Climate smart land management methods for enhancing the adaptive capacity of food production system in the tropical region

Velmurugan, A., [*]Swarnam, T.P., Burman, D., Mandal, S. and Subramani, T.

[1]ICAR-Central Island Agricultural Research Institute, Port Blair-744 101, India

ICAR-Central Soil Salinity Research Institute, Regional Research Station, Canning Town – 743329, West Bengal, India

*Corresponding author: swarna_8@yahooo.com

Abstract

Island ecosystem is influenced by maritime climate and endemic flora and fauna that predominate the food production system. The observed variations and projected changes in rainfall and temperature severely affect the small islands and island states (SIS) more than large countries. In this study we analyze the long-term changes in total rainfall, its seasonal variations, number of rainy days and extreme events based on standardized global data sets and ground observations for the SIS including Island region of India to identify suitable adaptation option to ensure sustainable food production. We link these climatic parameters with the observed waterlogging, moisture stress and salinity, compounded by sea water intrusion, which severely affect agricultural diversification and food production. In these areas climate smart alternative land management (ALM) methods *viz*. raised beds, paddy-fish, farm pond with broader dykes etc. were demonstrated and evaluated against these climate change linked challenges at smallholder farms in Andaman islands and Sunderban region of India. The results showed that ALM methods created favourable conditions for crop growth and agricultural diversification by excluding seawater intrusion, harvesting rainwater, reducing salinity and facilitating drainage amidst extreme events experienced during the observation period (2010-2020). ALM enhanced on-farm food production (2.7 to 34.6 t ha^{-1} rice equivalent yield),

sustainability (0.23 to 0.79 measured as sustainable yield index), net mitigation benefit (2.2 to 5.7 Mg CO_2eq yr^{-1}) providing greater scope for its upscaling in island and coastal region as adaptation measures.

Key words: *climate change, waterlogging, coastal and islands, adaptation, land shaping*

1. Introduction

Global climate change and food insecurity are the two major challenges for humanity, with the former appearing to escalate faster than the later[1]. Analysis of output from General Circulation Model (GCM) models and regional observations revealed the negative impact of climate change on agricultural growth by way of increase in the frequency and intensity of drought, heavy rainfall, flooding and high maximum temperatures which are projected to accelerate in many regions[2]. Small islands and island states (SIS) located in the tropical region including Indian Island territories are highly vulnerable[3] to these changes as many of the SIS have small land areas with a high population density and low economic resilience[4]. In this region, agriculture is a key economic sector and major employment source for 40-60% population, but more than 20% of them still remain food-insecure[5]. The current hydro-meteorological extreme events cause significant loss to GDP (17-59%) in this region[6]. Further, inter annual variability in temperature, rainfall and sea level related to the ENSO (El Niño/ Southern Oscillation) phenomenon makes these regions increasingly vulnerable to climate change[7]. In future, this increased climatic variability may exacerbate production risks and challenge farmers' coping ability particularly the landless and marginalized ethnic groups[8]. This concern has created strong demand for understanding the global climate change in regional context with high confidence so that long-term adaptation strategies could be formulated for sustainable development of SIS region.

Climate change and its associated events are normally witnessed in the form of low cropping intensity, lack of agricultural diversification and very low production in the SIS region[9,10]. Averting this challenge requires that farmers adapt by making changes in farming and land management decisions that reduce the negative consequences associated with land degradation and changing climate[11]. In recent years permanent raised bed systems (land shaping) have been adopted in a wide range of irrigated and dry land farming systems to harvest rain water and increase water use efficiency[12,13], provide better opportunities for leaching of salts[14,15] and growing rainfed crops[16] under changing climatic and waterlogged-saline areas. This is more pertinent to the islands and coastal regions of India which are geographically similar and part of SIS region.

Thus it is imperative to study the climate change and its spatio-temporal variations to understand the climate change imposed regional challenges to agricultural production. This paper presents large scale experimental evidences based on the demonstrations conducted at small holder farmers' field on the potential of climate smart alternative land management (ALM) methods as an adaptation options to address these challenges. This is explained in the conceptual model as given in Fig. 1. The present study also assessed the stability, green house gas (GHG) emission, size of C sink and net emission benefit due to adaptation of these methods under different farming situations. The main aim is to suggest upscaling of these practices to similar areas in the tropical region as an adaptation options as loss of adaptive capacity is the key risk associated with future climate change[9].

2. Materials and methods

2.1 Data sources

In this study data is derived for two different aspects *viz*., (i) climate change and its associated events impacting agriculture at global and regional scale and (ii) field evaluation of ALM methods as an adaptation option. The field data was from Component-3 of NAIP-Global Environmental Facility funded project that was implemented at farmers field distributed in 12 clusters in Andaman & Nicobar Islands and East Coast of India covering 32 villages and long-term continuous performance monitoring (2010-2020). This included baseline survey, design of different alternative land management options, implementation and periodic performance assessment before and after the intervention. The design configuration of different ALM methods suitable for varying conditions is presented in the technical option subsection. The performance was assessed till April 2020 and the production data was averaged to represent each method. Data sourced from several published reports and peer reviewed literatures on ALM methods pertaining to humid tropical coastal region constituted the secondary source of information. Data on climate and weather extremes was compiled from worldclim.org, NOAA, FAOSTAT[17] India Meteorological Department and ICAR-CIARI observatory. Global level data sources / GCM prediction outputs were used to understand the regional impact in the SIS with a detailed case example of Andaman and Nicobar Islands.

2.2 Technological options

Eight ALM methods were designed for specific farming situations and address the challenges imposed by climate change and its associated events. These ALM are evaluated at smallholder farms in Andaman Islands (170) and Sunderban region (50) of India whereas data was collected from some of the existing ALM (4) from Lakshadweep for comparison. The basic design in all the ALM was climate change adaptation and diversification of agriculture production centred on *in-situ* rainwater harvesting (Supplementary Fig. 1). The raised beds made in different size and shape was aimed to facilitate leaching of soluble salts and aeration in the root zone. On the raised beds of different ALM suitable cropping pattern with standard package of practices were followed. The technical details are elaborated below.

2.2.1 Permanent raised bed system (RBS)

This system was designed to harvest rainwater in the furrows and cultivate crops in the permanently raised beds. Broad beds (4-5 m width and 1 m height) and furrows (5-6 m width and 1.5 – 2.0 m deep) were made alternatively in the coastal lowlands where waterlogging during rainy season and soil salinity during dry season were the major problems for crop production[16].

2.2.2 Rice-Fish system

Deep trenches (3-5m width and 1.5 m depth) were dug around the periphery of the paddy land and the dugout soil was used for making broader dikes (2 - 3 m width and 1.5 m height) to protect free flow of water from the surrounding and harvest rain water in the field and trench. The dikes were used for growing vegetables /fruit crops and the central portion of the original land was used for rice + fish and leafy vegetable after rice harvest.

2.2.3 Three tier farming

In this method degraded coastal lowland was made into three equal portions as raised land, medium or original land and pond with a depth of 2.5-3 m. Dikes of 3 – 4 m wide and 1.5 m height was made around the field. Pond made at the lower part of the land was used for harvesting of rain water and poly-culture of fish. Paddy in the middle portion (original land) and vegetables on the raised land and surrounding dikes were cultivated.

