually and remarkably in the Colombo city resulting 7.16 m^2 per capita value (2015) below United Nations (30 m^2) or World Health Organization (9 m^2) standards (Rakhshandehroo *et al*., 2015). This indicates that well-planned ‘Green Infrastructure’ projects are needed to ensure sustainability and quality of life in most of the cities in Sri Lanka, undergoing rapid urbanization.

Environmental benefits

Evidence is mounting on many different environmental benefits of urban green spaces. These include natural biodiversity conservation while providing habitats to flora and fauna (Kong *et al*., 2010), improving urban climate by reducing air temperature and urban heat islands (Bowler *et al*, 2010), improving air quality by decreasing air pollution and carbon sequestration (Nowak *et al*., 2006), noise abatement (Jang *et al*., 2015) and cleaning up contaminants (Churkina *et al*., 2015). In addition, numerous researches have emphasized the long-term benefits of urban greening programs to mitigate the impacts of climate change and to make sustainable cities (Lo *et al*., 2017; Calvi, 2015; Jeanjean *et al*., 2015; Sicard *et al*., 2018).

Social benefits

Urban green spaces are essential for livable and sustainable cities as they significantly contribute to human and social wellbeing of the inhabitants. For the same reason, parks and greenways (green space facilitating walking, cycling and other activities) recently developed in many cities of the country have gained great attraction (Rakhshandehroo *et al*., 2015). Green spaces have a range of health benefits triggered by comfortable living environment, increased physical activities/ exercises, increased aesthetic appeal and relaxation (Van den Berg *et al*., 2015). More importantly, it is evident that surrounding greenness has positive impact on cognitive development and increased attention in school children of "smart" generation (Yi, 2015). Further, urban green spaces provide a good platform for local residents as a meeting place for their different social interactions (Li and Pussella, 2017).

Material benefits

Urban greening can supply food to support both food and nutrition security through back-yard gardening (Paganini *et al*., 2018) as well as through plant factories (Liaros *et al*., 2016). Apart from that, urban forests can be a source of timber (Gundersen *et al*., 2005) and non-timber forest products (Kaoma and Shackleton, 2015).

Although impacts of urban greenery on well-being of individuals are small, the potential cumulative benefit at the community level highlights the importance of policies to protect and promote urban green spaces for well-being of man-kind as a whole.

Ways of urban greening in Sri Lanka

The possible ways of urban greening such as green roofs, green walls, street trees, urban parks, urban forests, vegetation cover on ground and urban home gardens are discussed here (Figure 4).

Green roofs

Green roofs involve growing plants on rooftops, partially or completely covered with vegetation grown on a growth substrate, laid over a waterproofing membrane (Peck *et al*., 2001). The interest for green roofs is increasing because of the benefits that these offer, such as decreasing the urban heat island effect (Takebayashi and Moriyama, 2007), storm water runoff mitigation (Getter *et al*., 2007), saving on energy consumption of buildings and keep buildings cool (Wong *et al*., 2003; Niachou *et al*., 2001), increasing the life span of a typical roof (Carter and Keeler, 2006), ability to filter harmful air pollutants (Liesecke and Borgwardt, 1997) and water pollutants, improve urban biodiversity (Brenneisen, 2003) and on top of all, these green roofs provide aesthetically pleasing open space in ultra-urban areas. It has been reported that, well-established green roof surfaces can reduce the temperature under the roof by *c.a.* 4 °C (Dareeju *et al*., 2011; Dassanayake and Beneragama, 2011) and on the roof surface by *c.a.* 7.3 °C (Qin *et al*., 2012). However, the green roofs are still at its infant stages in Sri Lanka.

Green walls

Among the greening typologies, green walls are the intentionally covered vegetation on vertical built structures. They are also referred as living walls or vertical gardens. Green wall technologies can be categorized into two major categories as green facades and living walls. Green facades are a type of green wall system in which climbing plants or cascading groundcovers are trained to cover specially designed supporting structures. Self-clinging plants such as *Ficus pumila* or creeping type plants such as *Thumbergia* spp. are commonly being used to create green facades. In contrast, living wall systems are composed of pre-vegetated panels, vertical modules or planted blankets that are fixed vertically to a structural wall or frame. Due to the diversity and density of plant life, living walls typically require more intensive maintenance (supplying of nutrients to fertilize the plants) than green facades (Freed *et al*., 2008). In addition, selecting plants for the living walls requires special attention in relation to geotropism response in plants (Kariyawasam *et al*., 2017).

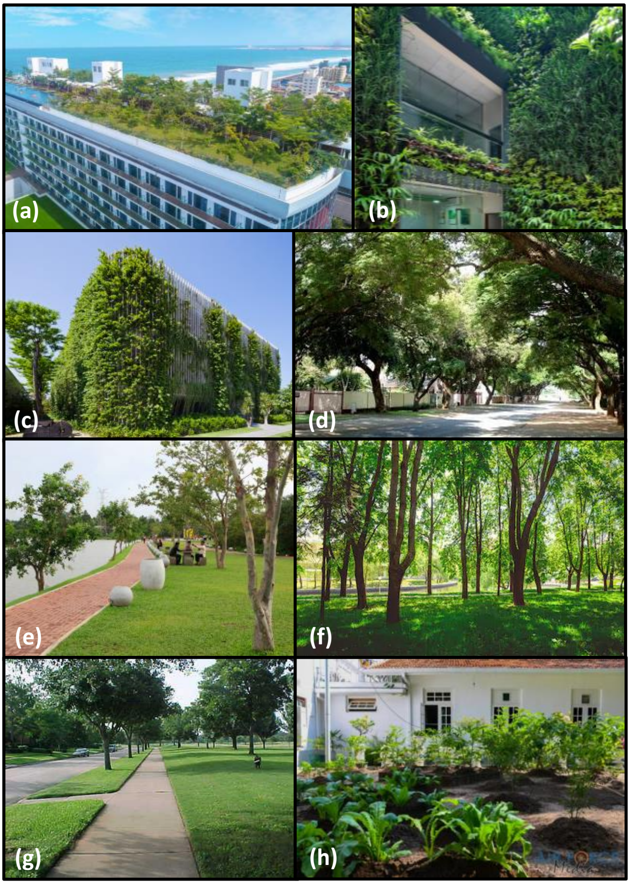


Figure 4: Ways of urban greening: (a) Green roof, (b) Living wall, (c) Green façade, (d) Street trees, (e) Urban parks, (f) Urban forests, (g) Vegetation cover on ground and (h) Urban home gardens.

(Photo credits: (a) https://www.marinobeach.com/, (b) https://www.skytech.lk/horticulture-solutions/, (c) https://www.homedit.com/green-facades-and-vertical-gardens/, (d) http://www.srilankaguardian.org/ 2008/06/save-street-trees.html, (e) https://www.timeout.com/sri-lanka/things-to-do/walking-tracks-in-colombo, (f) https://www.shutterstock.com/search/urban+forest, (g) https://www.mlive.com/ada-cascade/ 2012/07/hall_street_sidewalk_to_cross.html, (h) http://www.airforce.lk/news.php?news=4559)

Green walls have a number of benefits such as increasing the outdoor and indoor comfort, ecological value, biodiversity, insulation properties, improvement of air quality, improving the social well-being of citizens and most importantly, mitigation of the urban heat island effect (Rakhshandehroo *et al.*, 2015). Although the temperature reduction in the environment by the green walls is already well established and well documented (Price *et al*, 2015), a limited number of studies have been conducted in Sri Lanka in relation to green walls (Kariyawasam *et al*., 2017).

Street trees

Street trees, defined as trees growing along public streets and managed by the city are a prominent feature in urban greening because of their visual and physical impacts on the quality of urban life (McPherson *et al*., 2016).

Urban street trees provide a number of benefits that include reduced and more appropriate urban traffic speeds (Calvi, 2015), create safer walking, increased security, protecting skin from sun and heat (Burden, 2006), reduce harm from tailpipe emissions (Jeanjean *et al*, 2015), lowering Ozone (Sicard *et al.*, 2018), making cities more aesthetically pleasing environments (Todorova *et al.*, 2004), soften and screen necessary street features (Gul *et al.*, 2012), reduce blood pressure, improve overall emotional and psychological health (Polizel *et al.*, 2019) and connecting nature with the human senses (Burden, 2006). Most notably, street trees have the potential of reducing the environmental temperature (Mackey *et al.*, 2012) and as reported by Wang and Akbari (2016), that reduction is as high as *c.a.* 4°C.

The science and art of selection, placement and maintenance of street trees in cities will create a peaceful living environment while reducing the urban temperature significantly. The ideal street trees for urban environments must have straight trunks with a vertical top and a free trunk height of at least two metres. They should not bear large fruits or heavy seeds and brittle branches. Watering, staking, watering, pruning are the essential maintenance activities. *Lagerstroemia speciosa* (Murutha), *Pongamia pinnata* (Magul- Karanda), *Barringtonia asiatica* (Mudilla) and *Phyllanthus embilica* (Nelli) can be recommended as suitable native trees for street planting in Sri Lanka (Madurapperuma *et al.*, 2016). In addition, *Schleichera oleosa* (Kon), *Terminalia arjuna* (Kumbuk), *Syzygium cumini* (Maadan), *Terminalia bellirica* (Bulu), can also be recommended for selective approaches (Author compilation).

Urban parks

An urban park is a park-in-the-city to offer recreation and green space to residents of, and visitors to, the city. The design, operation and maintenance are usually handled by government agencies, typically at the local level. The urban parks are more inclusive green places than non-urban green areas, and that urban parks can promote social cohesion (Peters *et al*, 2009).

Areas of urban parks can be categorized as active and passive recreation areas. Active recreation areas which require intensive development, include sports fields, jogging paths, fitness trails, swimming pools and gymnasiums. Passive recreation areas emphasize the open-space aspects of a park and allows for the preservation of natural habitat. Passive recreation typically requires low level development, such as rustic picnic areas, benches/ sitting areas and summer huts surrounded by beautiful sceneries.

Benefits of urban parks include supporting high biodiversity, improve health and well-being, cooling effect, improve air quality and contribute to carbon sequestration, water regulation and storm water runoff mitigation and promoting tourism (Konijnendijk, 2013). The potential of urban parks in mitigating UHI effect has also widely been studies (Cao *et al.*, 2010; Chang and Li, 2014; Algretawee *et al.,* 2019). As reported by Feyisa *et al.* (2014), cooling effects of parks mainly depend on species and canopy cover of the trees that are used, in addition to the size and shape of parks.

Urban forests

Urban forests refer to the forests and associated vegetation growing in anthropogenic biomes (anthromes) with higher levels of population density (Tyrväinen *et al*., 2005). With the developmental activities, it is inevitable to see a reduction in the forest cover over the years, thus making people to think about the sustainability of urban forests. Diversity, connectedness, and dynamics of an urban forest are the key characteristics that determine its sustainability (Dwyer and Nowak, 2000).

In 2010, the forest cover in the Colombo District was 2,340 ha covering only 3% of the total land area and at present, these forests are at the verge of diminishing (FAO, 2018). It is extremely important to note the power of urban forests in mitigating the UHI effect as already reported by Ying *et al*. (2010) and many others.

Vegetation cover on ground

When the urban development take place, the ground is usually covered with hard surfaces to facilitate free movements, that lead to an increase in environmental temperature causing UHI effect. Therefore, having a vegetation cover on ground at all possible places will help reducing the temperature. Turfgrass and low-grown cover-plants (bedding plants) can be used for this purpose. Temperature in cities can be reduced significantly by placing turfgrass in large parking spaces (Takebayashi and Moriyama, 2009).

Urban home gardens

Apart from the food-related benefits that the urban home gardens provide, the therapeutic value of such gardens has always been in the spot-light (Adevi and Mårtensson, 2013). Although often under-valued, urban home gardens will also help reduce the UHI effect. As reported by Tsilini *et al*. (2015), either with horticultural plants or aromatic herbs, urban gardens decreased the surface temperature by 10 °C compared to those without vegetation.

Challenges and opportunities for urban greening

If the urban greening is to be popularized aiming to mitigate the UHI effect, it is of paramount importance to identify the challenges and the opportunities ahead

Challenges for urban greening

- Finding new locations for urban greening, especially for urban parks and urban forests could be one of the major challenges that urban planners might face in densely populated and compact urban environments. With the land fragmentation, the available space for greening is dwindling even at the home garden scale.
- With the improved quality of living, urban dwellers are willing to pay for the green facilities. However, placing a value on the green spaces is another challenge faced by urban planners as intangible benefits of urban greening surpass the tangible benefits.
- The level and scale of urban greening depend largely on the capacity of the government to fund these projects. The budgetary

allocations of a country like Sri Lanka will always directed towards food security and other social welfare of the people.

- In addition to the aforesaid financial challenges, having several governmental Ministries and institutions involved in urban greening adds a different dimension to the challenges.
- Land tenure could also be a challenge in urban greening as people those who do not own a land, generally do not want to grow anything in their gardens. On the other hand, people seldom volunteer in maintaining public parks or any other public green spaces expecting the government to look after the maintenance.
- On top of all, ecological challenges such as soil conditions, built environment (pavings and hard surfaces) and polluted air might also hinder the development of urban greening.

Opportunities for urban greening

- The greatest opportunity to expand the urban greening is the increasing awareness among people about the environmental pollution and health hazards that it creates. Unlike early days, the health-consciousness of people is becoming more and more that demands more green spaces in cities, even at a reasonable price.
- With the development of green roof and green wall technologies, urban planners can now look for better alternative spaces for greening without compromising the space for human use.
- Many organizations are now promoting green-building concept, in which the main idea is to use the renewable energy in a sustainable manner while increasing the use of greenery. This also creates a new avenue to promote urban greening.
- The Sri Lankan government has already planned to increase the urban green spaces and to develop educational and awareness programmes for people.

Way forward

Rising Urban Heat Island (UHI) effect with the climate change, will create discomfort to humans and all the living creatures in the environment. Though there are several methods to mitigate the UHI effect, urban greening is the most viable sustainable solution in the long run. Urban greening can be made possible through green roofs, green walls, street trees, urban parks, vegetation cover such as grass, urban forests and home gardens. The potentials to implement urban greening solutions outdo the challenges, thus making the planning process easier. However, more research work will be required on the UHI effect, appropriate greening solutions, impact assessment and ecosystems services in Sri Lanka to implement validated typologies in urban greening.

References

Adevi, A.A. and Mårtensson, F. (2013). Stress rehabilitation through garden therapy: The garden as a place in the recovery from stress. *Urban Forestry and Urban Greening*, 12(2): 230-237.

Akbari, H., Cartalis, C., Kolokotsa, D., Muscio, A., Pisello, A.L., Rossi, F., Santamouris, M., Synnefa, A., Wong, N.H. and Zinzi, M. (2016). Local climate change and urban heat island mitigation techniques–the state of the art. *Journal of Civil Engineering and Management*, 22(1): 1-16.

Algretawee, H., Rayburg, S. and Neave, M. (2019). Estimating the effect of park proximity to the central of Melbourne city on Urban Heat Island (UHI) relative to Land Surface Temperature (LST). *Ecological Engineering*, 138: 374-390.

Bowler, D.E., Buyung-Ali, L., Knight, T.M. and Pullin, A.S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, 97(3): 147-155.

Brenneisen S. (2003). The benefits of biodiversity from green roofs, key design consequences. *In: Proceedings of the First North American Green Roof Conference: Greening Rooftops for Sustainable Communities*, Chicago, 29–30/05/2003. The Cardinal Group, Toronto, 323–329.

Burden D. (2006). *Urban street trees. 22 benefits, Specific applications*. 3-9.

Calvi, A. (2015). Does roadside vegetation affect driving performance? Driving simulator study on the effects of trees on drivers' speed and lateral position. *Transportation Research Record*, 2518(1): 1-8.

Cao, X., Onishi, A., Chen, J. and Imura, H. (2010). Quantifying the cool island intensity of urban parks using ASTER and IKONOS data. *Landscape and Urban Planning*, 96(4): 224-231.

Carter T. and Keeler, A. (2006). *Life-cycle cost–benefit analysis of extensive vegetated roof systems*. River Basin Center, Institute of Ecology, University of Georgia, Athens.

Chang, C.R. and Li, M.H. (2014). Effects of urban parks on the local urban thermal environment. *Urban Forestry and Urban Greening*, 13(4): 672-681.

Churkina, G., Grote, R., Butler, T.M. and Lawrence, M. (2015). Natural selection? Picking the right trees for urban greening. *Environmental Science and Policy*, 47: 12-17.

Dareeju, B.S.S.S., Meegahage, J.N. and Halwatura, R.U. (2011). Performance of green roof against the global warming. *Annual Transactions of IESL*, pp.297-302.

Dassanayake, D.H.B.R. and Beneragama, C.K. (2011). Development of roof vegetation as influenced by substrate composition and depth in an extensive green roof. *In: Proceedings of the Peradeniya University Research Sessions*, Sri Lanka, Vol. 16: 170

DESA. (2012). *World Urbanization Prospects: The 2011 Revision*. New York: United Nations.

Dunnett, N. and Kingsbury, N. (2004). *Planting green roofs and living walls*. Portland, Timber Press.

Dyer, J.E, Childs, G.M. and Nowak, D.J. (2000). Forestry in urban and urbanizing areas of the United States: Connecting people with ecosystems in the 21st century. *In*: B. Krishnapillay, E. Soepadmo, N. Arshad, A.Wong, S. Appanah, S. Chik, N. Manakaran, H. Trong, and K. Choon (Eds.). *Forests and Society: The Role of Research*. Sub-plenary Sessions Vol 1. XXI IUFRO World Congress, 7-12 August 2000, Kuala Lumpur, Malaysia. pp 629-637.

Emmanuel, R. and Fernando, H.J. (2007). Urban heat islands in humid and arid climates: Role of urban form and thermal properties in Colombo, Sri Lanka and Phoenix, USA. *Climate Research*, 34(3): 241-251.

EPA (2013). *Reducing urban heat islands: compendium of strategies*. http://www.epa.gov/hiri/resources/pdf/BasicsCompendium.pdf.

European Commission (2013). *Building a green infrastructure for Europe*. Publications Office of the European Union ISBN 978-92-79-33428-3 doi:10.2779/54125.

FAO, (2018). Assessing and planning city region food system Colombo (Sri Lanka). *Synthesis Report*. Rome, Licence: CC BY-NC-SA 3.0 IGO.

Feyisa, G.L., Dons, K. and Meilby, H. (2014). Efficiency of parks in mitigating urban heat island effect: An example from Addis Ababa. *Landscape and Urban Planning*, 123: 87-95.

Freed R., Garner, G., Kelly, P.S., Debisingh, S., Peck, S. and Irwin, G. (2008). Introduction to green walls technology, benefits and design. *Green roofs for healthy Cities*, www.greenroofs.org. 5-8.

Getter K.L., Rowe, D.B. and Andresen, J.A. (2007). Quantifying the effect of slope on extensive green roof stor mwater retention. *Ecological Engineering,* 31: 225–231.

Gul, A., Kamil, O.O. and Eraslan, S. (2012). Design of the urban street trees and problems in Turkey. *Miestų želdynų formavimas*, 1(9): 43-53.

Gundersen, V., Frivold, L.H., Löfström, I., Jørgensen, B.B., Falck, J. and Øyen, B.H. (2005). Urban woodland management–the case of 13 major Nordic cities. *Urban Forestry and Urban Greening*, 3(3-4): 189-202.

Jang, H.S., Lee, S.C., Jeon, J.Y. and Kang, J. (2015). Evaluation of road traffic noise abatement by vegetation treatment in a 1: 10 urban scale model. *The Journal of the Acoustical Society of America*, 138(6): 3884-3895.

Jeanjean, A.P., Hinchliffe, G., McMullan, W.A., Monks, P.S. and Leigh, R.J. (2015). A CFD study on the effectiveness of trees to disperse road traffic emissions at a city scale. *Atmospheric Environment*, 120: 1-14.

Kaoma, H. and Shackleton, C.M. (2015). The direct-use value of urban tree non-timber forest products to household income in poorer suburbs in South African towns. *Forest Policy and Economics*, 61: 104-112.

Kikon, N., Singh, P., Singh, S.K. and Vyas, A. (2016). Assessment of urban heat islands (UHI) of Noida City, India using multi-temporal satellite data. *Sustainable Cities and Society*, 22: 19-28.

Kaufman A., Cox, L.J., Muira, T. and Easterday, D. (2007). The potential for green roofs in Hawaii. Departments of Tropical Plant and Soil Sciences and Natural Resources and Environmental Management; Belt Collins Hawaii Ltd.

Kariyawasam, K.P.N.H., Krishnaraja, S., Karunarathne, C.L.S.M., Ariyaratne, M. and Beneragama, C.K. (2017). Influence of the position angle of six ornamental plants on their sensitivity to gravity and their suitability for vertical gardening. *In: Proceedings of Annual Sessions of Young Scientists Forum of National Science and Technology Commission*, Sri Lanka. 6: 50-53.

Keim, S.M., Guisto, J.A. and Sullivan Jr, J.B., (2002). Environmental thermal stress. *Annals of Agricultural and Environmental Medicine*, 9(1): 1-15.

Kong, F., Yin, H., Nakagoshi, N. and Zong, Y. (2010). Urban green space network development for biodiversity conservation: Identification based on graph theory and gravity modeling. *Landscape and urban planning*, 95(1-2): 16-27.

Konijnendijk C.C., Annerstedt, M., Nielsen, A.B. and Maruthaveeran, S. (2013), Benefits of urban parks: A systemic review, IFPRA.

Kuddus, M.A., Tynan, E. and McBryde, E. (2020). Urbanization: A problem for the rich and the poor? *Public Health Review,* 41:1 https://doi.org/10.1186/s40985-019-0116-0.

Le, M.T., Shukurov, I., Shukurova, L. and Dmitrieva, A. (2019). A case study of mathematical calculation of urban heat island intensity based on urban geometry. *In: International Scientific Conference on Energy, Environmental and Construction Engineering*. Springer, Cham. 373-388.

Lee, K. and Levermore, G.J. (2019). Sky view factor and sunshine factor of urban geometry for urban heat island and renewable energy. *Architectural Science Review*, 62(1): 26-34.

Li, L. and PGRNI, P. (2017). Is Colombo City, Sri Lanka secured for urban green space standards? *Applied Ecology and Environmental Research*, 15(3): 1789-1799.

Liaros, S., Botsis, K. and Xydis, G., (2016). Technoeconomic evaluation of urban plant factories: The case of basil (*Ocimum basilicum*). *Science of the Total Environment*, 554: 218-227.

Liesecke, H.J. and Borgwardt, H. (1997). Degradation of air pollutants by extensive green roofs. 33: 245-251.

Lo, A.Y., Byrne, J.A. and Jim, C.Y. (2017). How climate change perception is reshaping attitudes towards the functional benefits of urban trees and green space: Lessons from Hong Kong. *Urban Forestry and Urban Greening*, 23: 74-83.

Mackey, C.W., Lee, X. and Smith, R.B. (2012). Remotely sensing the cooling effects of city scale efforts to reduce urban heat island. *Building and Environment*, 49: 348-358.

McPherson E.G., Doorn N.V. and Goede, J.D. (2016). Structure, function and value of street trees in California, USA. *Urban Forestry and Urban Greening,* 17: 104-115.

Madurapperuma B.D., Kuruppuarachchi, K.A.J.M. and Herath, W.N. (2016). Arboricultural assessment of street trees in Colombo City, Sri Lanka, *In*: Proceedings, *21st International Forestry and Environment Symposium*, Part I, 44.

Niachou A., Papakonstantinou, K., Santamouris, M, Tsangrassoulis, A. and Mihalakakou, G. (2001). Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Buildings*. 33: 719-729.

NIOSH (National Institute of Occupational Safety and Health), (1986). Criteria for a recommended standard: occupational exposure to hot environments, revised criteria. Publ No. 86-113.

Nowak, D.J., Crane, D.E. and Stevens, J.C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry and Urban Greening*, 4(3-4): 115-123.

O'Malley, C., Piroozfarb, P.A., Farr, E.R. and Gates, J. (2014). An investigation into minimizing urban heat island (UHI) effects: A UK perspective. *Energy Procedia*, 62: 72-80.

Paganini, N., Lemke, S. and Raimundo, I. (2018). The potential of urban agriculture towards a more sustainable urban food system in food-insecure neighbourhoods in Cape Town and Maputo. *Economia agro-alimentare*.

Price, A., Jones, E.C. and Jefferson, F. (2015). Vertical greenery systems as a strategy in urban heat island mitigation. *Water, Air and Soil Pollution*, 226(8): 247.

Peck S., Kuhn, M. and Arch, B. (2001). Design guidelines for green roofs. Ontario Association of Architects, Canada. 3-20.

Peters K., Elands, B. and Buijs, A. (2009). Social interactions in urban parks: stimulating social cohesion? Science Direct, *Urban Forestry and Urban Greening,* 9(2), 93-100.

Polizel, J., de Souza Santos, I., Bensenor, I. and Mauad, T. (2019). Green spaces, land cover, street trees and cardiovascular health in a megacity. *Environmental Epidemiology,* 3: 250.

Qin, X., Wu, X., Chiew, Y. and Li, Y. (2012). A green roof test bed for stormwater management and reduction of urban heat island effect in Singapore. *British Journal of Environment and Climate Change*, 2(4): 410-420.

Raj, S., Paul, S.K., Chakraborty, A. and Kuttippurath, J. (2020). Anthropogenic forcing exacerbating the urban heat islands in India. *Journal of Environmental Management*, 257: 110006.

Sen, S. and Roesler, J. (2019). Thermal and optical characterization of asphalt field cores for microscale urban heat island analysis. *Construction and Building Materials*, 217: 600-611.

Shahbaz, M., Sbia, R., Hamdi, H. and Ozturk, I. (2014). Economic growth, electricity consumption, urbanization and environmental degradation relationship in United Arab Emirates. *Ecological Indicators*, 45: 622-631.

Sicard, P., Agathokleous, E., Araminiene, V., Carrari, E., Hoshika, Y., De Marco, A. and Paoletti, E. (2018). Should we see urban trees as effective solutions to reduce increasing ozone levels in cities? *Environmental Pollution*, 243: 163-176.

Rakhshandehroo, M., Yusof, M.J.M., Arabi, R., Parva, M. and Nochian, A. (2015). The environmental benefits of urban open green spaces. *Journal of Landscape Ecology*, 9(3): 5-13.

Rakhshandehroo, M., Yusof, M., Johari, M., and Arabi, R. (2015). Living wall (vertical greening): Benefits and threats. *Applied Mechanics and Materials*, 747: 16-19.

Ranagalage, M., Estoque, R.C. and Murayama, Y. (2017). An urban heat island study of the Colombo metropolitan area, Sri Lanka, based on Landsat data (1997-2017). *ISPRS International Journal of Geo-Information*, 6(7): 189.

Ranagalage, M., Estoque, R.C., Zhang, X. and Murayama, Y. (2018a). Spatial changes of urban heat island formation in the Colombo District, Sri Lanka: Implications for sustainability planning. *Sustainability*, 10(5): 1367.

Ranagalage, M., Dissanayake, D.M.S.L.B., Murayama, Y., Zhang, X., Estoque, R.C., Perera, E.N.C. and Morimoto, T. (2018b). Quantifying surface urban heat island formation in the world heritage tropical mountain city of Sri Lanka. *ISPRS International Journal of Geo-Information*, 7(9): 341.

Sachindra, D.A., Ng, A.W.M., Muthukumaran, S. and Perera, B.J.C. (2016). Impact of climate change on urban heat island effect and extreme temperatures: A case-study. *Quarterly Journal of the Royal Meteorological Society*, 142(694): 172-186.

Sailor, D.J. (2006). Mitigation of urban heat islands-Recent progress and future prospects. *In*: Papers presented on American meteorological society 6th symposium on the urban environment and forum on managing our physical and natural resources.

Takebayashi H. and Moriyama, M. (2007). Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Building Environment,* 42: 2971–2979.

Takebayashi, H. and Moriyama, M. (2009). Study on the urban heat island mitigation effect achieved by converting to grass-covered parking. *Solar Energy*, 83(8): 1211-1223.

Tam, B.Y., Gough, W.A. and Mohsin, T. (2015). The impact of urbanization and the urban heat island effect on day to day temperature variation. *Urban Climate*, 12: 1-10.

Todorova, A., Asakawa, S. and Aikoh, T. (2004). Preferences for and attitudes towards street flowers and trees in Sapporo, Japan. *Landscape and urban planning*, 69(4): 403-416.

Tsilini, V., Papantoniou, S., Kolokotsa, D.D. and Maria, E.A. (2015). Urban gardens as a solution to energy poverty and urban heat island. *Sustainable cities and society*, 14:323-333.

Tran, H., Uchihama, D., Ochi, S. and Yasuoka, Y. (2006). Assessment with satellite data of the urban heat island effects in Asian mega cities. *International Journal of Applied Earth Observation and Geoinformation*, 8(1): 34-48.

Tyrväinen, L., Pauleit, S., Seeland, K. and de Vries, S. (2005). Benefits and uses of urban forests and trees. *In*: *Urban Forests and Trees*, Springer, Berlin, Heidelberg, pp. 81-114.

Ukwattage, N. and Dayawansa, N. (2012). Urban heat islands and the energy demand: An analysis for Colombo City of Sri Lanka using thermal remote sensing data. *International Journal of Remote Sensing and GIS,* 1: 124–131.

UNESCAP (2013). Statistical yearbook on Asia and the Pacific 2013. United Nations Economic and Social Commission for Asia and the Pacific.

Van den Berg, M., Wendel-Vos, W., van Poppel, M., Kemper, H., van Mechelen, W. and Maas, J. (2015). Health benefits of green spaces in the living environment: A systematic review of epidemiological studies. *Urban Forestry and Urban Greening*, 14(4): 806-816.

Vij, D. (2012). Urbanization and solid waste management in India: present practices and future challenges. *Procedia-Social and Behavioral Sciences*, 37: 437-447.

Wang, Y. and Akbari, H., (2016). The effects of street tree planting on Urban Heat Island mitigation in Montreal. *Sustainable Cities and Society*, 27: 122-128.

Weeraratne, B. (2016). Re-defining urban areas in Sri Lanka. Working paper Series No.23, Institute of Policy Studies of Sri Lanka, Colombo

World Bank (2020). Urban population - Sri Lanka. United Nations population division. World urbanization prospects: 2018 Revision. Available online at https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?locations=LK . [Accessed on 02.06.2020].

Wong, N.H., Chen Y., Ong C.L. and Sia A. (2003). Investigation of thermal benefits of rooftop garden in the tropical environment. *Building Environment*, 38: 261-270.

Yi, Y.K. (2015). Restorative effects of natural landscape on university students' stress reduction and cognitive enhancement. *Journal of the Korean Institute of Landscape Architecture*, 43(6): 127-137.

Ying, T., Li, M., Fan, W. and Zhang, X. (2010). Analysis of urban forests and heat island effect based on GIS. *Journal of Northeast Forestry University*, 38(8): 63-101.

CHAPTER 04

Response of Crops to Heat Stress in a Warming World: Adaptation Measures under Sri Lankan Context

K.W.L.K. Weerasinghe*[1], N. Geekiyanage[2] and M.D.P. Kumarathunge[3]

[1]Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Sri Lanka.
[2]Department of Plant Sciences, Faculty of Agriculture, Rajarata University of Sri Lanka.
[3]Plant Physiology Division, Coconut Research Institute, Lunuwila, Sri Lanka.
*lasanthaw@pdn.ac.lk

Response of Crops to Heat Stress in a Warming World: Adaptation Measures under Sri Lankan Context

Abstract

Rising temperatures impose heat stress for a wide variety of crops, negatively influencing their growth and development leading to yield losses. Each crop species has its own thermal thresholds at different growth stages beyond which all these processes get affected. Among different growth stages, reproductive stage has been found to be the most vulnerable to heat stress, and therefore, its influence on yield components is substantial. A comprehensive understanding of crop responses to heat stress has important implications for deciding suitable adaptation measures and for management options. This review provides an account of the influence of heat stress on the above processes giving special emphasis on the thermal thresholds of several crops. Further, conventional as well as potential novel approaches to heat stress adaptation, along with some management options to avert the impacts of high temperature stress in plants have been discussed in this chapter with regard to Sri Lankan context.

Keywords: *Adaptation, crops, heat stress, warming*

Introduction:

Temperature (T) is a critical environmental factor that affects plant growth, development, and yield. Crops require certain basic level of temperature to complete either a given phenophase or the whole lifecycle (Luo, 2011). Cardinal temperatures and lethal temperatures are threshold temperatures that are associated with the crop production processes. Cardinal temperatures include base temperature (T_{base}), optimum temperature (T_{opt}), and ceiling temperature (T_{cel}) of which plant growth and development take place ideally at T_{opt} while at a slower rate from T_{opt} to T_{base} (i.e. sub optimal range) and T_{opt} to T_{cel} (i.e. supra optimal range). Porter and Gawith, (1999) indicated that though the recovery of function is possible from T_{base} to T_{cel} (i.e. within the range of cardinal temperatures) same will not be possible beyond the lethal limits. The rise in temperature even by a single degree beyond these thresholds may impose heat stress on plants (Hasanuzzaman *et al*., 2013).

Abiotic stresses including temperature extremes threaten the productivity and sustainability of many economically important crops worldwide. It is projected to an increase in global mean ambient temperature by 1- 3.4˚C due to the global anthropogenic climate change by the end of 21st century (IPCC, 2007). Results of global climate models analysis reveal that tropical and subtropical regions are more prone to heat stress events arise due to global warming than relatively cooler regions of earth. Given the magnitude, direction and frequency of change in temperature thresholds is largely unknown, the effects on exceeding the temperature thresholds on crop yields and their yield components is an active field of study. More importantly the probability of crossing temperature thresholds likely to be even higher in the future, when compared to present temperature regimes (Luo, 2011).

At present heat stress is considered as one of the major limiting factors for crop production worldwide as it substantially effects on a wide variety of economically important crops leading to decreased crop yields. In this chapter we review the basic responses of crop growth, development, and yield with respect to heat stress in a variety of crops. Further, an indication has been given on the thermal thresholds above which crop processes are ceased. Finally, we summarise the effects of heat stress on selected crops under Sri Lankan context while providing current and prospective adaptation measures and management options.

Effects of heat stress

Seed germination and vegetative growth

High temperature effects are apparent at all critical growth stages of a crop starting from seed germination. Poor stand establishment resulted by poor seed germination is expected under elevated temperature as it reduces the germination ability of the seeds (Fahad *et al*., 2016) in many crop species (Burke, 2001; Wahid, 2007). Restricted emergence and elongation of hypocotyls in pea (*Pisum sativum*) in response to heat stress has been found under experimental conditions (Tian *et al*., 2018). Given that, root growth that function under a narrow optimum temperature range, is also reduced due to heat stress (Porter and Gawith, 1999). Other root traits such as root length, root diameter and root numbers may also reduce (Batts *et al*., 1998). Further, heat stress often leads to reduce stem growth and plant height (Simonneau *et al*., 1993; Prasad *et al*., 2006; Wahid, 2007) in many crops with substantial reduction in internodal length such as in sugarcane (Ebrahim *et al*., 1998). Another obvious features that heat stress cause are scorching of the twigs and leaves along with discoloration of fruits and leaves (Vollenweider and Günthardt-Goerg, 2005) which would ultimately effect on the final quality of the produce.

Developmental processes

Development processes of crops depend basically on two factors; day length/photoperiod and temperature of which the latter act as a major driving force that determine the developmental processes of tropical crops. Thermal duration (i.e. degree days) for a given developmental event is a constant, hence warmer temperatures stimulate developmental events reducing the duration needed to complete a given developmental event.

Floral initiation (rate of panicle initiation) vary under heat stress conditions. For example, duration from panicle initiation to anthesis is reduced under moderate temperature stress; however, the same is increased and panicle development could be ceased under severe temperature stress (Prasad *et al*., 2006). Moreover, failure of fertilization as a result of reduced pollen or ovule function and inhibition of pollen development leading to sterility is another possibility under heat stress conditions (Prasad *et al*., 2000). Heat stress could also leads to shorten the duration of seed filling leading to smaller seed size (Prasad *et al*., 2006), and seed yields. Thus heat stress could result lower yield by reducing grain filling duration in cereals.

Reproductive processes

Reproductive processors are considered highly sensitive to high temperature (Prasad *et al*., 2008; Wahid *et al*., 2012). The most sensitive reproductive events due to high temperature include poor pollen germination and poor pollen tube growth, loss of ovule viability, reduced retention of pollen grain by the stigma, loss of stigma receptivity, impaired fertilization and post fertilization processors (Zinn *et al*., 2010), loss of buds, flowers, fruits and whole seeds and there by substantial reduction in final yield of many crops.

Flowering and fertilization

Flowering is affected by heat stress reducing number of flowers and flower size. In some instances, malformed floral organs (Morrison and Stewart, 2002) are reported resulting loss of flowers along with reduced yields in common beans (*Phaseolus vulgaris*) (Suzuki *et al*., 2001) and mung bean (Tickoo *et al*., 1996). Moreover, boll and flower bud abortion in pea, and brassica is reported at high temperature, which is potentially coupled with limited nutrient and water (Guilioni *et al*., 1997; Young *et al*., 2004). In contrast to high day-time temperatures, cowpea (*Vigna unguiculata*) show susceptibility to high night-time temperatures at early flowering and pod set as a result of anther indehiscence coupled with low pollen viability (Warrag and Hall, 1984). Mature pollens are highly sensitive to heat stress hence demonstrate frequent failures to fertilize under high heat stress conditions (Dupuis and Dumas, 1990).

No pollination or reduced pollination, abscission of flower buds and flowers report in response to heat stress in legumes (Nakano *et al*., 1998). Fertilization may also affected either by inhibiting male (Jain *et al*., 2007) or female (Snider *et al*., 2009) gametophytic development depending on the time of the life cycle, duration of exposure and the severity of the heat stress.

