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Influence of Climate Change on Forest Fire Occurrence and Distribution of Sri Lanka and Modeling of Forest Fire

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Influence of Climate Change on Forest Fire Occurrence and Distribution of Sri Lanka and Modeling of Forest Fire.

By

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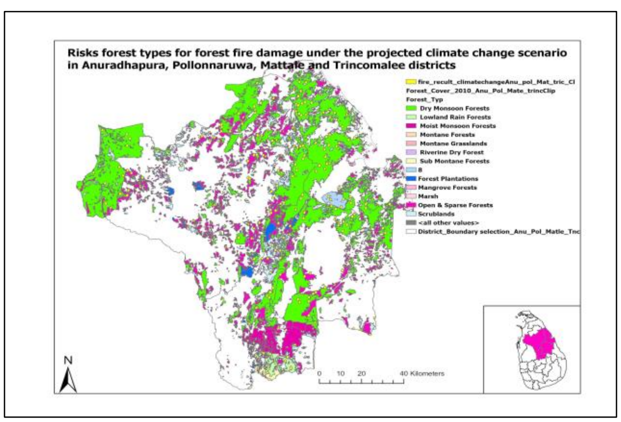
Executive summery.

Nowadays, forest fires are one of the most important drivers of forest degradation and deforestation. There are several factors that act as important drivers of forest fires, which are changes on landscape, weather pattern changes, invasion of Invasive species, and anthropogenic activities (Pausas et al., 2021). Sri Lanka is an island which has suffered intensely from frequent extreme weather events such as excessive floods in the wet zone and severe drought conditions in the dry zone. In 2016, Sri Lanka faced a severe drought period which received record low levels of rainfall from the North East Monsoon which affected all natural and anthropogenic activities in the Dry and Intermediate zones of Sri Lanka. In that year, Sri Lanka reported the highest forest fire damages of 2884 hectors of forest resources all around the inland, the highest ever reported. When analyzing the past twenty years of fire data, an increasing trend of fire damages can be seen. Dry monsoon forests and monoculture homogenous forests like forest plantations (pine) have high dry fuel loads compared to other forest types, which range from 35 to 42tons/ha (Ariyadasa.2002). No of fire incidence that were reported annually varies from 50 to 100(Ariyadasa.2002). Still Unfortunately, Sri Lanka gives less priority for fire related research and studies even though those damages make significant contributions to addressing the forest resource damage. Therefore, the main goal of the project is to identify the climate change impact on forest fire occurrence and distribution in different Sri Lankan forest types and to predict future forest fire risk area. The project has four main objectives those are,

- Identify the relationship between forest fire and climate change in Sri Lanka.

- Develop fire model platform capable of simulating a library of plausible fire under current and future conditions.
- Identify and map forest fire vulnerable area for climate change.
- Proposed recommendation for preparation of forest fire management plan.

Forest fire simulation methods were used to identify baseline forest fire situations and future climate change impacted scenarios. Minimum Travel Time algorithm call FConstMTT were used as the simulation methods. Under the baseline and projected climate change scenarios, 1000 iterations were done to find the 10 to 20 year future fire impact under the climate change scenarios compared to the baseline condition for six forest categories with custom fuel models. As figure A show that most dry monsoon forests have a high level of future climate change impacted forest fire damages followed by open and spare forest and scrublands. Simulation results also implied that 56,617 acres of forest would be destroyed under the base line conditions while 293,758 acres of forest would be damaged under the future climate change scenario.



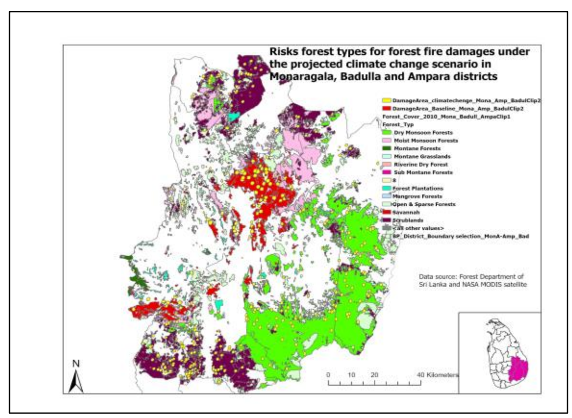


Figure A: Simulated Forest fire damages under the climate change impacted scenario (left: Anuradhapura, Polonnaruwa, Trincomalee and Mattale districts, right: Monaragala, Badullla, Ampara districts.