2.2.4 Farm pond with broader dikes

About 20% of the farm area was converted into on-farm pond of about 1200m^2 area (40 x 30m size) with 3m depth to harvest rainwater / run-off from the field. Unlike the conventional farm pond, the dug-out soil was used to raise the land to form broader dike (bund) of 4 m width with atleast 1 m height. Raised land /dike were used for growing high value vegetables and fruit crops round the year while pond was used for fish polyculture.

2.2.5 Paired bed system

In this system only two beds of 5 - 6m width in either side of the central furrow with 10m width and minimum 1.5m depth were made in a narrow land patch in low-lying areas. There was a provision for shallow furrow at the centre of each bed to improve the drainage or leaching during monsoon season. In this technique a nursery pond of 5 m x 9 m size was also created at one end of the furrow for raising fingerlings while broad furrow was used for brooders.

2.2.6 Deep furrow and high ridge

In the Sunderban delta areas about 50 % of the degraded individual farm holding was shaped into alternate high ridges (1.5 m top width x 1.0 m height x 3m bottom width) and deep furrows (3m top width x 1.5 m bottom width x 1.0 m depth) aimed at reclamation of degraded land and enhancing its productivity. Rainwater harvested in the inter-connected deep furrows facilitated fish cultivation and provide supplemental irrigation for crops during *Kharif* (monsoon season) and initial irrigation during *Rabi* (winter season).

2.2.7 Shallow ridges and furrow system

In coastal / island regions away from the coast where the land is converted into series of ridges and furrows ranging from 1.0 to 1.5 m with 0.3 to 0.5 m height mainly to facilitate drainage during monsoon and conserve moisture all through the dry season.

2.2.8 Brackish / mangrove based aquaculture

There are many areas in the coastal region particularly near the creek / back water or sea coast remain highly saline throughout the year that are influenced by tropical cyclones and sea surges. These lands were shaped into brackish water pond of varying size (0.13 - 0.4 ha) and depth (1.5 – 2.0 m). The height of the embankment of the pond is determined by the tidal height occurring in the area or atleast 30 cm above the maximum flood level. Sometimes the surrounding natural or manmade mangrove is integrated with the production system.

2.3 Estimation of resilience and GHG emission

Resilience of the ALM (unit area) methods was estimated from the sustainable yield index (SYI) and sustainable value index (SVI). This was compared with the rice monocrop / farmers existing practice. These indicators were estimated as follows,

$$SYI = (AY - Sd)/Y_{Max} \quad (1)$$

where, AY – Average rice grain equivalent yield of the respective crops or system, Sd – standard deviation and Y_{Max} – Maximum yield obtained from the respective crops

$$SVI = (NR – Sd)/MNR \quad (2)$$

where, NR – Mean Net returns from respective crops and or whole farm and MNR – Maximum Net Returns from each enterprise and or whole farm

GHG emissions from different components practiced in ALM methods were calculated using the GHG Estimation Tool V.1 developed by ICAR-Indian Institute of Farming Systems Research[18]. The tool consists of generic set of empirical models which are used to estimate farm level product emissions based on life cycle assessment (LCA) using Tier 2 approach of IPCC[19] where the emission sources are broken down into different categories for convenient quantification of major emissions of CO_2, CH_4 and N_2O.

2.4 Data collection and statistical analyses

The input data on farm production comprised of crop (cereals, vegetables, pulses, oil seeds), fish (prawn, fishes, crab), poultry (meat, egg) and milk. Production from different crops were first converted into values (Indian currency) and then rice equivalent yield (REY) (1kg rice = 16 Indian rupees) for quantification, homogenization and comparison. The primary data were analyzed using descriptive statistics such as average, percentage, coefficient of variation and standard deviation in Microsoft excel. The economics of various crops (total cost, gross return and net return) was calculated by farm budgeting technique. Statistical significance of different ALM methods based on '*t*' test was carried out using SAS package.

3 Results and discussion

3.1 Changes in climatic parameters over SIS

Climate change is a global change driver that is projected to affect climate variability, increase the frequency and severity of tropical cyclones, hurricanes and storm/tidal surges[20]. But this challenge can be addressed to reasonable extent through downscaling of climate model projections which would aid in developing adaptation strategies[6]. Thus in this study global monthly precipitation for two time periods (2020 and 2050) was used to assess the total, wet and dry season changes in precipitation. Verification over Indian Ocean and Caribbean region by comparing (Supplementary Fig 2) the monthly area-averaged mean rainfall with observed values (2019-20) indicated close agreement of predicted values with the observed values (r^2=0.9056 and 8661, respectively). More details can be found in worldclim.org[21] and data source file.

Interestingly, the results showed only a marginal change (1.5 - 9%) in current total annual rainfall (2019-20) over most of the SIS as compared to the long-term average but the concern is with the extremes that are superimposed on the mean changes. On a seasonal basis, the data projected enhanced rainfall during northern hemisphere (NH) monsoon season over most SIS (JJAS), however significant decrease in summer season monsoon was observed (JFMA - 2020) in almost all the SIS in the tropical region. A decline in summer season precipitation for the Atlantic Ocean, Caribbean Sea and the Indian Ocean Island States suggested possibility of emerging severe water stress in this region. Similarly, the projected changes in seasonal (wet and dry season) precipitation in 2050 as compared to 2020 indicated significant impact of climate change having profound impact on freshwater availability. The area-averaged monsoon season mean precipitation is projected to increase (in 2050) in the range of 2.9 ± 3.5%; 3.3 ± 5.1% and 3.9 ± 7.3% over Pacific, Indian Ocean and Caribbean region SIS, respectively. In contrast, the area-averaged dry season mean precipitation will decrease in the range of - 6.2 ± 5.8%; -2.6 ±9.5% and -1.9 ± 11.6% in Pacific, Indian Ocean and Caribbean region SIS, respectively (Fig. 2A & B). Numerous studies have described the likely intensification of rainfall over Tropical Oceans and adjoining land regions[22].

It is evidenced from the historical records that SIS region was frequently affected by tropical cyclones which are projected to intensify further by 2050. Under the effect nearly 9-

35% of the agriculture area is affected by waterlogging and coastal salinity. Compounding the challenges, seawater intrusion associated with storm surges (0.6 – 1.8 m) will also amplify the negative impacts of climate change on agricultural diversification and food security in SIS[9].

3.2 Observed changes: A case example of Andaman Islands

Trend in total rainfall, seasonal rainfall, rainy days and extreme events were calculated for 20 years period (2000-2020) to capture the spatio-temporal changes and understand the regional pattern. In general, the trend analysis by non-parametric methods indicated non-significant decreasing trend in total annual rainfall (0.8 mm y^{-1}) with a mean of 3089±480 mm across different locations from Great Nicobar to North Andaman (Nancowrie, Car Nicobar, Hutbay, Port Blair, Rangat and Mayabunder). However, significant changes in its seasonal distribution were observed for most of the stations in the islands. Monsoon season rainfall trend indicated increasing pattern of rainfall ranging from 18.4 to 31.2 mm $y^{-1}$with the exception of Nancowry while summer season rainfall significantly decreased ranging from -0.2 to -2.6 mm y^{-1} (Fig 3A & B). The observed trend was in agreement with the downscaled values from global level prediction.