Grain filling and yield

Heat stress lead to substantial yield losses in several important crops including cereals, legumes and vegetables. Heat stress affect the kernel development (Monjardino *et al*., 2005) and kernel quality during grain filling in maize leading to poor final quality in cereals and oil seeds (Wilhelm *et al*., 1999). Reduced individual grain weight as a result of high night temperatures cause declines in substantial grain production in rice (Fahad *et al*., 2016). Moreover, in common beans (Prasad *et al*., 1999), groundnut (Rainey and Griffiths, 2005), cowpea (Hall, 1992) and soybean (Board and Kahlon, 2011) reduced seed filling under heat stress is reported. Obvious reduction in tomato (*Lycopersicum esculentum* Mill.) yield has been reported more likely due to the influence on meiosis, fertilization, and growth of fertilized embryo by the heat stress (Camejo *et al*., 2005). The influence of heat stress on seed filling may exhibit differences depending on crop species.

Threshold temperature of various crops

In agriculture, surface air temperature that usually measured with a thermometer placed 1.5 – 1.8 m above soil is taken into consideration in order to estimate thermal resources and restrictions for cultivated crop plants. However, the temperature of the organs of plants is the most worthwhile parameter to understand the underlying plant processes, which act as a function of temperature. For example, under well-watered condition, leaf temperature could be closer to air temperature as increasing leaf temperature is mitigated through transpiration on the other hand, leaf temperature could substantially be greater when compared to air temperatures when leaf stomata are closed under reduced soil moisture (Drake *et al*., 2017). Similar to leaf temperature, temperature of the soil layer that include the roots also critically affect the root function. Even though soil temperature can be measured at different depths, temperature measured at 10 cm depth is considered to be adequate for agricultural purposes since daily variation is most prominent in superficial soil layer (Ferrante and Mariani, 2018).

In order to understand effect of temperature on crop plants, the knowledge on the actual temperatures to which plant organs expose as well as temperature thresholds under which crop production takes place is vital. A mechanistic understanding on how crop plants operate near temperature thresholds will provide a basis for estimating extreme temperature related risks thereby providing an opportunity to seek for potential adaptation measures in advance (Luo, 2011). The following information reported in past literature provide an indication regarding temperature thresholds and effects that cause under exceeding temperature thresholds on crop growth, development and yield components across a range of crop types (Table 1).

Present distribution and predicted changes of temperature in Sri Lanka

Being a tropical island surrounded by Indian Ocean and presence of a central highland mass, Sri Lanka exhibit a wide variation of temperature across time and space. The mean annual temperature of lowlands of Sri Lanka often exhibits consistent temperatures while it shows decreasing temperatures with increasing elevation towards the central highlands. For example, mean annual temperature of 27°C at an altitude of 100-150 m drops up to 15°C at an altitude of about 1800 m at Nuwara Eliya. Especially

Table 1: Threshold temperature of some crops at different stages of plant growth and development

	Plant species	Threshold temperature (°C)	Growth/ process development stage	References
Cereals	Maize (*Zea mays*)	33 - 38	Photosynthesis	(Crafts-Brandner and Salvucci, 2002)
		35	Leaf growth	(Dubey, 1996)
		35	Pollen viability	(Luo, 2011)
	Rice (*Oryza sativa*)	33 for 5 days	Photosynthesis	(Asseng *et al*., 2009)
		33	Biomass /Dry matter production	(Matsushima *et al*., 1982)
		>35	Spikelets sterility	(Yoshida and Hasegawa, 1982)
	Sorghum (*Sorghum bicolor*)	40/30 for 45 days	Photosynthesis	(Djanaguiraman *et al*., 2010)
		> 40	Germination	(Singh and Dhaliwal, 1972)
		26-34	Vegetative growth	(Maiti, 1996)
		36/26	Seed size	(Prasad *et al*., 2006)
Legumes	Ground nut (*Arachis hypogaea*)	31	Pollen viability and seed set	(Vara Prasad *et al*., 2003)

	Common beans (*Phaseolus vulgaris*)	> 30	Flowering	(Konsens *et al*., 1991)
	Mung bean (*Phaseolus aureus*)	28 - 30	Growth	(Poehlman, 1991)
	Soybeans (*Glycine max*)	30.2	Pollen germination	(Boote *et al*., 2005)
		36.1	Pollen tube growth	(Hatfield *et al*., 2008)
		39	Yield production	(Thomas, 2001)
Other crops	Potato (*Solunum tuberosum*)	20	Photosynthesis	(Burton, 1981)
	Tomato (*Lycopersicon esculentum*)	37	Vegetative growth	(Reddy *et al*., 2005)
		28 - 30	Reproductive growth	(Reddy *et al*., 2005)
Plantation Crops	Sugarcane (*Sacharum officinarum*)	35/30	Photosynthesis	(Wahid, 2007)
	Tea (*Camellia sinensis*)	> 35	Shoot growth	(Shoubo, 1989)
	Coconut (*Cocos nucifera*)	> 33	Reproductive growth	(Ranasinghe *et al*., 2015)

during the period of January to February diurnal temperature variations in the high elevation areas is wide (Marambe, 2012). It is accepted that in the coastal regions and in the highland diurnal range of temperature could vary between 8°C and 14°C respectively. In general, the warmest period throughout the island is from April to May and the coolest period is from December-January (Bhagat *et al.*, 2016). In contrast during May to September period (during *Yala* season) most of dry zone low land areas experience warm, dry windy conditions.

Approximately 2.9°C and 2.5°C mean temperature increase is predicted during northeast and southwest monsoon seasons respectively over the base line (1961-1990) by the year 2100 (Eriyagama and Smakhtin, 2010) giving warning signs in advance about incoming threats to crop cultivation. Recent analysis of long term temperature records have shown that the country is warming at a rate of 0.01 – 0.03°C per annum (i.e. increasing of countries mean ambient temperature (Premalal and Punyawardena, 2013) exhibiting a substantial increase in night time temperature compared to that of daytime maximum temperature (Marambe, 2012).

Increasing night time temperature has been noted in many parts of the country over recent decades causing narrow diurnal temperature variations (Marambe, 2012) which could highly impact on root and tuber crop production including potato cultivation in upcountry regions as high night time temperature delay tuber induction, prolong tuber setting, delay onset of rapid tuber growth due to reduced carbohydrate partitioning at early growth (Struik, 2007). Moreover, reduced sugar translocation to fruits leads to increase the sour taste of fruits while reduced palatability of fruits due to increase in the fibre content would also be possibilities that would occur under increased night time temperatures (Marambe, 2012).

Impact of increased temperature on key cultivated crops in Sri Lanka with their current and suggested adaptation measures and management options

Rice:

Rice (*Oryza sativa* L) is the staple food over 20 million Sri Lankans. As the temperature is the driving force for growth and development of rice, the response of rice plants to increase in temperature varies with the duration of exposure to the critical temperature, diurnal temperature variation and physiological status of the plant (Weerakoon *et al*., 2009). Time of the anthesis has been identified as the most sensitive stage in response to increasing temperature (Matsui *et al*., 1999). Spikelet temperatures exceeding 31°C decreased spikelet fertility while complete sterility occurs at 36°C (Weerakoon *et al*., 2008) reducing the productivity of rice in Sri Lanka. December/January and July/August are the periods where anthesis of rice usually occur in major rice growing areas in Sri Lanka. It has been reported that maximum temperature fluctuates between 31-33°C in all growing locations towards end of January while maximum temperature exceeded 35°C in some location in dry zone with fluctuating temperatures exhibiting between 29- 33°C in intermediate zone and wet zone during July – August period (Weerakoon *et al*., 2009). Thus, the existing evidence provide a clear indication that grain sterility driven by high temperatures would be a critical yield determining factor under the present situation and condition may aggravate with further increase in growth temperature.

Measures have been initiated and already taken in the rice cultivation sector to meet the challenges of increasing temperature. For example, high and low temperature of the rice growing locations have already been identified and appropriate date for the establishment of rice crops has been exactly decided (Rathnayake *et al*., 2016). Further, attention is given on finding the most adaptable varieties for sudden temperature changes have found that variety Bg94-2 is a promising variety for the said purpose (Silva *et al*., 2012). Further efforts have been made to develop short duration varieties that could be fit into short growing season (Harris and Shatheeswaran, 2005). Sri Lanka Department of Agriculture released an ultra-short age rice variety Bg250 that mature in 75-80 days which can cope with shifting season due to irregular fluctuations of temperature and rainfall. Meanwhile the attention has been given on short age traditional varieties such as *Hata Da Vee* (maturing in 70 days) in this regard (Marambe, 2012). Further research needs to be conducted in developing multiple stress tolerance varieties in rice meanwhile making the farmers aware about potential adaptation measures further.

Tea:

Diurnal variation of temperature is greater when compared to annual variation of temperature within tea growing regions of Sri Lanka with February to March recorded as the months with highest diurnal range of the temperatures. The optimum ambient temperature required for growth of tea is considered to be 18-25°C with reduced growth found at air temperature below 13°C and above 30°C (Carr, 1972; Carr and Stephens, 1992).

Assessments carried out during 2002-2004 exploring climate change impact on tea cultivation shows that apart from the tea plantations found at higher elevations (i.e. > 1200 m), majority of the tea plantations in Sri Lanka will be affected due to higher temperatures and dry weather conditions as a result of climate change. Increased ambient temperatures (maximum and minimum) over the last five decades of most of the tea growing regions (except maximum temperature in Nuwara Eliya) provides a sound indication about the direction towards the temperature build taking place (Bhagat *et al*., 2016). In the Report of the Working Group on Climate Change of the FAO Intergovernmental Group on Tea, Bhagat *et al*. (2016) suggested the following as adaptation measures for tea cultivation in Sri Lanka.

As the initial cost incurred with replanting/new planting is very high, it is essential that most suitable regions with lands be identified at regional and plantation level through land suitability classification and used for future planning processes. Through these suitable lands could be retained for tea cultivation while marginal/less productive lands could be diversified into other uses.

Assisting tea growers with high precision weather forecast would enable them to make decision and make their lands ready with regard to facing adverse weather conditions would be a high priority. The growers who are not in a position to make decisions alone should be supported to identify suitable adaptation measures to minimize the potential adverse impacts caused by extreme temperatures.

More importantly providing of financial assistance to tea growers whenever necessary will increase the adoption rates of the strategies to a greater extent.

In the long run, crop improvement will be the best adaptation measure to climate change hence attention given to developing new varieties and graft combination to combat rising temperatures would be highly essential despite the high cost involved in the process.

Among tea growing areas in Sri Lanka, low country regions experience the highest temperature regimes with ambient temperatures above the optimum required for tea hence, further increase in ambient temperatures will negatively effect on the yield as well as the quality of tea. Moreover, it will be highly likely that further increase in temperatures would lead to make the mid elevation tea plantations less productive though the present ambient temperatures that exist is considered conducive. Appropriate stands of low and high shade trees that occupy the vertical space at different height in tea plantations lead to reduces heat and excessive light radiation and thereby ambient temperature around tea bushes and increase RH (Sivapalan, 1993; Mukhopadhyay and Mondal, 2017) hence care given to establish and maintain of shade trees at low elevations and mid country Intermediate Zone having comparatively dry conditions is very important.

Coconut:

The mean annual temperature of 27-30°C is considered as the optimum temperature conditions for growth and yield of coconut (Perera *et al*., 2009; Ranasinghe *et al*., 2015). When compared to vegetative components, reproductive organs of coconut palm are considered highly sensitive to stress including high temperature (Ranasinghe *et al*., 2015). During the reproductive development, number of sensitive stages can be found including three months prior to the opening of the inflorescence during which ovule and pollen formation takes place (Perera *et al.*, 2010). During the first month after inflorescence opening, pollination and button nut formation take place and three months after inflorescence opening number of set fruits is determined. Among above, fruit set is the key yield determining factor which is strongly influenced by high temperature stress in different ways including production of poor quality female flowers and pollen, reduced pollen germination and reduced supply of assimilates to fruits leading to reduced fruit set under heat stress conditions. Moreover, quality of fruits and rate and duration of assimilate production may subject to the intensity of exposure and sensitivity. Empirical studies have revealed that reduced number of female flowers and reduced fruit set leading to poor yield (under temperature stress coupled with water stress) is more prominent in the Dry Zone of Sri Lanka when compared to Intermediate Zone in Sri Lanka (Ranasinghe *et al*., 2015).

The success of fruit set in coconut relies on extent to which pollen germination and pollen tube growth occur under heat stress conditions therefore developing improved coconut varieties with enhanced reproductive heat tolerance will be highly beneficial to the industry in the long run. Results of empirical studies provide evidence that the coconut hybrids; Sri Lankan Green Dwarf × Sri Lanka Tall and Sri Lanka Brown Dwarf × Sri Lanka Tall are the most tolerant hybrids to high temperature stress (Ranasinghe *et al*., 2018).

Incorporation of coconut based agroforestry systems/mixed cropping is found to be highly beneficial as that helps to improve the microclimate of coconut plantations through occupying the vertical as well as ground space by different plants/trees that performs different functions (Ranasinghe *et al*., 2014). Practicing mixed cropping systems have reported reduced air temperatures at canopy level when compared to monoculture systems (Ranasinghe, 2009). Therefore, more attention needs to be given to practice intercrop/agroforestry system as an adaptation measure with a special focus on selection of the correct intercrop/agroforestry system to be practiced.

When the thresholds temperatures given in Table 1 is considered, it is evident that most of the key cultivated crops in Sri Lanka function near their threshold temperature/s beyond which the growth, development and yield is adversely affected. As the frequency of occurring high temperature events has increased especially at dry and intermediate zones during *Yala* season spikelet sterility couple with lower photosynthesis at high temperatures (Table 1) could leads to substantial yield reduction in our staple crop, rice. Similarly, most of the listed crops in the Table 1 will be affected due to either increasing temperature events or due to heat stress.

National Adaptation Plan for Climate Change Impacts in Sri Lanka: 2016 – 2025 have proposed the following strategies to be used for different crop sectors as a measure to adapt to climate change impacts including rising temperature.

Enhance resilience against heat stress could be achieved for other field crops and horticultural crops via developing heat tolerant varieties, enhancing the efficiency of water management and developing the capacity for conducting research on tolerant varieties and enhancing the water efficiency farming practices.

For Export Agriculture Sector (e.g. coffee, cocoa, spices etc.) germplasm improvement for heat stress, **s**creen of existing cultivars for heat tolerance, deep planting at nursery and field level in addition to capacity building for research has been proposed.

Special attention has also been given on this report highlighting the importance of establishment of an efficient climate information and management communication system and improvement of disaster risk preparedness and management plan. The latter to be achieved via developing a system to strengthen the early warning system, preparation of hazard vulnerability maps for all crops and developing guidelines for managing of extreme events in vulnerable areas.

Even though wild fires are not very commonly found in Sri Lanka need of developing a very comprehensive plan for mitigating wild fires has been highlighted as depending on the magnitude and the extent under wildfire could create heat waves which could cause a substantial damage to crops at any given point of the life cycles. Thus identification and preparation of maps related to hazard prone areas, acquire new equipment and training staff to combat uncontrolled wildfires will be essential.

Conclusions and way forward

Many plant processes are a function of temperature. However, rising temperatures exceeding thresholds values for plant growth, development and yield formation cause heat stress, which is a major limiting factor for crop productivity around the world. Among different phases, the reproductive stage is more prone to heat stress, hence crop yields are affected leaving uncertainty for the food security in a warming world.

Heat stress, which affect crop plants at any time in the life cycle is considered as the second most important stress after drought that impose limitations to plant functions. Therefore, a mechanistic understanding on the responses of crops to their supra optimal temperatures at both spatial and temporal scale is required for proposing adaptation strategies to heat stress. Lack of comparative physiological studies on adaptive responses of existing crop cultivars to heat stress is a substantial knowledge gap. Segregation of adaptive responses from acclimation potential of crop plants to heat stress together with understanding of the biochemical and molecular basis of heat tolerance may set the baselines for making agronomic decision such as choosing suitable cultivars for dry and arid regions. Further, reorientation of current varietal improvement and breeding program of the country with the use of more modern breeding techniques including easy to measure physiological parameters for screening against heat and drought stresses is another high priority area that needs immediate attention. Moreover, research on strengthening early warning systems, developing crop specific vulnerability maps and manuals for field practices in farming communities for managing extreme events in vulnerable areas would be beneficial. Since the heat and drought stress occur in combination under the field conditions, understanding how crops response to the combined effects of both stresses and improving crop models to accurately stimulate interactive effects of heat and drought stresses on crop growth, development and yield processes is essential to combat against future warming conditions.

Acknowledgement:

This study was supported by the Accelerating Higher Education Expansion and Development (AHEAD) Operation of the Ministry of Higher Education funded by the World Bank.

References

Asseng, S., Cao, W., Zhang, W. and Ludwig, F. (2009). Crop physiology, modelling and climate change: impact and adaptation strategies. *Crop Physiology*, 511-543.

Batts, G., Ellis, R., Morison, J., Nkemka, P., Gregory, Y.P. and Hadley, P. (1998). Yield and partitioning in crops of contrasting cultivars of winter wheat in response to CO_2 and temperature in field studies using temperature gradient tunnels. *The Journal of Agricultural Science,* 130: 17-27.

Bhagat, R., Ahmed, K., Gupta, N., Baruah, R., Wijeratne, M., Bore, J., Nyabundi, D., Han, W., Li, X. and Yan, P. (2016). Report of the working group on climate change of the FAO intergovernmental group on tea. *Food and Agriculture Organization of the United Nations, Rome*.

Board, J.E. and Kahlon, C.S. (2011). Soybean yield formation: what controls it and how it can be improved. *Soybean Physiology and Biochemistry*, 1-36.

Boote, K.J., Allen, L.H., Prasad, P.V., Baker, J.T., Gesch, R.W., Snyder, A.M., Pan, D. and Thomas, J.M. (2005). Elevated temperature and CO_2 impacts on pollination, reproductive growth, and yield of several globally important crops. *Journal of Agricultural Meteorology,* 60: 469-474.

Burke, J.J. (2001). Identification of genetic diversity and mutations in higher plant acquired thermotolerance. *Physiologia Plantarum,* 112: 167-170.

Burton, W. (1981). Challenges for stress physiology in potato. *American Potato Journal,* 58: 3-14.

Camejo, D., Rodríguez, P., Morales, M.A., Dell'amico, J.M., Torrecillas, A. and Alarcón, J.J. (2005). High temperature effects on photosynthetic activity of two tomato cultivars with different heat susceptibility. *Journal of Plant Physiology,* 162: 281-289.

Carr, M. (1972). The climatic requirements of the tea plant: A review. *Experimental Agriculture,* 8: 1-14.

Carr, M. and Stephens, W. (1992). Climate, weather and the yield of tea, I*n: Tea* (pp. 87-135). Springer, Dordrecht.

Crafts-Brandner, S.J. and Salvucci, M.E. (2002). Sensitivity of photosynthesis in a C4 plant, maize, to heat stress. *Plant Physiology,* 129: 1773-1780.

Djanaguiraman, M., Prasad, P.V. and Seppanen, M. (2010). Selenium protects sorghum leaves from oxidative damage under high temperature stress by enhancing antioxidant defense system. *Plant Physiology and Biochemistry,* 48: 999-1007.

Drake, J.E., Vårhammar, A., Kumarathunge, D., Medlyn, B.E., Pfautsch, S., Reich, P.B., Tissue, D.T., Ghannoum, O. and Tjoelker, M.G. (2017). A common thermal niche among geographically diverse populations of the widely distributed tree species Eucalyptus tereticornis: No evidence for adaptation to climate-of-origin. *Global Change Biology,* 23: 5069-5082.

Dubey, R.S. (1996). Photosynthesis in plants under stressful conditions. *Handbook of Photosynthesis*, 859-875.

Dupuis, I. and Dumas, C. (1990). Influence of temperature stress on in vitro fertilization and heat shock protein synthesis in maize (*Zea mays* L.) reproductive tissues. *Plant Physiology,* 94: 665-670.

Ebrahim, M.K., Zingsheim, O., El-Shourbagy, M.N., Moore, P.H. and Komor, E. (1998). Growth and sugar storage in sugarcane grown at temperatures below and above optimum. *Journal of Plant Physiology,* 153: 593-602.

Eriyagama, N. and Smakhtin, V. (2010). Observed and projected climatic changes, their impacts and adaptation options for Sri Lanka: a review. *Proceedings of the National Conference on Water, Food Security and Climate Change in Sri Lanka*, 2010. 99-117.

Fahad, S., Hussain, S., Saud, S., Hassan, S., Tanveer, M., Ihsan, M.Z., Shah, A.N., Ullah, A., Khan, F. and Ullah, S. (2016). A combined application of biochar and phosphorus alleviates heat-induced adversities on physiological, agronomical and quality attributes of rice. *Plant Physiology and Biochemistry,* 103: 191-198.

Ferrante, A. and Mariani, L. (2018). Agronomic management for enhancing plant tolerance to abiotic stresses: High and low values of temperature, light intensity, and relative humidity. *Horticulturae,* 4: 21.

Guilioni, L., Wery, J. and Tardieu, F. (1997). Heat stress-induced abortion of buds and flowers in pea: is sensitivity linked to organ age or to relations between reproductive organs? *Annals of Botany,* 80: 159-168.

Hall, A.E. (1992). Breeding for heat tolerance. *Plant Breeding Reviews,* 10: 129-168.

Harris, K. and Shatheeswaran, T. (2005). Performance of improved four test rice entries of short duration (2.5 months) in the eastern region of Sri Lanka. *Proceedings of the 61st Annual Session of Sri Lanka Association for the Advancement of Science (SLASS)*, 21.

Hasanuzzaman, M., Nahar, K., Alam, M., Roychowdhury, R. and Fujita, M. (2013). Physiological, biochemical, and molecular mechanisms of heat stress tolerance in plants. *International Journal of Molecular Sciences,* 14: 9643-9684.

Hatfield, J., Boot, K. and Kimball, B. (2008). The effects of climate change on agriculture, land resources, water resources, and biodiversity. *Synthesis and Assessment Product,* 4.

IPCC (2007). IPCC fourth assessment report: summery for pilicy makers. *The Physical Science Basis,* 2: 580-595.

Jain, M., Prasad, P.V., Boote, K.J., Hartwell, A.L. and Chourey, P.S. (2007). Effects of season-long high temperature growth conditions on sugar-to-starch metabolism in developing microspores of grain sorghum (Sorghum bicolor L. Moench). *Planta,* 227: 67-79.

Konsens, I., Ofir, M. and Kigel, J. (1991). The effect of temperature on the production and abscission of flowers and pods in snap bean (Phaseolus vulgaris L.). *Annals of Botany,* 67: 391-399.

Luo, Q. (2011). Temperature thresholds and crop production: A review. *Climatic Change,* 109: 583-598.

Maiti, R. (1996). Sorghum science. Lebanon, NH. USA: Science Publishers.

Marambe, B. (2012). Current status and issues of food and nutrition security in Sri Lanka. *National food and nutrition security conference Sri Lanka–towards a nutritious and healthy nation*, Colombo.

Matsui, T., Omasa, K. and Horie, T. (1999). Mechanism of anther dehiscence in rice (Oryza sativa L.). *Annals of Botany,* 84: 501-506.

Matsushima, S., Ikewada, H., Maeda, A., Honma, S. and Niki, H. (1982). Studies on rice cultivation in the tropics. *Japanese Journal of Tropical Agriculture,* 26: 149-156.

Monjardino, P., Smith, A.G. and Jones, R.J. (2005). Heat stress effects on protein accumulation of maize endosperm. *Crop Science,* 45: 1203-1210.

Morrison, M.J. and Stewart, D.W. (2002). Heat stress during flowering in summer Brassica. *Crop Science,* 42: 797-803.

Mukhopadhyay, M. and Mondal, T.K. (2017). Cultivation, improvement, and environmental impacts of tea. *Oxford Research Encyclopedia of Environmental Science.*

Nakano, H., Kobayashi, M. and Teraushi, T. (1998). Sensitive stages to heat stress in pod setting of common bean (*Phaseolus vulgari*s L.). *Japanese Journal of Tropical Agriculture,* 42: 78-84.

Perera, L., Perera, S.A., Bandaranayake, C.K. and Harries, H.C. (2009). Coconut. *Oil Crops.* Springer.

Perera, P.I., Hocher, V., Weerakoon, L.K., Yakandawala, D., Fernando, S.C. and Verdeil, J.-L. (2010). Early inflorescence and floral development in *Cocos nucifera* L. (Arecaceae: Arecoideae). *South African Journal of Botany,* 76: 482-492.

Poehlman, J.M. (1991). *The Mungbean*, Oxford and IBH Publishing Co., Pvt. Ltd. New Delhi.

Porter, J.R. and Gawith, M. (1999). Temperatures and the growth and development of wheat: a review. *European Journal of Agronomy,* 10: 23-36.

Prasad, P., Staggenborg, S. and Ristic, Z. (2008). Impacts of drought and/or heat stress on physiological, developmental, growth, and yield processes of crop plants. *Response of crops to limited water: Understanding and modeling water stress effects on plant growth processes,* 1: 301-355.

Prasad, P.V., Boote, K.J. and Allen Jr, L.H. (2006). Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [*Sorghum bicolor* (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. *Agricultural and Forest Meteorology,* 139: 237-251.

Prasad, P.V., Craufurd, P. and Summerfield, R. (1999). Fruit number in relation to pollen production and viability in groundnut exposed to short episodes of heat stress. *Annals of Botany,* 84: 381-386.

Prasad, P.V.V., Craufurd, P.Q., Summerfield, R.J. and Wheeler, T.R. (2000). Effects of short episodes of heat stress on flower production and fruit-set of groundnut (*Arachis hypogaea* L.). *Journal of Experimental Botany,* 51: 777-784.

Premalal, K. and Punyawardena, B. (2013). Occurrence of extreme climatic events in Sri Lanka. *Proceedings of the international conference on climate change impacts and adaptations for food and environment security*. Hotel Renuka, Colombo, 2013. 49-57.

Rainey, K.M. and Griffiths, P.D. (2005). Evaluation of Phaseolus acutifolius A. Gray plant introductions under high temperatures in a controlled environment. *Genetic Resources and Crop Evolution,* 52: 117-120.

Ranasinghe, C. (2009). Climate change impacts on coconut production and potential adaptation and mitigation measures: a review of current status. *Proceedings of the Workshop on Present Status of Research Activities on Climate Change Adaptations*. Sri Lanka Council for Agricultural Research Policy, Colombo, 71-82.

Ranasinghe, C., Kumarathunge, M. and Kiriwandeniya, K. (2018). Genotypic differences in cardinal temperatures for in vitro pollen germination and pollen tube growth of coconut hybrids. *Experimental Agriculture,* 54: 731-743.

Ranasinghe, C., Premasiri, R., Pradeep, A., Wachira, M., Rabar, B. and Magaju, C. Vulnerability of coconut based agroforestry system in Sri Lanka to climate change. *3rd World Congress on Agroforestry: Trees for life: Accelerating the Impact of Agroforestry*, 2014. 287.

Ranasinghe, C., Silva, L. and Premasiri, R. (2015). Major determinants of fruit set and yield fluctuation in coconut (*Cocos nucifera* L.). *Journal of the National Science Foundation of Sri Lanka,* 43: 253-264.

Rathnayake, W., De Silva, R. and Dayawansa, N. (2016). Assessment of the suitability of temperature and relative humidity for rice cultivation in rainfed lowland paddy fields in Kurunegala district, *Tropical Agricultural Research*, 27: 370– 388.

Reddy, K.R., Vara Prasad, P. and Kakani, V.G. (2005). Crop responses to elevated carbon dioxide and interactions with temperature: cotton. *Journal of Crop Improvement,* 13: 157-191.

Shoubo, H. (1989). Meteorology of the tea plant in China: A review. *Agricultural and Forest Meteorology,* 47: 19-30.

Silva, L., Weerakoon, W., Piyasiri, C., Dissanayake, D., Basnayake, B. and Geethika, W. (2012). Effect of high nightime temperature on pollen and spikelet sterility. *Annals of the Sri Lankan Department of Agriculture,* 14: 135-143.

Simonneau, T., Habib, R., Goutouly, J.-P. and Huguet, J.-G. (1993). Diurnal changes in stem diameter depend upon variations in water content: direct evidence in peach trees. *Journal of Experimental Botany,* 44: 615-621.

Singh, N. and Dhaliwal, G. (1972). Effect of soil temperature on seedling emergence in different crops. *Plant and Soil,* 37: 441-444.

Sivapalan, P. (1993). Shade and green manure trees in tea. A historical appraisal. *Sri Lanka Journal of Tea Science,* 62: 41-46.

Snider, J.L., Oosterhuis, D.M., Skulman, B.W. and Kawakami, E.M. (2009). Heat stress-induced limitations to reproductive success in *Gossypium hirsutum*. *Physiologia Plantarum,* 137: 125-138.

Struik, P.C. (2007). Responses of the potato plant to temperature. *Potato Biology and Biotechnology* (pp. 367-393). Elsevier Science BV.

Suzuki, K., Tsukaguchi, T., Takeda, H. and Egawa, Y. (2001). Decrease of pollen stainability of green bean at high temperatures and relationship to heat tolerance. *Journal of the American Society for Horticultural Science,* 126: 571-574.

Thomas, J.M.G. (2001). Impact of elevated temperature and carbon dioxide on development and composition of soybean seed. (Doctoral dissertation, University of Florida).

Tian, L., Yuan, S. and Quiring, S.M. (2018). Evaluation of six indices for monitoring agricultural drought in the south-central United States. *Agricultural and Forest Meteorology,* 249: 107-119.

Tickoo, J., Mahto, G. and Manji, C. (1996). Plant type in mungbean (*Vigna radiata* L. Wilczek). Indian Society of Pulses Research and Development. 197-213.

Vara Prasad, P., Boote, K.J., Hartwell Allen JR, L. and Thomas, J.M. (2003). Super-optimal temperatures are detrimental to peanut (*Arachis hypogaea*a L.) reproductive processes and yield at both ambient and elevated carbon dioxide. *Global Change Biology,* 9: 1775-1787.

Vollenweider, P. and Günthardt-Goerg, M.S. (2005). Diagnosis of abiotic and biotic stress factors using the visible symptoms in foliage. *Environmental Pollution,* 137: 455-465.

Wahid, A. (2007). Physiological implications of metabolite biosynthesis for net assimilation and heat-stress tolerance of sugarcane (*Saccharum officinarum*) sprouts. *Journal of Plant Research,* 120: 219-228.

Wahid, A., Farooq, M., Hussain, I., Rasheed, R. and Galani, S. (2012). Responses and management of heat stress in plants. *Environmental* *adaptations and stress tolerance of plants in the era of climate change* (pp. 135-157). Springer, New York.

Warrag, M. and Hall, A. (1984). Reproductive responses of cowpea (*Vigna unguiculata* (L.) Walp.) to heat stress. II. Responses to night air temperature. *Field Crops Research,* 8: 17-33.

Weerakoon, W., Abeywickrama, T., De Costa, W. and Maruyama, A. (2009). Out-crossing of heat stress affected spikelets of lowland rice in the sub-humid zone of Sri Lanka and its long-term implications. P*roceedings of the 3rd Annual MARCO Symposium*, Tsukuba, Japan, 2009, 5-7.

Weerakoon, W., Maruyama, A. and Ohba, K. (2008). Impact of humidity on temperature-induced grain sterility in rice (*Oryza sativa* L). *Journal of Agronomy and Crop Science,* 194: 135-140.

Wilhelm, E.P., Mullen, R.E., Keeling, P. and Singletary, G. (1999). Heat stress during grain filling in maize: effects on kernel growth and metabolism. *Crop Science,* 39: 1733-1741.

Yoshida, S. and Hasegawa, S. (1982). The rice root system: its development and function. Drought resistance in crops with emphasis on rice. Manila (Philippines): International Rice Research Institute. p 97-114. Yoshida S, Satake T, Mackill D. 1981. *High temperature stress. IRRI Research Paper Series,* 67, 1-15.

Young, L.W., Wilen, R.W. and Bonham-Smith, P.C. (2004). High temperature stress of *Brassica napus* during flowering reduces micro-and megagametophyte fertility, induces fruit abortion, and disrupts seed production. *Journal of Experimental Botany,* 55: 485-495.

Zinn, K.E., Tunc-Ozdemir, M. and Harper, J.F. (2010). Temperature stress and plant sexual reproduction: uncovering the weakest links. *Journal of Experimental Botany,* 61: 1959-1968.

The Role of Policy in Facilitating Adaptation to Climate Change in Sri Lanka

H.I.U. Caldera*

Department of Plant Sciences, Faculty of Science, University of Colombo, Colombo, Sri Lanka
*iroja@pts.cmb.ac.lk

The Role of Policy in Facilitating Adaptation to Climate Change in Sri Lanka

Abstract

Climate change is the change of earth's climate which is attributed directly or indirectly to human activities that alter the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. Both mitigation and adaptation mechanisms are crucial to face this global challenge. Climate change adaptation strategies are based upon actions taken to moderate, cope or take advantage of actual or anticipated changes in climate. This chapter focuses on the policy related to climate change adaptation and some of the relevant literature on the subject is reviewed. First, the international background of climate change related policy is examined. Thereafter, policy-driven adaptation to climate change is introduced. Sri Lanka's National Climate Change Policy of 2012 is discussed in detail in the context of adaptation, with relevant aspects of the National Adaptation Plan for Climate Change Impacts (2016-2025) given special consideration. Finally, needs in terms of amendments and scope for future policy drafting are assessed.

Keywords: *Adaptation, climate change, national adaptation plan, national climate change policy, Sri Lanka*

Introduction:

Climate change refers in general to a change in the state of the climate which persists for an extended period of time. Under Article 1 of the United Nations Framework Convention on Climate Change it is defined as, 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'.

When dealing with climate change, both mitigation and adaptation mechanisms are important. Mitigation refers to the reduction or prevention of emission of greenhouse gases (GHG) and stabilizing their levels in the atmosphere. Mitigation methodologies include using new technologies and renewable energies, increasing the energy efficiency of older equipment as well as changing management practices or consumer behaviour to favour emission reduction (UNEP, n.d).

Adaptation is regarded as the key strategy available for facing the impacts of climate change and reducing the associated vulnerability. It is widely defined as actions taken to moderate, cope or take advantage of actual or anticipated changes in climate (IPCC, 2007). This applies to both human and natural systems as in the latter, human intervention may support natural adjustments. Well planned early adaptation methodologies in human and natural systems can lead to economic benefits as well as save lives. The Paris Agreement (United Nations, 2015) established a global goal on adaptation, focusing on enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change. According to Article 7 of the Paris Agreement (United Nations, 2015), adaptation is regarded as a key component of the long-term global response to climate change in order to protect people, livelihoods and ecosystems. While stating that adaptation has national, regional and international dimensions, it recognizes that needs of developing countries are important as they are particularly vulnerable to adverse effects of climate change. According to UKCIP (2011), adaptation includes both building adaptive capacity as well as delivering adaptation actions. The former involves creating conducive regulatory, institutional and managerial conditions to support adaptation. With regard to the latter, actions that reduce vulnerability to climate change risks and those that exploit opportunities are included. On a positive note, adaptation often provides short-term local benefits in contrast to mitigation strategies. Therefore, communities are more likely to adopt certain adaptation strategies at the local level, though these strategies may be challenging for those economically underprivileged. However, early and strong mitigation strategies are paramount as otherwise the costs of adaptation will further rise, negatively impacting the ability of countries and individuals to adapt to climate change (Stern, 2007).

The international background

It was as far back as 1988 that the UN General Assembly determined that "climate change is a common concern of mankind" and therefore, required urgent action by all member countries. The Intergovernmental Panel on Climate Change (IPCC) was established at this time by the United Nations Environmental Program (UNEP) and the World Meteorological Organization. The initial task of the IPCC was to prepare a comprehensive report on the causes of climate change, its potential environmental and socio-economic impacts and the means to respond to these impacts. Accordingly, three Working Groups were established with Working Group I examining the scientific aspects of climate change, Working Group II addressing impacts, adaptation and vulnerability, and Working Group III exploring the options for climate change mitigation (IPCC, 2007). In the present day, many of these Working Groups are working in collaboration and thereby providing a better understanding of climate change in an interdisciplinary manner. The objective of the IPCC is to provide governments with scientific information that they can use to develop climate policies and this is mainly achieved through Assessment Reports. A strong positive aspect of the periodic publication of IPCC Assessment Reports is the increase in climate change related national policy as well as legislation worldwide. The first Assessment Report was created in 1990 and laid the ground work for the creation of the 'United Nations Framework Convention on Climate Change' (UNFCCC) in 1992. The ultimate aim of the UNFCCC is to stabilize GHG concentration at a level that would allow ecosystems to adapt naturally to climate change and at a level that would not interfere with the climate system. The UNFCCC led the way to the Kyoto Protocol in 1997 as it was found that the commitments in the UNFCCC itself was insufficient to achieve its main goal. The Kyoto Protocol was based upon national GHG emission reduction targets of developed countries. The Paris Agreement (United Nations, 2015) aims to strengthen the global response to the threat of climate change by maintaining a specific global temperature increase (limiting warming to 1.5 to 2^{0}C above pre-industrial levels) while strengthening the ability of countries to deal with the impacts of climate change. The Agreement introduces nationally determined contributions (NDCs) as a means of achieving these long-term goals. According to Article 4 of the Paris Agreement, each party shall prepare and communicate NDC's which embodies efforts to reduce national emissions and adapt to the impacts of climate change.

Policy-driven climate change adaptation

Policies in general are regarded as actions that contain goals and the means to achieve them. Public/national policies are made by a government in order to find solutions to specific issues in a targeted manner and these affect the people under its jurisdiction (Howard and Cashore, 2014).

While there is a keen interest in climate change adaptation worldwide, what is crucial is the translation of this attention to implementation strategies. One of the principal ways in which tangible action with regard to climate change adaptation can be achieved is through national policy creation by the State and by its subsequent implementation.

Implementation relates to the stage of the policy process where policy outputs, often in the form of actions, regulations, information, or goods and services, are directed at the objectives of the policy (Dupuis and Knoepfel, 2013).

Policy-driven adaptation is due to a deliberate policy decision, usually by a public body and is often referred to as 'planned adaptation' (Stern, 2007). However, for successful implementation, commitment is required not only from the State but also from other stakeholders including national and international organizations, public and private sectors and civil society (Takao, 2012).