On the other hand, most forest fire ignitions arise from the open and sparse forest and then disperse to the dense forest, so it can be assumed that from other land use categories such as agricultural lands fire burning is not happening. As figure A show that Monaragala districts has the highest vulnerability for forest fire damages under the future projected climate change scenario followed by the Annuradhapura and Mullaitive districts. At the current situation (ground level conditions) Badulla districts show the highest forest fire vulnerability, but it would change with the future climate change scenario.

Applicability of findings for forest policy and forest management programs

The Sri Lankan national forest sector target is to improve the existing forest cover from 29.7% to 32% by the end of 2030. In order to achieve that target, we need to conserve the existing forest cover. These findings give more reliable data that future climate change will impact forest types and districts that need to give more priority in conservation activities. For those districts such as Monaragala, Anuradhapura, Mulaitive districts need to allocate more financial and human resources to protect the existing forest cover, especially dry monsoon and open and spare forest. In the dry zone and intermediate zones, of Sri Lanka there are considerable quantities of abundant land which are not considered as the forest, but can be used to improve the forest cover through forest restoration and reforestations. My findings are vital for the identification of the suitability of those lands for forestry activities.

Abstract.

Forest fire is one of the main causes for forest degradation and deforestation which affect ecosystem services provided by the given landscapes. Weather variables like temperature, wind speed and direction, rainfall, and relative humidity also govern the forest fire regime and vulnerability. On the other hand, forest fuel characteristics, human impacts, population density, forest canopy density, slope, elevation, road density, closeness to the human settlement areas are other factors that determine the forest fire impact and potential of damage. Annually, 100 to 2500 hectares of forest resources are damaged due to forest fires in Sri Lanka. From the past few years, forest fire impacts on the forest resources have increased. This increase of forest fire damages may be closely related to climate change. In order to assess the impact of climate change on forest fire damage, this study analyzed the occurrence and distribution of forest fires in Sri Lanka using forest fire simulation techniques. The variability of dry weather patterns in Sri Lanka have increased in the last few years, especially during North East monsoon season, which is the season of highest rainfall in the dry zone. This has caused the dry warm conditions in the dry zone to have increased. In Sri Lanka the weather pattern is strongly associated with the *El Nino* Southern oscillation (ENSO). As a result of climate change and global warming, the Indian ocean surface temperature varies, which changes the pattern and duration of ENSO, warmer conditions and dry weather patterns. In that context, there has been an increase of dry conditions throughout the inland, which has created the worst impact for the dry zone of Sri Lanka.

The simulation algorithm call FconstMTT was used in this study to identify the baseline condition and future projected climate change impact on forest fire damages. Under both conditions, 1000 time iterations for each scenario were done. Sri Lankan forest types were categorized into six categories based on the elevation, rainfall and fuel characteristics. For each and every forest type, custom fuel models were prepared and the numbers 30 to 36 were assigned to these models. Baheveplus application was utilized to produce custom fuel models. The ArcFuel extension of ArcGIS 10.4 was used to derive landscape file using three geographic raster layers (elevation, slope, aspect) and five forest characteristics raster layers. Findings from this research suggested that the forest fire hazards in the dry zone of Sri Lanka could significantly increase for the near future under projected climate change conditions. Most interestingly, fire damage under the future projected climate change scenario in the Mulaitive district has significantly increased. Out of the total forest fire damages, about 53% was reported in Monaragala districts under climate change conditions and this would be about 50% in baseline level in Badulla districts. Based on the fire damages, number of fires, and fire damage per fire occurrence, 25 districts in Sri Lanka were classified into risk, moderate and low risk areas. Fire simulation output results of burn probability, damage areas and fire intensity level provide evidence that under the projected climate condition fire severity, fire intensity is significantly increased in the dry zone of Sri Lanka, especially in the Monaragala, Anuradhapura, Polonnaruwa, Badulla districts. Moreover, forest types like dry monsoon forest, shrublands, open and spare forest, and savannah forest have higher forest fire vulnerability and hazardous levels under the climate change.