At the same time the rainfall frequency analysis indicated 0.5% increase in extreme rainfall events as compared to climatic normal that corroborate with the increase in monsoon rainfall. The rainfall covers the potential evapotranspiration (ET) demands during monsoon season but seasonal water deficit of 30-40 cm from December to April was experienced (Fig. 4). Combining with the seasonal change in rainfall pattern, it indicated more intensive rainy days during monsoon while dry season witnessed increasing dry spells. Similar to this, many tropical areas are also projected to be significantly wetter or drier than they were a century ago although none of the model predictions is made with high confidence[23]. This will have consequential impact on cropping systems and crop physiological process and soil microbial activities[24]. This constitute emergent demanding situation wherein climate smart land and water management practices are the key to address these challenges so as to enhance the production, sustainability and food security.

3.3 ALM as an adaptation strategy

Implementing innovative alternative land management practices in combination with productive utilization of rainwater and vast brackish water resources besides land could be the best approach towards climate change adaptation[25]. Towards this the resilience and performance of different ALM methods demonstrated as adaptation measures at farmers' fields are given in table 1.

3.3.1 Performance of different ALM methods

In freshwater type ALM *viz*., permanent raised bed, rice-fish, three tier, farm pond with broader dikes, paired bed and deep furrow and high ridge systems rainwater is harvested in furrow, pond or trenches that facilitates freshwater fish culture and supplemental irrigation to the crops grown in the raised beds. ALM methods facilitated *in-situ* harvesting of rainwater ranging from 1875 – 8000 m^3 ha^{-1} depending on the size and configuration. The amount of water stored at a particular time is primarily the function of water storage space, rainfall and losses in the form of evapotranspiration and percolation. The harvested fresh water was used for irrigating the crops grown on the bunds, fish culture in the furrows besides it prevented the entry of saline water from below due to higher head pressure. Alternatively, the raised bunds (dike) made around the low or original land effectively prevented the entry of sea water during high tide, storm surges and runoff upto 1 m height. For this reason the salinity was below 1.0 dS m^{-1} that favoured normal crop growth in the raised beds. Among the fresh water types, farm pond with broader dikes (FPBD) harvest and store larger quantity of rainwater (6500 m^3 ha^{-1}) while deep furrow and high ridge (DFHR) recorded the lowest volume of stored water (1875 m^3 ha^{-1}) by virtue of its storage capacity. Unlike farm pond, DFHR was designed for more cultivable area than water storage space that was reflected in the higher yield potential of this system (Supplementary Fig. 3).

The raised beds of different ALM were used for either crop rotation of two medium and one short duration vegetables *viz*., okra-brinjal-radish from mid April to mid January or for single long duration crop like ginger or turmeric from May to January due to favourable soil condition and availability of fresh water for supplemental irrigation. These systems also favoured polyculture of freshwater fishes with the stocking density of 2-4 fingerlings m^{-3}. Among these methods, farm pond recorded highest fish yield whereas rice-fish system exhibited high flexibility as it dynamically shifts from rice dominance to fish culture and *vice-versa* depending on the rainfall conditions[26]. As a result all the fresh water types ALM methods have recorded significantly higher yield varying from 21.3 to 34.6 t ha^{-1} REY than existing farmers practice (2.7t ha^{-1} REY). This implied that fresh water types are highly suitable for enhancing the total production and diversity centered on rainwater harvesting and its use even under climatic variations. Other details on crop type, fish culture and specific advantage can be inferred from table 1.

In the present study shallow ridges and furrow was made as a means of improving drainage and conserving water in the gently sloping land with sandy loam to sandy clay loam soils for growing banana, papaya and some local fruit crops. In certain sporadic waterlogged locations close to the coast, hardy / leafy vegetables were grown in the raised ridges meanwhile furrows were used for cultivating off-season short duration legume vegetables utilizing the residual moisture. For this reasons, this system recorded on an average 27.3 t ha^{-1} REY which is 900% higher than farmer practices.

Areas close to the coast and adjoining to mangroves periodically experience rise and fall of tidal wave and consequent waterlogging. In those areas, brackish water aquaculture and mangrove-based integrated farming could be the ideal choices for agricultural diversification and enhancing production. In brackish pond polyculture with tiger shrimp (*Penaeusmonodon*) along with brackish water fish like golbhangon / bhangon (*Liza tade*) and aansbhangon (*Mugilcephalus*) was practiced. By raising the bunds around the pond, saline tolerant perennial vegetables and fruits were cultivated as rainfed crops. In mangrove based system the brackish ponds were stocked with mullet - *Mughilcephalus (300 Nos*), Scat – *Scatophagus argus (150 Nos*), Tilapia – *Oreochromismos sambica (200 Nos*) and Tiger Prawn – *Penaeus monodon (200 Nos*) under polyculture system. A mangrove nursery (*Bruguiera gymnorrhiza*, *Rhizophora apiculata* and *Acanthus ilicifolius*) constructed bordering the ponds helped to establish bioshield to protect the system from tidal waves. On an average these methods recorded total production of 8.6 - 11.8 t/ha REY even in saline environment.

3.3.2 Climate change resilience

Intensive monsoon rain (maximum 30 minutes rainfall intensity index vary from 450 to 600) and recent increase (0.5%) in the extreme events (rainfall amount realized in a day is more than 124.5 mm) created waterlogged situation in the coastal lowlands even in the adjoining highlands. The depth of submergence varied from 0–95 cm which closely followed the rainfall trend (Fig. 5A). However, the depth of submergence was primarily influenced by time of occurrence of rainfall and extreme events, occurrence of dry spell before rainfall event, land elevation among other factors. For the same amount of rainfall, depth of waterlogging was different for mid of the monsoon and dry season. Further, the situation was compounded by sea water inundation during high tides. Consequently at many places farmers cultivated only rice and left the land fallow after rice harvest or standing saline water even affected coconut and other tree crops. In contrast, the raised beds / dikes with atleast 1-m height remained below the saturation level and effectively prevented intrusion of sea water directly into the system and mixing with harvested rain water in the furrows which varied from 0.5 to 1m depth at different time period (Fig. 5B). This was evidenced from minimum period of submergence even during wet season than the surroundings. At the same time soil moisture content (top 15cm) was 6–8% higher during dry season whereas soil salinity was less than 1.0 dSm^{-1}. This was due to improved drainage and cultivation enabled accumulation of organic matter in the soil. Therefore, supplemental irrigation up to 10–15% of available soil moisture was considered sufficient to meet the crop water demand during the dry period or unexpected long dry spell. On the other hand, during rainy seasons (19-40 standard meteorological weeks) the raised beds remained above the saturation point only for few hours before attaining the field moisture capacity (Fig. 5C).

The favourable conditions created by raised beds reflected in higher cropping intensity (>200%) and agricultural diversity. Inclusion of long and short duration crops, dual purpose sorghum, maize and rice (grain and / fodder), drought tolerant local vegetables and rice + catfishes imparted greater adaptability and provided insurance against observed changes in climate. This implies that high agricultural diversity and growth of robust famine crops will reduce damage to any one specific crop[27] and improve the resilience. Thus the long-term observation recorded the ability of ALM methods in addressing waterlogging, salinity and moisture stress that are the major climate related constraints in the coastal and island region.

3.5 Stability and mitigation benefits of ALM methods

Imparting resilience, enhancing adaptive capacity and improving the mitigation benefits of the production system are the most desirable impact expected from climate smart practices. In the present study, the system was made robust by diversifying agriculture and smart combinations of technologies through suitable ALM for different farming situations influenced by climatic parameters. As stability strongly depends on resilience, sustainable yield index (SYI) and sustainable value index (SVI) were calculated for different ALM for analyzing and comparing the resilience of these methods amidst 0.5% increase in extreme events, longer dry spell and decreasing rainy days during 2010-2019. The sustainability indices significantly increased from 0.23 (for rice monocrop at the beginning) to 0.79 (SYI) and 0.76 (SVI) at the endline (Fig. 6). Crop diversification and integration of animal components enabled by ALM methods besides climate resilient crop rotations played a major role in providing sustainability to smallholder farms against the climate change impacts. Among the individual components crop production was found to be highly sustainable based on SYI and SVI primarily due to the round the year vegetable production centered on rainwater harvesting and prevention of sea water intrusion by raising the dikes.