In Sri Lanka, the primary agency mandated to deal with climate change related issues is the Climate Change Secretariat of the Ministry of Environment and Wildlife Resources, which functions as the National Focal Point for the UNFCCC. Some of the important national policy initiatives taken with regard to climate change adaptation include; the National Climate Change Adaptation Strategy for Sri Lanka 2011-2016 (NCCAS) prepared in 2010, the National Climate Change Policy (NCCP) adopted in 2012 and the National Adaptation Plan for Climate Change Impacts in Sri Lanka 2016-2025 (NAP) prepared in 2016 (Climate Change Secretariat, 2016). In the following sections, the NCCP and to a lesser extent the NAP will be discussed in the context of climate change adaptation, as these policy documents detail the future national plans in this regard. The NAP which includes both adaptation needs of key sectors (e.g. health, food security etc.) and cross-cutting national needs of adaptation (e.g. research and development; policy, legal, economic and governance issues etc.) assists in practically implementing the NCCP statements (Climate Change Secretariat, 2016).

National climate change policy (NCCP) of 2012

The NCCP communicates broad national policy statements which are to guide decisions taken to face the challenges of climate change on the national and local level. The preamble to the NCCP recognises that present and future generations will have to live with climate change and the vulnerability of developing countries such as Sri Lanka due to lack of adaptive capacity. The need to develop the resilience of the country to the adverse impacts of climate change by prioritizing on the adaptive measures is stressed along-side the need for active involvement in the global effort to minimize GHG emissions within a sustainable development framework.

The overall goal of the NCCP is to adapt and mitigate climate change impacts within the framework of sustainable development. It seeks to provide guidance and direction to all stakeholders to achieve this goal effectively and efficiently. In working towards this goal, 07 objectives are focused upon with subsequent policy statements aimed at achieving these objectives. These are briefly given below;

- Sensitizing people on the country's vulnerability to climate change.
- Focusing on the need for adaptive measures to avoid/minimize adverse impacts of climate change to the people, their livelihoods and ecosystems.
- Mitigating GHG emissions during sustainable development.
- Promoting sustainable consumption and production.
- Enhancing climate change knowledge and developing societal capacity to make informed decisions.
- Developing the country's capacity to face impacts of climate change.
- Integrating climate change issues in the national development process.

The NCCP consists of twenty-five policy statements to achieve these objectives and they are broadly categorized under vulnerability, adaptation, mitigation, sustainable consumption and production, knowledge management and general statements. Statements particularly relevant to climate change adaptation are further discussed in the following sections (MoE, 2012).

Vulnerability

Vulnerability is the tendency to be adversely affected by climate change and includes different concepts such as susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2014). The Paris Agreement itself establishes reducing vulnerability to climate change within the context of the temperature goal mentioned in an earlier section of this chapter. The NCCP recognises that climate change vulnerability should be assessed in the socio-economic and environmental sectors. It is particularly important to pay attention to who is vulnerable to climate change impacts and how to increase their capacity to adapt while including them in the decision-making process on resource allocation and policy formulation (UKCIP, 2011). The NCCP further states that vulnerability should be addressed in the national, provincial, district and local development plans with regard to both natural and manmade environments. The need to have strategies for disaster management which protects the communities, ecosystems and both natural and build environment is also stressed.

The health related impacts of climate change is relatively limited at present and not well quantified. However, future climate change is expected to exacerbate existing health issues of low-income households particularly in developing countries along with an increase in the incidence of food, water and vector-borne disease (IPCC, 2014). Therefore, it is timely that the NCCP recognises the vulnerability of the health sector to the adverse effects of climate change and the need to take appropriate action in this regard. Some priority areas recognised under the NAP include; disease spread and outbreaks, health impacts of hazardous events and thermal stress. Selected priority actions further detailed in the NAP are; establishing a surveillance programme to detect and monitor climate induced diseases; developing the capacity of relevant research institutes; launching relevant awareness campaigns for healthcare workers and the public, and furthering research on effects of climate change on vector-borne and pathogenic diseases. A health sector related aspect that could be considered in future national policy statements is the impact on mental health by climate change related events.

Adaptation

With regard to adaptation, the policy document focuses on the key areas of; food production and food security, conservation of water resources and biodiversity, human settlement and land use planning, infrastructure design and development, and coastal resources management.

Taking timely action to ensure food security by addressing negative effects in sectors such as crop, animal and fisheries production is given under policy statements on food production and security. Climate resilient, innovative and environmentally friendly technologies are encouraged as is appropriate traditional knowledge in the food production sector. Rice, horticultural crops, other food crops, sugarcane, livestock, fisheries and agriculture, and land degradation have been selected as priority areas related to food security in the NAP. Developing climate resilient crop varieties, livestock and poultry breeds tolerant of heat stress and resistant to diseases; promoting water efficient farming methods; adjusting cropping calendars; timely communication of climate information to farmers are some of the priority actions identified by the NAP. Adaptation measures in the agriculture sector are diverse and include low cost individual level actions such as changes in planting date, switching from crops highly impacted by climate change to resilient crops, to economy-wide adjustments such as development of new cultivars and largescale expansion of irrigation (Stern, 2007; Lobell *et al*., 2008). In sectors such as marine fisheries, redistribution of fish stock may decrease supplies in tropical regions of the world thereby indirectly leading to reduction in income and employment (IPCC, 2014).

The NCCP recognises the need to take action to minimize impacts on water resources due to changes in the rainfall patterns, increase in temperature and sea level rise. These include; integrated watershed and water management, and efficient use of water. The NAP describes practical implementation steps such as reducing losses of irrigation water; mapping areas vulnerable to droughts and flood hazards, and preparing disaster risk management plans as well as designing strategies to harness periodic surpluses of water in storage facilities. Climate change is projected to pose risks to drinking water quality due to interacting factors such as increased temperature; increased sediments, nutrients and pollutants from heavy rainfall; increased concentration of pollutants during droughts; and disruption of water treatment facilities during floods (IPCC, 2014). Therefore, these aspects need further attention in local policy formulation.

A large number of species face increased extinction risk under projected climate change especially due to interactive effects of habitat modification, over-exploitation, pollution and invasive species. Furthermore, the composition, structure and function of ecosystems can also change (IPCC, 2014). The NCCP statement on enhancing climate change resilience of natural ecosystems and biodiversity addresses this issue. The NAP provides implementation strategies such as; conducting research studies on climate change impacts on ecosystems and biodiversity; establishing a programme to monitor impacts on key natural ecosystems and biodiversity; preparing adaptive management programmes for climate sensitive ecosystems, and recovery plans for highly threatened ecosystems and species.

Climate change related issues such as heat stress, air pollution and water scarcity are commonly seen in urban areas and these are further exacerbated due to poor infrastructure. The vulnerabilities associated with these risks can be lessened by incorporating adaptive measures when designing infrastructure. This applies for human settlements, land use planning and urban development as well. According to IPCC (2014), strengthening local government and community adaptation capacity, as well as suitable financing and institutional development would further benefit adaptation in this sector. The NAP provides priority actions in this sector such as; promoting climate resilient buildings; preparing hazard preparedness plans for urban, rural and estate settlements; conducting research on climate resilient building designs, green building concepts and alternative materials.

Low lying areas will experience coastal flooding and coastal erosion as an outcomes of sea level rise and the NAP details a number of adaptation strategies for this issue. These include; monitoring shore line changes; studying impacts of sea level rise on coastal habitats over different time lines and empowering coastal communities to face the risks of climate change.

Mitigation strategies in the NCCP are focused upon the areas of energy, transportation, industry, waste management, agriculture and livestock. These areas are not discussed herein as the present chapter is confined purely to adaptation to climate change.

Sustainable consumption and production

Sustainable utilization of natural resources, environmentally friendly lifestyles and the development of environmentally friendly products, processes and techniques are embodied in the NCCP statement related to sustainable consumption and production. It also includes improving the carbon storage facility of forests and their other ecosystem services. This is particularly important as the IPCC (2014) recognizes that carbon stored in forests is susceptible to loss to the atmosphere due to climate change, deforestation and ecosystem degradation. This could be further aggravated due to projected forest die back associated with higher temperature and drought.

Knowledge management

Studies have shown that salience of climate change issues to the public can lead to greater policy adoption and responsiveness (Bromley-Trujillo and Holman, 2020). Furthermore, public risk perceptions can induce or constrain political, economic and social actions to address climate change risks (Leiserowitz, 2006). Education, awareness creation and capacity building are therefore necessary in order to drive action in this regard and thereby face the multifaceted issues of climate change. In order to make climate change policy work, informed participation of all stakeholders is necessary (Takao, 2012). The NCCP further recognises the importance of co-operation and partnership among these different stakeholders and the sharing of knowledge. Finally, the creation of a climate change sensitive, proactive and responsible generation is envisaged in the long-term.

General statements of the NCCP

Strengthening institutional coordination is vital for effective implementation of national and sub-national activities related to climate change. Fostering good governance in order to develop trust among stakeholders is important to ensure accountability in the policy implementation steps as is monitoring and evaluating the performance of the NCCP at national and sub-national levels. Furthering research and sharing research findings on climate change among stakeholders along with appropriate technology and skill transfer is crucial for addressing issues at the national level. The NCCP also looks at market and non-market based mechanisms to improve climate change mitigation and adaptation measures. The need for sustainable financial mechanisms to support the investment required in implementing the NCCP is mentioned and the NAP proposes the formation of a National Adaptation Fund. Finally, strengthening the legal and regulatory framework is a must to encourage effective implementation of the policy statements applicable to different sectors. A Climate Change Commission Act is to be introduced in the future to further aspects in climate change mitigation and adaptation in Sri Lanka (MoMD&E, 2016).

Conclusion and future perspectives

Adaptation is a complex activity which needs to be well understood if appropriate action is to take place. Understanding the context within which adaptation decisions are made is important to avoid risk of inaction and maladaptation (UKCIP, 2011). The adaptation strategies contained within the policy statements of the NCCP will require further study as well as heavy investments in the relevant sectors. Therefore, there is a need to prioritize the adaptation strategies in each sector based on identified vulnerabilities, time scales and national needs. For example, according to IPCC (2014), in order to effectively reduce the vulnerability in the health sector in the short term, improving basic public health measures such as providing clean water and sanitation, essential health care such as vaccination, increasing capacity for disaster preparedness and response, and alleviating poverty are crucial. Similarly, urgent national-level attention is required on food security related aspects such as food access, utilization and price stability as these maybe potentially affected by climate change. The need for climate-resilient food production with a focus on sharing relevant research in discovery, development and deployment is also emphasised as a necessity for Sri Lanka (Marambe *et al*., 2014).

It is clear that adaptation to climate change needs both global strategies as well as national policies implemented in an integrated fashion. In order for policy-driven adaptation to work, collaborative action across diverse sectors with participation of multiple stakeholders is a must. However, adaptation methodologies alone cannot prevent or solve the problem of climate change and the relative effectiveness of adaptation measures will diminish as climate change intensifies (Stern, 2007). Hence adaptation, together with early and strong mitigation, is an important response strategy. Therefore, proactive climate change mitigation and adaptation policies with a well-defined implementation step would be the best way forward to face the uncertainties of climate change.

References

Bromley-Trujillo, R. and Holman, M.R. (2020). Climate change policymaking in the States: a view at 2020. *The Journal of Federalism*, 5 (3): 446-472.

Climate Change Secretariat (2016). National adaptation plan for climate change impacts in Sri Lanka. Ministry of Mahaweli Development and Environment. 176 p.

Dupuis, J. and Knoepfel, P. (2013). The adaptation policy paradox: the implementation deficit of policies framed as climate change adaptation. *Ecology and Society*, 18 (4):31.

Howlett, M. and Cashore, B. (2014). Conceptualizing public policy. In: I. Engeli, C.R. Allison (eds.). *Comparative Policy Studies*. *Research Methods Series*. Palgrave Macmillan, London.

IPCC (2014). Summary for policymakers. In: Climate change 2014: Impacts, adaptation, and vulnerability. Part A: *Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken,P.R. Mastrandrea, and L.L. White (eds.)].

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

IPCC (2007). Climate change 2007: Synthesis report. *Contribution of working groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Pachauri, R.K and Resinger, A (eds)]. IPCC, Geneva, Switzerland, 104 p.

Leiserowitz, A. (2006). Climate change risk perception and policy preferences: the role of affect, imagery, and values. *Climatic Change*, 77: 45–72.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon W.P. and Naylor R.L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science,* 319: 607-610.

Marambe, B., Punyawardena, R., Silva, P., Premalal, S., Rathnabarathie, V., Kekulandala, B., Nidumolu, U. and Howden, M. (2014). Climate, climate risk, and food security in Sri Lanka: Need for strengthening adaptation strategies. *In*: Leal Filho W. (ed.) *Handbook of Climate Change Adaptation*. Springer, Berlin, Heidelberg.

MoE (2012). *The National Climate Change Policy of Sri Lanka*. Colombo. Sri Lanka. Ministry of Environment.

MoMD&E (2016). *Nationally Determined Contributions*. Colombo, Sri Lanka. Ministry of Mahaweli Development and Environment.

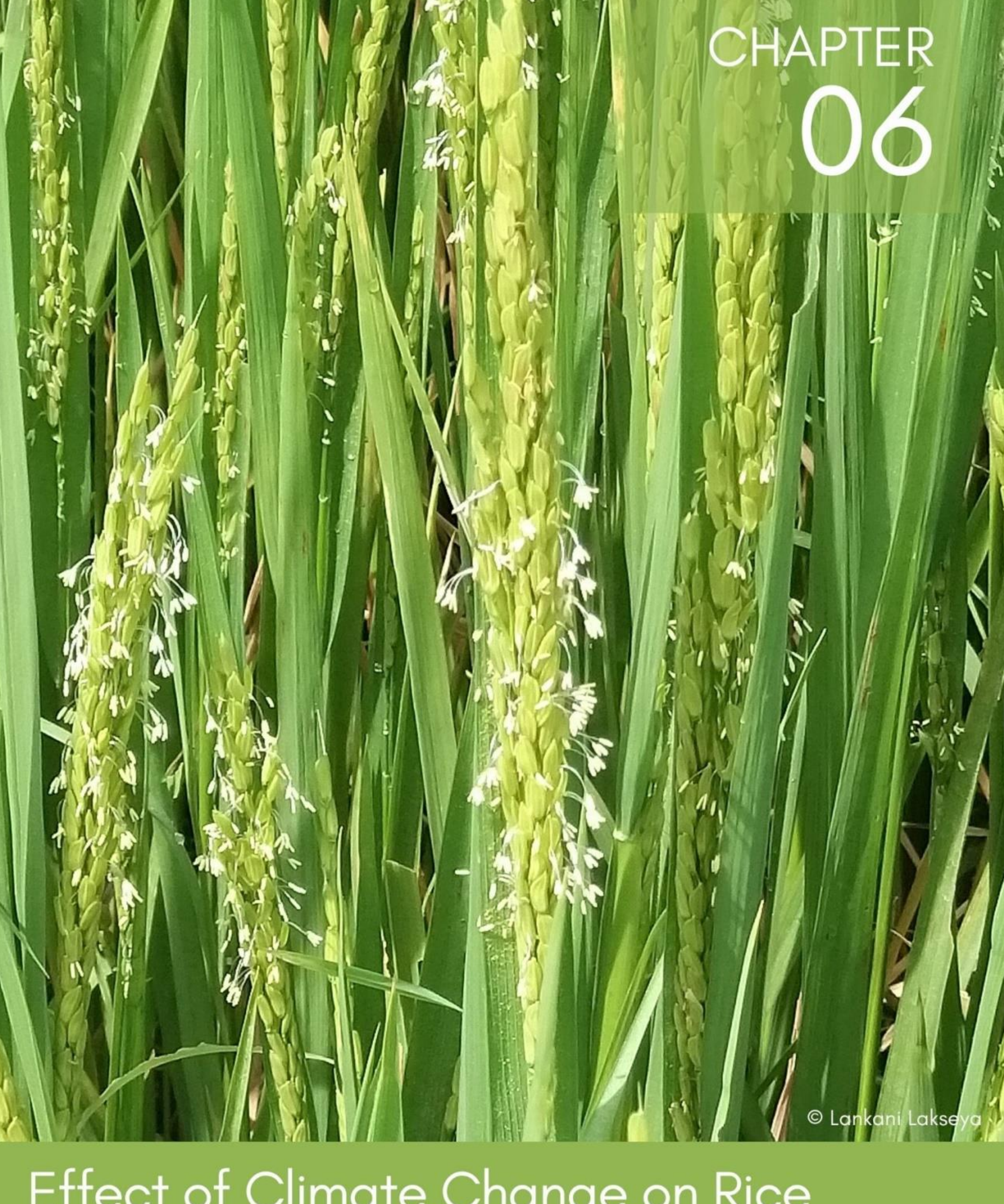
Stern, N. (2007). *The economics of climate change*: The Stern review, Cambridge: Cambridge University Press.

Takao, Y. (2012). Making climate change policy work at the local level: capacity-building for decentralized policy making in Japan. *Pacific Affairs,* 85 (4): 767-788.

UKCIP (2011). Making progress: UKCIP & adaptation in the UK. *UK Climate Impacts Programme*, Oxford, UK.

UNEP (n.d.) Mitigation. https://www.unenvironment.org/explore-topics/climate-change/what-we-do/mitigation. Accessed on 30th July 2020.

United Nations (2015). Paris agreement to the United Nations framework convention on climate change, Paris: United Nations. https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf. Accessed on 25th July 2020.



Effect of Climate Change on Rice Production and Mitigation

W.M.T.P. Ariyaratne*

Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Sri Lanka.
*mariyaratne@yahoo.com

Climate Change Effects on Rice Production and Mitigation

Abstract

The average global temperature has started to rise after the industrial revolution, relative to the pre-industrial historical period (1850–1900) with an increase of 0.87^{0}C for the period 2006–2015. These changes which are mainly due to anthropogenic activities have become a serious threat to agriculture, and especially the global rice production. As a consequence of climate change, severe abiotic influences such as droughts, high and low temperatures, heavy rains, floods, salinity, osmotic tension and destruction due to frost cause significant negative impacts on rice yields and hence on the livelihoods of rice farmers. Knowledge on the possible effects of climate change on rice cultivation is therefore critical for designing effective mitigation strategies. This review discusses the effect of some abiotic stresses that occur due to climate change on the growth and development of rice plant and possible options available for mitigation.

Keywords: *Abiotic stress, breeding, climate change, mitigation, rice*

Climate change

Global climate changes resulting from human activities and their potential impact took an important step in 2005 when the Kyoto Protocol was started to implement. Various greenhouse gases are released into the atmosphere due to the activities of human. Generation of methane and nitrous oxide gases from lowland rice cultivation, livestock and the deforestation are considered as major contributors to global climate changes in terms of agriculture. The greenhouse gases generated from aforesaid agricultural activities lead to changes in the radioactive balance of the earth and consequent changes in temperature, circulation pattern and weather patterns.

The average global temperature, has started to rise after the industrial revolution (Harvey, 2018; Klutse *et al*., 2018; Rogelj *et al*., 2018), relative to the historical period 1850–1900 (pre-industrial level) with an increase of 0.87^{0}C for the period 2006–2015 (Vuuren *et al*., 2011; Edenhofer and Seyboth, 2013; Zhao *et al*., 2017). According to the Paris

Agreement countries agreed to maintain the global surface temperature increase above pre-industrial rates at not more than 2.0°C and to intensify their attempts to minimize this increase to 1.5°C (Falkner, 2016; Rogelj *et al*., 2016; Blau, 2017).

In studies it was found that the negative impacts of climate change on crop yields relevant to ecology and agriculture have been of significant concern, as it increases food shortages that endanger society's regional stability (Hatfield *et al*., 2011; Jabloun *et al*., 2015; Danic *et al*., 2019; Nie *et al.*, 2019). Therefore, assessing the impacts of climate change on crops is urgently needed.

Effect of climate change on rice production

Rice is the main source of energy of over 3 billion people. In addition, rice production is the main occupation and source of income for more than 100 million households in Asian, African and Latin American countries. Various steps were taken in 1970s and 1980s to boost rice production by introducing new technology. This allowed global rice production to satisfy increasing population's demand, increased rice farmers' incomes, generated new jobs and increased availability of rice for poor communities living in urban centers around the world. But in recent years, rice production is declining due to various reasons causing a serious threat to rural poor people.

Experiments have shown that the growth and delivery of rice foods in various parts of the world will be significantly influenced by global climate change. As a consequence of climate change, severe abiotic influences such as droughts, high and low temperatures, heavy rains, floods, salinity, osmotic tension, and frost destruction cause significant risks to rice yield and are even harmful to rice farmers earning a livelihood.

Knowing the possible effect of climate change on rice cultivation is critical for designing effective mitigation strategies.

Impact of climate change on rice growing environments and rice plant

Temperature

Temperatures above threshold limits decrease the rice crop duration and also contribute to increased spikelet sterility (Jagadish *et al*., 2008), reduced grain filling time (Kim *et al*., 2011) and increased respiratory rate (Mohammed and Tarpley, 2009) resulting in lower yield and lower rice grain quality (Fitzgerald and Resurreccion, 2009). Rice especially at flowering stage is highly susceptible to high temperatures. The increase in temperature at night correlated with global warming lowers rice yields. Rice yield tends to be reduced through higher minimum temperature (Wassmann *et al*., 2009) and lower solar radiation (Peng *et al*., 2004), especially during the latter part of the growing season. The warming impacts on rice phenology have been researched, and it has been observed that climate warming has shortened duration for maturity (Zhang *et al*., 2013). Temperature stress during the flowering period of rice has been experimentally linked to spikelet sterility (Nakagawa *et al*., 2003).

The increased CO_2 level from 340 to 680 ppm could increase the yield of major crops by 10% -15%, particularly in C3 plants such as rice (Cure and Acock, 1986; Allen, 1990), but the beneficial effects may be overlooked as the incidence of Photosynthetic Active Radiation (PAR) is likely to decline by 1% (Hume and Cattle, 1990). A research conducted under elevated CO_2 reveals that physiological characteristics such as relative water content (RWC %), membrane stability index (MSI %), chlorophyll quality and photosynthetic rate increased, but reactions of these characteristics remained negative with elevated temperature (Dwivedi *et al*., 2015).

Low temperature conditions due to the climate changes can create changes in physiological and molecular processes and, results in the accumulation of reactive oxygen species (ROS) in plant cells.

Drought

Drought stress at reproductive stage can cause complete crop failure. Further it can be affected to plant morphology, physiology, biochemical processes and molecular functions and these changes causes a variation in rice yield (Pandey and Shukla, 2015).

Further, water stress at the reproductive stage result reduced grain formation, inhibited pollen development at meiosis stage and panicle exertion (O'toole and Namuco, 1983). Drought stress also inhibits processes such as anther dehiscence, pollen shedding, pollen germination, and fertilization (Ekanayake *et al*., 1990; Zaman *et al*., 2018) found that panicle initiation is the most vulnerable stage to water stress which, leads to a substantial reduction in rice yield.

Rainfall, submergence and flooding

Forty percent of the overall rice region is categorized as rain-fed (lowland or upland), and nearly 3.5 million ha of rice land are also listed as deep-water or flood-prone (Maclean *et al*., 2002). The most significant factor restricting the yield of rain-fed rice is variation in the volume and distribution of the rainfall. Variability in the rainy season due to the climate change creates problem in rain-fed rice farming as farmers cannot plan their cultural operations well in advance.

Rice is semi-aquatic in nature and tolerates partial submergence better than any other crops but dies when completely submerged for few days. Their survival is due to the special air channels called aerenchyma which connect the roots to the shoots and allow the transport of oxygen to submerged tissues. For rain-fed lowland, irrigated, and deep-water ecosystems, most rice varieties will survive full submergence for at least 6 days with 50% mortality. However, when submergence extends 14 days, the mortality rate is 100%. Anaerobic conditions influence glycolysis, which encourages the formation of ethanol and lactate by ethanolic fermentation (Chirkova and Yemelyanov, 2018). Produced ethanol can spread out of the cell and contributes to the production of acetaldehyde as a toxic intermediate (Rahman *et al*., 2001) which is harmful for the rice plant. Floods often inflict indirect harm to rice production by damaging lands, dams, dikes, and roads.

Acidic soil

Acid soils greatly hinder crop production globally. Around 50% of the currently arable soils in the world are acidic. The primary limitations for acid soils are hazardous amounts of aluminum (Al), manganese (Mn) and iron (Fe), and suboptimal amounts of phosphorus (P) (Kochian *et al*., 2004). In heavy rainfall excessive runoff and soil degradation causes soil acidity.

Effect on land and water resources available for rice

In the climate change scenario, the largest change in temperature could be anticipated on agricultural land in tropical regions of low latitude (Rosenzweig and Iglesias, 1994). Darwin *et al*. (2005) estimated that the amount of land classified as “land class 6” – i.e. the primary land class for rice, tropical maize, sugarcane and rubber in tropical areas would decline between 18.4 and 51.0 percent during the next century due to global warming.

Adaptation and mitigation

Adaptation refers to plants modification to decrease the vulnerability to climate changes, where mitigation focuses on reducing the emission of greenhouse gases.

Develop new cropping calendar

Germination and emergence of rice seedlings are more likely to be constrained by low than high temperatures. Rise in temperature under global climate change will not greatly impact the selection of the correct date for rice cultivation in tropical areas. As the temperature varies from month to month, the best date for crop establishment may be chosen in such a way that the rice reproductive and grain filling phases fall into certain months with a fairly low temperature. Hence, we have to develop new cropping calendar considering the changes occur in the temperature and rainfall (Peng *et al*., 2004).

Climate modeling

Developing models to predict how the local weather environment shifts with global warming will help establish early alert systems for severe weather events. Farmers should be advised and directed on appropriate varieties, their management and how to respond to climate changes. However, there are limits about how much change will take place for one year.

Genome editing for yield and stress tolerance improvement

New technology like CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) with CRISPR-associated protein Cas9 (CRISPR-Cas9) is an excellent technique that can be used for the development of new rice varieties. CRISPRCas9 can be used for single or multiple location genes manipulation. Further it easy to use and has high precision when compared with other methods (Wang *et al*., 2017). Some of the yield and stress improvements done in rice plants using this technique are given in the Table 1.

Selection and development of new appropriate rice varieties

Rice varieties can withstand elevated temperatures, salinity, drought and floods by adjusting their physiological activities in various ways. Genus Oryza is made up of 24 species. Out of the 24 species and *O. sativa, O.*

Table 1: Genes edited for yield and stress improvement in rice

Gene	Effect of gene on plant	Genome-editing system	References
Gn1a (Os01g0197700),	Regulators of grain number	CRISPR-Cas9	Li *et al.*, 2016
DEP1 (Os09g0441900)	Panicle architecture	CRISPR-Cas9	Li *et al.*, 2016
GS3 (Os03g0407400)	Grain size	CRISPR-Cas9	Li *et al.*, 2016
IPA1 (Os08g0509600)	Plant architecture	CRISPR-Cas9	Li *et al.*, 2016
OsRR22	Salt tolerance	CRISPR-Cas9	Farhat *et al.*, 2019; Zhang *et al.*, 2019
OsPIN5b, *GS3*, and OsMYB30	cold tolerance	CRISPR/Cas9	Zeng *et al.*, 2020
OsSAPK2	Abscisic acid sensitivity and tolerance to drought stress	CRISPRCas9	Lou *et al.*, 2017.

glabberima) are known for cultivation and human consumption. Other 22 species are in wild in nature and function as a source of multiple abiotic tolerance genes. Screening these varieties using molecular techniques and use of elite lines for breeding will help in utilizing the inherent potential of wild species for generating abiotic tolerant lines through introgression. For transferring the desired genes to develop stress tolerant new varieties can be done through conventional breeding (Figure 1). In this method not only the desired genes but other genes also transfer to the new variety and it one of the major disadvantages in this method. In genetic engineering (Figure 2) not like in the conventional breeding, targeted specific gens can be transferred to the new variety. Cost and technology involved in this method are the major barriers for the use biotechnology. New varieties developed by this method are commonly known as genetically modified crops (GMO). However, GMOs are banned in some countries.

Genome sequencing and expression analysis of genes in certain forms of *Oryza* genomes that have not been sequenced may accelerate the approach of developing varieties tolerant to abiotic stress. The *OsTHIC* gene (Hu *et al.,* 2018), which was highly induced in leaves and panicles in response to all stresses at different developmental stages, especially at the booting stage under cold stress is a good example for the aforesaid technique.

Optimization of high CO_2 concentration for higher yield

C4 plants are more productive than C3 rice and 30 to 35 percent more efficient in photosynthesis, particularly when the atmospheric CO_2 concentration levels are high. Genes which are responsible for leaf anatomy and biochemical processes of C4 plants should be incorporated into C3 rice pants by using genetic engineering approaches (Karki *et al*., 2013).

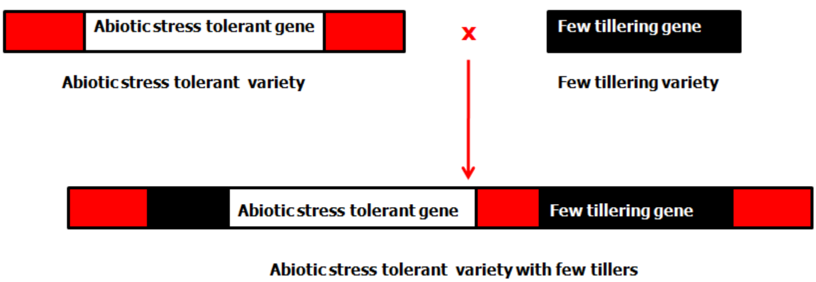


Figure 1: Schematic diagram showing the process of developing new varieties using conventional breeding.

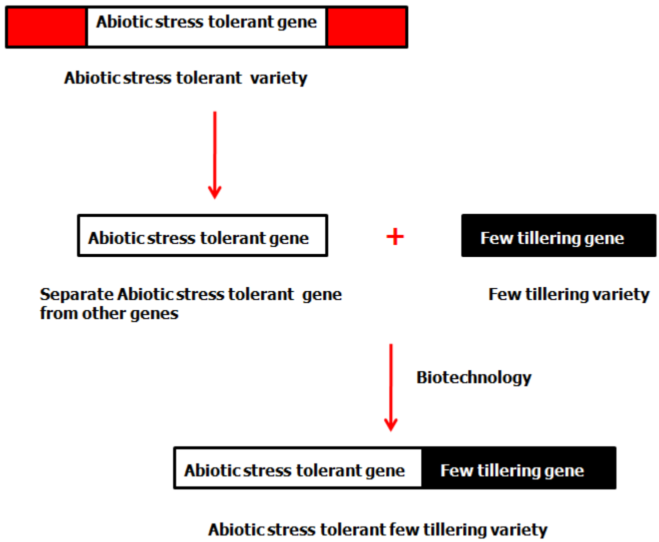


Figure 2: Schematic diagram showing the process of developing new varieties using genetic engineering.

Policy recommendations

Implementation of well formulated adaptation strategies with a well-coordinated institutional network with all the stakeholders will be helpful to face the problems created by the climate change. Policies to enhance commitment from all its stakeholders to its implementation, allocation of sufficient financial resources, strengthening human resource and the development of infra-structure is needed to mitigate impact of climate change.

Conclusions

Rice is world population's main food grain. The world population continues to rise exponentially although the land and water are on the decline. Studies show that temperature increase, rising oceans and shifts in rainfall trends and their distribution under global climate change may contribute to significant changes in land and water supplies for rice production as well as productivity of rice crops grown in different parts of the world.

New varieties and the improved agronomic practices may help for the rice production systems to respond to global climate change as well as reduce the impact on global warming from rice production. Policy support for rice research and development to establish and transition appropriate and productive technology would be essential for the implementation of sustainable rice production initiatives.

Climate change is recognized as a global issue which needs a global approach to reduce the greenhouse gas emissions with the enhanced likelihood that rising greenhouse gases would affect the environment.

References

Allen, L.H. (1990). Plant responses to rising carbon dioxide and potential interactions with air pollutants. *Journal of Environment Quality*, 19: 15-34.

Blau, J. (2017). The Paris Agreement; Springer: Berlin, Germany,

Chirkova, T. and Yemelyanov, V. (2018). The study of plant adaptation to oxygen deficiency in Saint Petersburg University. *Biological Communications*, 63: 17-31.

Cure, J.D. and Acock, B. (1986). Crop responses to carbon dioxide doubling: A literature survey. *Agriculture and Forest Meteorology*, 38: 127-45.

Danicˇic, M., Zekic, V., Mirosavljevic, M., Lalic, B., Putnik-Delic, M., Maksimovic, I. and Dalla Marta, A. (2019). The response of springbarley (*Hordeum vulgare*L.) to climate change in Northern Serbia. *Atmosphere*, 10: 14.

Darwin, R., Tsigas, M., Lewandrowski, J. and Raneses, A. (2005). World agriculture and climate change: economic adaptation. USDA *Agricultural Economic Report* No. 703: 86.

Dwivedi, S.K., Kumar, S., Prakash. V., Mondal, S. and Mishra, J.S. (2015). Influence of rising atmospheric CO_2 concentrations and temperature on morphophysiological traits and yield of rice genotypes in sub humid climate of Eastern India. *American Journal of Plant Sciences*, 6: 2239.

Edenhofer, O. and Seyboth, K. (2013). Intergovernmental panel on climate change (IPCC). *Encyclopedia of Energy, Natural Resource, and Environmental Economics*, 26: 48–56.

Ekanayake, I.J., Steponkus, P.L. and De Datta S.K. (1990). Sensitivity of pollination to water deficits at anthesis in upland rice. *Crop Science,* 30: 310-315.

Falkner, R. (2016). The Paris agreement and the new logic of international climate politics. *International Affairs*, 92: 1107–1125.

FAO (2005). The state of food and agriculture, Agricultural Series, vol. 36.

Farhat S., Jain N., Singh N., Sreevathsaa, R., Dash, P.K., Rai, R., Yadav, S., Kumar, P., Sarkar A.K., Jain, A., Singh, N.K. and Rai, V. (2019). CRISPR-Cas9 directed genome engineering for enhancing salt stress tolerance in rice. *Seminars in Cell and Developmental Biology*. 96: 91-99.

Fitzgerald, M. and Resurreccion, A.P. (2009). Maintaining the yield of edible rice in a warming world. *Functional Plant Biology,* 36: 1037-1045.

Harvey, L.D. (2018). Global Warming; Routledge: London, UK.

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A.M. and Wolfe, D. (2011). Climate impacts on agriculture: Implications for crop production. *Agronomy Journal*, 103: 351-370.

Hu, H., Changqian, Q., Jingmin, Z., Qiang, Y., Zhigang, B, Zhengjun, X., Xiaoling, G., Lihua, L, Jianqing, Z. and Rongjun, C. (2018). Identification and characterization of a novel abiotic stress responsive *OsTHIC*gene from rice. *Biotechnology and Biotechnological Equipment*, 32(4): 874-880.

Hume, C.J. and Cattle, H. (1990). The greenhouse effect meteorological mechanisms and models. *Outlook on Agriculture* 19: 17-23.

Jabloun, M., Schelde, K., Tao, F. and Olesen, J.E. (2015). Effect of temperature and precipitation on nitrate leaching from organic cereal cropping systems in Denmark. *European Journal of Agron*omy, 62: 55–64.

Jagadish, S.V., Craufurd, P.Q. and Wheeler, T.R. (2008). Phenotyping parents of mapping populations of rice for heat tolerance during anthesis. *Crop Science*, 48: 1140-1146.

Karki1, S., Rizal1, G. and Quick, W.P. (2013). Improvement of photosynthesis in rice (*Oryza sativa* L.) by inserting the C4 pathway. *Rice,* 6: 28.

Kim, J., Shon, J., Lee, C.K., Yang, W. and Yoon, Y. (2011). Relationship between grain filling duration and leaf senescence of temperate rice under high temperature. *Field Crop Research*, 122: 207-213.

Klutse, N.A.B., Ajayi, V.O., Gbobaniyi, E.O., Egbebiyi, T.S., Kouadio, K., Nkrumah, F., Quagraine, K.A., Olusegun, C., Diasso, U. and Abiodun, B.J. (2018). Potential impact of 1.5^{o}C and 2^{o}C global warming on consecutive dry and wet days over West Africa. *Environment Research Letters*., 13: 055013.

Kochian, L.V., Hoekenga, O.A. and Pineros, M.A. (2004). How do crop plants tolerate acid soils? Mechanisms of aluminum tolerance and phosphorous efficiency. *Annual Review of Plant Biology,* 55: 459-493.

Li, M., Li, X., Zhou, Z., Wu, P., Fang, M., Pan, X., Lin, Q., Luo, W., Wu, G. and Li, H. (2016). Reassessment of the Four Yield-related Genes Gn1a, DEP1, GS3, and IPA1 in Rice Using a CRISPR/Cas9 System. *Frontiers in Plant Science,* 7: 377.

Lou, D., Wang, H., Liang, G. and Yu, D. (2017). OsSAPK2 confers abscisic acid sensitivity and tolerance to drought stress in rice. *Frontiers in Plant Science*, 8: 993.

Maclean, J.L., Dawe, D.C., Hardy, B. and Hettel, G.P. (2002). Rice almanac (Third Edition). Philippines, IRRI, WARDA, CIAT and FAO.

Mohammed, A.R. and Tarpley, L. (2009). Impact of high nighttime temperature on respiration, membrane stability, antioxidant capacity, and yield of rice plants. *Crop Science*, 49: 313-322.

Nakagawa, T., Kitagawa, H., Yasuda, Y., Tarasov, P.E. and Nishida, K. (2003). Asynchronous climate changes in the North Atlantic and Japan during the last termination. *Science*, 299: 688-691.

Nie, H., Qin, T., Yang, H., Chen, J., He, S.; Lv, Z. and Shen, Z. (2019). Trend analysis of temperature and precipitation extremes during winter wheat growth period in the major winter wheat planting area of China. *Atmosphere*, 10: 240.

O'toole, J.C. and Namuco, O.S. (1983). Role of panicle exertion in water stress induced sterility. *Crop Science*, 23: 1093-1097.