Acknowledgements.

I am giving my heartfelt gratitude to my supervisors, Professor Max Nielsen-Pincus and Professor Sahan Dissanayaka. Because of their valuable support and guidance, I made the project output to a very optimal and successful level. Also, I would like to give my thanks to my community partner Mr. Anura Sathuringhe, who is allocating financial resources through the Ecosystem Conservation and Management project which was helpful to me to carry out my research work and study without having stress conditions and financial burden. Moreover, I am grateful for the support and contribution given by Dr. Cody Evers as well as Dr. Linnea Spitzer who helped me to correct my English writing and to improve my English skills. Because of facilitating the data collection, I would like to give my sincere regards to the Conservator General of Forests, senior offices of the Forest Department of Sri Lanka and the Director General of Meteorological Department. Finally, I am eternally grateful to my wife, L.M.C Iroshini who is allocating enough time to me and who looked after my children when I was studying in the US.

Dedication.

This project is dedicated to my loving parents, Seetha Dissanayake, Elvin Heenatigala, and Forest Department and Government officials who are honestly, effectively, and efficiently involving to protect my Motherland of Sri Lankan natural resources including forests.

Table of Contents

List of Tables

List of Figures

1. Introduction.

Nowadays, many sectors and human activities are impacted by climate change. Climate change is closely related to global warming, which is the result of uncontrolled and careless anthropogenic activities. Climate change is a continuous process and it is one of the main barriers to achieving sustainable development goals. It also contributes to increasing the poverty level of people which affects their health condition while creating many uncertainties in many sectors, including the policy making level. At the same time, we do not have proper solutions for fixing the problem arising from the climate change impact and how we can create opportunities from the burning problems of climate change (Kyte, 2014).

There are many studies which have been done on climate change, environmental impact, habitat alteration, economic impact on country level and global level. Much of this research has focused on the impact of climate change on weather patterns. Groves et al. (2012) suggest that weather pattern changes like seasonal alteration of rainfall seasons, extreme weather conditions like heavy rainfall that causes floods, and less rainfall under extreme drought conditions are the main effects of climate change. As a result of weather pattern changes at the global and national levels, there is excessive drought in some parts of the world while some areas receive flooding conditions. In addition, fire damages to forests in the global context have increased severely because of increased dry weather conditions.

1.1 Forest fire Hazard ,Land use patter and climate of Sri Lanka

1.1.1 Fire Hazard in different forest types on Global context

By causing the release of greenhouse gases (GHG), forest fires contribute significantly to climate change. 15 % of the global GHG emissions are attributed to forest fires – most of them caused by fire clearance in tropical rainforests and resulting land conversion. More specifically, forest fires cause 32 % of global carbon monoxide and 10 % of methane emissions, as well as over 86 % of soot emissions (Colombaroli et al.,2019). For example, fire smoke in the Brazilian savannah forest releases 1.7 to 4.1 billion tons of carbon dioxide annually into the atmosphere (Colombaroli et al., 2019). Additionally, these fires release around 39 million tons of methane as well as 20.7 million tons of nitrogen oxides (NOx) and 3.5 million tons of Sulphur dioxide (SO2) annually. In Indonesia, huge forest fires were reported in 2015 from June to November due to the *El Nino* effect which caused extreme drought in South Asia. Human and environmental conditions were affected by smoke particles and the 2015 forest fires released almost twice as many greenhouse gases as Germany emitted in 2014(Colombaroli et al., 2019). More GHG leads to a drier climate, which leads to forests becoming dryer and degraded, which increases their susceptibility to fire.