Adaptation and mitigation of coastal and island region are not always trade-offs, but can be regarded as complementary components. Yet this study recorded net mitigation benefits from ALM methods which are important aspect of climate smart technologies. Because total non-carbon-dioxide greenhouse gas (GHG) emissions from agriculture contribute 10–12% of global anthropogenic emissions[28]. The analysis indicated increased total GHG emission from 3.9 Mg CO_2eq yr^{-1} in rice monocropping with the addition of more components and diversification. At the same time the sink has increased by 1.5 to 2 fold than the emission thereby the ALM system provided net emission benefit varying from 2.2 to 5.7 Mg CO_2eq yr^{-1} even under waterlogged situations. The net emission benefit could be achieved due to waste recycling and compost addition, increased standing biomass, green manuring, mulching and improvement in soil C level enabled by ALM methods. Diversification of rice with suitable crop rotation significantly decreased the GHG emission. While round the year vegetable cultivation in raised beds with agro-forestry component contributed only 6% of the total emission indicating its potential in reducing GHG emission. Given that food production is utmost important under the emerging climate change situations, ALM methods helps to identify synergies and trade-offs among food security, adaptation and mitigation. This constituted strong evidence in support of ALM methods and crop diversification as a climate smart strategy with high food production efficiency in the SIS regions. The mitigation benefit of ALM besides enhanced food production is also highly pertinent to the coastal regions of India.

4. Conclusions

Though climate change affects every regions of the world, due to poor adaptive capacity, the severity is felt more on the food production systems of the small islands and island states located in the tropical region. Compounding this situation sea level rise, sea surges and other natural calamities consequently result in waterlogging, seasonal water scarcity, salinity and poor agricultural productivity. Under such situations, the present study demonstrated the effectiveness of alternative land management as a climate resilient method to enhance agricultural production centered on rainwater harvesting. These methods help to cope with the waterlogging, salinity, sea surges and moisture stress besides providing net carbon mitigation benefits than the rice monocropped surroundings. Further, the techno-economic evaluations of these systems indicated the economic feasibility primarily due to higher stability and sustainability of the production system and adaptability to the emerging situations. Thus, it is suggested to pursue these ALM methods as an adaptation options at smallholder level through the application of participatory approaches to capacity building and institutional changes.

5. Acknowledgements

The authors are grateful to National Agricultural Innovation Project – GEF, Director and Project Director (CSSRI, Karnal). We express our sincere gratitude to Director and all the staff of ICAR-CIARI, Port Blair.

Competing Interests

We declare there is no competing interest in publishing this article.

References

1. FAO. *Climate change adaptation and mitigation: Challenges and opportunities in the food sector*. FAO, Rome, 2012.
2. Porter, J. R. *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Part A: Global and Sectoral Aspects (ed. Field, C. B.) IPCC, Cambridge Univ. Press, 2014, pp. 485–533.
3. IPCC. Climate Change-2007: Synthesis Report, Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland, 2007, pp. 1-104.
4. Hess, A. Sustainable development and environmental management of small islands—an overview. In: *Sustainable development and environmental management of small islands* (eds. Beller W, D'ayala P, Hein P) UNESCO, Paris, 1990, pp. 3–14.
5. Wheeler, T. and von Braun, J., Climate change impacts on global food security. *Science*. 2013, **341,** 508–513.
6. Nurse, L.A., McLean, R.F. Agard, J. Briguglio, L.P. and Duvat-Magnan, V. N. Small islands. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, 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), Cambridge University Press, Cambridge, NY, USA, 2014, pp. 1613-1654.
7. Nurse, L.A, McLean, R.F. and Suarez, A.G. Small island states. In: The regional impacts of climate change: an assessment of vulnerability (eds. Watson, R.T, Zinyowera, M.C, Moss, R.H). A special report of IPCC Working Group II and WMO/UNEP. Cambridge University Press, Cambridge, pp. 331–354.

8. Thornton, P. K. and Gerber, P. Livestock production: recent trends, future prospects. *Mitig. Adapt. Strateg. Global Change*, 2010, **15,** 169–184.
9. Karim, Z., Hussain, S.G. and Ahmed, M. Salinity problems and crop intensification in the coastal regions of Bangladesh. *Soils publication No. 33*, Soils and Irrigation Division, BARC, Farmgate, Dhaka 1215, Bangladesh, 1990, pp. 1-20.
10. Rahman, M.M. and Ahsan, M. Salinity constraints and agricultural productivity in coastal saline area of Bangladesh, Soil Resources in Bangladesh: Assessment and Utilization, 2001.
11. Jarvis, A., Lau, C., Cook, S. Wollenberg, E., Hansen, J., Bonilla, O. and Challinor, A. An Integrated Adaptation and Mitigation Framework for Developing Agricultural Research: Synergies and Trade-offs. *Experimental Agriculture*, 2011, **47(02),** 185–203.
12. Sayre, K. and Hobbs, P. The raised-bed system of cultivation for irrigated production conditions. In: *Sustainable Agriculture and the Rice-Wheat System*. Lal, R., Hobbs, P., Uphoff, N., Hansen, D. (Eds.), pp. 337–355(Ohio State University Columbia, Ohio, 2004).
13. Ahmed, M.B., Qubal, G., Ahmad, N.H. and Shah, A. Maize yield, plant tissue and residual soil N as affected by nitrogen management and tillage system. 2009, *J. Agric.Biol. Sci.*, **1 (1),** 19–29.
14. Bakker, D.M., Hamilton, G.J., Hetherington, R. and Spann, C. Salinity dynamics and the potential for improvement of water logged and saline land in a Mediterranean climate using permanent raised beds. *Soil Tillage Res.*, 2010, **110 (1),** 8–24.
15. Velmurugan, A., Swarnam, T.P. and Lal, R. Effect of land shaping on soil properties and crop yield in tsunami inundated coastal soils of Southern Andaman Island. Agriculture, *Ecosystems and Environment*, 2015, **206,**1–9.

16. Bakker, D.M., Hamilton, G.J., Houlbrooke, D.J. and Spann, C. The effect of raised beds on soil structure: Waterlogging and productivity on duplex soils in Western Australia. *Aust. J. Soil Res.*, 2005, **43**, 575–585.

17. FAOSTAT. Country Statistics. Food and Agriculture Organization of the United Nations. http://faostat.fao.org/site/567/default.aspx#ancor 2014. Accessed 18 July 2021.

18. Subhash, N., Dutta, D., Ravisankar, N. and Panwar, A.S. IFS-GHG Estimation Tool Ver.1.0. 2018, AICRP-IFS, ICAR-IIFSR, Modipuram, India. http://www.iifsr.res.in/sites/IIFSR_Annual_Report_2018-19.pdf

19. IPCC. Intergovernmental Panel on Climate Change, In: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. (eds. Houghton J.T., Meira Filho L.G., Lim B., Tréanton K., Mamaty I., Bonduki Y., Griggs D.J. and Callander B.A.) IPCC/OECD/IEA, Paris, France. 1997.