Pandey, V. and Shukla, A. (2015). Acclimation and tolerance strategies of rice under drought stress. *Rice Science*, 22: 147-161.

Peng, S., Huang, J., Sheehy, J.E., Laza, R.C. and Visperas, R.M. (2004). Rice yields decline with higher night temperature from global warming. *Proceedings of National Academy of Science, USA,* 101: 9971-9975.

Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Khush, G.S. and Cassman, K.G. (2004). Rice yield decline with higher night temperature from global warming. In: E.D. Redona, A.P. Castro and G.P. Llanto (eds.). Rice Integrated Crop Management: Towards a rice check system in the Philippines, Nueva Ecija, Philippines, *PhilRice*. p. 46–56.

Rahman, M., Grover, A., Peacock, W.J., Dennis, E.S. and Ellis, M.H. (2001). Effects of manipulation of pyruvate decarboxylase and alcohol dehydrogenase levels on the submergence tolerance of rice. *Functional Plant Biology,* 28:1231-1241.

Rogelj, J., Den, E.M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K. and Meinshausen, M. (2016). Paris agreement climate proposals need a boost to keep warming well below 2°C. *Nature*, 534: 631–639.

Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T. and Marangoni, G. (2018). Scenarios towards limiting global mean temperature increase below 1.5°C. *Nature Climate Change*, 8: 325–332.

Rosenzweig, C. and Iglesis, A. (1994). Implications of climate change for international agriculture: Crop modeling study. Washington DC, US Environmental Protection Agency, Climate Change Division.

Vuuren, D.P.V., Stehfest, E., Elzen, M.G.J.D., Kram, T., Vliet, J.V., Deetman, S., Isaac, M., Goldewijk, K.K., Hof, A. and Beltran, A.M. (2011). Rcp2.6: Exploring the possibility to keep global mean temperature increase below 2°C. *Climate Change*, 109: 95–116.

Wang, M., Wang, S., Liang, Z., Shi, W., Gao, C. and Xia, G. (2017). From genetic stock to genome editing: gene exploitation in wheat. *Trends in Biotechnology,* 36: 160–172.

Wassmann, R., Hirano, T., Miyata, A., Kumar, A. and Padre. A. (2009). CO_2/heat fluxes in rice fields: Comparative assessment of flooded and non-flooded fields in the Philippines. *Agriculture and Forest Meteorology*, 149: 1737-1750.

Zaman, N.K., Abdullah, M.Y., Othman, S. and Zaman, N.K. (2018). Growth and physiological performance of aerobic and lowland rice as affected by water stress at selected growth stages. *Rice Science*, 25: 82-93.

Zeng, Y., Wen, J., Zhao, W., Wang, Q. and Huang, W. (2020). Rational improvement of rice yield and cold tolerance by editing the three genes OsPIN5b, GS3, and OsMYB30 with the CRISPR-Cas9 System. *Frontiers in Plant Science,* 4.

Zhang, A., Liu, Y., Wang, F., Li, T., Chen, Z., Kong, D., Bi, J., Zhang, F., Luo, X., Wang, J., Tang, J., Yu, X., Liu, G. and Luo, L. (2019). Enhanced rice salinity tolerance via CRISPR/Cas9-targeted mutagenesis of the OsRR22 gene. *Molecular Breeding*, 39: 47.

Zhang, T., Huang, Y. and Yang, X. (2013). Climate warming over the past three decades has shortened rice growth duration in China and cultivar shifts have further accelerated the process for late rice. *Global Change Biology*,19: 563-570.

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D.B., Huang, Y., Huang, M., Yao, Y., Bassu, S. and Ciais, P. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of National Academy of Science, USA*, 114: 9326–9331.

CHAPTER
07

© Binoshi Hettihewa

Legume-based Cropping Systems to Sustain Nutrient Efficiency of Farming Systems under Changing Climate

D.M.S.B. Dissanayaka* and B. Marambe

Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.
*dissanayakauop@yahoo.com

Legume-based Cropping Systems to Sustain Nutrient Efficiency of Farming Systems under Changing Climate

Abstract

Climate change has significantly threatened crop production with direct and indirect effects on both quality and quantity of economically important harvest. The main focus of many researchers on climate change impacts has been to assess the quantitative aspect of plant growth and yield. However, the detrimental impacts on the quality aspects such as reduction of nutrient profiles leading to micronutrient malnutrition known as "hidden hunger", is progressively evident under changing and variable climate. Over-reliance on major staple cereal crops in the food basket has been a main reason for the emerging nutritional risks particularly in the south Asian region. Therefore, preserving nutritional quality of edible crop products is known to be a greater challenge that needs urgent attention from all stakeholders of agriculture under changing climate. Diversifying crop production systems to generate improved nutritional outputs for a less carbon footprint as well as dietary shifts towards more nutritionally enriched crops is a part of the paradigm shift in achieving nutritional security of the population that mainly rely on plant based diets. In Sri Lanka, underutilized legumes have untapped potential to yield higher nutritional output even under low input farming systems while reducing greenhouse gas (GHG) emissions. Therefore, the current recommendation to incorporate legumes such as mung bean [*Vigna radiata* (L.) Wilczek] as the third or fourth season crop in rice production systems would provide a more sustainable adaptation as well as a mitigation strategy for climate change in Sri Lanka while minimizing yield losses and enriching nutritional output of the cropping system.

Keywords: *Adaption/ mitigation strategy, climate change, legumes, nutritional security, nutrient profiles*

Introduction

With a rapid increase in world population, the global demand for food is expected to rise throughout this century. Quality and the quantity of crop yields are extremely challenged by climatic conditions projected for the future and therefore, most of the food produced for human consumption is under threat (Burritt, 2019). Several efforts have been made to increase global food availability, however, the risk of malnutrition and nutrient deficiencies are rising at an alarming rate and closely related to climate changes, particularly in developing regions (FAO, 2017). This has highlighted the enormous importance of exploring more detail of the impacts of climate change on food security, malnutrition and its potential consequences for nutritional outcomes (Myers *et al*., 2017; Fanzo *et al*., 2018). Increasing the concentration of anthropogenic greenhouse gases (GHG) in the atmosphere, which has rapidly increased since the pre-industrial era, has been the key driver of climate change. Economic and population growth has led to increase GHGs to unprecedented levels causing further warming and aggravating changes of the climate system resulting in detrimental impacts for people and ecosystems (Myers *et al*., 2017; Soares *et al*., 2019). Therefore, in the coming decades, climate change is expected to be the greatest challenge for producing larger amounts of nutritious food to feed the rapidly growing global population (Pretty *et al*., 2018).

Many studies that assessed the impacts of climate change on food crops have been mainly focusing on the quantity of crop yields while less attention has been paid to nutritional quality, which is being progressively evident under changing climate. Several sustainable strategies have been recently proposed for preserving nutritional output of crops among which inclusion of legumes in different farming systems is a promising yet underexploited approach (Soares *et al*., 2019). Being the world's primary source of dietary proteins, legumes are well-known to provide proteins and other nutrients in human diets, but have been underexploited in agriculture and neglected in terms of cultivation and consumption thus, compromising human health and sustainable food production (Foyer *et al*., 2016; Rehman *et al.*, 2018; Robinson *et al*., 2019). Therefore, this chapter is aimed at discussing the legume-based cropping system as a sustainable strategy to preserve nutrient efficiency of farming systems in the context of climate change.

Recent trends of climate change in Sri Lanka

Consequences of climate change such as rise in temperature, extreme rainfall events and sea level rise are critically affecting almost all sectors of the country. Occurrences of natural disasters due to extreme weather conditions such as prolonged droughts, flash floods and landslides deprive lives and livelihoods of people (MMDE, 2016). Studies have shown that food security of the nation can be adversely affected due to impacts of climate change (Punyawardena, 2007; De Costa, 2008; De Silva, 2013; Marambe *et al*., 2015). Emerging evidence from various sources have suggested that climate change could alter natural systems connected to water cycle, ecosystems and biodiversity of the country (Eriyagama *et al*., 2010; Marambe *et al*., 2012). Observed climatic changes in Sri Lanka over the years are discussed below;

Temperature

Analysis of past data suggests that atmospheric temperature is gradually rising almost everywhere in the country (Nissanka *et al*., 2011; Sathischandra *et al*., 2014). Varied rates of increase in temperature have been reported from different locations and in recent years, the warming trend has become faster. The annual mean air temperature anomalies have shown significant increasing trends in all meteorological stations during the recent decades (Basnayake, 2007). It has been reported that mean daytime maximum and mean night time minimum air temperatures also have increased (Zubair *et al*., 2005; Basnayake, 2007). Data indicate that increase in night time minimum air temperature contributes more to average increase in annual temperature than day time maximum air temperature (Basnayake, 2007).

Precipitation

Unlike in the case of temperature, no clear pattern or trend has been observed in precipitation. Some researchers, comparing the mean annual precipitation of recent and earlier periods, suggest that average rainfall is showing a decreasing trend (Jayatillake *et al*., 2005; Basnayake, 2007; Chandrapala, 2007; De Costa, 2008). However, there is no consensus on this among researchers and opposing trends can be observed in different locations. Punyawardena *et al*. (2013a) observed that heavy rainfall events have become more frequent in central highlands during the recent period. However, many researchers seem to agree that the variability of rainfall has increased over time, especially in the *Yala* season (Chandrapala, 2007; Eriyagama *et al*. 2010; Punyawardena *et al*., 2013b). Moreover, the number of consecutive dry days has increased and the consecutive wet periods have decreased (Ratnayake and Herath, 2005; Premalal, 2009). Studies also indicate that spatial distribution of rainfall appears to be changing although a distinct pattern is not evident yet (Basnayake, 2007; Nissanka *et al*., 2011; Marambe *et al*., 2013; Sathischandra *et al*., 2014). Some studies have suggested that changes in the distribution can even lead to shifting of agro-ecological boundaries (Eriyagama *et al*., 2010; Mutuwatte and Liyanage, 2013).

Extreme events

The intensity and frequency of the extreme events such as floods and droughts have increased during recent times (Ratnayake and Herath 2005; Imbulana *et al*., 2006; Premalal and Punyawardena, 2013; Punyawadena and Premalal, 2013). Areas of high rainfall intensities and the locations of landslides show a strong correlation (Ratnayake and Herath, 2005).

Sea level rise

Sea level rise of 1-3 mm/year is observed in the Asian region and is marginally higher than the global averages (Cruz *et al*., 2007). An accelerated sea level rise has been observed during the period of 1993-2001 (3.1 mm/year) for the Asian region. However, specific levels of sea level rise in areas around Sri Lanka are yet to be assessed.

Challenge of preserving nutritional quality of crops under changing environments

The climate change is driven by elevated levels of anthropogenic GHGs in the atmosphere resulting from population growth and associated economic activities, which are being significantly increased after the pre-industrial era (Myers *et al*., 2017; Soares *et al*., 2019; Neukom *et al*., 2019). Continuous release of GHGs including CO_2 into the atmosphere has resulted in further warming and increasing the likelihood of severe and permanent impacts for people and ecosystems (Myers *et al*., 2017; Soares *et al*., 2019). The increased CO_2 (eCO_2) concentration in atmosphere is predicted to have a range of negative impacts not only on global food production but on nutritional sufficiency of the global population (Myers *et al*., 2017). The loss of a range of nutrients in many food crops has been demonstrated when they are grown under eCO_2. The experiments conducted in controlled indoor environments during recent decades have found significant reductions in the concentrations of many nutrients important for human health (Manderscheid *et al*., 1995; Seneweera and Conroy, 1997; Ziska *et al*., 2004). Moreover, subsequent Free Air CO_2 Enrichment (FACE) experiments in the past decade verified the results from indoor environments for many nutrients, particularly micronutrients and proteins. The reduction of nutrients is noticeable across a range of important staple food crops such as rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), potatoes (*Solanum tuberosum* L.), maize (*Zea mays* L.), and soybeans [*Glycine max* L. Merr] (Loladze, 2014; Myers *et al*., 2014). Reduction in the concentration of important micronutrients in such major food crops will place populations of the developing world at a huge risk. Iron (Fe) concentration was also significantly reduced in soybean grains, while zinc (Zn) and Manganese (Mn) concentrations varied among cultivars under eCO_2 (Li *et al*., 2018b). It was also demonstrated that eCO_2 lowers nitrogen (N) magnesium (Mg), Fe, and Zn concentrations in edible parts of vegetables without significantly affecting phosphorus (P), potassium (K), sulphur (S), copper (Cu), and Mn (Dong *et al*., 2018b).

There is clear evidence to prove that Zn deficiency is a global health constraint affecting 17% of the world's population, and rising CO_2 levels reduce Zn accumulation in edible part of major food crops thereby reducing the Zn intake of different populations that rely on those crops (Myers *et al*., 2014, 2015, 2017). The meta-analysis by Myers *et al*. (2014) combining previously published data from FACE and growth chamber experiments, showed a significant reduction of Zn concentration by 9.1% in wheat, 3.1% in rice, 13.6% in barley, 6.8% in field peas (*Pisum sativum* L) and 5% in soybean when they are grown at eCO_2. The recent modelling studies predicted that around 138–175 million people are at risk of Zn deficiency while 122–148 million could become at risk of protein deficiency by 2050 if the CO_2 continues to rise as predicted (Myers *et al*., 2015; Medek *et al*., 2017; Smith and Myers, 2018). Existing protein and Zn deficiencies will be exacerbated in over a billion people in the world (Smith *et al*., 2017). Smith and Myers (2019) pinpointed another grand challenge that predicted increase in CO_2 levels have been shown to lower the B vitamin content of rice by 17–30%, which may cause 132 million people to become at risk of folate deficiency leading to anemia, 67 million to thiamin, and 40 million in riboflavin deficiency. Highly vulnerable regions are Africa (West and East) and Asia (Southeast, East, and South) that are mostly depend on rice (Smith and Myers, 2019). Rice being the staple food crop, the emerging threat will be equally applicable to nutritional security in Sri Lanka in coming decades.

Climate change is also characterized by warming of the atmosphere and irregular pattern of rainfall leading to frequent occurrence of drought and flooding depending on the region. Fischer *et al*. (2019) studied the nutrient accumulation of food crops under drought conditions in two different regions of East Africa. Nutrient accumulation was decreased under severe drought whereas mild drought actually increased nutrient concentrations. The results suggest that the nutrient accumulation under changing climate is dependent not only on the type of climatic change but also on its intensity level. Contrasting findings have been observed with respect to the effect of increasing temperatures on nutrient composition of crops. From a greenhouse experiment, Sublett *et al*. (2018) found a decrease in leaf Mg, K, calcium (Ca), Mn and molybdenum (Mo) concentrations of lettuce under elevated temperature (+8 °C). However, when soybean and wheat were grown under eCO_2 and elevated temperature, seed Fe and Zn concentrations did not change suggesting a possibility that combination of both factors may restore grain Fe and Zn concentration (Köhler *et al*., 2018; Asif *et al*., 2019). A solid conclusion cannot be still made since there is a strong species and cultivar dependency on these responses. It will therefore be of interest to look at these aspects in detail. All the findings discussed above highlight that, in the coming decades, climate change will be a formidable challenge that needs to be tackled by all stakeholders involved in agriculture, natural ecosystems, and global economies for producing sufficient amounts of nutritious foods in achieving global food and nutrition security (Pretty *et al*., 2018).

Legume-based cropping systems: a sustainable yet underexploited approach to enhance nutrient efficiency in farming systems under changing climate

Several practices are under way to mitigate and/or adapt to climate change impacts while preserving nutritional output of farming systems (Soares *et al*., 2019). One of the efficient strategies for climate change adaptation and mitigation is the incorporation of legumes to farming systems as it naturally reduces the amount of inorganic N fertilizer, reduce GHG emissions, and maintain soil fertility (Figure 1, Karkanis *et al*., 2018). It is clearly evident that most input intensive monocropping systems could contribute to climate change and environmental degradation through different means such as excessive fertilizer use which could end up with GHG emission causing further warming of atmosphere and nutrient leaching to water bodies leads to eutrophication (Gilbert, 2009). However, legumes reduce GHG emissions in agricultural cropping systems compared to that of other crop groups (Petersen *et al*., 2011; Mitchell *et al*., 2013; Foyer *et al*., 2016). The total emission of a cropping land declined by 56% on a per hectare basis when white lupin (*Lupinus Albus* L.) was cultivated as a cover crop with wheat (Barton *et al*., 2014). Furthermore, a predictive model based on climate data of last 80 years has shown that the legume incorporation in a crop rotation would reduce 25% of the GHG emission (Ma *et al*., 2018). Moreover, legumes as mixed cropping and cover cropping enhance plant availability of P, Fe and Zn and improved growth and uptake of those nutrients respectively by neighbouring and subsequently cultivated crops (Figure 1, Xue *et al*., 2016). Therefore, this age-old sustainable practice might need to recommend to a greater degree in modern paradigm shift of 'sustainable intensification' of agricultural lands (Mungai *et al*., 2016; Pretty *et al*., 2018), where agriculture practices are expected be more sustainable and efficient, while meeting increasing needs of human beings with low inputs. In addition, legumes are known for a very long period to have better nutritional profiles for human diets but have been underexploited in agriculture and neglected in terms of cultivation, consumption and most importantly scientific research that this crop group deserves (Foyer *et al*., 2016; Robinson *et al*., 2019). If anthropogenic climate change is to be mitigated in the future, dietary shifts towards more nutritious and sustainable diets would also be a part of the paradigm shift of sustainable food systems. Pulse crops should be

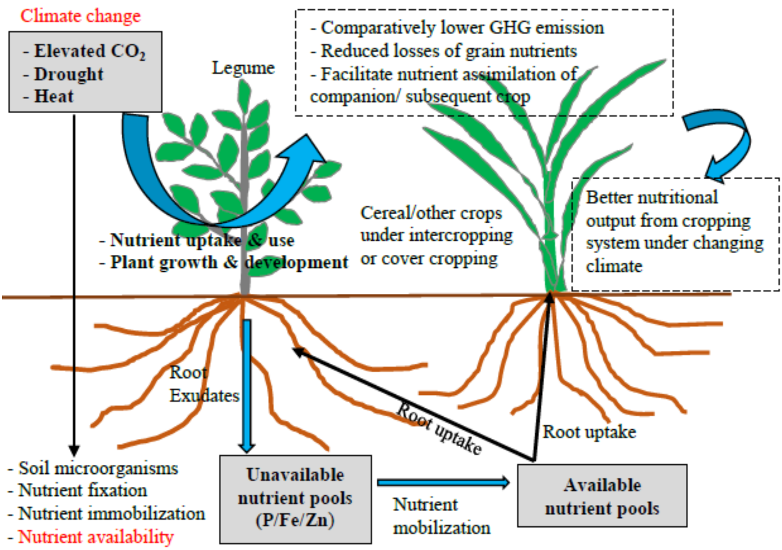


Figure 1: Schematic illustration demonstrating how legume based cropping systems could preserve nutritional output from the cropping system under changing climate

an important integral component of this change as they provide an environmentally sustainable source of protein, starch and micronutrients. This might also be a better approach to handle the dietary deficiencies of micronutrients (hidden hunger), an emerging global public health problem estimated to affect around two billion people worldwide (Haddad *et al*., 2015). A high consumption of cereal-based diets is the principle cause to Zn deficiency as cereals have low concentration and bioavailability of Zn and cannot meet human demand for Zn (Cakmak and Kutman, 2018). The Situation could be even worse for cereal-eating populations as predicted climate changes further reduce most of the micronutrients availability particularly Fe and Zn in major cereals (Cakmak *et al*., 2010; Cakmak and Kutman, 2018). Therefore, it is of prime importance to preserve nutritional composition of crops for human health by eliminating micronutrient deficiencies and reduce risk of some chronic diseases encountered in day to-day life (Robinson *et al*., 2019).

Among several legumes grown in Sri Lanka, mung bean [*Vigna radiata* (L.) Wilczek] is the most common grain legume grown by subsistence farming communities and ideally suitable to the dry season known as "*Yala*", the minor rainy season prevailing from March to August with very high spatial and temporal variability (De Costa and Shanmugathasan, 1999; Amarasinghe *et al*., 2017). The crop is predominantly grown in low-productive rain-fed upland cropping systems and/or in rice-based lowland cropping systems with supplementary irrigation (Malaviarachchi *et al*., 2015). Sri Lankan farmers are advised by the Departments of Agriculture and Irrigation to shift the rice cultivation to other field crops such as mung bean during *Yala* season in order to improve the productivity of low-land cropping systems where the irrigation water is inadequate to cultivate all the lowlands with rice (Amarasinghe *et al*., 2017). Such incorporation of legumes to different farming systems could definitely enhance the nutritional output under changing and variable climates particularly in drought prone environment as many legumes are well-adapted to limited moisture availability. Legumes are also a well-adapted plant group that have comparative advantage in securing grain nutrients over cereal under climate change. For example, a study that examined diets in 152 countries comprising 95% of the global population found that the aggregate daily Fe lost under eCO_2 was the greatest from cereals (Smith *et al*., 2017). Therefore, populations depending on cereal-based diets would be at a higher risk of Fe-deficiency under predicted future environmental conditions. The daily Fe lost from legume-based diets is significantly lower compared to those of cereals highlighting the potential of this crop group in strengthening nutritional security of farming system under changing environments (Smith *et al*., 2017). The GNR (2020) classifies Sri Lanka as a country experiencing one form of malnutrition-anaemia only. It is likely that with recently emerging evidences of climate change on nutritional quality degradation of the staple crop rice, the prevalence of anaemia would increase to even higher level in the future if proper approaches are not implemented in the country.

Nutritional imbalances of food systems are the key driver of dietary and nutrition inequities (GNR, 2020). This could result in low-quality diets and restrict access to healthier diets. Furthermore, agricultural policies are more biased towards increasing staple-grain productivity, particularly rice, wheat and maize, while requirements for dietary diversity are not being adequately addressed during past decades (Pingali, 2015). This necessitates the diversifying of food production systems to generate more sustainable and healthier foods which might be achieved through reducing the dominance of energy producing cereals and incorporation of crops that produce healthier foods into cropping systems (GNR, 2020). Legumes that adapt well to resource poor environments could be a promising group to make this change. This approach could also align with National Nutrition Policy of Sri Lanka released in 2010 which aim to ensure food and nutrition security for all citizens in the country. For example, in the national nutrition policy, dietary diversification is promoted to include a wide variety of foods ensuring intake of all macro and micronutrients to prevent deficiency disorders and diet related chronic diseases. Furthermore, nutrient enhancement of crops is suggested to improve the quality of food items thereby ensuring micronutrient supplementation for vulnerable groups. In a recent review, legumes have been identified as a crop group that has underexploited potential of bio-fortification to further enrich grain micronutrients and protein (Rehman *et al*., 2019). Although there is diverse range of legumes in Sri Lanka, little or no attention has been paid to most legumes remain underutilized. In an era where nutritional profiles of major cereals including rice, are being degraded due to changing climate, promotion of legume based cropping systems with further government policies would be indeed worth to strengthen the household’s nutritional security which are mainly dependent on cereal diets.

Conclusions and future directions

World's population need to have affordable access to sufficient amount of nutritious foods to achieve nutritional security in the face of climate change. Variations of climatic factors have detrimental impacts on nutritional quality of crop yield which is expected to aggravate in the future. Hence, sustainable approaches need to be implemented to secure nutritional security of households. Among the sustainable strategies, inclusion of legumes to cropping systems is a key driver in preserving nutritional output of a cropping system. However, legume cultivation has not gained the sufficient attention this crop group deserve in Sri Lanka. Advantage of legumes originates from comparatively higher strength of accumulating micronutrients in their grains than staple cereals. Adoptability to low input systems is another unique asset of legumes to generate more nutritious diets from cropping systems with low economic cost and carbon footprint. The degree of nutrient particularly micronutrient losses under rising CO_2 levels is also lower in grain legumes compared to those of major cereals. Therefore, inclusion of legumes in some cereal cultures as intercrops or cover crops would partly compensate the significant losses of micronutrients derived from cereals under changing climate. Facilitation of nutrient uptake (N, P, Fe, and Zn) by companion crop in mixed cultures helps the system to be sustainable in long run. Recent research evidences also demonstrate that inclusion of legumes to cropping systems reduces GHG emission which is the main driver of global climate change. Hence, legume based cropping systems can be effectively used to generate yield with improved nutritional profiles from the cropping system while contributing to sustainable agriculture under changing and variable climate. Therefore, strengthening the remaining policy approaches or implementing new strategies to promote legume based cropping system would be worth to achieve nutritional security in Sri Lanka in future.

References

Amarasingha, P.R.K., Suriyagoda, L.D.B., Marambe, B., Rathnayake, W.M.U.K., Gaydon, D.S., Galagedara, L.W., Punyawardena, R., Silva, G.L.L.P, Nidumolu, U. and Howden, M. (2017). Improving water productivity in moisture-limited rice-based cropping systems through incorporation of maize and mung bean: A modelling approach. *Agricultural Water Management*, 189: 111-122.

Asif, M., Tunc, C.E., Yazici, M.A., Tutus, Y., Rehman, R., Rehman, A. and Ozturk, L. (2019). Effect of predicted climate change on growth and yield performance of wheat under varied nitrogen and zinc supply. *Plant and Soil,* 434: 231-244.

Barton, L., Thamo, T., Engelbrecht, D. and Biswas, W.K. (2014). Does growing grain legumes or applying lime cost effectively lower greenhouse gas emissions from wheat production in a semi-arid climate? *Journal of Cleaner Production,* 83: 194–203.

Basnayake, B.R.S.B. (2007). Climate Change. *In*: *The National Atlas of Sri Lanka*. Survey Department of Sri Lanka, Colombo, Sri Lanka, 54-55.

Burritt, D.J. (2019). Crop Plant Adaption to Climate Change and Extreme Environments. *In*: Melton L, Shahidi F, Varelis P (eds.). *Encyclopedia of Food Chemistry*. Academic Press, Oxford, 196–201.

Cakmak, I., Kalayci, M., Kaya, Y., Torun, A., Aydin, N., Wang, Y., Arisoy, Z., Erdem, H., Yazici, A., Gokmen, O., Ozturk, L. and Horst, W.J. (2010). Biofortification and localization of zinc in wheat grain. *Journal of Agricultural and Food Chemistry,* 58: 9092–9102.

Cakmak, I. and Kutman, U.B. (2018). Agronomic biofortification of cereals with zinc: a review. *European Journal of Soil Science,* 69: 172–180.

Chandrapala, L. (2007). Rainfall. *In*: *The National Atlas of Sri Lanka*. Survey Department of Sri Lanka, Colombo, Sri Lanka, 58-59.

Cruz, R.V., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., Honda, Y., Jafari, M., Li, C. and Huu Ninh, N. (2007). Asia. Climate change 2007: Impacts, adaptation and vulnerability. *Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change.* M.L. Parry, O.F Canziani, J.P. Palutikof, P.J. Van der Linden and C.E. Hanson. (Eds.) Cambridge, UK: Cambridge University Press, 469-506.

De Costa, W.A.J.M. (2008): Climate change in Sri Lanka: myth or reality? Evidence from long-term meteorological data*. Journal of National Science Foundation of Sri Lanka,* 36: 63–88.

De Costa, W.A.J.M. and Shanmugathasan, K.N. (1999). Effects of irrigation at different growth stages on vegetative growth of mung bean, *Vigna Radiata* (L.) Wilczek, in dry and intermediate zones of Sri Lanka. *Journal of Agronomy and Crop Science,* 183: 137-143.

Dong, J., Gruda, N., Lam, S.K., Li, X. and Duan, Z. (2018). Effects of elevated CO_2 on nutritional quality of vegetables: A review. *Frontiers in Plant Science,* 9: 924.

Eriyagama, N., Smakhtin, V., Chandrapala, L. and Fernando, K. (2010). *Impacts of climate change on water resources and agriculture in Sri Lanka: a review and preliminary vulnerability mapping*. Colombo, Sri Lanka: International Water Management Institute, (IWMI Research Report 135), 51 pp.

Fanzo, J., Davis, C., McLaren, R. and Choufani, J. (2018). The effect of climate change across food systems: Implications for nutrition outcomes. *Global Food Security,* 18: 12–19.

FAO. (2017). The future of food and agriculture – Trends and challenges. Rome. FAO, 180 pp.

Fischer, S., Hilger, T., Piepho, H.P., Jordan, I. and Cadisch, G. (2019). Do we need more drought for better nutrition? The effect of precipitation on nutrient concentration in East African food crops. *Science of the Total Environment,* 658: 405–415.

Foyer, C.H., Lam, H.M., Nguyen, H.T., Siddique, K.H.M., Varshney, R.K., Colmer, T.D., Cowling, W., Bramley, H., Mori, T.A., Hodgson, J.M., Cooper, J.W., Miller, A.J., Kunert, K., Vorster, J., Cullis, C., Ozga, J.A., Wahlqvist, M.L., Liang, Y., Shou, H., Shi, K., Yu, J., Fodor, N., Kaiser, B.N., Wong, F.L., Valliyodan, B. and Considine, M.J. (2016). Neglecting legumes has compromised human health and sustainable food production. *Nature Plants,* 2: 16112.

Gilbert, N. (2009). The disappearing nutrient. *Nature,* 461: 716–718.

Global Nutrient Report (2020). Development Initiatives Ltd, North Quay House. Quay side, Temple Back Bristol, United Kingdom, ISBN: 978-1-9164452-6-0

Haddad, L, J., Hawkes, C., Achadi, E., Ahuja, A., Ag Bendech, M., Bhatia, K., Bhutta, Z., Blossner, M., Borghi, E. and Eriksen, K. (2015). Global Nutrition Report 2015: Actions and accountability to advance nutrition and sustainable development. International Food Policy Research Institute, 169 pp.

Imbulana, K.A.U.S., Wijesekara, N.T.S. and Neupane B.R. (2006). Sri Lanka Water Development Report 2010. UNESCO and Ministry of

Irrigation and Water Resources Management, Colombo, Sri Lanka. ISBN:955-8395-01-3, 221 pp.

Jayatilake, H.M., Chandrapala, L., Basnayake B.R.S.B. and Dharmaratne G.H.P. (2005). Water Resources and Climate Change. *In*: S. Wijesekara, K.A.U.S. Imbulana and Bhanu Neupane (eds). *Proceedings of the preparatory workshop on Sri Lanka national water development Report*. Ministry of Irrigation, Mahaweli and Rajarata Development, Colombo, Sri Lanka, 62-87.

Karkanis, A., Ntatsi, G., Lepse, L., Fernández, J.A., Vågen, I.M., Rewa, B., Alsin, I., Kronberga, A., Balliu, A., Olle, M., Bodner, G., Dubova, L., Rosa, E. and Savvas, D. (2018). Faba bean cultivation – revealing novel managing practices for more sustainable and competitive European cropping systems. *Frontiers in Plant Science,* 9: 1115.

Köhler, I.H., Huber, S.C., Bernacchi, C.J. and Baxter, I.R. (2018). Increased temperatures may safeguard the nutritional quality of crops under future elevated CO_2 concentrations. *Plant Journal,* 97: 872– 886.

Li, Y., Yu, Z., Jin, J., Zhang, Q., Wang, G., Liu, C., Wu, J., Wang, C. and Liu, X. (2018). Impact of elevated CO_2 on seed quality of soybean at the fresh edible and mature stages. *Frontiers in Plant Science,* 9: 1413.

Loladze, I. (2014). Hidden shift of the ionome of plants exposed to elevated CO_2 depletes minerals at the base of human nutrition. *eLife,* 3: e02245.

Ma, Y., Schwenke, G., Sun, L., Liu, L., Wang, B. and Yang, B. (2018). Modeling the impact of crop rotation with legume on nitrous oxide emissions from rain-fed agricultural systems in Australia under alternative future climate scenarios. *Science of the Total Environment,* 630: 1544–1552.

Malaviarachchi, M.A.P.W.K., De Costa, W.A.J.M., Kumara, J.B.D.A.P., Suriyagoda, L.D.B. and Fonseka, R.M, (2015). Response of mung bean to increasing natural temperature gradient under different crop management systems. *Journal of Agronomy and Crop Science,* 202: 51–68.

Marambe, B., Punyawardena, R., Silva, P., Premalal, S., Rathnabharathie, V., Kekulandala, B., Nidumolu, U. and Howden, M. (2015). Climate, climate risk, and food security in Sri Lanka: need for strengthening adaptation strategies. *In*: *Handbook of Climate Change Adaptation* (W. Leal ed.). Springer-Verlag Berlin Heidelberg (ISBN 978-3-642-38669-5), 1959-1789.

Marambe, B., Pushpakumara, G. and Silva, P. (2012). Biodiversity and Agro-biodiversity in Sri Lanka: A case in Village Tank Systems. *In*: S-I Nakano, T. Yahara, and T. Nakashizuka (eds) *Biodiversity Observation Network in the Asia-Pacific Region: Towards Further Development of Monitoring*. Springer, Japan, 403-430.

Medek, D.E., Schwartz, J. and Myers, S.S. (2017). Estimated effects of future atmospheric concentrations on protein intake and the risk of protein deficiency by country and region. *Environmental Health Perspectives,* 125(8): 087002.

Mitchell, D.C., Castellano, M.J., Sawyer, J.E. and Pantoja, J. (2013). Cover crop effects on nitrous oxide emissions: Role of mineralizable carbon. *Soil Science Society of America Journal,* 77: 1765–1777.

MMDE (2016): National Adaptation Plan for Climate Chang Impacts in Sri Lanka 2016-2025. Climate Change Secretariat, Ministry of Mahaweli Development and Environment, Sri Lanka, 176 pp.

Mungai, L.M., Snapp, S., Messina, J.P., Chikowo, R., Smith, A., Anders, E., Richardson, R.B. and Li, G. (2016). Smallholder farms and the potential for sustainable intensification. *Frontiers in Plant Science,* 7: 1720.

Mutuwatte, L.P. and Liyanage, P.K.N.C. (2013). Impacts of Climate Change on Agro-Ecological Regions of Sri Lanka. *In*: H.P.M. Gunasena, H.A.J. Gunatilake, J.M.D.T. Everard, C.S. Ransinghe and A.D. Nainanayake (eds.) *Proceedings of the International Conference on Climate Change Impacts and Adaptations for Food and Environmental Security*. Coconut Research Institute, Lunuwila, Sri Lanka, 59-66.

Myers, S.S., Smith, M.R., Guth, S., Golden, C.D., Vaitla, B., Mueller, N.D., Dangour, A.D. and Huybers, P. (2017). Climate change and global food systems: potential impacts on food security and undernutrition. *Annual Review of Public Health,* 38: 259–277.

Myers, S.S., Wessells, K.R., Kloog, I., Zanobetti, A., Schwartz, J. (2015). Effect of increased concentrations of atmospheric carbondioxide on the global threat of zinc deficiency: A modelling study. *The Lancet Global Health,* 3(10): e639–e645.

Myers, S.S., Zanobett i, A., Kloog, I., Huybers, P., Leakey, A.D., Bloom, A.J., Carlisle, E., Dietterich, L.H., Fitzgerald, G., Hasegawa, T., Holbrook, N.M., Nelson, R.L., Ottman, M.J., Raboy, V., Sakai, H., Sartor, K.A., Schwartz, J., Seneweera, S., Tausz, M. and Usui, Y. (2014). Increasing CO_2 threatens human nutrition. *Nature,* 510 (7503): 139–142.

Neukom, R., Barboza, L.A., Erb, M.P., Shi, F., Emile-Geay, J., Evans, M.N., Franke, J., Kaufman, D.S., Lücke, L., Rehfeld, K., Schurer, A., Zhu, F., Brönnimann, S., Hakim, G.J., Henley, B.J., Ljungqvist, F.C., McKay, N., Valler, V. and von Gunten, L. (2019). Consistent multidecadal variability in global temperature reconstructions and simulations over the Common Era. *Nature Geoscience,* 12: 643–649.

Nissanka, S.P., Punyawardena, B.V.R., Premalal, K.H.M.S. and Thattil, R.O. (2011). Recent trends in annual and growing seasons' rainfall of Sri Lanka. *Proceedings of the International Conference on the Impact of Climate Change in Agriculture*. Faculty of Agriculture, University of Ruhuna, Mapalana, Sri Lanka. December 20, 249-263.

Petersen, S.O., Mutegi, J.K., Hansen, E.M. and Munkholm, L.J. (2011). Tillage effects on N_2O emissions as influenced by winter cover crop. *Soil Biology and Biochemistry,* 43: 1509–1517.

Pingali, P. (2015). Agricultural policy and nutrition outcomes – getting beyond the preoccupation with staple grains. *Food Security,* 7: 583–591.

Premalal, K.H.M.S. (2009). Weather and climate trends, climate controls and risks in Sri Lanka. *Presentations made at the Sri Lanka Monsoon Forum*, April 2009. Department of Meteorology, Sri Lanka.

Premalal, K.H.M.S. and Punyawardena, B.V.R. (2013). Occurrence of extreme climatic events in Sri Lanka. *In*: H.P.M. Gunasena, H.A.J. Gunathilake, J.M.D.T. Everard, C.S. Ranasinghe and A.D. Nainanayake (eds), *Proceedings of the International Conference on Climate Change Impacts and Adaptations for Food and Environment Security*. Hotel Renuka, Colombo, 49-57.

Pretty, J., Benton, T.G., Bharucha, Z.P., Dicks, L.V., Flora, C.B., Godfray, H.C.J., Goulson, D., Hartley, S., Lampkin, N., Morris, C., Pierzynski, G., Prasad, P.V.V., Reganold, J., Rockström, J., Smith, P., Thorne, P. and Wratten, S. (2018). Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability,* 1: 441–446.

Punyawardena, B.V.R. (2007). Agro-ecology (map and accompanying text), *National Atlas of Sri Lanka*, 2nd Edition. Department of Survey, Colombo.

Punyawardena, B.V.R., Dissanaike, T.and Mallawatantri, A. (2013b). Spatial variation of climate change induced vulnerability in Sri Lanka.; An analysis of the components of vulnerability at district level. Published by the Department of Agriculture in collaboration with UNDP/SGP, Sri Lanka.