Fires due to drier climates have been increasing all over the world. For example, according to Holtz et al. (2012), the annual area in southwestern South America burned due to wildfire varies widely depending on the climate drivers of *El Nino* Southern Oscillation (ENSO) and Antarctic Oscillation. These climatic drivers are impacted by climate change (Holz et al., 2012). Because of changes in sea surface temperature due to climate change and global warming, wind patterns and amount of moisture carried by the wind varies, leading some areas to become drier and more vulnerable to fire. In the future, the coincidence of warmer and drier conditions in landscapes dominated by flammable and fuel-rich forest plantations and mixed native-exotic and sclerophyll forests are likely to further promote large fires in areas of South America like south-central Chile (McWeth et al., 2018). In India, most of the time it is the dry forest types that are most affected by forest fires in dry seasons. Throughout the Indian subcontinent, forest fire seasons have varied with the spatial and temporal pattern of vegetation climate, demographic conditions, forest fuel characteristics, resources allocation for the forest conservations and various other factors. Though the major forest fire season in the country varies from February to June, some forests are not safe from fires throughout the year (Sahu et al., 2018). Some forest resources in India, like dry monsoon forests, forest plantation, tropical forest and climatic factors are similar to those found in Sri Lanka.

1.1.2 Sri Lanka Land use pattern.

There are three main climate zones in Sri Lanka. These are the wet zone, intermediate zone and dry zone. The wet zone receives more than 2500mm rainfall annually, while intermediate zones receive 1200mm to 2500mm rainfall, and the dry zone receives annual rainfall below 1200mm. Since agriculture is the main economic activity in Sri Lanka, the land cover in the intermediate and dry zone of Sri Lanka are predominated by agriculture. According to the Agriculture Department of Sri Lanka, Sri Lanka is categorized into 43 agro-ecological zones. Except for the hill country (high elevation region), the coastal and the northern part of Sri Lanka, rice paddies as the dominant form of agriculture can be found all around the country, followed by tea and rubber cultivation (Abesekara et at., 2019). Forest lands and their abundant lands are more common in the north–central and the northeastern (Figure 01) parts of the country, where the human population is sparse. In the areas with forest cover (forested lands), Sri Lanka maintains a high biodiversity and ecosystem diversity. Those forested areas are the main catchments of the main rivers and tributaries in Sri Lanka. Under the provisions of forest ordinances and wildlife conservation ordinances, some of the forest areas are declared as conservations, reserve or protected areas to conserve ecosystem services, biodiversity and, specifically, elephant habitats (Maddhumabandara, 2005). These forest resources are managed by the Sri Lankan Forest Department (Forest Ordinance no. 9, 2009)and the Department of Wildlife Conservation.

Based on the 2010 national forest inventory, the total forest in Sri Lanka covers 2.1million of hectares and that covers 29.7% of the total land extent (Figure 01). Dry monsoon forests cover 2/3 of the total forest resources. These forests are located in the dry zone of Sri Lanka, which receives less than 900mm total rainfall annually. Dry monsoon forests and monoculture homogenous forests like forest plantations (pine) have high dry fuel loads compared to other forest types, which range from 35 to 42tons/ha (Ariyadasa, 2002). The location and forest types where the fuel loads are comparatively high have a high risk for forest fires because of having a high load of ignition source (organic fuels) that can create favorable conditions for fire ignition under dry weather conditions with suitable wind conditions.