20. Parry M. L. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2007.

21. Fick, S.E. and Hijmans, R.J. WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. International Journal of Climatology, 2017, **37(12),** 4302-4315.

22. Walsh, K. and Pittock, A.B. Potential changes in tropical storms, hurricanes, and extreme rainfall events as a result of climate change. *Clim Change*, 1998, **39,** 199–213.

23. IPCC. Climate Change 2013: The Physical Science Basis. Working Group 1 contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013.

24. St Clair, S.B. and Lynch, J.P. The opening of Pandora's Box: climate change impacts on soil fertility and crop nutrition in developing countries. *Plant Soil, 2010,* 335: 101–115.

25. Burman, D., Mandal, S., Bandopadhyay, B.K., Maji, B. and Sharma, D.K. Unlocking Production Potential of Degraded Coastal Land through Innovative Land Management Practices: A Synthesis *Journal of Soil Salinity and Water Quality,* 2015, **7(1),** 12-18.

26. Campbell, J., Islandness: vulnerability and resilience in Oceania. Shima: *The International Journal of Research into Island Cultures*, 2009, **3(1),** 85-97.

27. Urruty, N., Tailliez-Lefebvre, D. and Huyghe, C. Stability, robustness, vulnerability and resilience of agricultural systems. A review. *Agron Sustain Dev,* 2016, **36(1),**1-5. https://doi.org/10.1007/s13593-015-0347-5.

28. Lipper, L., Thornton, P., Bruce, M.. Campbell and Baedeker, T. Climate-smart agriculture for food security. *Nature climate change*, *2014*, ***4(12),*** 1068-1072. .

Table 1 Performance of alternative land, crops and livestock management in the coastal areas

Sl.No	Alternative land management methods & No of interventions	Rainwater harvested (m^3ha^{-1})	Climate resilient production components	Constraints addressed	Production t/ha (Rice grain equivalent)[#]
I	**Fresh water type**				
1	Permanently raised beds (broad beds and furrow) (40)	3812-4476	Seasonal vegetables in beds, rice-fish (in furrow), fodder in the slopes, banana in the boundaries	Salinity and waterlogging, diversification	34.3[a] (3.11)
2	Rice-Fish system (25)	1385-3564	Seasonal vegetables in dike, rice-vegetable in the central original portion, fish (polyculture) in the trench. Dike slope was used for green manure / MPT's	waterlogging	29.2[b] (2.65)
3	Three tier farming (8)	4500	Seasonal vegetables in the raised portion, rice-pulse or rice-vegetable in the original central portion, fish (polyculture) in the pond (lower portion)	waterlogging and dry period	27.2[b] (2.47)
4	Farm pond with broader dykes (30)	5000-8000	High value / seasonal vegetables, sunflower, groundnut, cotton (summer season) in dikes, fish (polyculture) in pond. It also facilitates irrigation of surrounding land during summer months.	Salinity and waterlogging, diversification	21.3[c] (1.90)
5	Paired bed system (26)	3750	Seasonal vegetables in beds, Fish (in furrow), fodder in the slopes, banana in the boundaries	acid-saline soils, lowland holding, diversification	34.6[a] (3.08)
6	Deep furrow and high ridge (12)	1875	Vegetables in dike, sunflower, groundnut, cotton (summer season), fish (polyculture) in furrow	Salinity and waterlogging, diversification	33.6[a] (3.00)
II	**Drainage and water conservation type**				
7	Shallow ridges and furrow system (10)	-	Seasonal vegetables, banana, pine apple, border plating with multipurpose trees	flooding, unseasonal rain	27.3[b] (2.67)
III	**Mixed water type**				
8	Brackish water aquaculture (6)	2000-3000	Poly culture system of brackish water fish farming with tiger shrimp, some	Salinity, waterlogging	11.8[de] (1.04)

			perennial vegetables and grasses		
IV	**Direct use of waterlogged space type**				
9	Coastal lowland (Farmers practice) (30)	-	Rice or fallow	waterlogging, salinity; tidal flooding,	2.7^{g} (0.26)

#Values in parenthesis are standard deviation; MPT’s- multi-purpose trees; values with different letters are significant (p<0.05)

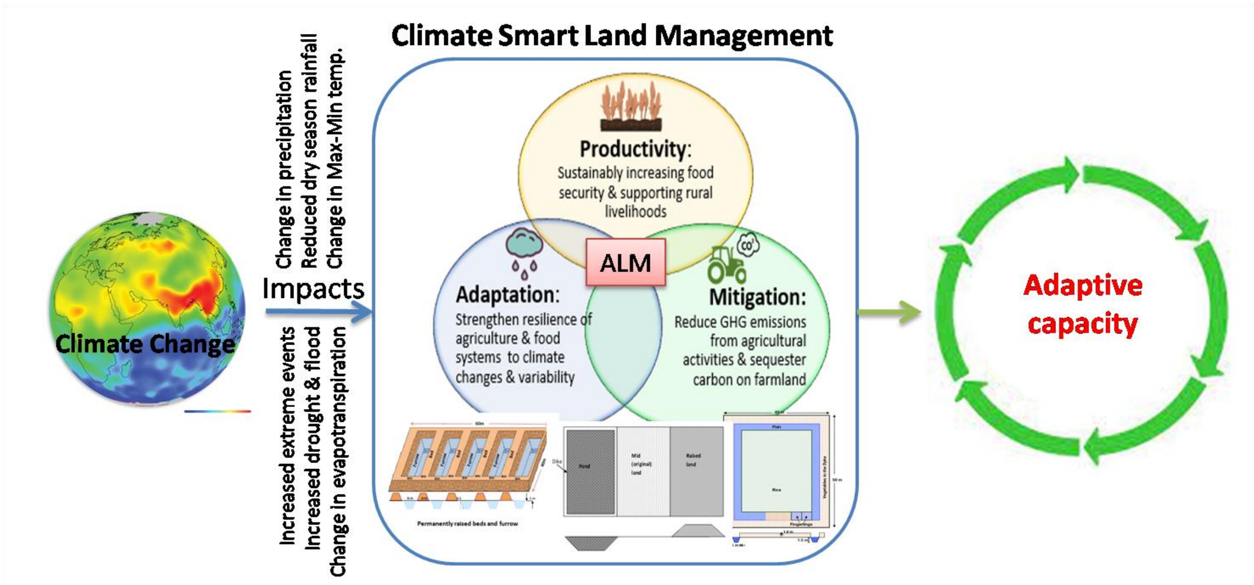

Fig. 1. Conceptual diagram showing the role of climate smart land management methods in enhancing the adaptive capacity