Punyawardena, B.V.R., Mehmood, S., Hettiarachchi, A.K., Iqbal, M., Silva, S.H.S.A. and Goheer, A. (2013a). Future Climate of Sri Lanka: An approach through dynamic downscaling of ECHAM4 General Circulation Model (GCM). *Tropical Agriculturist,* 161: 35-50.

Punyawardena, B.V.R., Premalal, K.H.M.S. (2013). Do trends in extreme positive rainfall anomalies in the Central highlands of Sri Lanka exist? *Annals of the Sri Lanka Department of Agriculture,* 15: 1-12.

Ratnayake, U. and Herath, G. (2005). Changes in Water Cycle: Effect on Natural Disasters and Ecosystems. *In*: S. Wijesekara, K.A.U.S. Imbulana, B. Neupane (eds.), *Proceedings of the Preparatory Workshop on Sri Lanka National Water Development Report,* World Water Assessment Programme, Paris, France, 192-205.

Rehman, H.M., Cooper, J.W., Lam, H-M. and Yang, S.H. (2018). Legume biofortification is an underexploited strategy for combatting hidden hunger. *Plant Cell and Environment,* 42: 52–70.

Robinson, G.H.J., Balk, J. and Domoney, C. (2019). Improving pulse crops as a source of protein, starch and micronutrients. *Nutrition Bulletin,* 44: 202–215.

Sathischandra, S.G.A.S., Marambe, B. and Punyawardena, R. (2014). Seasonal changes in temperature and rainfall and its relationship with the incidence of weeds and insect pests in rice (*Oryza sativa* L) cultivation in Sri Lanka. *Climate Change and Environmental Sustainability,* 2(2): 105-115.

Seneweera, S.P. and Conroy, J.P. (1997). Growth, grain yield and quality of rice (*Oryza sativa* L.) in response to elevated CO_2 and phosphorus nutrition. *Soil Science and Plant Nutrition,* 43: 1131–1136.

Smith, M., Golden, C.and Myers, S. (2017). Anthropogenic carbon dioxide emissions may increase the risk of global iron deficiency. *GeoHealth,* 1(6): 248–257.

Smith, M.R. and Myers, S.S. (2018). Impact of anthropogenic CO_2 emissions on global human nutrition. *Nature Climate Change,* 8(9): 834–839.

Smith, M.R., Myers, S.S. (2019). Global health implications of nutrient changes in rice under high atmospheric carbon dioxide. *GeoHealth,* 3: 190-200.

Soares, J.S., Santos, C.S., Carvalho, S.M.P., Pintado, M.M. and Vasconcelos, M.W. (2019). Preserving the nutritional quality of crop plants under a changing climate: importance and strategies. *Plant and Soil,* 443: 1–26.

Sublett, W., Barickman, T. and Sams, C. (2018). Effects of elevated temperature and potassium on biomass and quality of dark red 'Lollo Rosso' lettuce. *Horticulturae,* 4: 11.

Xue, Y., Xia, H., Christie, P., Zhang, Z., Li, L. and Tang, C. (2016). Crop acquisition of phosphorus, iron and zinc from soil in cereal/ legume intercropping systems: a critical review. *Annals of Botany*, 117: 363–377.

Ziska, L.H., Morris, C.F. and Goins, E.W. (2004). Quantitative and qualitative evaluation of selected wheat varieties released since 1903 to increasing atmospheric carbondioxide: can yield sensitivity to carbon dioxide be a factor in wheat performance? *Global Change Biology,* 10(10): 1810–1819.

Zubair, L., Hansen, J., Chandimala, J., Siraj, M.R.A., Siriwardhana, M., Ariyaratne, K., Bandara, I., Bulathsinghala, H., Abeyratne, T. and Samuel, T.D.M.A. (2005). Current climate and climate change assessments for coconut and tea plantations in Sri Lanka. *IRI, FECT, NRMS and UoP Contribution to AS12 Project Report to be submitted to START*, Washington, DC, USA.

CHAPTER 08

Tea Industry of Sri Lanka: Are We Ready for the Climate Change Impacts?

A.J. Mohotti[1]* and K.M. Mohotti[2]

[1]Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.
[2]Tea Research Institute, Talawakele, Sri Lanka.
*mohottij@yahoo.com

Tea Industry of Sri Lanka: Are We Ready for the Climate Change Impacts?

Abstract

Tea industry in Sri Lanka has been identified as highly vulnerable to climate change. At present, it provides the livelihood for approximately a 10% of the population of Sri Lanka, in addition to the significant contribution to the economy of the country. This chapter summarizes the climate change effects on the productivity, quality, and, pest and disease proliferation of tea, and suggests mitigation and adaptation measures for the future sustenance of the industry.

Keywords: *Camellia sinensis (L.) O. Kuntze, drought, high temperature, productivity, quality*

Introduction

Agriculture plays a key role in the economy of Sri Lanka, and it is the main source of livelihood of the rural community. Tea [*Camellia sinensis* (L.) O. Kuntze] is an important crop to Sri Lanka, in terms of land use, export volume, foreign exchange earnings and employment generation. The revenue earned with tea in 2019 was 1.24 billion USD (EDB, 2020), while about 2.2 million of the population of the country is engaged in tea industry as a livelihood, which is approximately 10% of the population of Sri Lanka (Jayasinghe and Kumar, 2019). A land extent of 193,000 ha is under tea at present (Central Bank, 2019). Being the fourth largest producer of tea in the world, Sri Lanka produced 300.1 million kilograms to the global tea production in 2019, and contributed to about 0.7% of gross domestic production (Central Bank, 2019).

In Sri Lanka, tea grows from almost sea level to the highest elevation, which is 2500 m amsl (above mean sea level) (Jayasinghe and Kumar, 2019). Based on the elevation, the tea growing areas in Sri Lanka could be broadly categorized as low country (<600m), mid country (600m-1200m) and up country (>1200m). Varying extent of tea lands are found in 23 out of the 46 agro-ecological regions, which experience wide differences in climatic conditions including temperature and rainfall (Watson, 2008a). For example, the mean temperature in the low country is around 26.6-27.7°C, which decreases to around 15.5°C at Nuwara Eliya (1890m masl) (Wijeratne *et al*., 2011). The optimum climatic conditions are important to obtain a sustainable yield with high quality.

Increase in anthropogenic greenhouse gas emissions have created a global trend of systematic changes in average climate conditions. It is now widely accepted that the climate of the earth (Ahmed *et al*., 2019; Nowogrodzki, 2019; Reay, 2019; Eckstein *et al*., 2020) and that of Sri Lanka has already changed (De Costa, 2008; Eriyagama *et al*., 2010; Esham and Garforth, 2013; NAP, 2016; Jayasinghe and Kumar, 2019). Sri Lanka has been identified as one of the 10- topmost climate change-affected countries, as per the Global Climate Risk Index (Eckstein *et al*., 2020). In the year 2018, Sri Lanka was ranked in the 2nd place, and in year 2019, in the 6th place as per the above index. This implies that Sri Lanka is prone for extreme weather events caused by climate change, leading to warming and an overall decrease in precipitation but with more occurrences of rainfall variability with prolonged drought spells, heavy rain, flash floods and landslides, and sea level rise. The consequences of climate change are known to critically affect almost all economic sectors of the country including the tea industry, depriving lives and livelihoods of people (NAP, 2016).

Effects of climate change on tea plantations are already well experienced (Wijeratne, 1996; Wijeratne *et al*., 2007; Eriyagama *et al*., 2010; Karunaratne *et al*., 2015). Further, tea crop has been identified as a vulnerable crop to climate change (Ahmad *et al*., 2018; Wijeratne, 2018), and tea in Sri Lanka is also predicted to be negatively affected in the future due to climate change (Jayasinghe and Kumar, 2019). Tea is a perennial, thus the tea plants experience multiple decadal effects of climate change, which can have profound effects on tea quality and yield (Ahmed *et al*., 2019). Climate change magnifies land degradation and loss of soil fertility, and thereby reduce the tea growth, yield and quality while increasing pest, disease and weed incidences on tea. This communication summarizes the available information on climate change effects on tea and adaptation/mitigation strategies, with a special emphasis to the information generated in Sri Lanka.

Climatic requirements of tea

Tea is a crop of wide adaptability, which is grown in a wide range of soils and climates around the world (Watson, 2008a). Almost all climatic parameters, namely; solar radiation, rainfall, temperature, vapour pressure deficit (VPD) and wind affect the growth of tea. An annual rainfall of 2500 to 3000 mm is considered as optimum whereas the ideal ambient temperature for tea growth is considered to be between 18-25^{o}C, with a lower and an upper seasonal average of 13^{o}C and 30^{o}C respectively (De Costa *et al*., 2007; Watson, 2008a).

Jayasinghe and Kumar (2019) reported that tea prefers an annual mean temperature between 13-28°C with an upper ceiling of 40°C and a mean diurnal difference ranging from 5.0-9.5°C. Tea also prefers high precipitation ranges as 2000 to 5000 mm every year. An annual and a monthly rainfall of 1200 mm and 50 mm respectively is considered as minimum (Watson, 2008a).

In higher elevations, solar radiation can be limiting on overcast days during the monsoons (Watson, 2008a). However, high light intensity also can inhibit photosynthesis, especially under poor soil N nutrition, which may decrease productivity (Mohotti and Lawlor, 2002). Soil moisture stress, high vapour pressure deficit and high ambient temperature reduce shoot population density (Wijeratne, 2001). Tea is considered to be highly sensitive to atmospheric VPD of the growing environment (De Costa *et al*., 2007).

Climate change effects in tea growing areas of Sri Lanka

The CO_2 level in the atmosphere is predicted to be the range of 600 to 700 ppm by the year 2100 (Wijeratne *et al*., 2007), causing changes in the temperature and rainfall. Surface air temperature and precipitation are two key climatic variables that influence the agricultural sector in South Asia. Increases in temperature have been observed during recent decades in some parts of South Asia such as India, Bangladesh, Nepal, Pakistan and Sri Lanka, ranging between 0.07-1^{o}C per decade (Esham and Garforth, 2013).

Majority (almost 100%) of the tea plantations in Sri Lanka is rain-fed. A considerable area grown with tea are in the preferable range of temperature. Hence, any variation in the rainfall and temperature will have profound effects on tea in a tropical country such as Sri Lanka. Most locations in Sri Lanka have exceeded the global average rate of warming (Esham and Garforth, 2013). During 1961-1990, Sri Lanka's mean air temperature increased by 0.016°C per year, and mean annual precipitation decreased by 144 millimeters (mm) (7%) compared to that of 1931-1960 (Eriyagama *et al*., 2010). Using an analysis comprising of temperature and rainfall data of 140 years, De Costa (2008) showed that several locations including Ratnapura, Badulla and Nuwara Eliya regions, which contains a larger percent of the tea lands of the country, decadal mean air temperatures showed highly significant ($p<0.001$) linear increasing trends. The rates of continuous warming in all the studied locations except Ratnapura exceeded by a substantial margin from the global mean (i.e. 0.074°C decade^{-1}) during the period from 1906 to 2005.

The quantity and the variability of rainfall are known to be crucial for agricultural production, which also has changed over time due to climate change. A downward trend in rainfall could be seen as the annual average rainfall during 1931–1960 estimated at 2005 mm, declined to 1861 mm during 1961–1990 (Esham and Garforth, 2013). In the study conducted by De Costa (2008), three areas grown with tea (i.e. Kandy, Badulla and Nuwara Eliya) showed statistically significant ($p<0.05$) linear declining trends of decadal mean annual rainfall with time over the whole 140-year period. Of the locations studied, the highest rate of decline of rainfall was shown in Nuwara Eliya at 52 mm decade^{-1}. Nuwara Eliya grows tea of high quality and contains many large tea estates. The effects on the climate can have drastic consequences on both the quantity and quality of tea. Marx *et al*. (2017) mentioned that the tea plants are affected by both excesses and shortages of water and suffer from increased climatic stress. They further reiterated that the weather is becoming more extreme and intense, more erratic and less predictable; longer dry periods, heavier downpours over many days, more hail, and cyclonic storms. The rainfall pattern and the average and maximum temperatures in all main tea production regions in Sri Lanka seem to have undergone marked changes in the recent past.

Jayasinghe and Kumar (2019), using two models, projected that monthly average temperature and precipitation in Sri Lanka would increase in the future, for the time windows of 2020–2039, 2040–2059 and 2060–2079. Precipitation seasonality, annual mean temperature and annual precipitation were identified as the most important factors determining the distribution of *C. sinensis*, whereas the temperature seasonality affecting to a lesser degree. Present optimal and medium suitability thresholds exist in the tea growing districts of Nuwara Eliya, Badulla, Kandy, Ratnapura, Galle, Matara, Matale, and Kegalle. Tea lands of these districts of optimal suitability for tea cultivation represented 9.3% (6090 km^2) of the total land area of the country, and a 7.8% (5086 km^2) and 8.8% (5769 km^2) of land that could be considered as marginal and in medium suitability respectively. It was also projected that by 2050, most of the areas of medium and optimal suitability in the low elevation (e.g. Galle and Matara) will be lost by more lands in these areas becoming marginally suitable. On the other hand, by the year 2050, most of the current optimal land extents for tea in the central hills (i.e. Nuwara Eliya and some parts of Kandy district) will increase (Jayasinghe and Kumar, 2019).

Climate change effects on growth and yield of tea

Climate change differently affects each region in the world. However, under current irrigation levels and lowest climate change scenarios, tea yields are expected to decrease in major producing countries (Beringer *et al*., 2020). Tea yields across the globe are affected by altered precipitation levels and durations, increasing temperatures, shifting the timing of the seasons, and pest and disease occurrences. High intense rains cause soil erosion and waterlogging, affecting root growth and development thus reducing the yield. Drought increases the susceptibility of tea plants to insect pests (Nowogrodzki, 2019).

Using a process-based modeling approach accounting for the effects of temperature, water availability, CO_2 fertilization and crop management (irrigation and harvest), Beringer *et al*. (2020) projected that in most climate scenarios, tea yields are set to increase in China, India, and Vietnam. However, yield losses are expected in Kenya, Indonesia, and Sri Lanka. They also projected that if abundant water supply and full irrigation is assumed for all tea cultivation areas, yields are to increase in all regions.

Shoot density and mean shoot weight are the yield components of tea (Watson, 2008 b), which tend to be affected by the changing climate. Optimum temperature for growth and shoot replacement cycle of tea was found to be around 22°C (Wijeratne *et al*., 2007; Jayasinghe *et al*., 2018), and beyond the range of 18 to 25°C, tea shoot growth and development gets negatively affected (Jayasinghe *et al*., 2018). During high cropping months with wet weather conditions, an apparent reduction in the population of harvested shoots was observed when ambient temperatures increased above 27-29°C (Wijeratne, 2001). Further, a 1°C rise in mean temperature created a 4.6% reduction in tea production (Wijeratne *et al*., 2007).

High vapour pressure deficit above 1.2 kPa and soil moisture deficit above 35 mm in the low-country Wet Zone of Sri Lanka also reduced the harvested shoot density. The density of harvestable shoots is low during a dry period when the proportion of dormant shoots is high (Wijeratne, 2001).

Increase in ambient CO_2 concentration from 370 ppm (present level) to 435 ppm (predicted for the year 2050) projected an increase in tea yield of 16.5 % depending on the elevation (Wijeratne *et al*., 2007). Further, the projected yield increased by 37% with the increase of ambient CO_2 concentration to 600 ppm. The study, based on General Circulation Models, also indicated that reduction of monthly rainfall by 100 mm could reduce the productivity by 30-80 kg of made tea ha^{-1}. In different tea growing regions, the optimum rainfall for tea cultivation varied from 223 to 417 mm per month. Yield projections for the year 2050 showed that increasing temperatures may reduce tea yields in agroecological regions of up-country intermediate (IU), mid-country wet (WM) and low-country wet (WL) zones, while increasing the yield in up-country wet (WU) region (Wijeratne *et al*., 2007). Hence, the tea production is predicted to increase at high elevations of Sri Lanka, whereas it is likely to decrease at low elevations.

Similar trends have been reported from other tea growing countries as well. In Yunnan, more rain during the monsoons has been shown to decrease tea yield. Further, in the Southern China where most of China's tea is produced, increased rainfall and more frequent incidences of heavy rain has damaged tea crops (Nowogrodzki, 2019). In India and China, climate change seems to be shifting the timing of the seasons. In Yunnan, the onset of the monsoon season is falling earlier, which cuts short the drier spring. In Assam, a shift in the seasons is reported, leading to a shorter growing season for tea, which lowers yields of the first and the second flush, which are the earliest and most valuable harvests. Further, in India and China, increasingly frequent hot spells are harming yield (Nowogrodzki, 2019). However, exposure of tea plants to elevated CO_2 (800 $\mu mol\ mol^{-1}$ for 24 days) remarkably improved both photosynthesis and respiration in tea leaves. Elevated CO_2 also increased the soluble sugar, starch and total carbon contents, but decreased the total nitrogen content, resulting in an increased C:N ratio in tea leaves (Li *et al*., 2017).

Climate change effects on pest, disease and weed proliferation affecting tea

Productivity and profitability of agricultural operations are greatly affected by pests and diseases. These impacts are expected to become more serious as the global climate warms up. Although it is well known that insects are sensitive to temperature, how they will be affected by ongoing global warming remains uncertain because these responses are multifaceted and ecologically complex.

A review that used responses of 31 major global pest species to ongoing climate warming (Lehmann *et al*., 2020) suggested that a single species can both increase and decrease in severity exhibiting mixed responses among possible categories (range expansion, life history, population dynamics, and trophic interactions). The responses of insect pests also varied according to geographical region and biological traits, and were not easily generalizable. They concluded that species must be assessed individually so their responses can be predicted more accurately (Lehmann *et al*., 2020).

However, many believe that the incidence and proliferation of pests, diseases and weeds will increase with climate change (Han *et al*., 2018; Nowogrodzki, 2019). In temperate countries such as China, warmer weather helps insects and pathogens to survive in winter, which is a critical time for their reduction. This helps to shorten the damaging period by increasing the number of annual generations and reproduction rates in some pests (Han *et al*., 2019). A greater number of insect pests have been noticed on tea plants in Assam (Nowogrodzki, 2019). Higher rainfall, humidity and temperature have been linked to faster insect pest population growth and an increase in attacks on tea leaves. A higher number of rainy days in North Eastern India seem to allow the pests to extend their attacks much later into the growing season (Reay, 2019). Han *et al*. (2018) reported in his review that the pest tea geometrid (*Ectropis obliqua*) in China, Phomopsis canker disease in South India, thrips (*Scirtothrips dorsalis* Hood) and the tea green leafhopper (*Empoasca flavescens* Fabricius) in North Bengal, leaf disease 'blister blight'

(*Exobasidium vexans* Massee) and anthracnose disease (*Colletotrichum gloeosporioides*) in China were on the rise due to the increased temperature.

Ambient temperature of 30°C is considered as optimum for the shot hole borer (*Xyleborus fornicatus*), a key pest in tea in Sri Lanka (Walgama and Zalucki, 2007). Rates of development of this pest increased linearly over a wide range of temperatures, and the degree days for development of eggs, larvae and pupae were 70±4.4, 95±8.5 and 72±5.1 respectively. Therefore, an increasing temperature would increase the number of generations of shot hole borer per year. Fluctuations of ambient temperature also was found to favour the development of the pest. Therefore, rising temperatures with climate change raise concerns of this major pest affecting tea in newer habitats in Sri Lanka.

In the recent past, the most predominant tea nematode and a key pest in tea in Sri Lanka, *Pratylenchus loosi*, was recorded to have spread in all tea growing districts despite its previously known preferred range of soil temperature of 18-24°C. Amarasena *et al*. (2019) conducted a study where the soil temperature and *P. loosi* population densities were monitored in six locations of Sri Lanka over a period of 18 months and concluded that the nematode appeared to have adapted to the above normal soil temperatures ranging from 24.3±1.4°C to 30.0±0.7°C causing widespread disease. However, the population density of *P. loosi* correlated positively with the mean rainfall, and negatively with soil temperature and soil moisture content in majority of the tested locations (Amarasena *et al.*, 2016).

Climate change effects on the quality of tea

Plants synthesize an array of secondary metabolites, which are non-nutrient plant constituents, to defend themselves against exogenous biotic and abiotic constraints (Guerriero *et al*., 2018). These compounds possess functional properties influencing the flavour, stability, appearance, aroma and health promoting attributes (Roberts and Smith, 1963). An inverse relationship exists between tea growth and concentrations of individual secondary metabolites (Ahmed *et al*., 2014).

Inherent quality of tea is brought about by these secondary plant metabolites present in green tea leaves, which are, polyphenols, caffeine, amino acids, saponins, tannins, etc. (Pan *et al*., 2003). These compounds also give tea its bitter taste and astringent quality, and can make up to more than 30% of mass of tea (Nowogrodzki, 2019), of which, the polyphenols can account for 10-30% (w/w) and caffeine 2-4% (w/w). Tea polyphenols include catechines, flavanols, flavanones, phenolic acids, glycosides and the aglycons of plant pigments. The tea polyphenols have strong, natural antioxidant properties and scavenging effect on active oxygen radicals, hence have important applications in food industry and medicine (Pan *et al*., 2003; Nowogrodzki, 2019).

Changing climate conditions are known to impact the concentration of secondary metabolites (Marx *et al*., 2017), and hence, impact the functional quality of tea (Ahmed *et al*., 2014). The concentrations of caffeine and various polyphenolic catechin compounds are highly correlated with rainfall patterns. Rising temperatures too, have been found to deteriorate tea quality (Ahmed *et al*., 2014). Elevated CO_2 (800 $\mu mol\ mol^{-1}$) for 24 days changed tea quality parameters, increasing tea polyphenol, free amino acid and theanine concentrations, while decreasing the caffeine content (Li *et al*., 2017). Elevated CO_2 also differentially altered the individual catechin concentrations resulting in an increased total catechin concentration. Real-time qPCR analysis in this study revealed up-regulated expression levels of catechins and theanine biosynthetic genes, and down-regulated expression levels of caffeine synthetic genes under elevated CO_2.

Functional properties of tea are affected by temperature and rainfall (Ahmed *et al*., 2018; Nowogrodzki, 2019). Increased amount of rainfall increased the overall antioxidant level, even though the levels of certain antioxidants decreased. The profile of these antioxidants varied with the elevation due to the difference in the temperature. The compounds that are potentially beneficial to health (such as antioxidants) and present in tea grown at higher elevations (at lower temperature) were absent in tea grown at lower elevations. This implied that with the climb in temperature, tea would lose some of its purported health benefits. The volatile compounds that perceive flavour may be greatly affected, since they are present in very small quantities (i.e. up to about 0.1% by mass), which may decrease the tea prices, impacting the livelihoods of the farmers (Nowogrodzki, 2019).

The decrease in tea quality was also linked to the early commencement of the monsoon season as a result of climate change. The decline was partly attributed to a dilution of the flavour-imparting compounds due to extra rainfall. Early beginning of the monsoon and higher temperatures also resulted in less antioxidant activity indicating negative effects on tea's potential health benefits (Ahmed *et al*., 2014; Nowogrodzki, 2019). Many studies have shown an increase in levels of phenolic compounds or their bioactivity with drought stress (Ahmed *et al*., 2014). However, the effects of climate change on the quality aspects of tea are inadequately studied in Sri Lanka.

Mitigation and adaptation of the effects in tea ecosystems

Sri Lanka has committed to address climate change and related issues by ratification of the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement (NAP, 2016). However, being a developing country, building resilience of vulnerable communities and ecosystems over climate change effects within a broader framework of sustainable development has been set as the countries' priority (NAP, 2016). Concurrently, assessment of the environmental impact and reducing the emissions and environmental degradation also have become extremely important, and hence 'sustainable consumption and production (SCP) strategy' was named as the 12th sustainable development goal (SDG) by UNEP in 2015 (Wijeratne, 2019). Along with this, Sri Lanka's National Adaptation Plan has been prepared expecting to provide opportunities for all stakeholders for developing policies, strengthening cooperation, institutional setup, resource mobilization, technology development and transfer, awareness and capacity building to increase resilience of vulnerable communities, areas and sectors in the country.

Following adaptation measures for the tea sector of Sri Lanka have been proposed as "No Regret Strategies" (FAO, 2016), and the following high priority strategies have been identified; Land selection for replanting and expansion of tea cultivation by selecting the most suitable agro-ecological regions with good soil conditions; Crop diversification to reduce risk of mono-cropping, use of a basket of cultivars incorporating drought, pest and disease tolerant tea cultivars in addition to those of high yield potential; Soil and soil moisture conservation and improvement; Proper establishment and management of shade trees; Rainwater harvesting and irrigation; Judicious use of chemical fertilizers and afforestation. Further, the need for policy interventions in the areas of strengthening R&D

institutions and their extension arms to conduct further assessments on climate change impacts, develop technologies applicable to different regions and farm sizes and conduct awareness programmes, providing guidance and financial assistance for climate change adaptation and mitigation (reduce Green House Gas –GHG emissions and increase Carbon sequestration) strategies, nature conservation and eco-tourism, establishment of national and international network on climate change to share knowledge and technologies, investments on field infrastructure development such as drainage systems, irrigation systems, road networks and ecosystem diversity to improve level of adaptability of tea growers to climate change and introducing crop insurance schemes to minimize the impacts on tea growers and other stakeholders are also emphasized (FAO, 2016).

Sri Lanka has the highest cost of production of tea in the world. Replanting/new-planting are very costly exercises with comparatively long pay-back periods. In order for the tea industry to be a profitable venture in the future, with the anticipated changes in suitability of areas for growing tea in Sri Lanka and elsewhere, land selection for these exercises should be done extremely carefully with scientific validation. Further, the tea lands earmarked to be preserved for the future should be equipped with appropriate soil and moisture conservation and fertility increasing strategies along with other necessary measures for improving plant productivity. Less productive and marginal lands could be diversified into other uses such as mixed-cropping and fuel wood or timber plantations. Appropriate policy interventions and legislative measures should be undertaken for these actions. In Sri Lanka, usually tea is grown as an agroforestry system, under a cover of shade trees which imparts many benefits. Introducing agroforestry approaches to areas where tea is not so cultivated have improved the deteriorating quality due to climate change (Ahmed *et al*., 2019; Nowogrodzki, 2019). Rainwater harvesting and collection within large plantations and re-use of them for irrigation is another approach (FAO, 2016). Breeding and selection for climate resilient tea cultivars, use of improved seedling materials which consists of a taproot, is of utmost importance. Organic cultivation also has been suggested as an adaptation strategy (Mohotti *et al*., 2013).

While concentrating on the activities of adaptation, it is extremely urgent to implement climate change mitigation measures. Adopting measures with improved carbon sequestration capacity in tea systems by appropriate selection of tea cultivars, and associated species such as shade trees is extremely important. As a measure of environmental impact due to tea cultivation, carbon footprints (CFP) have been determined for the life cycle of tea, which are also being used as market promotion strategies in certain companies. Here, life cycle analysis has been performed considering the entire production cycle including cultivation, manufacturing, packaging, transportation and consumption up to the teacup. The CFP of tea varies from 200 g CO_2 per cup to −6 g CO_2 per cup depending on how it is grown, processed, shipped, packed, brewed and discarded (Wijeratne, 2018). Also, it was mentioned that loose leaf tea would have an average of 20 g CO_2 per cup whereas, that of a teabag would be ten times higher due to the use of carbon-intensive packaging (Wijeratne, 2018). Vidanagama and Lokupitiya (2016) reported a mean emission of greenhouse gases ranging from 0.406±0.086 (Uva) to 0.410±0.147 kg CO_2 kg^{-1} (high-grown) for made tea, which did not statistically differ between two regions. In this study, 70-80 % of the GHG emission was due to electricity consumption whereas green leaf transportation contributed to around 9-21 %. Hu *et al*. (2018) determined a CFP of 7.035 kg CO_2-e for a traditional Taiwan Dongshan tea, of which the main contributors were the raw material (35.15%) and consumer use (45.58%) phases. They also concluded that the hotspots of the life cycle of environmental impact of Taiwanese tea mainly came from fertilizer input during the raw material phase, electricity use during manufacturing, and electricity use during water boiling in the consumer use phase (which contributed as the largest impact). Reay (2019) reported CFP of 25g of emissions per cup (equivalent to 12 kilograms per kilogram of dry tea), mostly contributed by the energy used to boil water.

Conclusions and future directions

Climate change, and its negative effects on the global tea industry, and largely on that of Sri Lanka, are inevitable as at present. It has been predicted that the global demand for tea will increase in future. However, actions of people may determine whether the tea industry will remain as a sustainable and profitable venture in the future. Hence, immediate, concerted, global action in terms of mitigation and adaptation to climate change and its impacts is required before irreversible effects occur in the environment.

References

Ahmed, S., Griffin, T.S., Kraner, D., Schaffner, M.K., Sharma, D., Hazel, M., Leitch, A.R., Orians, C.M., Han, W., Stepp, J.R., Robbat, A., Matyas, C., Long, C., Xue, D., Houser, R.F. and Cash, S.B. (2019). Environmental Factors Variably Impact Tea Secondary Metabolites in the Context of Climate Change. *Frontiers in Plant Science*, 13 August 2019, https://doi.org/10.3389/fpls.2019.00939.

Ahmed, S., Stepp, J.R., Orians, C., Griffin, T., Matyas, C., Robbat, A., Cash, S., Xue, D., Long, C., Unachukwu, U., Buckley, S., Small, D. and Kennelly, E. (2014). Effects of Extreme Climate Events on Tea (*Camellia sinensis*) Functional Quality Validate Indigenous Farmer Knowledge and Sensory Preferences in Tropical China. *PLoS ONE*, 9(10): e109126. doi:10.1371/journal.pone.0109126.

Amarasena, P.G.D.S., Mohotti, K.M. and De Costa, D.M. (2016). Effects of Changing Rainfall and Soil Temperature on Population Density of *Pratylenchus loosi* in Tea Lands at Different Elevations. *Tropical Agricultural Research*, 27(3): 265– 276.

Amarasena, P.G.D.S., Mohotti, K.M., De Costa, D.M. and A.K. Prematunga (2019). Unexpected incidences of root lesion nematode, *Pratylenchus loosi*, under changing climate scenario in Sri Lanka. *In*: *Proceedings of International Symposium on Sustainable Soil Management (ISSSM)*. Held on 5-6 December 2019, Kandy. 72-74.

Beringer, T., Kulak, M., Müller, C., Schaphoff, S. and Jans, Y. (2020). First process-based simulations of climate change impacts on global tea production indicate large effects in the World's major producer countries. *Environment Research Letters*, 15:034023. doi.org/10.1088/1748-9326/ab649b.

Central Bank (2019). National Output, Expenditure and Income. *In*: Annual Report of the Central Bank of Sri Lanka, 2019, Available at https://www.cbsl.gov.lk/sites/default/files/cbslweb_documents/publications/annual_report/2019/en/6_Chapter_02.pdf, 12 pp, Retrieved on 10 July 2020.

De Costa W.A.J.M., Mohotti A.J. and Wijeratne M.A. (2007). Ecophysiology of tea. *Brazilian Journal of Plant Physiology*, 19(4): 299-332.

De Costa, W.A.J.M. (2008). Climate change in Sri Lanka: myth or reality? Evidence from long-term meteorological data. *Journal of National Science Foundation of Sri Lanka,* Special Issue, (36): 63-88.

Eckstein D., Künzel V., Schäfer L. and Winges M. (2020). *Global Climate Risk Index 2020*. Germanwatch e.V., ISBN 978-3-943704-77-8. Available at www.germanwatch.org/en/cri. Retrieved on 21 July 2020.

EDB (2020). The Trade & Export Landscape of Sri Lanka 2019 -2020, Official website of the Export Development Board, Sri Lanka, Available at https://www.srilankabusiness.com/blog/sri-lanka-export-trade-lanscape-2019-2020.html, Browsed on 09 July 2020.

Eriyagama, N., Smakhtin, V., Chandrapala, L. and Fernando, K. (2010). Impacts of climate change on water resources and agriculture in Sri Lanka: a review and preliminary vulnerability mapping. Colombo, Sri Lanka: *International Water Management Institute*. 51p. (IWMI Research Report 135). doi:10.5337/2010.211.

Esham M. and Garforth C. (2013). Climate change and agricultural adaptation in Sri Lanka: a review. *Climate and Development*, 5(1): 66 –76, http://dx.doi.org/10.1080/17565529.2012.762333.

FAO (2016). 2. Impact of Climate Change on Tea and Adaptation Strategies (Sri Lanka). *In*: *Report of the Working Group on Climate Change of the FAO Intergovernmental Group on Tea. Food and Agriculture Organization of the United Nations Rome*, ISBN 978-92-5-109279-8. 27-44.

Guerriero, G., Berni, R., Muñoz-Sanchez, J.A., Apone, F., Abdel-Salam, E.M., Qahtan, A.A., Alatar, A.A., Cantini, C., Cai, G., Hausman, J.F., Siddiqui, K.S., Sotomayor, S. M.T.H. and Faisal, M. (2018). Production of Plant Secondary Metabolites: Examples, Tips and Suggestions for Biotechnologists. *Genes*, 9(6): 309, https://doi.org/10.3390/genes9060309

Han, W., Li, X., Yan, P., Zhang, L. and Ahammed, G.J. (2018). Tea cultivation under changing climatic conditions. *In*: Sharma, V. S. and Gunasekare, M.T.K. (Eds.). *Global tea science: Current status and future needs*. Burleigh Dodds Science Publishing, Cambridge, UK, 2018, ISBN: 978 1 78676 160 6; www.bdspublishing.com, 1-18.

Jayasinghe S.L. and Kumar L. (2019). Modelling the climate suitability of tea [*Camellia sinensis* (L.) O. Kuntze] in Sri Lanka in response to current and future climate change scenarios. *Agricultural and Forest Meteorology*, 272–273: 102–117. https://doi.org/10.1016/j.agrformet.2019.03.025.

Karunaratne, G.M.M.R.B., Nissanka, S.P., Punyawardena, B.V.R. and Gunawardena A.R. (2015). Vulnerability of Tea Sector for Climate Change in the Major Tea Growing Regions in Central Hills of Sri Lanka. *Journal of Environmental Professionals Sri Lanka*, 4(1): 29-48.

Lehmann, P., Ammunét, T., Barton, M., Battisti, A., Eigenbrode, S.D., Jepsen, J.U., Kalinkat, G., Neuvonen, S., Niemelä, P., Terblanche, J.S., Økland, B., and Björkman, C. (2020). Complex responses of global insect pests to climate warming. *Frontiers in Ecology and the Environment*, 18(3):141-150. https://doi.org/10.1002/fee.2160.

Li, X., Zhang, L., Ahammed, G. J., Li, Z.-X., Wei, J.-P., Shen, C., Yan, P., Zhang L.-P. and Han, W.-Y. (2017). Stimulation in primary and secondary metabolism by elevated carbon dioxide alters green tea quality in *Camellia sinensis* L. *Scientific Reports*, 7(1): doi:10.1038/s41598-017-08465-1

Mohotti, A.J. and Lawlor, D.W. (2002). Diurnal variation of photosynthesis and photoinhibition in tea: effects of irradiance and nitrogen supply during growth in the field. *Journal of Experimental Botany*. 53(367): 313-322.

Mohotti, A.J., Mohotti, K.M., Amarasena, P.G.D.S., Rasanji, N.G.N., Arachchi U.K. and Jayawardana, T.G.N. (2013). Organic tea cultivation as adaptation strategy: A case study in rural smallholder tea community in Galle district. *In*: Coping with climate change and variability: Lessons from Sri Lankan communities. *Proceedings of the National Workshop on Community Based Adaptation*, Colombo, Sri Lanka, July 16-18. Global Environmental Facility/ Small Grants Programme (UNDP, GEF/SGP), Sri Lanka. ISBN: 978-955-1031-55-8, 73-78.

NAP (2016). *National Adaptation Plan for Climate Change Impacts in Sri Lanka: 2016 – 2025*. Climate Change Secretariat, Ministry of Mahaweli Development and Environment, Sri Lanka. ISBN 978-955-0033-98-0. 178 pp. available at https://www4.unfccc.int/sites/NAPC/Documents%20NAP/National%20Reports/National%20Adaptation%20Plan%20of%20Sri%20Lanka.pdf. Browsed on 21 June 2020.

Nowogrodzki, A. (2019). The changing seasons of tea. *Nature* S10, 566, 7 February 2019. Available at https://www.nature.com/articles/d41586-019-00399-0. Browsed on 21 June 2020.

Pan, X., Niu G. and Liu H. (2003). Microwave-assisted extraction of tea polyphenols and tea caffeine from green tea leaves. *Chemical Engineering and Processing*, 42: 129-133.

Reay, D. (2019). Climate-smart tea. *In*: *Climate-Smart Food*. Palgrave Pivot, Cham, Switzerland, 35-48. ISBN 978-3-030-18206-9 (eBook), https://doi.org/10.1007/978-3-030-18206-9.

Roberts, E.A.H. and Smith, R.F. (1963). The phenolic substances of manufactured tea. IX.—the spectrophotometric evaluation of tea liquors. *Journal of the Science of Food and Agriculture*, 14(10): 689-700.

Vidanagama J. and Lokupitiya E. (2016). Energy usage and greenhouse gas emissions associated with tea manufacturing process in Sri Lanka. *In*: *Proceedings, University of Colombo Annual Research Symposium 2016*, University of Colombo, Sri Lanka, October 2016. Available at https://www.researchgate.net/publication/312376894_Energy_Usage_and_Greenhouse_Gas_Emissions_Associated_with_Tea_Manufacturing_Process_in_Sri_Lanka, Browsed on 30 July 2020.

Walgama, R.S. and Zalucki, M.P. (2007). Temperature-dependent development of *Xyleborus fornicatus* (Coleoptera: Scolytidae), the shot-hole borer of tea in Sri Lanka: Implications for distribution and abundance. *Insect Science*, 14: 301-308.

Watson, M. (2008a). Climatic requirements and soil. Revised by A.K.N. Zoysa. A.K.N. Zoysa (Ed.), *In*: *Tea Hand Book*. Tea Research Institute, Talawakele, Sri Lanka. ISBN 955-9023-00-4. 10-15.