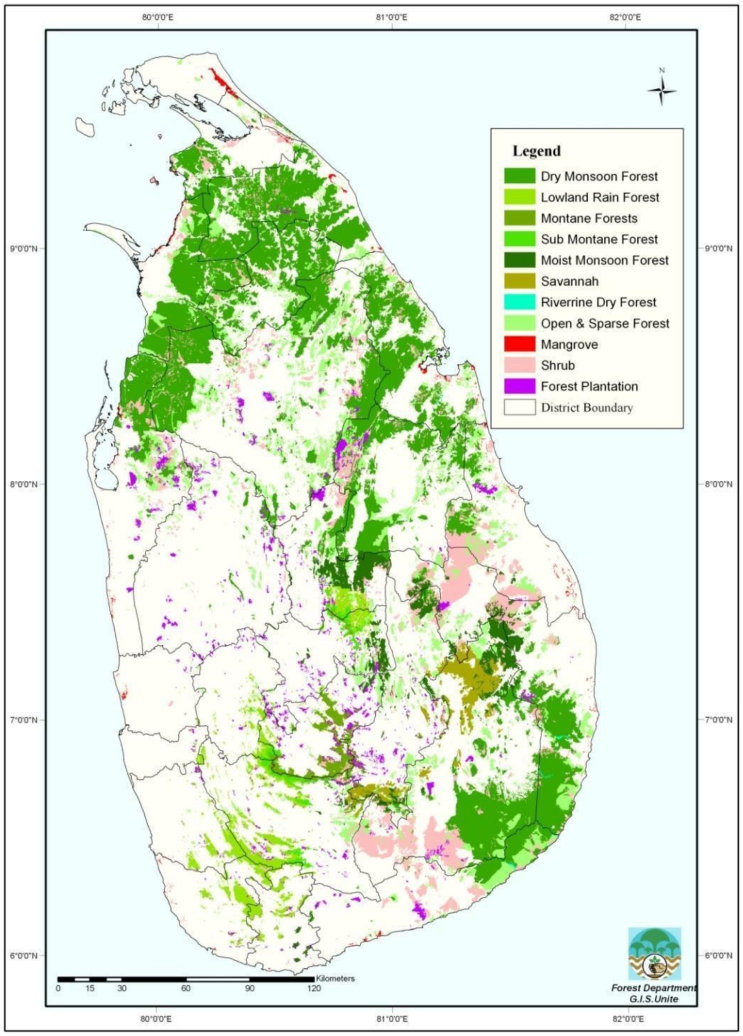


Figure 01: Forest Cover in Sri Lanka based on 2010 forest inventory data (Source: Forest Department of Sri Lanka)

Under the South West monsoon seasons, the dry zone and intermediate zone of Sri Lanka face a dry wind condition which carries less moisture content and creates favorable conditions for fuel ignition. Due to less rain received and under high temperatures in this period, the fuel load becomes drier, which creates more optimum conditions for the forest fires (Ariyadasa, 2002). Those are the main reasons why forest fire damages are very high in the months between July and October.

Forest fuel characteristics, human activities, elevation and weather factors govern the fire regime of Sri Lanka. Human activities, such as carelessness, slash and burn cultivation, and animal husbandry, are the only causes for forest fire in Sri Lanka, while there are not any natural causes for forest ignitions, such as lightning, heavy winds, or volcanic explosions. The results of unfavorable weather factors (dry and warmer condition, high dry wind, less rainfall) and the huge level of human impact are the main contributors to forest fire damages in the dry zone forest types (Bandara, 2019).

1.1.3 Climate of Sri Lanka.

Sri Lanka has monsoon weather patterns, and prevailing wind patterns govern the weather conditions in Sri Lanka. South West (SW) and North East (NE) monsoons are the main two monsoons which bring considerable rainfall all around the island. These monsoons happen from May to September and November to February respectively. The central highlands located on the windward slopes for the SW monsoon receive significant amounts of moisture to central highlands (Kandy, Matale, Ratnapura districts) and the Western and Southern parts of Sri Lanka, while lee side of central highlands for SW monsoon, areas like the Northern and Eastern parts (Badulla, Monaragala, Pollennaruwa, Anuradhapura districts) face a very dry condition in SW monsoon season. When considering the forest fires in Sri Lanka, temperature, precipitation, relative humidity, and wind are the main four weather variables that control the forest fires (Hapuarachchi et al., 2015).