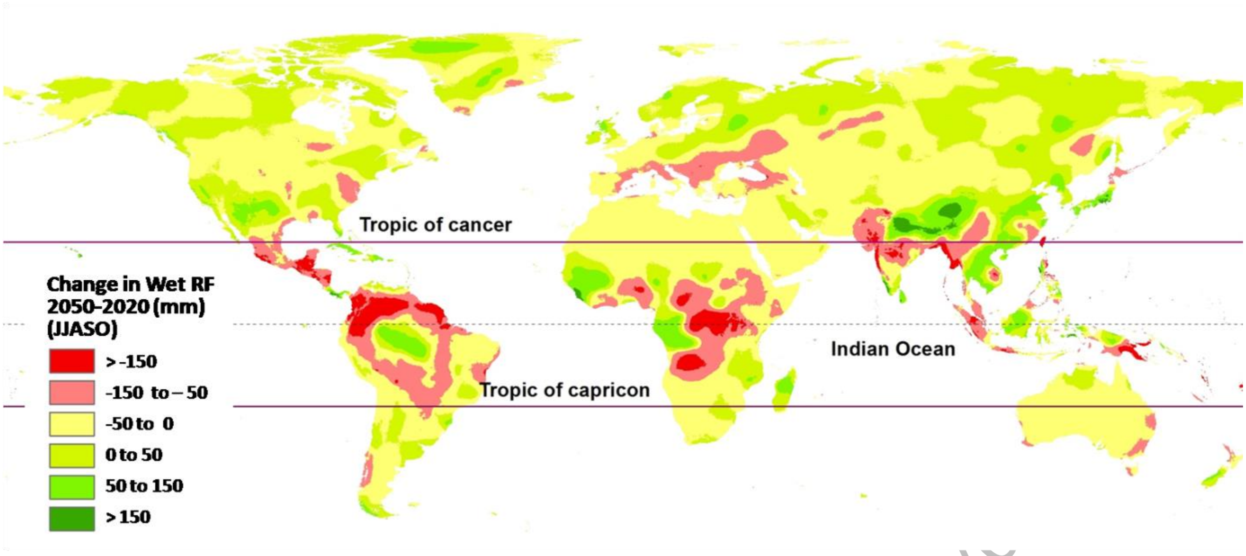

Fig. 2 A. Changes in global area-averaged wet season mean precipitation (inferred for Small Island States in the tropics) for 2050s as compared to 2020 due to future increases in greenhouse gases

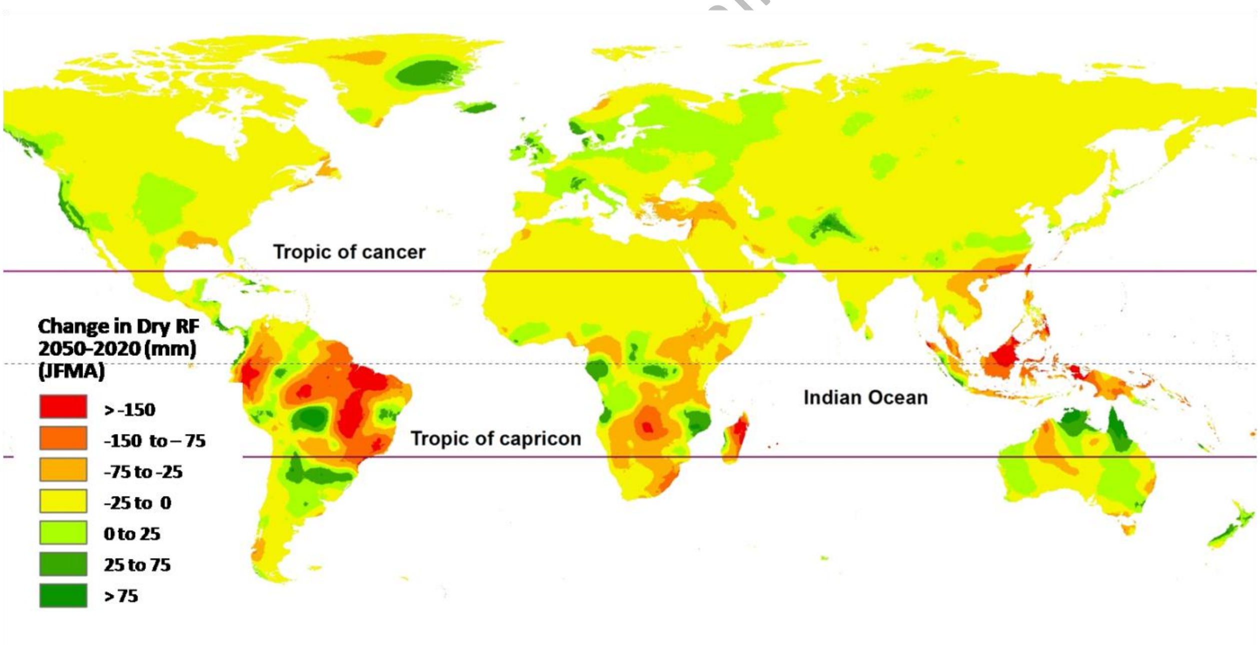

Fig 2 B. Changes in global area-averaged dry season mean precipitation (inferred for Small Island States in the tropics) for 2050s as compared to 2020 due to future increases in greenhouse gases

Fig.2 Global area averaged seasonal precipitation for current and projected period

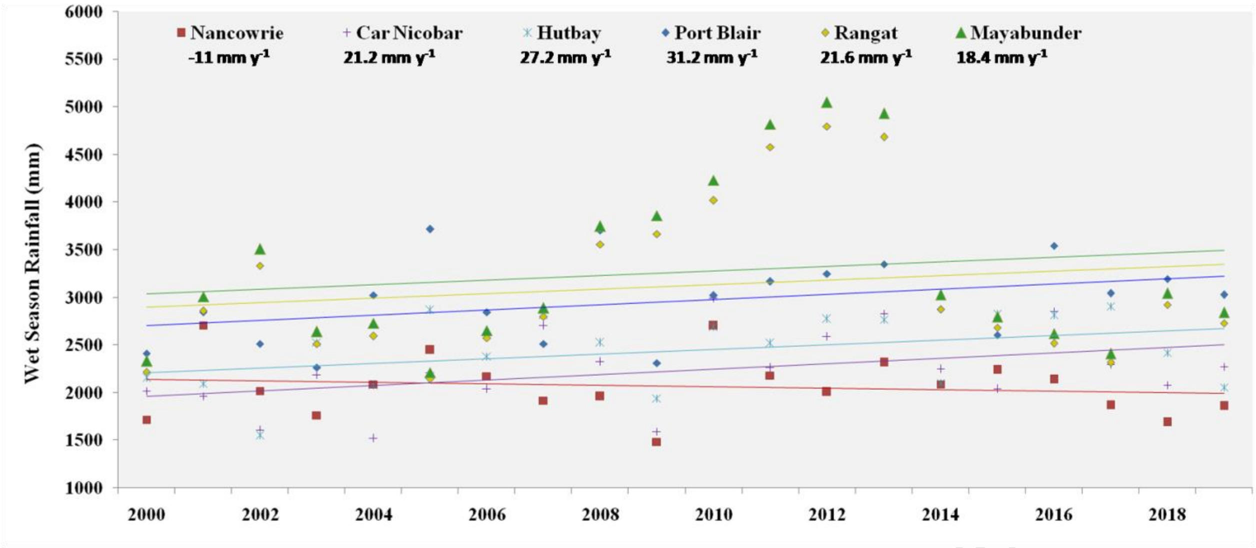

Fig 3a. Long-term trend in wet season (JJASON) total rainfall (locations are from South to North, 8.1° N to 13.2 °N)