Watson, M. (2008b). Harvesting of tea. Revised by M.A. Wijeratne. *In*: A.K.N. Zoysa (Ed.), *Tea Hand Book*. Tea Research Institute, Talawakele, Sri Lanka. ISBN 955-9023-00-4. 10-15.

Wijeratne M.A. (1996). Vulnerability of Sri Lanka tea production to global climate change. *Water, Air and Soil Pollution*, 92: 87-94.

Wijeratne M.A. (2001). *Shoot growth and harvesting of tea*. Tea Research Institute of Sri Lanka. ISBN 955-9023-02-0. 45pp.

Wijeratne, M.A., Anandacoomaraswamy, A., Amarathunga, M.K.S.L.D., Ratnasiri, J., Basnayake, B.R.S.B. and Kalra, N. (2007). Assessment of impact of climate change on productivity of tea (*Camellia sinensis* L.) plantations in Sri Lanka. *Journal of National Science Foundation of Sri Lanka*, 35(2):119-126.

Wijeratne, M.A., Anandacoomaraswamy, A., Amarathunga, M.K.S.L.D., Ratnasiri J., Basnayake, B.R.S.B. and Kalra N. (2011). Assessment of impact of climate change on productivity of tea (*Camellia sinensis* L.) plantations in Sri Lanka. *Journal of National Science Foundation of Sri Lanka*, 35(2): 119-126.

Wijeratne, T.L. (2018). Assessing and reducing the environmental impact of tea cultivation. *In*: Sharma, V. S. and Gunasekare, M.T.K. (Eds.). *Global tea science: Current status and future needs*. Burleigh Dodds Science Publishing, Cambridge, UK, 2018, ISBN: 978 1 78676 160 6; www.bdspublishing.com, 1-18.

Importance of Underutilized Crops under Changing Climate Scenario

R. Wimalasekara*

Department of Botany, Faculty of Applied Sciences,
University of Sri Jayewardenepura, Gangodawila, Nugegoda, Sri Lanka.
*rinukshi@sci.sjp.ac.lk

Importance of Underutilized Crops under Changing Climate Scenario

Abstract

The entire world is dependent on a handful of crops, mainly maize, rice and wheat for its staple food requirements and yet another approximately 170 crops are grown on a commercial scale. In the past, humans relied on a broader variety of species for nutrition and other requirements. However, the importance of most of these species has decreased over time and many species have become neglected or underutilized. Crop production is extremely vulnerable to climate change, threatening the global food security. Therefore, enhancing crop production under changing climate is a great challenge and there is a timely requirement for reorientation of crop production from conventional species to a more diverse range of crops. Among the significant attributes of underutilized crops are their higher tolerance to drought, extreme temperatures, resistance to pests and diseases and food production with fewer inputs. The promotion of underutilized crops offers opportunities for strengthening the adaptation, mitigation and resilience in agricultural systems to climate change. Underutilized crops can be successfully used in diversification for food security under changing climate.

Keywords: *Climate change, food security, sustainability, underutilized crops*

Introduction

Today the global staple food supply counts chiefly on maize, rice and wheat leaving an abundance of other crop resources neglected or underutilized. Underutilized crops are domesticated crop species that have been reduced in importance over time for many agronomic and socio-economic factors. Cultivation of these crop species has decreased mainly due to the failure in competing with the commercial crops.

Climate change is a global challenge and extreme weather events have increased recently in many agricultural regions in the world resulting variable impacts on crop production around the world. Climatic change has shown great impact on yield reductions in major food crops (Ray *et al.*, 2019). There is a timely need for climate-smart approach to secure sustainable food security under climate change (Godfray, 2010). Many of the underutilized crops are known to be highly adapted to severe environments and able to withstand the impacts of climate change. Paradigm shift in agriculture by re-introducing and/or expanding the cultivation of underutilized crops is one possibility in enhancing the resilience of agroecosystems to withstand the impacts of climate change scenarios (Bavec *et al*., 2017). Sound understanding of the limits of the green revolution is another important factor that influence today's increased interest in underutilized plants. Across Sri Lanka, climate change related weather aberrations and resultant extreme weather events are becoming increasingly common. As a result, yields of major crops including rice have been severely decreased in the past few years. Sri Lanka is rich in several underutilized species and strategic framework to cultivate them in more of drought affected regions and increasing awareness in society has an enormous potential to address future food security.

Major food crops around the world

Crops are grouped into six categories as food crops, feed crops, fiber crops, oil crops, ornamental crops, and industrial crops based on their use. Although there are extensive numbers of food crop species around the world, only a limited number is domesticated and humans depend on a limited number of crops to meet the dietary needs and associated needs. Top ten global crops that provide the bulk of consumable food calories are maize (corn), rice, wheat, soybeans, oil palm, sugarcane, barley, rapeseed (canola), cassava and sorghum (Hoeschle-Zeledon and Jaenicke, 2007). Among them, the world food supply today relies mainly on maize, rice and wheat accounting to 40% of our daily calories leaving an abundance of other genetic resources and potentially beneficial traits neglected. Maize, a staple food in many countries is extensively grown throughout the world and has the highest production of all the crops (FAOSTAT, 2015, 2019). Rice is another major food for over half the world's population and records as the second largest cereal production after maize (FAOSTAT, 2015, 2019). Wheat is staple food in many regions of the world and widely grown under diverse climatic conditions claiming third most produced cereal (FAOSTAT, 2015, 2019). Generally, in present agriculture, humans depend on a small number of crop species and they occupy large cultivated areas. Climate, accessibility, trade, and culture are some of the factors that have impact on domestication and popularity of a food crop in a given region. In the past humans depended on a broad variety of species for the nutrition and other needs.

Major food crops grown in Sri Lanka

Agriculture is the most important sector of the Sri Lankan economy. Sri Lanka's agriculture is dominated by four major crops: rice, tea, rubber, and coconut. Rice is the most important crop occupying 34% of the total cultivated area and it is grown under more diverse environmental conditions as a rain fed crop (http://www.statistics.gov.lk/agriculture/). Coconut is one of the major crops grown in about 440,000 ha in different agro-climatic zones (Ranasingha, 2019). Various other food crops are grown in different agro-ecological zones primarily for local consumption. They include maize, potato, sweet potatoes, cassava, green gram, onion, gingelly, sugar cane, variety of vegetables and fruits. Some of the seasonal vegetables and fruits are exclusively cultivated in home gardens (http://www.statistics.gov.lk/agriculture/). Today, people depend on a limited number of food crops although crop diversification in the country has taken place at different time periods in different agro-ecological regions.

Underutilized crops

Today in modernised agricultural practices about 30 crop species are grown on a commercial scale and provide 95% of the worlds' food requirement. Over 7,000 species are known to be partly or fully domesticated but have been neglected to varied degrees over periods (Malik and Chaudhary, 2011; Massawe *et al*., 2015).

Underutilized crops are domesticated crop species that have been reduced in importance over time for many reasons. According to International Centre for Underutilized Crops, underutilized plant species are defined as "species with under-exploited potential for contribution to food security, health, income generation and environmental services". Terms such as 'underutilized', 'neglected', 'orphan', 'minor', 'promising', 'niche' and 'traditional' are often used interchangeably to characterise range of plant species (FAO, 2017).

There are thousands of neglected or underutilized crops in numerous agricultural ecosystems and often survive in specific regions of the world mainly in marginal areas and may be widely distributed beyond their centres of origin (Godfray *et al*., 2010). These underutilized crops are generally indigenous or traditional crops that thrive in specific regions of the world and primarily grown by traditional farmers and typically not traded as commodities. There is an extensive number of underutilized plant species around the world. A few of them are listed in Table 1.

Underutilized crops in Sri Lanka

It has been estimated that Sri Lanka has around 60 underutilized crops (Table 2) with rich potential as major crops (Bandula *et al*., 2016;

Table 1: Some examples of underutilized crops in the world.

Crop Category	Underutilized species
Cereal/ pseudocereal crops	*Amaranthus caudatus, Chenopodium quinoa, Chenopodium pallidicaule, Digitaria exilis, Echinochloa frumentacea, Eragrostis tef, Fagopyrum esculentum, Panicum miliaceum, Panicum miliare, Paspalum scrobiculatum, Setaria italica,*
Root and tuber crops	*Alocasia spp. Arracacia xanthorrhiza, Calathea allouia, Canna edulis, Colocasia esculenta, Dioscorea spp. Harpagophytum procumbens, Oxalis tuberosa, Pachyrhizus erosus*
Fruits and nuts species	*Adansonia digitate, Aegle marmelos, Anacardium occidentale, Annona cherimola, Annona muricate, Annona squamosa, Artocarpus heterophyllus, Averrhoa carambola, Bactris gasipaes, Canarium indicum, Carissa edulis*
Vegetable and pulse crops	*Adansonia digitate, Amaranthus spp. Artemisia dracunculus, Basella alba, Basella rubra, Borago officinalis, Boscia coriacea, Brassica carinata, Campanula rapunculus, Canavalia spp., Chenopodium album, Cichorium intybus, Cleome gynandra, Corchorus spp.*

Table 2: Some examples of underutilized crops in Sri Lanka

Crop Category	Underutilized species
Cereal/ pseudocereal crops	*Eleusine coracana* (Kurakkan/Finger millet)*, Panicum sumatrense* (Heen Meneri)*, Setaria italica* (Thana hal)*, Paspalum scrobiculatum* (Amu/Kodo Millet)
Root and tuber crops	*Colocasia* sp (Gahala), Dioscorea alata (Kiriala), *Maranta arundinacea* (Hulankeeriya)
Fruits and nuts species	*Aegle marmelos* (Beli), *Annona muricata* (Katu anoda), *Pouteria campechiana* (Lawulu), *Syzygium jambos* (Jambu), *Drypetes sepiaria* (Weera), *Manilkara hexandra* (Palu), *Syzygium cumini* (Ma-dan), *Flacourtia inermis* (Lovi), *Dimocarpus longan* (Mora)
Vegetable and pulse crops	*Artocarpus heterophyllus* (Kos/Jack)*, Solanum torvum* (Thibbatu), *Amaranthus tricolor* (Thampala), Boerhavia diffusa (Sarana), *Costus speciosus* (Thebu), *Celosia argentea* (Kirihenda), *Ipomoea alba* (Alanga), *Momordica dioica* (Thumba karawila), *Vigna mungo* (Black gram), *Sesamum indicum* (Gingili), *Brassica juncea* (Aba/Mustard)
Leafy vegetables	*Sauropus androgynus* (Japan batu), *Coccinia grandis* (Kowakka), *Osbeckia octandra* (Heen bovitiya), *Olax zeylanica* (Mella), *Wattakaka volubilis* (Kiri anguna)

Malkanthi, 2017; Ratnayake *et al*., 2020). However, there is no sufficient information on underutilized plants and much of the knowledge is restricted to traditional societies. Most of the traditional varieties remain as underutilized crops.

In the attempt of intensifying crop production to feed the increasing global human population, new high yielding varieties have been introduced. Subsequent selection, crop improvement and agronomic practices allowed better domestication and developed as high demand commercial crops. Cultivation of underutilized crops has decreased mainly due to the failure in competing with the commercial crops in terms of consumer acceptance and low demand. The demand for the low yielding traditional varieties declined and most of them today remain as underutilized. Often these crops exist as minor or niche crops for low subsistence purposes. Food consumption pattern changed dramatically over periods and people especially residing in urbanized areas are not accustomed of using traditional varieties.

In the past, Sri Lankan people cultivated a large variety of plants to fulfil their own food requirements. But nowadays agriculture is primarily based on commercial crops and many other crop species has decrease their consumer demand due to popular characters of the main crops or hybrids. Population growth, urbanization, change in food habits, lack of awareness among farmers on importance of these crops are some reasons for displacement or underutilizing many crops previous greatly in use (Malkanthi, 2017). Underutilized crops have been overlooked by research, extension services, policy makers and governments rarely allocate resources for their promotion and development. However, currently a growing trend for underutilized/exotic fruits, vegetables and other crops has been developed in the country. This new trend may create an opportunity for farmers to find a good income source by generating a market place.

Importance of underutilized crops

Importance of underutilized plants whether they are cereals, roots/tubers, vegetables or fruits are manifold. They can contribute significantly to improved health and nutrition, livelihoods, household food security and ecological sustainability. Underutilized crops can play an important role in sustainable nutritional security. Most of the underutilized plants are rich in nutrient profile (Table 3), for example, pearl millet is remarkably rich in proteins, finger millet has the highest calcium content among all the food grains, sorghum and pearl millet

Table 3: Nutrient composition of major crops (per 100 g edible portion; 12 percent moisture)

Crop	Protein (g)	Carbohydrate (g)	Fat (g)	Crude fibre (g)	Ca (mg)	Fe (mg)	Riboflavin (mg)
Rice (brown)	7.9	76.0	2.7	1.0	33	1.8	0.04
Wheat	11.6	71.0	2.0	2.0	30	3.5	0.10
Maize	9.2	73.0	4.6	2.8	26	2.7	0.20
Sorghum	10.4	70.7	3.1	2.0	25	5.4	0.15
Finger millet	7.7	72.6	1.5	3.6	350	3.9	0.19
Kodo millet	9.8	66.6	3.6	5.2	35	1.7	0.09
Pearl millet	11.8	67.0	4.8	2.3	42	11.0	0.21

Sources: Hulse. Laing and Pearson, 1980; United States National Research Council/National Academy of Sciences, 1982; USDA/HNIS, 1984.

records high fibre content and whole grains are rich in B-complex vitamins (FAO, 1995).

Extensive growth of these crops could be useful in addressing nutrient deficiencies and diversifying diets especially in rural communities in Asia and Africa (Hoeschle-Zeledon and Jaenicke, 2007; Chibarabada *et al*., 2017; Govender *et al*., 2017).

Underutilized crops (Figure 1) can be used in increasing functional biodiversity and has a positive effect on enhancing sustainable behaviour of cultivated plants with good balance of pests and plant diseases,

Figure 1: Underutilized crops in Sri Lanka. a, b: *Eleusine coracana* (Finger millet); c, d: *Panicum sumatrense* (Heen meneri); e, f: *Setaria italica* (Thana hal); g, h: *Colocasia esculenta* (Gahala); I, j: *Maranta arundinacea* (Hulankeeriya); k, l: *Pouteria campechiana* (Lawulu); m: *Annona muricate* (Anoda); n: *Amaranthus tricolor* (Thampala); o: *Solanum torvum.*

enhancing pollination services, and increasing soil microbiome (Bavec *et al*., 2017). Underutilized crops are also important in keeping traditional knowledge alive and boost the livelihoods of small-scale farmers and local producers (FAO, 2020).

Effect of climate change on crop production

Climate change as observed by increased occurrences of drought, unpredictable rainfall, extreme temperatures and cyclones has variable impacts on agriculture around the world. In recent years, crop production all over the world especially in the developing countries is badly affected by climate changes. Rapid climate change is widely acknowledged as the greatest challenge facing life on earth.

The production of cereal crops has been affected by 9–10% due to adverse climatic conditions such as drastic increase in temperature and prolonged drought (Lesk *et al*., 2016). Climatic change has caused reduction of yield in major food crops such as wheat, rice, maize and soybean. According to the climate change projections, up to 30% reduction of maize production in Southern Africa, up to 10% reduction of rice and more than 10% reduction of maize yield in South Asia are expected by 2030 (Lobell *et al*., 2008; 2012). Increasing evidence shows a strong correlation between the increasing atmospheric levels of CO_2 and decreasing nutrient/ micronutrient content of staple crops. Rise in temperature and varying rainfall pattern has adversely affected the rice production in Sri Lanka (Ratnasiri *et al*., 2019). Coconut production in Sri Lanka has been highly vulnerable to drought and heat stress during fruit set (Ranasingha, 2019). Low crop production is a key problem for future food security, risk of undernourishment and livelihood of farmers.

Climate change is expected to increase the frequency of drought, heat stress, submergence and increased soil salinity. We need to prepare for the worst, while hoping for the best by exploring opportunities for identifying and using exceptional traits with market potential of crops in the context of climate change. Underutilized crops have great potential to food production in challenging climates where major crops are severely limited.

Underutilized crop species and climate change

Evidences exists that many underutilized species are able to withstand the extrema weather conditions such as drought, high temperature, chilling and cyclones in the face of climate change (FAO, 2013; 2017). In the arid/semi-arid environments specific traits and physiological responses contribute significantly to enhance crops' ability to withstand climatic changes. A key strategy to adapt to a changing climate is the promotion of underutilized crop species which would provide a more diversified agricultural system and food sources to address food security (Hoeschle-Zeledon and Jaenicke, 2007). Global attention has been already paid on popularizing and capacity building on underutilized crops for diversification of crops in the era of climate change.

"Crops for the Future" is such a global organization that works together with "International Centre for Underutilized Crops" with a mandate of systematic evaluation, diversification of agricultural value, nutritious and economically viable options and development of underutilized plants for wider use (Mayes *et al*., 2012). "Food and Agriculture Organization" and "The African Orphan Crop Consortium" is directly involved in new efforts to promote wider use of neglected and underutilized crop species and their varieties in Africa and Asia (FAO, 2013; 2017).

It is evident that production of major crops is increasing around the world, whereas other crops such as barley, millet, rye and sorghum show generally decreasing trends depending on the region. Several underutilized crop species presently restricted to some regions can be introduced or re-introduced into mainstream food production considering their diverse adaptability to a range of climatic conditions also including climate change (Padulosi *et al*., 2017). Although there are a large number of underutilized crop species around the world only a few of such promising cereal crops that can be potentially expanded to wider area is described below;

Millets (Eleusine sp.)

Millets are a collection of small-seeded annual grasses e.g. pearl millet, finger millet, proso millet and foxtail millet that are cultivated as grain crops (FAO, 2017; 2020). Pearl millet is the most important species that accounts for almost half of global millet production. Millets are cultivated in different regions of the world and require different growing conditions. These are grown as subsistence crop for local consumption in many dry regions of the world as rain-fed crops under marginal conditions of soil fertility and moisture. Asia and Africa account for about 94% of global production (FAO, 2013; 2017; Upadhyaya and Vetriventhan, 2017). Millet production in Africa is distributed among a much larger number of countries while in Asia it is grown mainly in China and India. Recent surveys show that the area under millet cultivation is decreasing in Europe and China (Upadhyaya and Vetriventhan, 2017; Saxena *et al*., 2018).

Since millets thrive at relatively higher temperatures and reproduce with limited water input, millet cultivation can be expanded to semi-arid and arid regions to get substantial yield. Finger millet is able to tolerate higher temperatures and high soil salinity. Finger millet (Kurakkan) is primarily cultivated as shifting cultivation (Chena) mainly in in the Dry zone and Intermediate zone of Sri Lanka. However, the extent of finger millet cultivation has decreased from 21000 ha in late 1980s to 7000 ha 2016 mainly due to forest clearance and replacement of cultivated lands with competitive crops such as maize and vegetables (https://www.doa.gov.lk/FCRDI). Finger millet cultivation can be popularized in Sri Lanka especially considering its' ability to withstand temperature up to 36^{o}C and low rainfall requirement of 500 mm per year. Foxtail millet is more water efficient compared to maize and sorghum and has better resistance to pests and diseases. Kodo millet is said to possess the highest drought resistance among all minor millets (Saxena *et al*., 2018). Foxtail millet and Kodo millet commonly known as "*Thana hal*" and "Amu" respectively, have been used in Sri Lanka as minor food crops and indigenous medicine. However, in the recent years these varieties become less important economically and as a food due to poor yields and less popularity. Millet, as a low water-intensive and adapted to adverse conditions species can be grown in almost every region of the world (Gari, 2002). Further, millet has an excellent nutritional profile and is a non-glutinous food. It is evident that this nutritionally rich crop has a good potential to be developed and popularized to feed the growing population.

Sorghum (Sorghum bicolor)

Sorghum also called as great millet, Indian millet, milo, durra is a cereal grain plant of the grass family. Sorghum is the fifth most economically important cereal in the world (FAO, 2013; 2017). It has been domesticated in Ethiopia and spread to many regions. Of the total world area devoted to sorghum, over 80% is in most arid parts of Africa and South Asia where rainfall is too low for the successful cultivation of maize (Venkateswaran *et al*., 2019). Sorghum is grown extensively as a rainfed crop in dry regions with low or erratic rainfall. Sorghum has been an important crop species in Sri Lanka some decades ago but failed to continue mainly due to poor demand. It can be cultivated on the uplands during the *Maha* season, both in the dry and arid zones as well as in the intermediate zones of the country. Recently a programme to increase sorghum production has been launched to spread its multiple benefits to farmers and increase food production in the country.

Sorghum is more drought-resistant than crops like maize and wheat mainly due to an extensive root system, effective control of evapotranspiration (Haussmann *et al*., 2012). It is able to recover rapidly after periods of water stress, and has an ability to withstand desiccation and able to tolerate a range of temperature regimes of 15-35^{o}C without any yield losses but varying days taken to mature. Sorghum is relatively tolerant to short periods of waterlogging and moderately tolerant to soil salinity (Reddy *et al*., 2011). These characteristics support that cultivation of sorghum can be expanded to several more regions. "International Crops Research Institute for the Semi-Arid Tropics" is finding more possibilities to develop sorghum as an important crop to resist climate change. Some of the efforts are; sorghum genetic enhancement to increase grain yield, tolerance to drought and heat, grain mold and shoot fly resistance, and grain micronutrient density (Fe and Zn) to face the newer challenges in sorghum production (Reddy *et al*., 2011).

Quinoa (Chenopodium quinoa)

Quinoa, a dicotyledonous annual plant belonging to family Amaranthaceae is grown as a crop for its edible seeds (pseudo cereal) and possess rich nutrition properties. Quinoa is native to the Andean region of South America and in recent years' cultivation of this crop has been expanded to many countries across US, Europe and Asia (Bazile *et al*., 2016). Outstanding characteristics such as broad genetic variability, adaptability to adverse climate and soil conditions and other abiotic stress conditions and low production cost makes quinoa an excellent crop to be grown in several ecological zones (Al-Naggar *et al*., 2017). Depending on the ecotype, quinoa withstand high temperatures up to 38°C and low soil moisture and nutrients yet producing acceptable yields (Al-Naggar *et al*., 2017). Despite the nutritional richness and remarkable adaptability to different agro-ecological regions, quinoa has not received due recognition as a high scope crop (Jacobsen *et al*., 2003). Due to the diverse characteristics of the different ecotypes, quinoa can be grown under different climatic conditions across the world. Sri Lanka has no history of growing quinoa. Under the assistance of FAO, field adaptability trials has been carried out in different location of Sri Lanka and based on the results quinoa has been identified as a suitable commercial cultivation crop in the country (http://www.fao.org/srilanka/news). Despite these recommendations quinoa is not cultivated in the country.

Fonio/acha/iburu (Digitaria exilis /Digitaria iburua)

Fonio is an annual grass cultivated for its edible seed for thousands of years in savannas of West Africa and is the staple food in various parts of West Africa. Whole grains are rich in carbohydrates, fibres, phenolics and minerals. It is one of the world's fastest growing cereals, reaching maturity in as little as six to eight weeks (Jideani, 2012). Fonio is adapted to perform well in low fertility soils, rocky soils, acidic clay soils with high aluminium content and able to withstand prolonged droughts as well. Since this underutilized crop is low demanding and can cope with unfavourable climate and soil conditions it is well suited to be grown in regions of extreme conditions.

Underutilized species in Sri Lanka and climate change

Increasing temperatures and extreme rainfall variants like droughts and floods strongly affect the crop production in the country. There is need of appropriate strategies in order to reduce the impacts on production and ensure food security. Sri Lanka has rich diversity of crop species although mainly depend only on few crop species for human nutrition. Finger millet is an important food crop grown in the Dry zone and Intermediate zone of Sri Lanka. However, the extent of finger millet cultivation has declined sharply from about 50,246 acres in 1971 to about 10,000 acres in 2010/2011 (Central bank of Sri Lanka, 2011). Popularizing sorghum cultivation on the uplands during the Maha season, both in the dry and arid zones as well as in the intermediate zones of the country has already in the agenda as a crop that can withstand climatic changes (Akinseye *et al*., 2020). Taken into consideration nutritional quality, genetic variability, adaptability to adverse climate and soil conditions and low production cost, quinoa is a strategic crop that can be introduced to Sri Lanka.

In line with global plans of action in promoting cultivation of underutilized crops, Sri Lanka has taken several measures to popularize underutilized crops in collaboration with International Centre for Underutilised Crops (ICUC) with input from the Global Facilitation Unit for Underutilized Species (GFU). Several programs are in progress including mapping indigenous knowledge on important underutilized crops, develop increased awareness among the farmers, give support to commercialize the underutilized crops and develop market, promote increased consumption, provision of marketing facilities, necessary inputs, storage and processing facilities. Public-private partnerships foster agricultural projects to popularize underutilized crops by providing necessary inputs, knowhow and marketing facilities.

Conclusion and future directions

Global food production is increasingly dependent on a few crops. There are several hundreds of underutilized plant species grown in discrete regions of the world but not contributing significantly to global food production. Underutilized species can be regarded as promising species for fighting hunger and malnutrition, medicinal use, income generation and ecological protection. The ability of many underutilized species to tolerate adverse environmental stresses can be highlighted in addressing future food needs under changing climate scenario around the world. Strategic framework is urgently in need for development and popularization of these crops in regions where badly affected by climate changes. Other important aspects are to promote awareness in society about the benefits and to create good markets for these crops.

References

Al-Naggar, A.M.M.A., Mohamed, R.M.A., Badran, A.E. and El-Moghazi, M.M.A. (2017). Effects of genotype and drought stress on some agronomic and yield traits of quinoa (*Chenopodium quinoa* Willd.) *Bioscience Research,* 14: 1080-1090.

Akinseye, F.M., Ajeigbe, H.A., Traore, P.C.S., Agele, S.O., Zemadim, B. and Whitbread, A. (2020). Improving sorghum productivity under changing climatic conditions: A modelling approach. *Field Crops Research*, 246: 107685.

Bandula, A., Jayaweera, C., De Silva, A., Oreiley, P., Karunarathne A. and Malkanthi, S.H.P. (2017). Role of underutilized crop value chains in rural food and income security in Sri Lanka. *Procedia Food Science*, 6: 267-270.

Bavec, F., Lisec, U. and Bavec, M. (2017). Importance of underutilized field crops for increasing functional biodiversity. *In: Selected studies in biodiversity*, 377-388.

Bazile D., Jacobsen S.E. and Verniau, A. (2016). The global expansion of quinoa: trends and limits. *Frontiers in Plant Science,* 7: 622.

Central bank of Sri Lanka (2011). Economic and Social Statistics of Sri Lanka.

Chibarabada, T.P., Mabhaudhi, T. and Modi, A.T. (2017). Expounding the value of grain legumes in the semi-and arid tropics. *Sustainability,* 9: 60.

FAO (1995). Sorghum and millets in human nutrition (FAO Food and Nutrition Series, No. 27) FAO, Rome, Italy.

FAO (2013). Climate-smart agriculture Sourcebook. FAO, Rome, Italy Rome.

FAO (2017). Promoting neglected and underutilized crop species. http://www.fao.org/in-action/inpho/crop-compendium/cereals-grains. Accessed 08.06.2020.

FAO (2020). Once neglected, these traditional crops are our new rising stars http://www.fao.org/fao-stories/article/en/c/1154584/. Accessed 08.06.2020.

FAOSTAT (2015). Food and Agriculture Organization of the United Nations (FAO). FAOSTAT Database. Accessed 08.06.2020.

FAOSTAT (2019). Food and Agriculture Organization of the United Nations (FAO). FAOSTAT Database. Accessed 08.06.2020.

Gari, J.A. (2002). Review of the African millet diversity. FAO - Food and Agriculture Organisation of the United Nations. Rome. Italy.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir JF, *et al*. (2010). Food Security: The Challenge of Feeding 9 Billion People. *Science*. 327: 812–818.

Govender, L., Pillay, K., Siwela, M., Modi, A., Mabhaudhi, T. (2017). Food and nutrition insecurity in selected rural communities of KwaZulu-Natal, South Africa – linking human nutrition and agriculture. *International Journal of Environmental Research and Public Health,* 14: 17.

Haussmann, B.G.I., Fred, Rattunde, H., Weltzien-Rattunde, E., Traoré, P.S.C., vom Brocke, K., and Parzies, H.K. (2012). Breeding strategies for adaptation of pearl millet and sorghum to climate variability and change in West Africa. *Journal of Agronomy and Crop Science,* 5: 327-339.

Hoeschle-Zeledon I. and Jaenicke, H. (2007). A strategic framework for global research and development of underutilized plant species: A contribution to the enhancement of indigenous vegetables and legumes. *Acta Horticulturae* ,752: 103-110.

Jacobsen, S.-E., Mujica, A. and Jensen C.R. (2003). The resistance of quinoa (*Chenopodium quinoa* Willd.) to adverse abiotic factors. *Food Reviews International,* 19: 99-109.

Jideani, I.A. (2012). *Digitaria exilis* (acha/fonio), *Digitaria iburua* (iburu/fonio) and *Eluesine coracana* (tamba/finger millet) Non-conventional cereal grains with potentials. *Scientific Research and Essays,* 7: 3834 -3843.

Lesk, C., Rowhani P. and Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. *Nature*, 529: 84-87.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, WP. and Naylor, R.L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319: 607-610.

Lobell, D.B. and Gourdji, S.M. (2012). The influence of climate change on global crop productivity. *Plant Physiology*, 160: 1686-1697.

Malik A.A. and Chaudhary, G. (2019). A truncated yield of underutilized and orphan crops. *In*: *Biotechnology products in everyday life*. Springer International Publishing. 161-171.

Malkanthi, S.H.P. (2017). Importance of underutilized crops in Thanamalwila divisional secretariat division in Moneragala district in Sri Lanka. *The Journal of Agricultural Sciences,* 12: 197-206.

Massawea, F.J., Mayes, S., Cheng, A., Chai, H.H., Cleasby, P., Symonds, R., Ho, W.K. and Siise, A. (2015). The potential for underutilised crops to improve food security in the face of climate change. *Procedia Environmental Sciences,* 29: 140-141.

Mayes, S., Massawe, F.J., Alderson, P.G., Roberts, J.A., Azam-Ali, S.N. and Hermann, M. (2012). The otential for underutilized crops to improve security of food production. *Journal of Experimental Botany*, 63: 1075–1079.

Padulosi, S., Heywood, V., Hunter, D. and Jarvis, A. (2017). Crop underutilized species and climate change: Current status and outlook. *In*: *Adaptation to climate change*, First edition. (Yadav, S.S., Redden, R.J., Hatfield, J.L., Lotze-Campen, H. and Hall, A.E. (Eds.)) 507-521.

Ranasinghe, C.S. (2019). Climate change impacts on coconut production and potential adaptation and mitigation measures: A review of current status. http://www.slcarp.lk/wp-content/uploads/2019/01/Full-Book-Climate- change_77.pdf.

Ratnasiri, S., Walisinghe, R., Rohde, N. and Guest, R. (2019). The effects of climatic variation on rice production in Sri Lanka, *Applied Economics*, 51: 4700-4710.

Ratnayake, S.S., Kumar, L, Kariyawasam, C.S. (2020). Neglected and underutilized fruit species in Sri Lanka: Prioritisation and understanding the potential distribution under climate change. *Agronomy*, 10: 34.

Ray, D.K., West, P.C., Clark, M., Gerber, J.S., Prishchepov, A.V. and Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS ONE*, 14: [: e0217148].

Reddy, B.V.S., Kumar, A.A., Ramesh, S. and Reddy, P.S. (2011). *Sorghum genetic enhancement for climate change adaptation in crop adaptation to climate change*. John Wiley & Sons, Inc.

Saxena, R., Vanga, S.K., Wang, J., Orsat, V. and *Raghavan*, V. (2018). Millets for food security in the context of climate change: A review. *Sustainability*, 10: 2228.

Upadhyaya, H.D. and Vetriventhan, M. (2017). Underutilized climate-smart nutrient rich small millets for food and nutritional security. *In: Thematic, Strategic Papers and Country Status Reports*.

Venkateswaran, K., Elangovan, M. and Sivaraj, N. (2019). Origin, domestication and diffusion of *Sorghum bicolor* in breeding Sorghum for diverse end uses. Woodhead publishing series in food science, *Technology and Nutrition,* 15-31.

Extreme Weather Events and Crop Yields: A Case Study with Coconut

K.P. Waidyarathne[1] and S.A.C.N. Perera[2]*

[1]Plant Physiology Division, Coconut Research Institute, Lunuwila, Sri Lanka.
[2]Department of Agricultural Biology, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka.
*chandrikaperera2003@yahoo.com

Extreme Weather Events and Crop Yields: A Case Study with Coconut

Abstract

Weather events individually or as averages over time affect critically on biomass and crop yields, making them vital in addressing the effects of climate on agricultural productivity. Potential detrimental effects of extreme weather events related to ambient temperature and rainfall have been a growing concern, especially in view of the global climate change. Drought is the most crucial extreme weather event for coconut in Sri Lanka. Coconut is an economically important palm species and being a perennial plant, it is adversely affected by weather fluctuations throughout its life cycle. Coconut is especially sensitive to drought during the post-fertilization phase of growing bunches. This reduces nut set resulting from a reduction in assimilate production and ultimately affecting quantity as well as the quality of nuts. As per the distribution of coconut by agro-ecological environments, the low country intermediate zone, IL1 and IL1b contributes to approximately 50% of the annual national coconut production. Coconuts grown in the intermediate zone are exposed to supra optimal or high temperatures, especially during the months of drought. Long term precipitation data has provided evidence for the increasing occurrences of drought events in agro-ecological region IL1b. The correlation of drought events with long term yield data has revealed the patterns of adverse effects of drought on coconut yield. The increased frequency of drought events necessitates the implementation of drought preparedness measures for the sustainability of the coconut industry.

Keywords: *Cocos nucifera L., climate change, crop yields, drought, Sri Lanka*

Introduction

The term ‘weather’ represents the state of the atmosphere, with respect to precipitation temperature, cloudiness, rain etc. at a particular place during a short period of time. In contrast, ‘climate’ is the weather conditions that prevail in an area, averaged over a long period. Further, the term ‘climate change’ refers to the average level changes in weather outcomes (e.g. degree of temperature) that occur over a long period of time. A specific feature of climate change is the increasing frequency of weather shocks which are referred to as extreme weather events. Globally, the extreme weather events are threatening humans in various ways, the reduction in agricultural productivity being one of the major issues. Weather events individually or as averages over time affect critically on biomass and crop yields, making them vital in addressing the effects of climate on agricultural productivity.

Coconut, as a commercial crop, has been cultivated in Sri Lanka since the 17th century. By 2014, the total coconut extent of the country was 443,538 ha, which is about 20% of total extent under agriculture in the Island (Department of Census and Statistics, 2017). Out of this, the total extent of coconut in bearing stage is about 342,662.2 ha producing 2500-3000 million nuts per annum. This production, however, is insufficient to meet the industrial demand and for the sustainability of the coconut industry in the country.

Being a perennial plant, coconut is adversely affected by weather fluctuations throughout its life cycle. Potential detrimental effects of extreme weather events related to ambient temperature and rainfall have been a growing concern in Sri Lanka, especially in view of the global climate change. The information derived from systematic studies on the effect of climate change on coconut production is highly useful in maintaining the production and ensuring the sustainability of coconut cultivations. Such information is especially important with the expansion of coconut plantations into drier areas, where the effects of extreme weather events are expected to be more detrimental than in the areas in the traditional coconut triangle, which are better suited for coconuts. Although the literature provides evidence for the effect of weather parameters on coconut production (Peiris, 1993; Peiris *et al*., 1993; Peiris and Thattil, 1997; Hansen and Zubair, 2008) the studies on the effect of extreme weather events on coconut production remain comparatively scarce.

Drought is the most important extreme weather event that causes extensive damage in coconut plantations, adversely affecting the production and productivity. The definition of drought itself is complex, but in many textbook examples, drought is considered as a natural stochastic phenomenon that arises from a considerable deficiency in precipitation. There are many quantitative measures of drought that have been widely used depending on the discipline affected, amount of data needed for computation, and the particular application (Svoboda and Fuchs, 2016). Several indices developed by Wayne Palmer (Palmer

Drought Severity Index, Palmer Z Index) and Standardized Precipitation Index on different time scales are among them for describing the many scales of drought and these are being widely used because of their simplicity. Accordingly, this chapter describes the effect of extreme weather event; drought, on coconut yields in Sri Lanka using the commonly used simple computational methods.

Drought in Sri Lanka

Drought is considered the most crucial natural disaster in Sri Lanka (UNDRR, 2019), causing severe hardships on the livelihoods in terms of water scarcity, resulting in the second-highest agricultural crop damage. In the last few decades, South Asian countries, including Sri Lanka have reported increased drought events as frequently as once in every three years (Aadhar and Mishra, 2017). Over the past 40 years, the country experienced the worst drought in 2016-2017, affecting 20 districts and approximately 1.8 million people (CFE-DM, 2017). Occurrences of drought is inevitable in almost all regions of Sri Lanka due to noticeable changes in major meteorological situations. The changes such as low-level disturbances, depressions and cyclones in the formation of weather systems in the bay of Bengal and the highly variable activity of the Inter-Tropical Convergence Zone are responsible in the formation of different weather systems in different seasons (Chithranayana and Punyawardena, 2008).

Developing a definition to describe drought or an index to measure it are difficult tasks. Many quantitative measures of drought have been developed in the United States, depending on the discipline affected, the region being considered, and the particular application. Several indices developed by Wayne Palmer, as well as the Standardized Precipitation Index, are useful for describing the many scales of drought.

Observing the long-term monthly Moisture Availability Index, Chithranayana and Punyawardena (2008) claim that there is no risk of occurring drought in agro-ecological regions (AERs) in the up-country intermediate zone. However, compared to the wetter part of the island, drought proneness is relatively higher in the intermediate zone. The majority of AERs in the low country intermediate and dry zones are vulnerable to drought during January–March and June-August periods. There is a low chance for the occurrence of frequent droughts in the wet zone except for the period of January–February (Chithranayana and Punyawardena, 2008).