1.2 Background and problem identification.

Climate change affects many sectors in the Sri Lankan economy and environment. Sectors like forestry, agriculture, power (hydroelectricity), and health are affected by fires caused by climate change, so contributions from those sectors to the national income (GDP and GNP) may be also affected. Due to weather pattern changes, an increased number of unexpected forest fires were reported in the last few years. At the same time, the intensity of forest fires also increased in the last few years (Ariyadasa, 2002). According to the Forest Department data (Forest Inventory and Management division) about 100ha to 2000ha of forest and forest plantations were destroyed due to forest fire annually. There are trends of increased occurrences of fire and the extent of damage with time. It may also be a result of climate change because the dry weather conditions and wind speeds have increased with time and changes in the rainy seasons. At the same time, forest fire burn rates of smoldering logs are up to five times greater during the day due to lower humidity, increased temperatures, and increased wind speeds. Sunlight warms the ground during the day which creates air currents that travel uphill. At night the land cools, creating air currents that travel downhill. Forest fires are fanned by these winds and often follow the air currents over hills and through valleys. (Bandara, 2019).

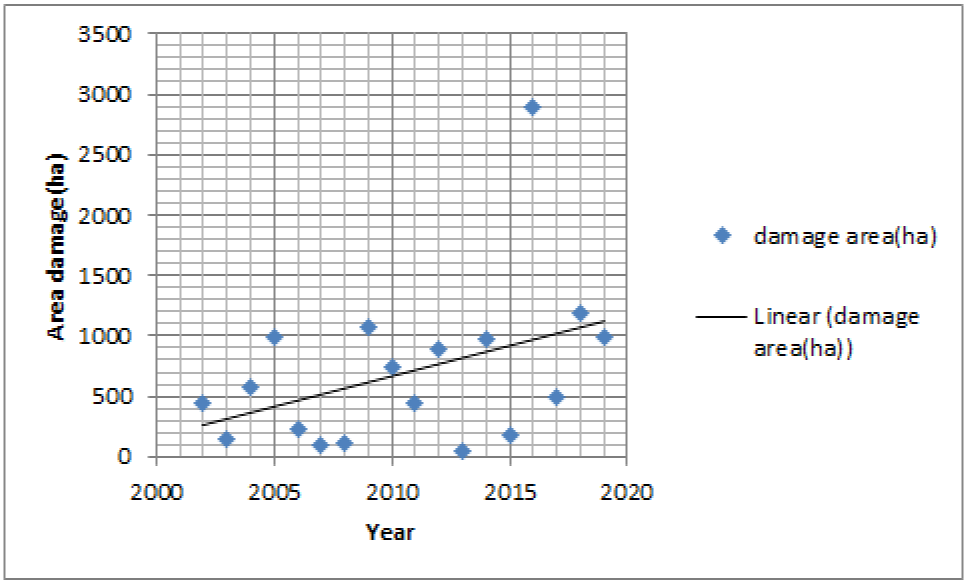


Figure 02: Extend of damage due to forest fire from 2002 to 2019(Source: Forest Department).

Figure 02 shows how the extent of damage due to forest fires in Sri Lanka have increased with time. The damage increased when the drought period was reported. As the Forest Department data have shown, in 2016, more than 2000ha of forest were destroyed due to forest fires which were caused by long drought periods that were reported in that year. That is the highest annual forest fire damages that have ever been reported in Sri Lanka. Climate change has created unfavorable weather events (drought) that have caused forest fire damages to increase. Normally, forest fire damages are highly reported in forest plantations like pine (Pathirana, 1998). However, when we consider the last few years, forest fire damages in the dry monsoon forests from the forest fires have also significantly increased. Meanwhile, in the 2016 fire outbreak, the damages due to forest fire in dry zone forests drastically increased to s the highest peak ever seen. At that time, the dry zone of Sri Lanka was affected by severe drought.

Rainfall received from the North-East Monsoon was the lowest amount that had ever been reported. These droughts happened due to climate change impact. As a result of the increase in forest damage, most of the ecosystem functions get stagnated and people and animals and whole systems have suffered.