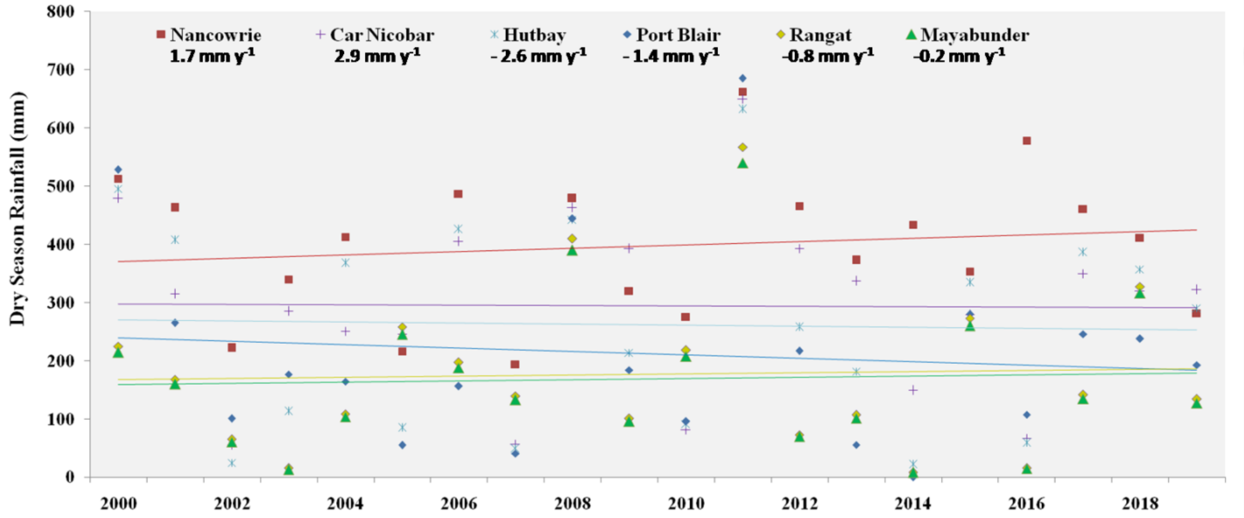

Fig 3b. Long-term trend in dry season (JFMA) total rainfall (locations are from South to North, 8.1° N to 13.2 °N)

Fig. 3 Long-term trend in seasonal rainfall distribution over Andaman and Nicobar Islands in the Indian Ocean region

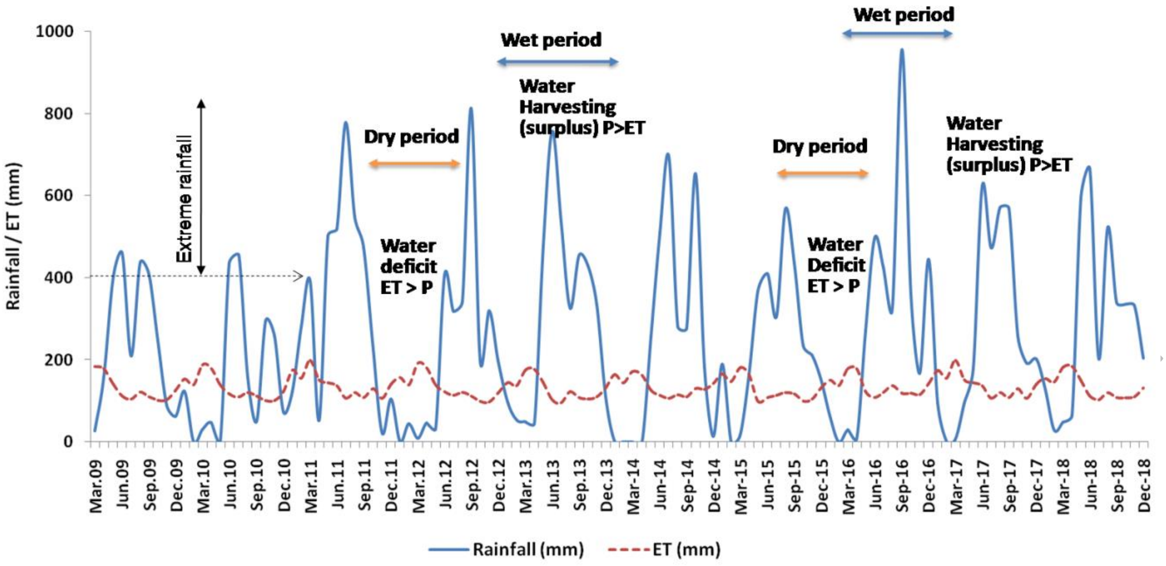

Fig. 4 Rainfall and ET observed over Andaman and Nicobar Islands indicating the dry and wet period. Excess of 400 mm indicates the occurrence of extreme events

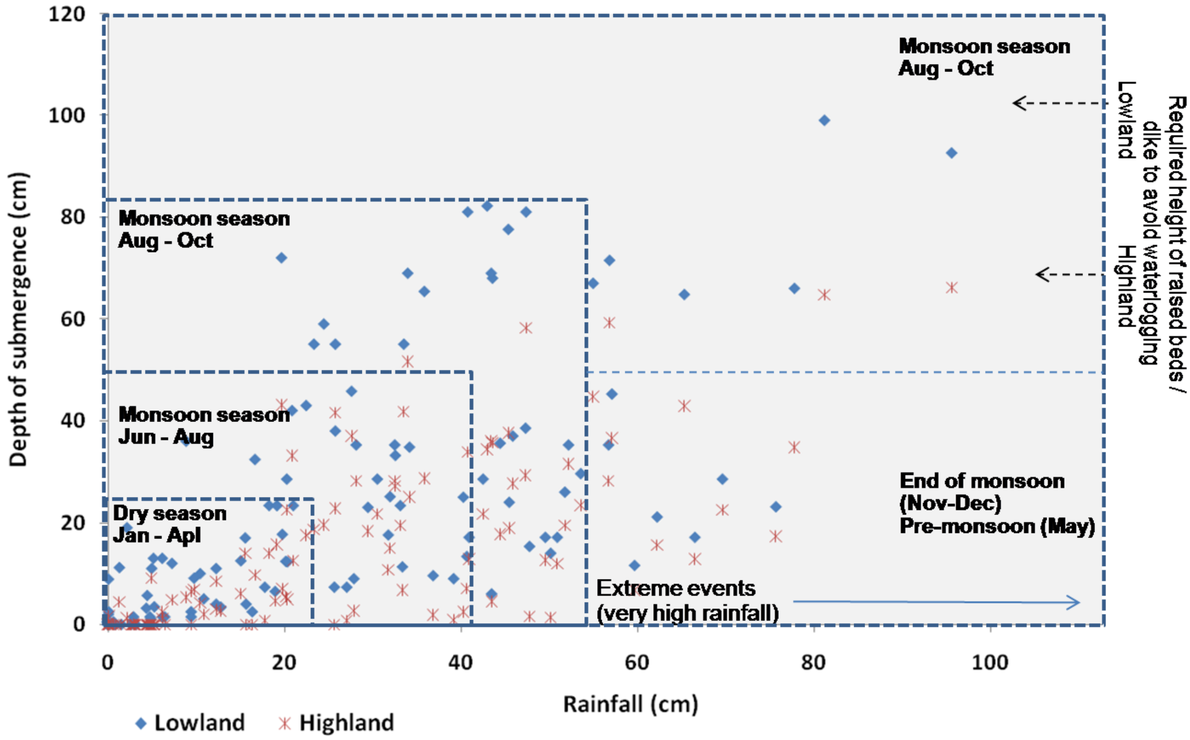

Fig. 5a. Relationship between depth of submergence and rainfall in different time periods observed in lowland and highland