A study conducted by Gunda *et al*., (2010) revealed a strong association between the Northeast monsoon and *El-Niño* in recent decades. They further suggested that the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI) at a 9-month scale (SPI-9) can appropriately be used as agricultural drought monitoring tools, respectively in the intermediate and the dry zones (Gunda *et al.*, 2016).

Comparing SPIs at different time scales, a recent study revealed that more drought events (SPI≤ −1) and a greater increase in the trend occurred during *Yala* (effective during the period from May to end of August) than *Maha* cropping season (from September to March in the following year) (Abeysingha and Rajapaksha, 2020). The authors further revealed more frequent drought occurrence in the dry zone than the wet and intermediate zones at the annual time scale.

Effect of drought on coconut yields

The International Panel on Climate Change (IPCC) claims that the negative impacts on crop production will be more common in future, resulting in decreased crop productivity with an expected local temperature increase of 1-2^{o}C and an increase in the frequency of droughts and floods in countries of low latitude (IPCC, 2014). The ill-effects of drought can be more prominent on plantation crops such as coconut due to their perennial nature making future coconut supply uncertain due to climate change and its unknown impacts (Pathiraja *et al*., 2015). This uncertainty may create adverse effects on domestic consumers, producers and the coconut processing industries, but, effective application of adaptation measures may minimize the vulnerability depending on the severity of change.

Physiological effects of drought on coconut

Coconut is especially sensitive to drought during the post-fertilization phase of growing bunches, reducing the nut yield (Abeywardena, 1956). Coconut palm takes ~44 months to produce a mature bunch of nuts from the initiation of inflorescence primordia with longer pre-fertilization period (~32 months) than post-fertilization (12 months) period. Therefore, the impact of weather changes beyond the comfort zone at any of the critical stages of the development of inflorescence affects nut yield.

The first few months before and after the opening of the coconut spathe are identified as the most 'sensitive stages' of inflorescence development.

Of them, ovule and pollen formation take place within the last three months before the opening of the spathe (Perera *et al*., 2010) and pollination and button nut formation occur within the first month of spathe opening. High temperature and water stress on these sensitive stages decide the fruit set, the main yield determining factor, by negatively affecting the viability of female flowers and pollen. Bai *et al*. (1988) revealed the possibility for radiation above 265 Wm^{-2}, temperature beyond 33 ^{0}C and vapour pressure deficit of 2.6 KPa to cause moisture stress in coconut and the further aggravation by soil water deficit due to rain-free periods exceeding two months (Bai *et al*., 2003). In addition to reduced fruit set, changing climate is shown to affect the quality of fruits and the rate and duration of assimilate production (Ranasinghe, 2017).

The dry matter (DM) requirement of vegetative organs has the priority over fruits (Navarro *et al*., 2008) in perennial crops because of the simultaneous growth of vegetative and reproductive organs. It was found out in a recent study (Ranasinghe and Premasiri, 2016) that the total DM requirement of coconuts (fruits) was at the highest during November to February and the lowest in June irrespective of the year to year variations. The authors suggested that these variations are mainly associated with low number of fruit setting in February–March period resulting in a lower number of rapidly growing fruits in June-July and a higher number of fruit setting in May-August resulting in a high number of rapidly growing fruits in September-January (Ranasinghe and Premasiri, 2016). The flowers and young fruits are not able to compete for assimilates with the fast-growing fruits (6-10 months old nuts) when the total DM requirement of the palm is high and hence abort, resulting in low fruit set. In coconuts, female flowers become receptive and ready for pollination in 22 days after spathe opening (Thomas and Josephrajkumar, 2013) and the climatic conditions during the first three months after inflorescence opening determines the number of set fruits.

Supra-optimal temperatures can affect photosynthesis because the fixation of CO_2 via rubisco enzyme and regeneration of the ribulose-1-5-bisphosphate (RuBP) through the Calvin Cycle is highly influenced by temperature variation, leading to a reduction in the DM production of palms. Moreover, the DM requirement for maintenance respiration of palms also increases at high temperatures (Amthor, 1984). Both imbalances can widen the gap between dry matter requirement and supply to developing fruits leading to the abortion of young fruits and flowers as there is a high competition for assimilates between vegetative organs and developing fruits. Even though there is a short-term mechanism in coconut (Navarro *et al*., 2008) to adjust source-sink imbalances by changing the light use efficiency and partly compensating transitory reserves in leaf petioles, long term and frequent occurrences of droughts and high temperature events may be detrimental to the palms.

Drought in major coconut growing areas and coconut yields

There should be a minimum rainfall of 5mm to satisfy the daily water requirement of an adult coconut palm (Peiris and Kularathne, 2008). Regression analyses between coconut productivity and the number of extreme events (number of days with maximum temperature (T_{max}), rainfall exceeding the 90th percentile of the daily distributions, and number of days with rainfall below the 10th percentile of the daily distribution) during the first four months after flowering in three major climatic zones revealed negative influence on productivity on high T_{max} days in the dry zone. The number of high rainfall events and the mean T_{max} of the same period had a negative impact on coconut productivity in the intermediate zone and the number of extreme weather events had no influence yet, on the coconut productivity in the wet zone (Pathmeswaran *et al*., 2018).

Out of the total extent under coconut cultivation in Sri Lanka, about 69% is concentrated in the districts belonging to the "Coconut Triangle; Kurunegala, Puttalam and Gampaha", while another 9.5 percent is confined to "Southern Coconut Belt" consisting the districts Kalutara, Galle, Matara and Hambantota (Figure 1). Kurunegala district alone claims 38 percent of the country's total coconut extent (Department of Census and Statistics, 2017).

As per the distribution of coconut by agro-ecological environments, the low country intermediate zone (IL1 and IL1b – part of the Puttalam and Kurunegala districts) contributes for approximately 50% of the annual national coconut production. Coconuts grown in the intermediate zone are exposed to supra optimal or high temperatures, especially during the months of drought.

A recent study that analyzed the long-term trends in weather parameters; rainfall and maximum temperature in the low country dry intermediate zone (IL1b) revealed significant climate changes especially

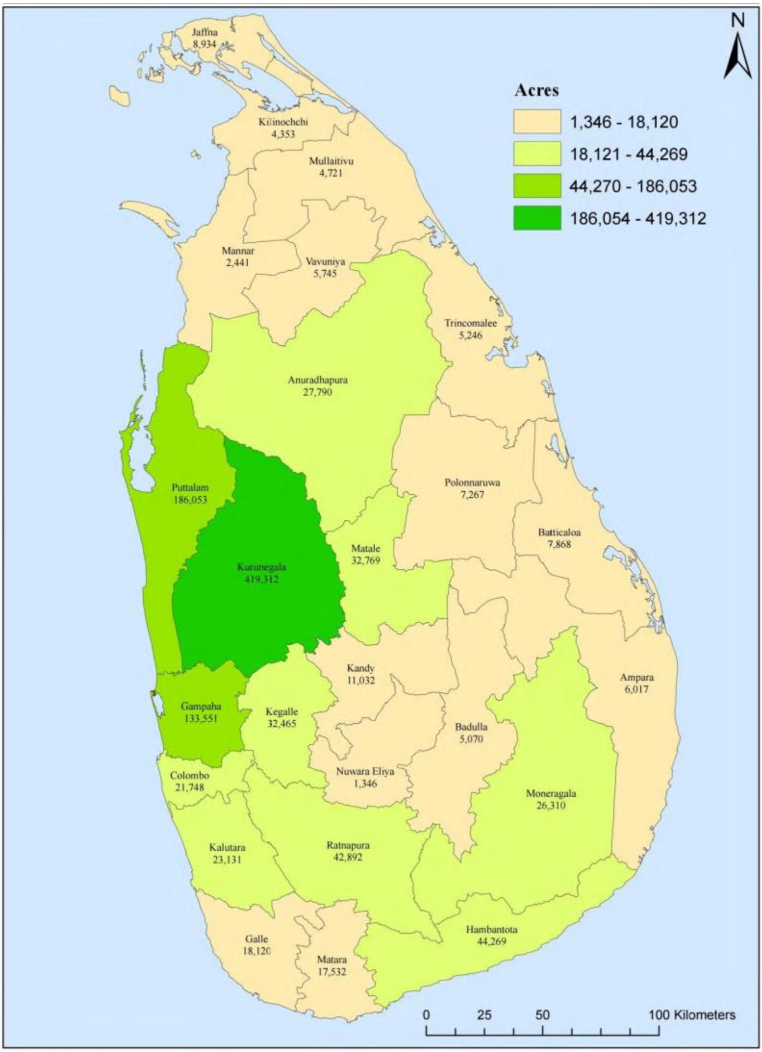


Figure 1: Distribution of coconut cultivation by districts in Sri Lanka.

Source: (Department of Census and Statistics, 2017).

during the South West Monsoon (SWM-May to September) (Waidyarathne *et al*., 2019). This change has occurred due to the increased severity of drought and heat in the recent decades caused by the increment of maximum temperature and the reduction of the length of rainy spells. The study further revealed the combinatorial effect of high temperature and low rainfall in the First Inter Monsoon (FIM – March and April) and SWM, to negatively influence the coconut production in the area. Accordingly, the changes in the amount and duration of precipitation, dry days, maximum temperature and their cumulative effect causing dryness were revealed to determine 90% of the annual yield variability. However, records on studies to identify the effect of drought on coconut using any quantitative measures of drought remain scarce.

Case study on the effect of drought on coconut in AER IL1b

In addition to the large extent of commercial coconut cultivations, the entirety of the hybrid seednuts and about 60% of the genetically improved tall coconut seednuts are produced in the AER IL1b in Sri Lanka (Waidyarathne *et al*., 2019). Accordingly, addressing climate change effects on coconut production in IL1b region of Sri Lanka is a priority concern to ensure the coconut production and the improvement of coconut seednut production.

A study conducted on a Sri Lankan Tall (cultivar CRIC60) coconut population revealed the effect of drought on coconut production in the AER, IL1b. The study population consisted of 300 palms, grown in Isolated Coconut Seed Garden (ISG), Ambakelle, Sri Lanka. Secondary bimonthly yield production data of the palms over 25 years, from 1975–2000, beginning from the age of 16 years, were analyzed.

ISG contributes for more than 50% of the hybrid seednut production as it is dedicated for the production of genetically improved coconut cultivars; CRIC60, CRIC65, Kapruwana and Kapsuwaya. The area records a semi-dry climate with a mean annual maximum temperature of $31^{0}C$ and precipitation of 1250 mm. The soil is well-drained and highly suitable for growing coconuts and the estate is managed following all the standard recommended management practices at the optimum level compared to farmers' coconut holdings.

The AER IL1b was hit by moderate to severe droughts over a minimum period of 3-months in 1974, 1975, 1983, 1987, 2004, 2008, 2011, 2012, 2016 and 2017 providing evidence for the frequent occurrence of droughts in the most recent decade (Figure 2). The longest and the most severe drought was on for more than 12 months beginning from late 2016.

The drought in the first four months of nut development was found to have a negative influence on the final yield as PDSI and the yield were positively correlated at 95% confidence. The Pearson correlation coefficients of yield were 0.29 with PDSI lag 11-12 and 0.17 with PDSI lag 9-10. In addition, drought was compared at different time scales based on SPI. Short-term SPIs (3 and 6 months) can be considered as

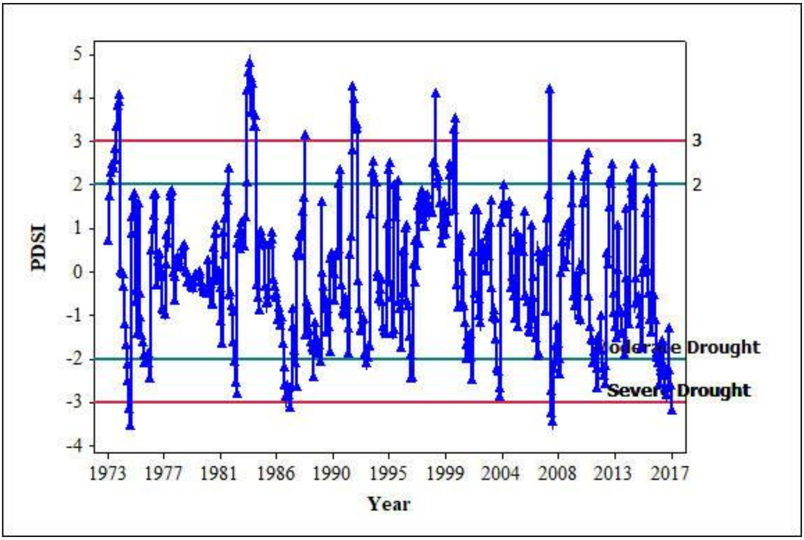


Figure 2: Distribution of PDSI from 1973 to 2017 in ISG, Sri Lanka (PDSI is grouped into 11 categories to define the intensity of the droughts: ≥4 – extreme wet, 3.00 – 3.99 – severe wet, 2.00 – 2.99 – moderate wet, 1.00 – 1.99 – mild wet, 0.5 – 0.99 – incipient wet, 0.49 - -0.49 – normal, -0.5 – -0.99 – incipient drought, -1.00 – -1.99 – mild drought, -2.00 – -2.99 – moderate drought, -3.00 – -3.99 – severe drought and ≤ -4 – extreme drought).

Source: (Waidyarathne *et al*., 2019).

agricultural drought indicators representative of immediate impacts such as soil moisture reduction; hence, short accumulation periods of SPI can be best linked to yield stress. Long-term SPIs (12 months) reflect long-term precipitation patterns in the area and that can also be linked to coconut yield considering the perennial nature of the palm and long development cycle of a coconut bunch. Results revealed that SPIs below -2.00, which are referred to be extreme drought events, in the area were comparatively high in the recent years in all time scales. Further, Sequential Mann Kendall analysis revealed that SPIs in all three-time scales declined after the year 2000, indicating the temporal progress of drought. The coconut yield did not show any significant correlation with SPI in 6- and 12-months scales but was negatively correlated with SPI in 3-months scale. It was hard to explain such relationships using knowledge on crop phenology. However, it appeared that drought might not be the dominant factor affecting the coconut yield during those specific months and/or climate change with respect to drought had no significant variation during the period of yield was concerned.

In summary, the case study provided ample evidence for the increasing occurrences of drought events in AER IL1b, reiterating the need for the adoption of moisture conservation methods in coconut lands to sustain the cultivations.

Conclusion and future directions

The majority of coconut growing areas in Sri Lanka is concentrated in the intermediate zone where the negative effects of climate change on coconut production have already become evident. Being, a perennial palm, coconut will have to face the adverse effects of extreme weather events, especially drought, throughout its long-life cycle. The drought induces the combined abiotic stresses of moisture and heat in coconut, disturbing the physiological functions and reduction in nut set, leading to low yields. Accordingly, in view of the anticipated increased frequency and severity of drought events, it is essential to adopt proper moisture conservation strategies to minimize yield reduction and damage to palms and assure the sustainability of the coconut industry.

References

Aadhar, S., and Mishra, V. (2017). High-resolution near real-time drought monitoring in South Asia. *Scientific Data*, 4(1): 170145. https://doi.org/10.1038/sdata.2017.145.

Abeysingha, N.S., and Rajapaksha, U.R.L.N. (2020). SPI-based spatiotemporal drought over Sri Lanka. *Advances in Meteorology*, 2020:9753279. https://doi.org/10.1155/2020/9753279.

Amthor, J.S. (1984). The role of maintenance respiration in plant growth. *Plant, Cell and Environment*, 7(8): 561–569.

Bai, K.V.K., Reddy, D.V.S., Ratnambal, M.J. and Laxman, R.H. (2003). Factors contributing to female flower production and button shedding in coconut. *Journal of Plantation Crops*, 31(2): 33–36.

CFE-DM. (2017). *Sri Lanka: Disaster Management Reference Handbook*. Ford Island Center for Excellence in Disaster Management and Humanitarian Assistance.

Chithranayana, R., and Punyawardena, B.V.R. (2008). Identification of drought prone agro-ecological regions in Sri Lanka. *Journal of National Science Foundation of Sri Lanka*, 36(02): 117–123.

Department of Census and Statistics. (2017). Economic Census 2013/14 - Agricultural Activities. Department of Census and Statistics, Sri Lanka.

Gunda, T., Hornberger, G.M. and Gilligan, J.M. (2016). Spatio temporal patterns of agricultural drought in Sri Lanka: 1881-2010. *International Journal of Climatology*. https://doi.org/10.1002/joc.4365

IPCC. (2014). IPCC 2014: Summary for policymakers in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: *Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (Christopher B Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, R. C. Genova, (Eds.), Contrib. Work. Gr. II to Fifth Assess. Rep. Intergov. Panel Clim. Chang.

Kasturibai, K.V, Voleti, S.R. and Rajagopal, V. (1988). Water relations of coconut palms as influenced by environmental variables. *Agricultural and Forest Meteorology*, 43(3–4): 193–199.

Navarro, M.N.V, Jourdan, C., Sileye, T., Braconnier, S., Mialet-Serra, I., Saint-André, L. and Bonnefond, J.-M. (2008). Fruit development, not GPP, drives seasonal variation in NPP in a tropical palm plantation. *Tree Physiology*, 28(11): 1661-1674.

Pathiraja, P., Griffith, G.R., Farquharson, R.J. and Faggian, R. (2015). The Sri Lankan coconut Industry: current status and future prospects in a changing climate. *Australasian Agribusiness Perspectives*, 1-23.

Pathmeswaran, C., Lokupitiya, E., Waidyarathne, K.P., and Lokupitiya, R.S. (2018). Impact of extreme weather events on coconut productivity in three climatic zones of Sri Lanka. *European Journal of Agronomy*, 96: 47–53. https://doi.org/https://doi.org/10.1016/j.eja.2018.03.001.

Peiris, T.S.G. and Kularathne, J.D.J.S. (2008). Assessment of climate variability for coconut and other crops: A statistical approach. *CORD*, 24(1): 19.

Perera, P.I.P., Hocher, V., Weerakoon, L.K., Yakandawala, D.M.D., Fernando, S.C. and Verdeil, J.-L. (2010). Early inflorescence and floral development in *Cocos nucifera* L.(Arecaceae: Arecoideae). *South African Journal of Botany*, 76(3): 482–492.

Ranasinghe, C.S. (2017). Climate change impacts on coconut production and potential adaptation and mitigation measures: a review of current status. *In*: B. Marambe (Ed.), Th*e Workshop on Present Status of Research Activities on Climate Change Adaptations Sri Lanka*. Council for Agricultural Research Policy, Colombo, 71-82.

Ranasinghe, C.S. and Premasiri, R.D.N. (2016). Dry matter requirement for growth and respiration of coconut. *COCOS,* 21:21-31.

Thomas, R.J. and Josephrajkumar, A. (2013). Flowering and pollination biology in coconut. Journal of Plantation Crops, 41(2):109-117.

UNDRR. (2019). Disaster Risk Reduction in Sri Lanka: Status Report 2019. Bangkok, Thailand. Retrieved from https://www.unisdr.org/files/68230_10srilankadrmstatusreport.pdf.

Waidyarathne, K.P., Dissanayake, H.D.M.A.C., Perera, S.A.C.N. and Chandrathilake, T.H. (2019). Impact of extreme weather events on coconut production in IL1b Agro-ecological region of Sri Lanka. In V.H.L. Rodrigo, B.W. Wijesuriya, D.G. Edirisinghe and N.M.C. Nayanakantha (Eds.), I*n: Proceedings of the seventh symposium on plantation crop research*, Rubber Research Institute of Sri Lanka, Dartonfield, Agalawatta, 12200, Sri Lanka. 1–1).

World Meteorological Organization (WMO) and Global Water Partnership (GWP), 2016: Handbook of Drought Indicators and Indices. M. Svoboda and B.A. Fuchs (Eds.), Integrated Drought Management Programme (IDMP), Integrated Drought Management Tools and Guidelines Series 2. Geneva.

Climate Change Induced Variations in Rainfall Patterns & Potential Adaptation Options of DL1b Agro-Ecological Zone of Sri Lanka : A Case Study

N.W.B.A. Lahiru Udayanga[1] and M.M.M. Najim[2]*

[1]Department of Bio-Systems Engineering, Faculty of Agriculture & Plantation Management, Wayamba University of Sri Lanka, Makandura , Sri Lanka.
[2]Department of Zoology and Environmental Management, Faculty of Science, University of Kelaniya, Kelaniya, Sri Lanka.
*mnajim@kln.ac.lk

Climate Change Induced Variations in Rainfall Patterns and Potential Adaptation Options of DL_{1b} Agro-Ecological Zone of Sri Lanka: A Case Study

Abstract

An analysis of the shifts and trends of climate patterns with respect to wet and dry events and rainfall seasonality is vital for the effective planning and management of water resources in tropical countries such as Sri Lanka, which have agriculture-based economies. Hence, temporal and spatial variations of climate extremes and rainfall seasonality in Sri Lanka, were evaluated in the DL1b Agro-Ecological Zone through the Standardized Precipitation Index (SPI) and Seasonality Index (SI) utilizing 58 years of daily rainfall data of five selected localities. The Chi-square test of independence was used to statistically compare the percentage occurrence of each event recorded during 1961-1988 and 1989-2018. The dryness of all study areas denoted increments in terms of both severity and frequency of occurrence in accordance with SPI. However, among the studied localities of the DL_{1b} agro-ecological zone, only the increment of dryness in Vavuniya remained statistically significant ($X^2_{(df\ =\ 4)}$ <9.78; P=0.04) at 95% level of confidence. Rainfall seasonality of the localities was characterized with a markedly seasonal climatic condition with a long, dry season (0.95 – 0.97) with no significant variations and shifts. Cultivation of low water demanding crops, adjustment of cropping seasons, use of more efficient water smart irrigation methods, implementation of agro-forestry systems and employment of smart and integrated watershed management practices could be recommended as potential adaptation measures to compensate the impacts of climatic change.

Keywords: *Climate adaptations, climate change, rainfall, seasonality, Standardized Precipitation Index (SPI)*

Introduction

Any change in climate over the time whether due to natural variability or as a result of human activity has been described as climate change (IPCC, 2007). At present the whole world is experiencing adverse impacts of climate change, which is one of the most serious threats to sustainable development, including impacts on environment, health, agriculture, food security, economic activity, natural resources and physical infrastructures (IPCC, 2007). Southeast Asia is already experiencing the adverse impacts of climate change, which have affected the quantity and quality of available water resources. Extreme weather events such as droughts, floods, and other tropical cyclones are increasing in frequency and intensity and have contributed to decline in the production of crops (Zougmoré *et al*., 2016).

Climatic patterns of tropical islands are characteriozed by rainfall. Recent observations indicate significant alterations in rainfall patterns in both dry and wet zones in many tropical islands including Sri Lanka. Erratic rainfall events such as higher intensity of rains with less number of rainy days have increased significantly in Sri Lanka, along with increased possibility of climatic extremes like irregular monsoon patterns, droughts, floods and heat stroms (Naveendrakumar *et al.*, 2018). Intensity of rainfall events is predicted to increase, particularly within tropical and higher latitude areas that are expected to experience increments in mean precipitation. Even in areas where mean precipitation decreases, precipitation intensity is predicted to increase yet with longer periods between rainfall events. A possible tendency of increasing of dryness of the mid-continental areas during summer, indicating a greater risk of droughts in those regions has also been recognized. Rainfall extremes have shown more increase than the mean in most of the tropical and mid- and high-latitude areas (Meehl, 2007).

Climatic changes should be understood in terms of their hydrological, agricultural, and socio-economic impacts. As the agriculture of most of the tropical countries is often restricted by patterns of rainfall, the planning and management of water resources especially within the dry zone play vital roles in achieving self-sufficiency in agricultural productions (Eriyagama *et al.*, 2010). Thus, due consideration should be given to the climate patterns, shifts and trends in seasonality and dry and wet events since the climatic patterns of tropical countries are often characterized by both severity and frequency of occurrence of dry and wet events. The proper planning of water resources should be done in accordance with specific climatic patterns such as seasonality, severity and frequency of occurrence of dry and wet events (Udayanga and Najim, 2013).

A drought is characterized by an abnormally dry weather that lasts long enough to result an imbalance (mild to severe) in the water cycle (Liu *et* *al*., 2011). Although the causes of a drought could be multiple, the on-set of a drought is usually caused by decrease in or absence of precipitation. A wet period is dominated by high precipitation and less dryness. For each event, the probability of occurrence and the magnitude (severity) act as the factors that are devoted to define each specifically (Udayanga and Najim, 2013). At present, many methods, procedures, indices etc. have been developed and are being employed to analyze the wetness and dryness and other weather extremes by using monthly precipitation data, where droughts are considered as precipitation deficits with respect to average values and floods as the opposite (Morid *et al*., 2006).

Among the numerous methods of extreme event predictions such as Effective Drought Index, Palmer Drought Severity Index, Surface Water Supply Index etc., the Standardized Precipitation Index [SPI] (McKee *et al*., 1993), outstands specifically due to its simplicity, flexibility, effectiveness and capability of acting as an objective measurement of meteorological droughts effectively in dry regions (Morid *et al*., 2006). The SPI also allows an analyst to determine the magnitude (severity) and the occurrence frequency of both droughts and anomalously wet events within a considered time scale for any region or a specific location that has continuous precipitation readings throughout consecutive number (usually for 25-30 years) of years. Thus, the SPI doesn't require complex land surface conditions and can be applied to different climate regions and at different time scales to predict short- and long-term drought conditions (McKee *et al*., 1993). SPI provides magnitude, period of occurrence and longevity of climate extremes identifying the trends of weather extremes (Lee *et al*., 2013).

The trends in rainfall seasonality represent one of the most important aspects of climatic variation, which is often not addressed in Southeast Asia. Meaningful comparisons of rainfall seasonality of different areas can be done via quantification of this aspect of rainfall regimes. The Seasonality Index (SI) developed by Walsh and Lawler (1981) is one of the widely used methods of rainfall seasonality analysis, which emphasizes on the relative seasonality of rainfall regimes or degree of variability in monthly rainfall throughout the year. Unlike the SPI, the SI assesses seasonal contrasts in rainfall rather than analyzing wet or dry and temporal patterns of Rainfall Seasonality. Studies of rainfall seasonality is vital for planning and management of water resources, adjust cropping patterns and to select and modify suitable cropping varieties (Udayanga and Najim, 2013).

Proper and well-coordinated planning and management of water resources is vital to withstand unfavorable weather extremes such as drought events that cause potential harmful impacts on agriculture and water resources. Thus, thorough, updated and localized study of climate patterns and prediction of climate extremes is vital (Udayanga and Najim, 2013). As the dry zones of tropical islands often face both temporal and spatial shortage of water, an analysis of the shifts, variations and trends of the climate patterns at present with respect to the past, focusing on dry and wet events and rainfall seasonality is highly important to assist the planning and management of water resources. Current, study applies SPI and SI to analyze trends in dryness, wetness and rainfall seasonality within the Northern and North Central regions of the DL_{1b} agro ecological zone of the dry zone of Sri Lanka, while providing adaptation measures to enhance climatic resilience.

Methodology

Study area

DL_{1b} agro-ecological zone covering the Northern and North Central regions located within the dry zone of Sri Lanka was selected as the study area. DL_{1b} is a prominant agro-ecological zone with a higher tank density, which is important as the major source of water for agricultural practices. The rainfall indicates a bimodal distribution pattern due to monsoons and the annual mean rainfall of this zone exceeds 900 mm and remains below 1750 mm (Udayanga and Najim, 2013). Rain dependent shifting cultivation is traditionally practiced within the DL_{1b} while paddy cultivation, mixed crop cultivation and agro forestry too are practiced. Yet severe crop failures can be experienced during the "off" season due to less rainfall often leading to drought events. This agro ecological zone has a high potential on the agricultural and water resources management aspects as most major and minor tanks are located within this zone (Punyawardena *et al*., 2003).

Data collection and analysis

Daily rainfall data covering the period from January 1961 to March 2018 of Anamaduwa, Anuradhapura, Kottukachchiya, Maradankadawala and Vavuniya rain gauging stations (Figure 1) located within the North Central region of the DL_{Ib} agro ecological zone were obtained from the Department of Meteorology, Sri Lanka. Monthly precipitation was computed based on the aggregated daily rainfall values for each station, under two approximately equal periods as 1961-1988 and 1989-2018.

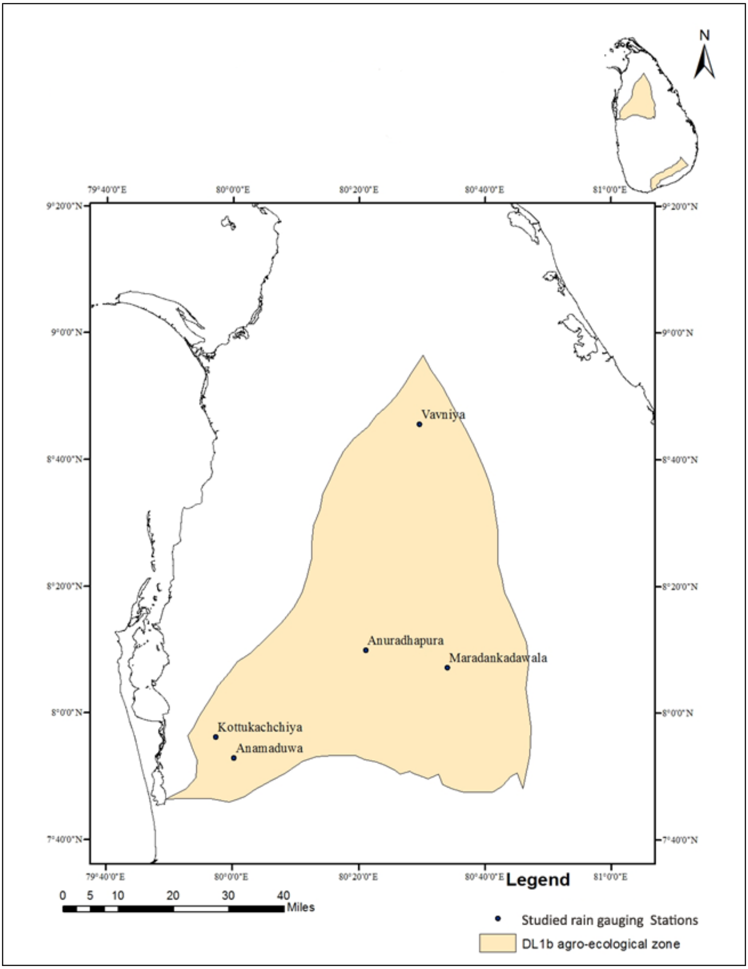


Figure 1: Spatial location of the studied rain-gauging stations in the DL_{Ib} agro ecological zone.

Standardized Precipitation Index (SPI)

SPI values for each month for the time intervals 1961-1988 and 1989-2018 were calculated at each station as the difference between precipitation on a time scale (x_i) and the mean value ($\bar{x}$), divided by the standard deviation (S), as given in the Equation 1.

$$SPI = \frac{x_i - \bar{x}}{s} \text{.......................Equation 1}$$

Based on SPI range, dry periods were broadly classified into five classes as normally dry (0 to -0.49), mild drought (-0.50 to -0.99), moderate drought (-1.00 to -1.49), severe drought (-1.50 to -1.99), extreme drought (-2.00 or lesser) events (Liu *et al.*, 2011). Drought length or duration (D) was taken as the number of consecutive months where SPI remains below -0.49. Similarly, the anomalously wet events were assumed to be present over a consecutive number of months, where SPI values remain over a threshold of 0.49. As recommended by Liu *et al.* (2011), the wet periods were also classified into five classes based on the SPI range, as normally wet (0 to 0.49), mild wet (0.50 to 0.99), moderate wet (1.00 to 1.49), severe wet (1.50 to 1.99) and extreme wet events (2.00 or higher).

Seasonality Index

As defined by Walsh and Lawler (1981), the Seasonality Index (SI) for 1961-1988 and 1989-2018 for each station was calculated as the simple sum of the absolute deviations of mean monthly rainfalls ($\bar{x}$) from the overall monthly mean, divided by the mean annual rainfall of the considered time period ($\bar{R}$) as indicated in the Equation 2.

$$SI = \frac{1}{\bar{R}} \sum_{n=1}^{n=12} \left| \bar{x} - \frac{\bar{R}}{12} \right| \text{ .... 2}$$

The mean SI values for each time period were calculated for each locality and were compared with each other to identify prominent trends in seasonality. According to Walsh and Lawler (1981), the value of the SI ranges from 0 to 1.83. The nature of the seasonality is defined as, very equable (0 - 0.19), equable but with a definite winter (0.20 – 0.39), rather seasonal with a short drier season (0.40 – 0.59), seasonal (0.60 -0.79), markedly seasonal with a long drier season (0.80 – 0.99), most rains received within 3 months or less (1.00 – 1.19) and extreme where all most all rain received within 1-2 months (1.20-1.83).

Data interpretation and analysis

The generated negative and positive values of SPI were categorized in accordance with the boundaries of different classes of drought and wet events, as proposed by Liu *et al.* (2011). The total number of events in both the periods were calculated and the percentage of each class of events were calculated separately and were statistically compared with respect to the classes of the events recorded during 1961-1988 and 1989-2018 by using the Chi-square test at 95 % level of confidence.

Results and discussion

Variations in dry and wet events

The percentage of climatic events belonging to each class that occurred within each time period at different localities are tabulated in Table 1. According to SPI, all the rainfall stations, denoted notable reductions in moderate, severe and extreme wet events within the 1989-2018 period compared to 1961-1988, suggesting a decrement in wetness. However, statistics of Chi-square test, emphasized that all the above trends were statistically non-significant ($X^2_{(df\ =\ 4)}$ <6.93; P>0.05) at 95 % level of confidence (Figure 2).

An increasing trend in mild, moderate, severe and extreme dry events were observed in all the localities within the recent year period (1989-2018), depicting an overall increase in dryness (Table 1). According to the results of Chi-square test, only the increment of dryness in Vavuniya remained significant ($X^2_{(df\ =\ 4)}$ =9.78; P=0.04) at 95 % level of confidence. According to De Silva (2006), the rainfall is predicted to decrease in several areas of dry zone such as Anuradhapura, Trincomalee and Batticaloa. Based on the SI values, all the study locations (0.95-0.97) were characterized with markedly seasonal climatic conditions with long drier seasons (0.80 – 0.99) as suggested by Walsh and Lawler (1981). Further, notable variations in rainfall seasonality were not observed among the two periods according to the SI (Figure 2).

Table 1: Percentage occurrence of dry and wet events at different study localities.

Event	SPI Value	Category	Percentage Occurrence of Events %									
			Kottukachchiya		Anuradhapura		Vavuniya		Maradankadawala		Anamaduwa	
			1961-1988	1989-2018	1961-1988	1989-2018	1961-1988	1989-2018	1961-1988	1989-2018	1961-1988	1989-2018
Wet Events	≥ 2.00	Extreme wet	5.3	3.1	5.5	2.1	4.7	4.3	1.3	1.1	3.5	1.9
	1.50 to 1.99	Severe wet	9.7	8.4	10.2	5.9	6.8	6.5	8.5	8.1	9.8	8.4
	1.00 to 1.49	Moderate wet	17.8	15.7	24.3	16.6	17.6	16.1	19.6	17.9	20.3	20.6
	0.50 to 0.99	Mild wet	32.7	34.9	29.5	31.9	34.5	34.3	33.3	32.4	30.8	29.5
	0 to 0.49	Normal wet	34.5	37.9	30.5	43.5	36.4	38.8	37.3	40.5	35.6	39.6
Dry Events	0 to -0.49	Normally dry	42.4	38.9	41.9	31.5	38.9	33.7	43.5	35.6	38.1	12.5
	-0.50 to -0.99	Mild droughts	32.1	30.6	30.3	32.9	33.1	43.2	29.8	33.1	31.9	43.2
	-1.00 to -1.49	Moderate droughts	18.2	19.8	14.8	19.7	17.9	12.3	17.6	20.7	19	24.6

	-1.50 to -1.99	Severe droughts	6.1	7.9	9	10.7	9.4	9.4	7.6	8.7	9.2	15.9
	≤ -2.00	Extreme droughts	1.2	2.8	3.9	5.2	0.7	1.4	1.5	1.9	1.8	3.8

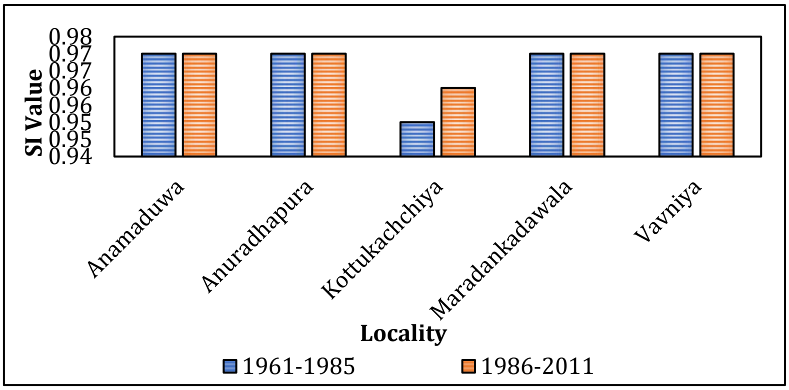


Figure 2: Variations in rainfall seasonality depicted by the SI index

A previous study conducted by Jayawardene *et al.* (2005) using a century-long rainfall dataset has also reported that regardless of increasing or decreasing trends in annual rainfall patterns in Sri Lanka, majority of those remains non-significant. In addition, several recent studies are also in agreement with the findings of the current study, suggesting an increase in overall dryness within areas such as Anuradhapura, Batticaloa, and Kurunegala (Naveendrakumar *et al.*, 2018).

Climate in tropical countries often exhibit significant spatial and temporal variations. Especially microclimate variations at regional levels could be often experienced in the climate patterns in tropical islands such as Sri Lanka. Thus, unlike most of the recent studies that have been conducted to investigate the trends and impacts of climate change at national level in tropical countries, the present study focuses on the variations and trends in climate at the regional level, which are of higher importance for many aspects such as the degree of bio diversity, agriculture-based economy etc. Even though many studies that were carried out in Sri Lanka (De Silva, 2006; De Silva *et al*., 2007; Eriyagama *et al*., 2010) predict significant alterations throughout the country in the severity and occurrence frequency of climatic events in the recent years, only the dry events of Vavuniya indicated significant alterations in accordance with the results of the SPI approach.

Adaptations for increasing dryness

The study area in the DL_{1b} agro-ecological zone covers, several major localities of Sri Lanka in terms of agriculture, due to its high contribution to the agricultural productivity of Sri Lanka. A network of tanks fed by the monsoon rainfalls have been used to cater to agricultural water requirements in the study area. Hence, any alteration in rainfall amount and seasonality, as suggested in the current study, could result significant impacts on the availability of water for agriculture. Thus, a decrease in severity and frequency of occurrence of rainfalls could bear severe consequences on the agricultural productivity.

According to De Silva *et al*. (2007), by the year 2050, a possible reduction in the quantity and spatial distribution of rainfall may lead to an increased irrigation water requirement for paddy by 13-23 % during the main season compared to that of 1961-1990. Enlargement and de-siltation of tanks to enhance the water holding capacity would be of importance. Therefore, renovating the existing tanks in the DL_{1b} agro-ecological zone would facilitate collection of excess rainfall, especially during the South West Monsoon (SWM) that could be used in dry periods. Encouraging the community towards rainwater harvesting at the household level would also be an efficient low-cost adaptation strategy to face the expected increasing dryness of the study area (Eriyagama *et al*., 2010). Government could support this process via provision of soft loans and required technical knowledge under a well-coordinated “National Rainwater Harvesting Policy”. Shifting of crop species, from varieties with high water demands to varieties with low water demands, adjustment of the cropping seasons (Zougmoré *et al*., 2016), use of more efficient water smart irrigation methods such as drip irrigation (Fox *et al*., 2005), implementation of agro-forestry systems (Reij *et al*., 2009) and employment of Smart and Integrated Watershed Management Practices (SIWMP) etc. could also be recommended as potential measures to compensate the expected increments in dryness.

Sri Lanka and Western Ghats is considered as a sensitive and prominent biological hotspot in the world, which includes highly threatened diverse floral and faunal communities. The variations in climate triggered by the climate changes could significantly alter the environmental conditions of the diverse habitats on which many endemic species thrive upon, causing a significant impact on the distribution and survival of these flora and fauna (Garcia *et al*., 2014). The study area includes many dry deciduous monsoon forest patches with diverse vegetation structures and a rich biodiversity. Ritigala, one of the three Strictly protected Natural Reserves of Sri Lanka is also located within this region. In addition, Villpaththu, one of the most renowned national parks is also located very close to the border of the studied agro ecological zone. Extreme warming and drying events, are expected to mainly affect the tropical regions, causing severe threats on sensitive species (Garcia *et al*., 2014). Thus, the study of the recent trends in climate change play a crucial role in the conservation aspect of biodiversity. According to Garcia *et al.* (2014), improving habitat quality in areas shrinking climatically to help species adapt locally, or promoting landscape connectivity for species that need to move to track suitable climates through time, are sound conservation strategies. Hence, studying of such implications of climate change is essential for the drafting of policies, designing of management actions and plans etc. to preserve biodiversity and ecosystems.

Community involvement is a critical factor in successful implementation of any project. Thus, increasing the awareness of the community of the expected increments in dryness and appropriate adaptation measures and dissemination of technology know-how among selected groups in the community would be critical in enhancing the climate change resilience of the study area (Zougmoré *et al*., 2016). Findings of the current study could be used to identify the impacts of climate change and to develop proper adaptation plans to face the expected implications of climate change.

Conclusions

The results of this study suggest an increase in dryness within the DL_{1b} agro-ecological zone. Unlike the predictions of many studies that were carried out in Sri Lanka, which expect significant alterations in the severity and occurrence frequency of climatic events, significant increase in dryness was significant only in Vavuniya. The planning and management of the water resources and crop management practices in the DL_{1b} agro-ecological zone should be properly conducted based upon the observed present and expected future trends in climate patterns. In addition, the evaluation of the variations in climates is of potential importance in assessment of the future impacts of climate change on the rich biodiversity of Sri Lanka. Thus, rational and effective drafting of conservation strategies, biodiversity management and action plans etc. should be conducted taking such impacts of climate change into consideration.

References

De Silva C.S. (2006). Impacts of climate change on water resources in Sri Lanka. *32nd WEDC International Conference*, Colombo, Sri Lanka.

De Silva, C.S., Weatherhead, E.K., Knox, J.W. and Rodriguez-Diaz, J.A. (2007). Predicting the impacts of climate change—A case study of paddy irrigation water requirements in Sri Lanka. *Agricultural water management*, *93*(1-2): 19-29.

Eriyagama, N., Smakhtin, V., Chandrapala, L. and Fernando, K. (2010). *Impacts of climate change on water resources and agriculture in Sri Lanka: A review and preliminary vulnerability mapping* (Vol. 135). International Water Management Institute (IWMI).

Fox, P., Rockström, J. and Barron, J. (2005). Risk analysis and economic viability of water harvesting for supplemental irrigation in semi-arid Burkina Faso and Kenya. *Agricultural Systems*, *83*(3): 231-250.

Garcia, R.A., Cabeza, M., Rahbek, C. and Araújo, M.B. (2014). Multiple dimensions of climate change and their implications for biodiversity. *Science*, 344 (6183).

Intergovernmental Panel on Climate Change (IPCC) (2007). Climate change 2007: the physical science basis: summary for policymakers. Geneva*: IPCC*.

Jayawardene, H.K.W.I., Sonnadara, D.U.J. and Jayewardene, D.R. (2005). Trends of rainfall in Sri Lanka over the last century. *Sri Lankan Journal of Physics*, *6*.

Lee, T., Modarres, R. and Ouarda, T.B. (2013). Data-based analysis of bivariate copula tail dependence for drought duration and severity. *Hydrological Processes*, 27(10): 1454-1463.

Liu, C.L., Zhang, Q., Singh, V.P. and Cui, Y. (2011). Copula-based evaluations of drought variations in Guangdong, South China. *Natural Hazards*, 59(3): 1533-1546.

McKee, T.B., Doesken, N.J. and Kleist, J. (1993). January. The relationship of drought frequency and duration to time scales. *In*: *Proceedings of the 8th Conference on Applied Climatology*. 17(22): 179-183.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A. and Raper, S.C. (2007). Global climate projections. *Climate change*, 3495: 747-845.

Morid, S., Smakhtin, V. and Moghaddasi, M. (2006). Comparison of seven meteorological indices for drought monitoring in Iran. *International Journal of Climatology,* 26(7): 971-985.

Naveendrakumar, G., Vithanage, M., Kwon, H.H., Iqbal, M.C.M., Pathmarajah, S. and Obeysekera, J. (2018). Five decadal trends in averages and extremes of rainfall and temperature in Sri Lanka. *Advances in Meteorology*, 2018.

Punyawardena, B.V.R., Bandara, T.M.J., Munasinghe, M.A.K., Banda, N.J. and Pushpakumara, S.M.V. (2003). Agro-ecological regions of Sri Lanka. Natural Resource Management Centre, Department of Agriculture, Peradeniya, Sri Lanka.

Reij, C., Tappan, G. and Smale, M. (2009). Agroenvironmental Transformation in the Sahel: Another Kind of "Green Revolution" IFPRI Discussion Paper 00914. *Food Policy,* Washington DC, USA, p.52.

Udayanga, N.W.B.A.L. and Najim, M.M.M. (2013). Evaluation of the Trends in Climatic Change with Respect to Severity and Occurrence Frequency. *In*: *Proceedings of the Water Professional's Day – 2013*, Peradeniya, Sri Lanka, 51-62.

Walsh, R.P.D. and Lawler, D.M. (1981). Rainfall seasonality: description, spatial patterns and change through time. *Weather*, 36(7): 201-208.

Zougmoré, R., Partey, S., Ouédraogo, M., Omitoyin, B., Thomas, T., Ayantunde, A., Ericksen, P., Said, M. and Jalloh, A. (2016). Toward climate-smart agriculture in West Africa: a review of climate change impacts, adaptation strategies and policy developments for the livestock, fishery and crop production sectors. *Agriculture and Food Security*, 5(1): 26.

CHAPTER 12


© Dileka Kariyawasam

Fight Against Dengue in the Face of Climate Change: A Case Study from Districts of Colombo and Kandy, Sri Lanka

Lahiru Udayanaga[1] and Nayana Gunathilaka[2]*

[1]Department of Bio Systems Engineering, Faculty of Agriculture & Plantation Management, Wayamba University of Sri Lanka, Makandura, Sri Lanka.
[2]Department of Parasitology, Faculty of Medicine, University of Kelaniya, Ragama, Sri Lanka.
*n.gunathilaka@kln.ac.lk

Fight Against Dengue in the Face of Climate Change: A Case Study from Districts of Colombo and Kandy, Sri Lanka

Abstract

Dengue fever, which is primarily transmitted by *Aedes aegypti* and *A. albopictus*, is responsible for approximately 390 million infections per annum globally, and is thus a major health concern in the world. In Sri Lanka, the districts of Colombo and Kandy remain as the first and fourth high risk areas for dengue, respectively. Recent shifts in climatic patterns, rapid urbanization and poor waste management practices have enhanced the dengue risk in Sri Lanka. Evaluation of the vulnerability of dengue among endemic populations is a critical requirement in designing proactive programmes to improve resilience capacity of vulnerable communities. Accordingly, the current study assessed the climate change induced vulnerability of dengue in Colombo and Kandy districts of Sri Lanka using the composite index approach defined by the Intergovernmental Panel on Climate Change. Among 38 Medical Officer of Health (MOH) areas in the districts of Colombo and Kandy, the Colombo Municipal Council (CMC) MOH area denoted the highest vulnerability (45%; moderate vulnerability) to dengue, while the lowest indicated from Galaha MOH (15%; very low vulnerability) in Kandy. Interestingly, the KMC MOH area had a notable vulnerability of 41% (moderate vulnerability), which was the highest within Kandy. The climate change induced vulnerability for dengue was relatively higher within the district of Colombo, than in Kandy. Dengue controlling entities are recommended to consider the spatial variations in vulnerability of local communities to dengue in decision making, to facilitate dengue epidemic management.

Keywords: *Adaptive measures, climatic change, dengue, vulnerability*

Dengue as a major public health concern

Renowned as the most common and rapidly spreading mosquito-borne viral disease in the world, dengue is a major life-threatening infectious disease in many parts of the world. The alarmingly increasing incidence of dengue epidemics by 30-fold with a rapid geographical expansion within the past five decades, has elevated the global concerns on dengue from an intermittent disease to a major public health concern. At present, according to the World Health Organization (WHO), 100 million dengue infections have been estimated to occur annually along with 500,000 cases of Dengue Haemorrhagic Fever (DHF). Further, 2.5 billion people residing in more than 100 countries have been estimated to be at the risk of dengue (WHO, 2009). Population growth, poorly planned urban expansions, deforestation, global warming, co-circulation of different dengue serotypes, development of international trade and transport have been recognized as the major contributing factors for the rapid geographical expansion of dengue at the global level (Bhatt *et al.*, 2013; Liu-Helmersson *et al.*, 2014; Lourenço and Recker, 2014).

First records of dengue in Sri Lanka dates to mid-1960s, with 51 cases of DHF/DSS including 15 deaths that occurred within the period of 1965 to 1966 (Sirisena and Noordeen, 2014). Regular epidemics of dengue have been observed only since 1989 with an average number of cases exceeding 800 cases per year, mainly being reported from Colombo and nearby areas (Messer *et al.*, 2002). From 2009 onwards, the western province (especially the district of Colombo) has accounted for the highest percentage of dengue cases reported from the country. In addition, Gampaha, Kandy, Kalutara, Jaffna and Batticaloa have also reported severe outbreaks (Sirisena and Noordeen, 2014). The most severe outbreak of dengue was experienced in 2017, with 186, 101 suspected dengue cases and over 350 deaths accounting for more than a 3-fold increase in the number of dengue cases reported in previous years (Udayanga *et al.*, 2020). The dengue epidemic in 2017 occurred in an overwhelmed situation of the country due to heavy rains and flooding events that influenced 15 out of 25 districts leading to almost 600, 000 victims (WHO, 2017). Abundance of potential breeding sites, failure in clearing rain-soaked garbage, poor waste management and disposal practices could be attributed to the higher number of dengue cases reported in urban and suburban areas in the country.

Role of climate factors on the incidence of dengue epidemics

A. aegypti is the primary vector of dengue, while *A. albopictus* is known to be the secondary vector. Both species are highly efficient in transmission of dengue, being recognized as two of the most dangerous vectors in the world (Gubler, 1993). In addition to dengue, both of these *Aedes* vectors are capable of transmitting a variety of diseases such as yellow fever, chikungunya and zika (Besnard *et al*., 2014). Often *A. aegypti* tends to lead the dengue epidemics, while *A. albopictus*, acts as an inter-habitat bridge vector for the arboviruses (Lourenço-de-Oliveira *et al*., 2004).

Recent changes in climatic conditions and development of insecticide resistance pose a greater threat from vector borne diseases (Gubler, 1993; Kovats *et al.*, 2001; Sutherst, 2004). Changes in climate could cause direct impacts on the growth and development of mosquito vectors that transmit dengue, resulting in an elevated risk of dengue upon vulnerable communities. Often climate acts as a major barrier in restricting the geographic distribution of vector borne diseases, through influencing the survival of mosquito vectors (Hales *et al.*, 2002; McMichael *et al.*, 2006). On the other hand, numerous models have predicted that climate change would increase the geographic distribution and potential risk of dengue (Hagenlocher *et al.,* 2013). Such alarmingly severe dengue epidemics impose a serious challenge to managing the vulnerable populations.

Temperature

Temperature is known to play a notable role in dengue incidence, by directly influencing the reproduction, biting behavior, distribution patterns, survival rate and Extrinsic Incubation Period (EIP) of the *Aedes* mosquitoes (Harrington *et al.*, 2001; Promprou *et al.*, 2005). The average EIP of dengue viruses has been estimated as twelve days at 30°C, which may be shortened to seven days at 32 to 35°C, leading to higher transmission rates (Watts *et al.*, 1987; Focks *et al.*, 1995). Further, *Aedes* larvae can survive at 34°C water temperature, while the adults are capable of surviving even at 40°C atmospheric temperature. Hence, global warming would favour vector breeding and increase the abundance of *Aedes* mosquitoes, contributing to elevated risk levels of dengue.

Rainfall

Rainfall could also promote the breeding of *Aedes* vectors by increasing the abundance of potential vector breeding sites (Gubler *et al.*, 2001; Wu *et al.*, 2007). Normal rainfall events often replenish water levels or by create new breeding sites (Gubler *et al.*, 2001) while modifying the relative humidity to favourable levels for mosquito survival and longevity (McMichael *et al.*, 1996). On the contrary, extreme rainfall events may lead into flooding situations, which could flush the *Aedes* larvae from their breeding sites resulting in a negative impact on the vector abundance (Alkhaldy, 2017). Therefore, rainfall plays a key role in governing the population dynamics of *Aedes* vectors mosquitoes.

Relative humidity

By enhancing the feeding frequency, inter sexual attractions and oviposition rates of *Aedes* mosquitoes, relative humidity also plays a key role in dengue incidence (McMichael *et al.*, 1996; Wu *et al.*, 2007). Further, the adult longevity and survival success after being infected by dengue are also enhanced under high humid conditions (McMichael *et al.*, 1996) leading to a wide geographical dispersion of dengue (Promprou *et al.*, 2005). In addition, higher levels of humidity have shown elevations in the duplication process of dengue fever, increasing the risk of dengue incidence (Hales *et al.*, 1999).

Climate change induced vulnerability of dengue

Climate change induced vulnerability refers to the degree to which a population remains susceptible to or incapable of dealing with adverse impacts of dengue as a result of climate change (Parry *et al.,* 2007). According to Fritzsche *et al.* (2014), vulnerability is calculated as a function of three sub-indices, namely exposure, sensitivity and adaptive capacity. Both exposure and sensitivity exhibit a positive association with the vulnerability, while adaptive capacity indicates a negative relationship (Smit and Wandel, 2006).

Climate change induced vulnerability is a widely utilized concept that is often used to identify the potential risk factors that govern the incidence and severity of dengue epidemics and dengue epidemic occurrence. Further, it facilitates the identification of most vulnerable communities allowing to implement proactive programmes to reduce the risk imposed by dengue, while improving the resilience capacity (Hagenlocher *et al.*, 2013; Udayanga *et al.*, 2018b). A variety of methods, ranging from statistical methods to Geographic Information Systems (GIS) based mapping, are available for climate change induced vulnerability assessment (Hagenlocher *et al.,* 2013). Composite indexed base climatic change vulnerability analysis illustrated by Gesellschaft für Internationale Zusammenarbeit (GIZ) is a widely used approach in climate change vulnerability assessment (Fritzsche *et al.*, 2014).

The current study assessed the climate change induced vulnerability of dengue among the local communities in Colombo and Kandy districts at the Medical Officer of Health (MOH) level to aid the dengue epidemic management approaches. Monthly cumulative rainfall, average temperature, average relative humidity, average Breteau Index (BI) and

Premises Index (PI) were considered as the exposure parameters, while the total population, percentage area covered by built environment and the forests accounting, total number of households in each MOH areas, percentage of households practicing composting, percentage of houses that dispose waste through Municipal Council or Pradeshiya Sabha and that burn waste were considered as sensitivity parameters. Meanwhile, percentage of households with access to television and radios, percentage of population with no formal education and with education above GCE Ordinary Level (O/L), the number of medical officers and Public Health Inspectors (PHI) for 1000 residents in a MOH area were under adaptive capacity.

Based on the predictions, Colombo Municipal Council MOH area denoted the highest climate change induced vulnerability to dengue as 45 % (moderate vulnerability) as indicated in Figure 1. Among the other MOH areas, Dehiwela, Kolonnawa and Moratuwa areas denoted relatively higher vulnerability levels to dengue. On the contrary, Hanwella MOH area was characterized with the lowest vulnerability as 31 % (Figure 1).

In the district of Kandy, the Kandy Municipal Council MOH was showing a moderate vulnerability of 41 % (moderate vulnerability), as the highest among the 23 MOH areas in Kandy (Figure 2). With 15 % (very low vulnerability), Galaha MOH area showed the lowest vulnerability to dengue. In general, the vulnerability index values of the MOH areas in Kandy (15 % to 41 %) remained relatively lower than that of Colombo (31 % to 45 %).

Conclusion and future directions

Dengue spreads through unattended water pockets especially after rains. The *Aedes* vectors prefer breeding in these until the public and health systems realize its outbreak events. Improvement of the current vector surveillance, utilization of additional vector indices such as pupal indices, motivation of entomologists at the regional level and establishment of a well-coordinated response system for patient management remain as the key adaptation measures to control dengue. Promoting public awareness on different aspects of dengue such as vector control and patient management are also important as adaptive measures to control dengue in Sri Lanka. In addition, implementation of proper waste management systems at the regional level is essential in dengue epidemic management (Udayanga *et al.*, 2018a).

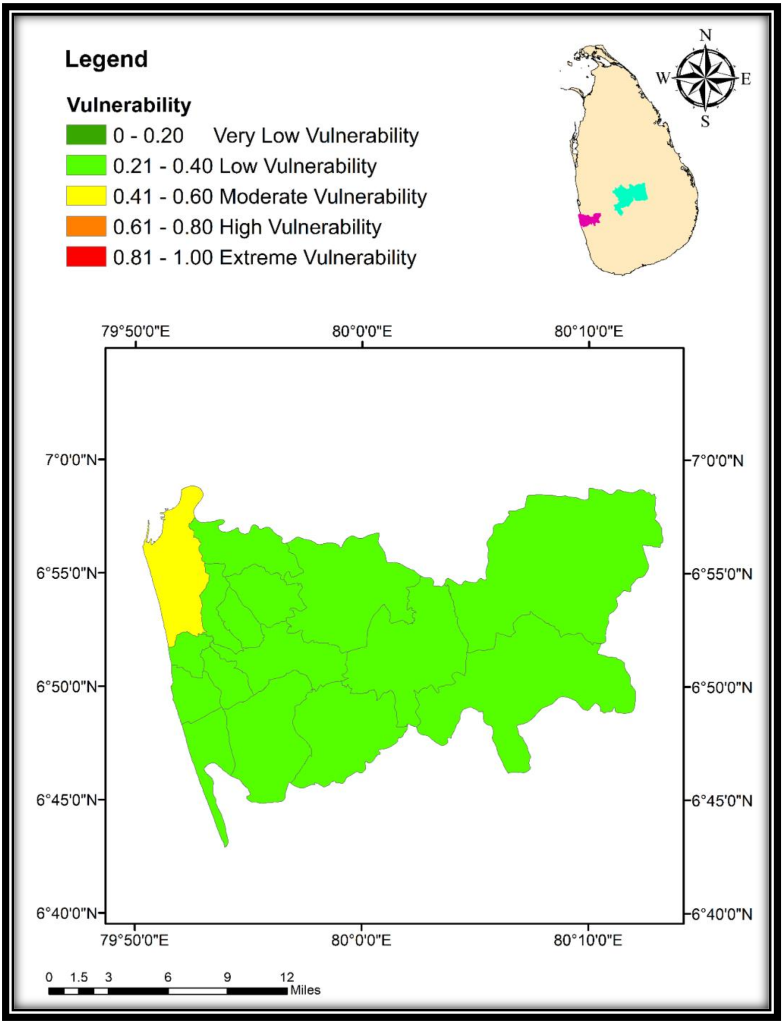


Figure 1: Climate change vulnerability of dengue within the district of Colombo at the MOH level

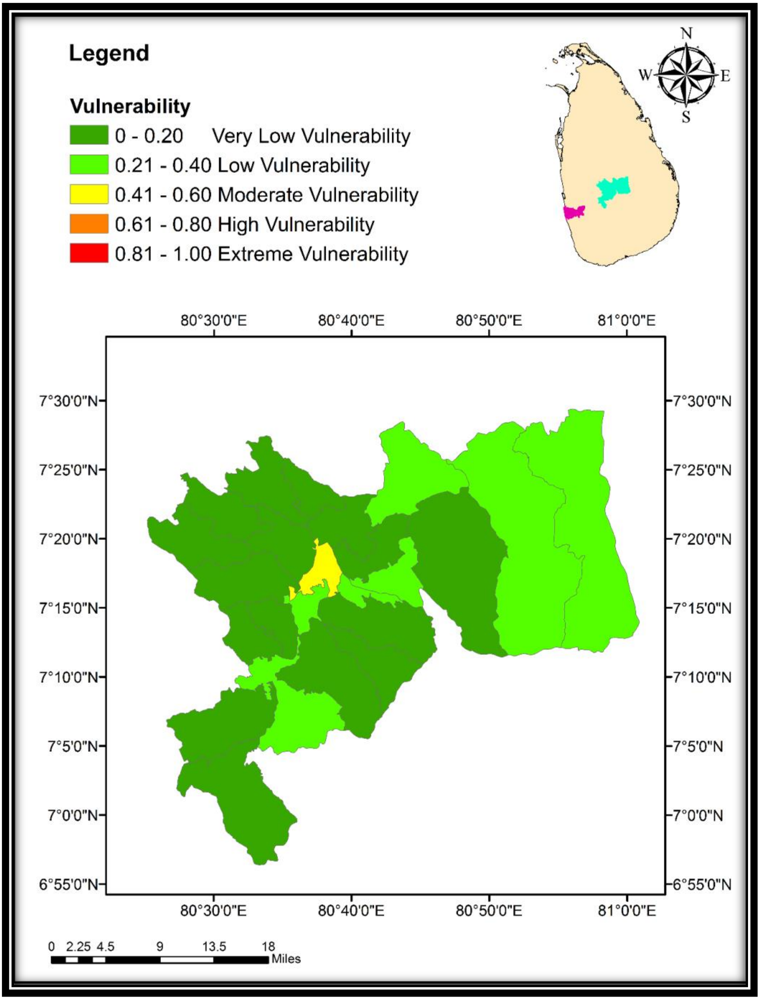


Figure 2: Climate change vulnerability of dengue within the district of Kandy at the MOH level

Real-time risk mapping and dengue risk modelling, and motivation of research studies on potential vectors and their vectorial capacity are important in dengue management. Meanwhile, proper motivation and training of vector controlling officers, encouragement of community participation and improvement of multi-institutional involvement for vector control that are practiced to date needs further strengthening (Udayanga *et al.*, 2018b). Implementation of integrated vector control methods and exploring feasibility of using novel vector control strategies such as Sterile Insect Technique and Incompatible Insect Technique are also recommended as adaptive measures to manage dengue (Udayanga *et al.*, 2019).

References

Alkhaldy, I. (2017). Modelling the association of dengue fever cases with temperature and relative humidity in Jeddah, Saudi Arabia—A generalised linear model with break-point analysis. *Acta Tropica*, 168: 9-15.

Besnard, M., Lastere, S., Teissier, A., Cao-Lormeau, V.M. and Musso, D. (2014). Evidence of perinatal transmission of Zika virus, French Polynesia, December 2013 and February 2014. *Eurosurveillance*, 19(13): 20751.

Bhatt, S., Gething, P.W., Brady, O.J., Messina, J.P., Farlow, A.W., Moyes, C.L., Drake, J.M., Brownstein, J.S., Hoen, A.G., Sankoh, O. and Myers, M.F. (2013). The global distribution and burden of dengue. *Nature*, 496(7446): 504-507.

Focks, D.A., Daniels, E., Haile, D.G. and Keesling, J.E. (1995). A simulation model of the epidemiology of urban dengue fever: literature analysis, model development, preliminary validation, and samples of simulation results. *The American Journal of Tropical Medicine and Hygiene*, 53(5): 489-506.

Fritzsche, K., Schneiderbauer, S., Bubeck, P., Kienberger, S., Buth, M., Zebisch, M. and Kahlenborn, W. (2014). The Vulnerability Sourcebook: Concept and guidelines for standardised vulnerability assessments.

Gubler, D.J. (1993). Dengue and dengue haemorrhagic fever in the Americas. *Monograph on dengue/dengue haemorrhagic fever. WHO regional publication SEARO*, (22): 9-22.

Gubler, D.J., Reiter, P., Ebi, K.L., Yap, W., Nasci, R. and Patz, J.A. (2001). Climate variability and change in the United States: potential impacts on vector-and rodent-borne diseases. *Environmental Health Perspectives*, 109(suppl 2): 223-233.

Hagenlocher, M., Delmelle, E., Casas, I. and Kienberger, S. (2013). Assessing socioeconomic vulnerability to dengue fever in Cali, Colombia: statistical vs expert-based modelling. *International Journal of Health Geographics*, 12(1): 36.

Hales, S., De Wet, N., Maindonald, J. and Woodward, A. (2002). Potential effect of population and climate changes on global distribution of dengue fever: an empirical model. *The Lancet*, 360(9336): 830-834.

Harrington, L.C., Buonaccorsi, J.P., Edman, J.D., Costero, A., Kittayapong, P., Clark, G.G. and Scott, T.W. (2001). Analysis of survival of young and old *Aedes aegypti* (Diptera: Culicidae) from Puerto Rico and Thailand. *Journal of Medical Entomology*, 38(4): 537-547.

Liu-Helmersson, J., Stenlund, H., Wilder-Smith, A. and Rocklöv, J. (2014). Vectorial capacity of *Aedes aegypti*: effects of temperature and implications for global dengue epidemic potential. *PloS one*, 9(3).

Lourenço, J. and Recker, M. (2014). The 2012 Madeira dengue outbreak: epidemiological determinants and future epidemic potential. *PLoS Neglected Tropical Diseases*, https://doi.org/10.1371/journal.pntd.0003083.

Lourenço-de-Oliveira, R., Castro, M.G., Braks, M.A. and Lounibos, L.P. (2004). The invasion of urban forest by dengue vectors in Rio de Janeiro. *Journal of Vector Ecology*, 29: 94-100.

McMichael, A.J., Woodruff, R.E. and Hales, S. (2006). Climate change and human health: present and future risks. *The Lancet*, 367(9513): 859-869.

Messer, W.B., Vitarana, U.T., Sivananthan, K., Elvtigala, J., Preethimala, L.D., Ramesh, R., Withana, N., Gubler, D.J. and De Silva, A.M. (2002). Epidemiology of dengue in Sri Lanka before and after the emergence of epidemic dengue hemorrhagic fever. *The American Journal of Tropical Medicine and Hygiene*, 66(6): 765-773.

Parry, M., Parry, M.L., Canziani, O., Palutikof, J., Van der Linden, P. and Hanson, C. (2007). *Climate change 2007-impacts, adaptation and vulnerability: Working group II contribution to the fourth assessment report of the IPCC* (Vol. 4). Cambridge University Press.

Promprou, S., Jaroensutasinee, M. and Jaroensutasinee, K. (2005). Climatic Factors Affecting Dengue Haemorrhagic Fever Incidence in Southern Thailand. *Dengue Bulletin,* 29: 41-48.

Sirisena, P.D.N.N. and Noordeen, F. (2014). Evolution of dengue in Sri Lanka: Changes in the virus, vector, and climate. *International Journal of Infectious Diseases*, 19: 6-12.

Smit, B. and Wandel, J. (2006). Adaptation, adaptive capacity and vulnerability. *Global Environmental Change*, 16(3): 282-292.

Udayanga, L., Aryaprema, S., Gunathilaka, N., Iqbal, M.C.M., Fernando, T., and Abeyewickreme, W. (2020). Larval Indices of Vector Mosquitoes as Predictors of Dengue Epidemics: An Approach to Manage Dengue Outbreaks Based on Entomological Parameters in the Districts of Colombo and Kandy, Sri Lanka. *BioMed Research International*, *2020*.

Udayanga, L., Gunathilaka, N., Iqbal, M.C.M., Lakmal, K., Amarasinghe, U.S. and Abeyewickreme, W. (2018a). Comprehensive evaluation of demographic, socio-economic and other associated risk factors affecting the occurrence of dengue incidence among Colombo and Kandy Districts of Sri Lanka: A cross-sectional study. *Parasites and Vectors*, 11(1): 478.

Udayanga, L., Gunathilaka, N., Iqbal, M.C.M., Najim, M.M.M., Pahalagedara, K. and Abeyewickreme, W., 2018b. Empirical optimization of risk thresholds for dengue: an approach towards entomological management of *Aedes* mosquitoes based on larval indices in the Kandy District of Sri Lanka. *Parasites and Vectors*, *11*(1): 368.

Udayanga, L., Ranathunge, T., Iqbal, M.C.M., Abeyewickreme, W. and Hapugoda, M. (2019). Predatory efficacy of five locally available copepods on Aedes larvae under laboratory settings: An approach towards bio-control of dengue in Sri Lanka. *PloS one*, 14(5): e0216140.

Watts, D.M., Burke, D.S., Harrison, B.A., Whitmire, R.E. and Nisalak, A. (1987). Effect of temperature on the vector efficiency of *Aedes aegypti* for dengue 2 virus. *The American Journal of Tropical Medicine and Hygiene*, 36(1): 143-152.

World Health Organization (2009). Special Programme for Research, Training in Tropical Diseases, World Health Organization. Department of Control of Neglected Tropical Diseases. In: *Dengue:*

Guidelines for diagnosis, treatment, prevention and control, World Health Organization.

World Health Organization: Dengue and severe dengue; Accessed 16th of August 2018. http://www.who.int/mediacentre/factsheets/fs117/en/.

Wu, P.C., Guo, H.R., Lung, S.C., Lin, C.Y. and Su, H.J. (2007). Weather as an effective predictor for occurrence of dengue fever in Taiwan. *Acta Tropica*, 103(1): 50-57.

Notes of the Sponsors

Climate Change Adaptation in Sri Lanka: Demonstrating Preparedness in Knuckles Landscape Coordinated by Global Environment Facility - Small Grants Programme (GEF-SGP, UNDP) and Knowledge Management Team, Sri Lanka Environment Exploration Society (SLEES)

Being a small tropical island, there is no significant annual variation in temperature in Sri Lanka due to latitude. However, significant regional variation in temperature could be observed due to altitude. In lowland areas, the average annual temperature usually varies around 26.5 – 28.5 °C and it falls quickly as altitude increases (e.g. Nuwara Eliya – 15.9 °C at 1800 meters above mean sea level). In the absence of high seasonal variation in temperature, the average pattern of climate in a given local area is determined mainly by the variations in precipitation. Sri Lanka's mean annual rainfall is around 1850 mm (ranging from 900 mm to 5000 mm). There are three major sources of rainfall in the country, namely; monsoonal, convectional and depressional. Based on the variation in precipitation, Sri Lanka's climate is generally divided into four seasons:

1. First inter-monsoon season (FIM): March –April (268 mm, 14%)
2. Southwest monsoon season (SWM): May –September (556 mm, 30%)
3. Second inter-monsoon season (SIM): October-November (558 mm, 30%)
4. Northeast monsoon season (NEM): December- February (479 mm, 26%)

The first inter-monsoon (FIM) rains are usually experienced around the March-April period. During the FIM, the southwestern quarter and certain parts of central highlands receive over 250 mm rainfall, with some localized areas on the Southwestern slopes experiencing rainfall over 700 mm. Most other parts get rainfall around 100-250 mm. Hazardous lightning associated with thunderstorms is a frequent incident and sometimes intensive rainfall may give rise to flash floods. The country experiences the Southwestern monsoon (SWM) around May-September. During the SWM season, mid-elevation western slopes of central highlands receive over 3000 mm rainfall and the southwestern coastal belt around 1000-1600 mm. Higher elevations in central highlands get rainfall around 800 mm. Long-lasting monsoon rains may result in floods in low lying areas and landslides in hilly areas. Rains can be experienced at any time during the day and night.

Changes of Climate Observed in Sri Lanka - Some Scientific Evidence

Temperature:

Analysis of past data suggests that atmospheric temperature is gradually rising almost everywhere in the country. Varied rates of increase in temperature have been reported from different locations and in recent years, the warming trend has become faster. Annual mean air temperature anomalies have shown significant increasing trends in all stations during recent decades. It has been reported that mean daytime maximum and mean night time minimum air temperatures also have increased. Data indicates that an increase in night time minimum air temperature contributes more to an average increase in annual temperature than day time maximum air temperature.

***Precipitation*:**

Unlike in the case of temperature, no clear pattern or trend has been observed in precipitation. Some researchers, comparing the mean annual precipitation of recent and earlier periods, suggest that average rainfall is showing a decreasing trend. However, there is no consensus on this fact among researchers and opposing trends can be observed in different locations. It has been observed that heavy rainfall events have become more frequent in central highlands during the recent period. However, many researchers seem to agree that the variability of rainfall has increased over time, especially in *Yala* season. Moreover, the number of consecutive dry days has increased and the consecutive wet periods have decreased. Studies also indicate that spatial distribution of rainfall appears to be changing although a distinct pattern cannot be recognized yet. Some studies suggest changes in distribution can even lead to shifting of agro-ecological boundaries.

Extreme events:

The intensity and the frequency of extreme events such as floods and droughts have increased during recent times. Areas of high rainfall intensities and the locations of landslides show a strong correlation.

Sea level rise:

Sea level rise of 1-3 mm/year is observed in the Asian region and is marginally higher than the global averages. An accelerated level of sea level rise has been observed from 1993 to 2001 (3.1 mm/year) for the Asian region. However, specific levels of sea level rise in areas around Sri Lanka are yet to be assessed.

Demonstration of preparedness for climate change adaptation in Sri Lanka

Global Environment Facility - Small Grants Programme (GEF-SGP, UNDP) with technical expertise of the National Steering Committee recognized the need of preparedness for climate change adaptation in Sri Lanka and has chosen vulnerable ecological landscapes in the country i.e. Knuckles Conservatory Area, Coastal region from Mannar Island to Jaffna and the Colombo Wetlands for implementation of appropriate practices with community participation. The activities were launched by Non-Governmental Organizations with financial and technical support and facilitation by the Knowledge Management Team, Sri Lanka Environment Exploration Society (SLEES). The key sectors and priority areas focused in respective three landscapes for climate change adaptation and cross-cutting needs are presented below. This paper presents selected examples of operations in Knuckles landscape during the period 2018-2020 to demonstrate preparedness for climate change adaptation.

Key sectors and priority areas focused on 3 landscapes (Knuckles Conservatory Area, Coastal region from Mannar Island to Jaffna and Colombo Wetlands) for climate change adaptation

Sector	Priority Areas
Food security: agriculture, livestock and fisheries	Rice Other food crops (OFC) Livestock Fisheries Agriculture and land degradation
Water resources	Water for agriculture Water for human consumption Degradation of watersheds
Coastal and marine sector	Coastal zone management Beach stability Coastal bio-diversity Ocean acidification
Health	Climate altering pollutants Diseases: Spread and outbreaks Hazardous events: Health impacts Heat/thermal stress
Human settlements and infrastructure	Urban settlements and infrastructure Rural settlements and infrastructure Coastal settlements and infrastructure
Ecosystems and biodiversity	Forests Wildlife Wetlands Agroecosystems: home gardens Loss of ecosystem services
Tourism and recreation	Coastal tourism Tourism and biodiversity Cultural assets
Export agriculture sector	Tea Rubber Coconut Export agricultural crops

Cross-cutting needs focused on 3 landscapes for adaptation

Building of adaptive capacity of communities	Assessing adaptive capacity and vulnerability Enhancing community participation Utilization of local knowledge Involvement of CSO Change in attitudes, lifestyles, and behaviour
Education, training, and awareness	Education (formal & informal) Training needs and skills Increasing awareness
Research and development	Research & development Critical research needs Research facilities Skills and training need
Climate information management	Climate forecasting: short-term & seasonal Long-term projections Communication of climate information

Figure 1: Climate Change Adaptation in Sri Lanka: Best Examples of Preparedness in Knuckles Landscape. (a) Conservatory area of Knuckles landscape experiencing climate change impacts on floral and faunal biodiversity, water availability, agriculture and life style of community; (b) Renovating a heavily eroded rubble road in Mahalakotuwa village; (c) Establishing rock dams in Etanwela village; (d) Renovated ancient Galpihilla watershed in Ranamure village; (e) Renovated Kahagala Gama Meda Wewa.

ISBN 955-8476-09-3

THE INSTITUTE OF BIOLOGY
SRI LANKA