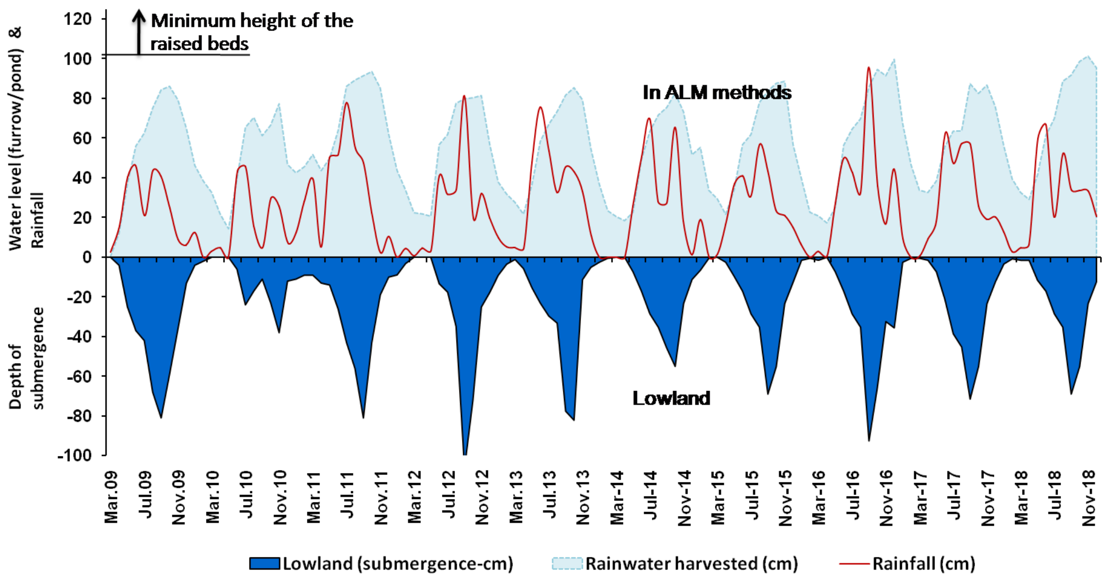

Fig. 5b. Effect of rainfall on submergence of lowland and water harvested in different ALM methods (Lowlands are outside the ALM sites)

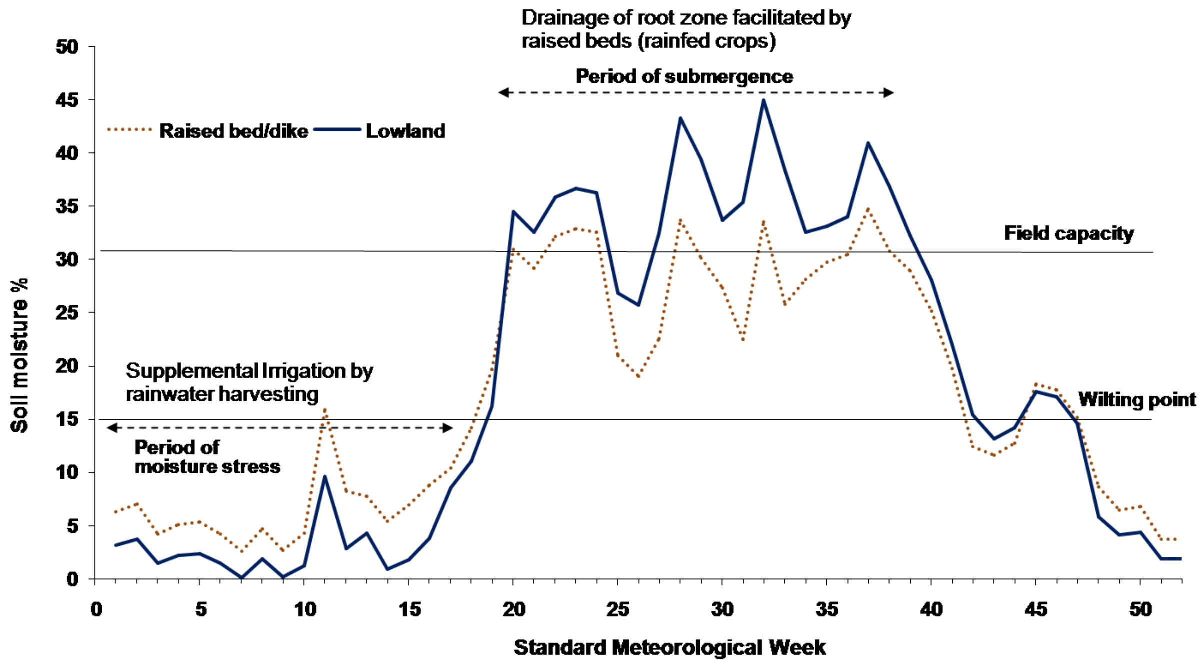

Fig. 5c. Changes in gravimetric soil moisture content observed in raised bed and adjoining lowland. The graph also indicates period of submergence and moisture stress for the same sites

Fig. 5 Relationship between rainfall, depth of submergence, ET and rainwater harvested in the coastal areas of Andaman and Nicobar islands, Indian Ocean region

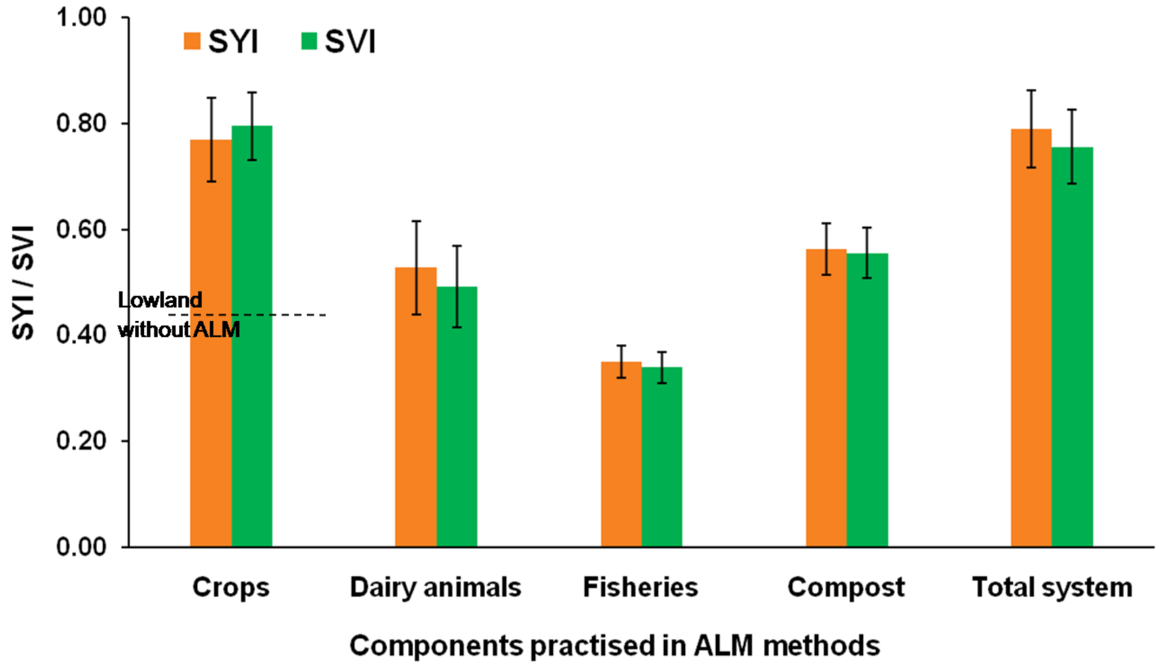

Fig. 6 Sustainability index of different components practised in ALM methods (Mean values are plotted with SD)