In the Sri Lanka context, there is a lower priority given for fire related research and studies even though those damages make significant contributions to the forest resource damages. Findings from such studies would be helpful for the offices and people in forestry related programs because they would improve the forest resources while managing the forest fire damage to the forest. Still, the Forest Department does not have proper forest fire models for the Sri Lankan forest and there is no detailed research that has been carried out for forest fire mapping or to see the effects of climate change. There are also many data gaps in existing data. For example, the Forest Department does not collect field level data that is needed to do a fire modeling such as fuel moisture content, fuel load, and canopy bulk density. On the other hand, most of the forest fire data are incomplete. Also, using available Forest Department data on forest fires to conduct the forest fire research is difficult. The difficulty comes from the lack of spatial reference with valid spatial coordinates for some existing data. However, other countries like, USA, Brazil, Japan, Australia, and India have carried out a considerable level of advanced forest fire research that can generate a huge level of valuable information that can be used for proper forest fire management planning, making forest policy and national level forest resources enhancement programs. Therefore, it is very important to do proper fire modeling and simulation related research in order to generate valuable information related to forest fire and identification of future risk areas, even though the Sri Lankan Forest Department is giving lower priority to this type of research.

1.2.1 Forest fire simulation for identification of fire risky areas.

There are several forest simulations models that have been developed by US Forest Services (USDA) to predict risks areas for wildfire under normal and climate change scenarios. These models are Fsim and FConstMTT, FSpro and FlamMap (Scott et al., 2013). Fsim is a large fire simulation tool used to model contemporary fire regime characteristics and wildfire exposure as well as the effect of climate change between 2040–2069 (mid-century). FSim uses a Monte Carlo approach to model the interaction of fuel, topography, weather and spatial ignition patterns on a daily time-step and simulate fire occurrence, growth and suppression in thousands of statistically plausible, unique fire seasons (McEvoy et at., 2020).

Some Sri Lankan forest resources are similar to the Brazilian and US forest types (some tropical forests, forest plantations), and therefore some approaches from those countries' forestry research can be applicable for the Sri Lankan forest context. For example, Guedes et al. (2019) carried out research in Brazil at Paraiba do sul river valley to identify the vulnerability of small forest patches for fires, using the FConstMTT fire simulation algorithm for simulation to identify the risk areas and burn probability. This study implied that forest patches of less than 10 ha were most vulnerable to fire exposure and fire damages. This danger happens due to most of the forest patches being surrounded by the pasture land and people's residence areas with high positive correlation with the burn probability while larger forested areas have a negative correlation with burn probability (Guedes et al., 2019). Moreover, according to McEvoy et al. (2020), in the temperate regions which have seasonal weather patterns with warm summer periods, the future wildfires in these regions may grow larger as weather and other variables create more favorable conditions for the ignitions and fire spead. The study also found that projected changes in temperature and relative humidity led to longer fire seasons and more severe fire weather in three of the four tested scenarios. Under the hottest and driest scenarios, annual burn probabilities were similar to those found in higher frequency fire regimes. All climate and baseline scenarios illustrate that probability of occurrence of extremely large, intense fires are higher and that they will become more plausible under hotter and drier climate scenarios. The range of plausible impacts to fire regimes should be cause for managers and planners to adopt robust approaches to climate adaptation and risk mitigation (McEvoy et al 2020).

In order to find out the impact of weather and changing of weather conditions on wildfire from their ignition points and sources, fire simulation is used for various landscapes. There are large fire simulations methods like Fsim which are used under the changing weather and moisture content conditions, while FConsMTT can be used for large and small fires with the constant or changing weather conditions (Anderson et al., 1982; Finney, 1998; Richards, 1995). Several studies have investigated methods of fire simulations and relationship with fire and fire quality like burn probability, fire line intensity, fire damage area with other variables like weather patterns, ignitions, climate (Ager et al., 2007, Brown et al., 1959, Moritz et al., 2005, Bessie et al., 1995).

Management ability of fire, tree mortality (Hood et al., 2007) as an ecological attribute, the fire line intensity varies (Andrews & Rothermel, 1982), while it also depends between fire and portions of fires (Alexander, 1982; Byram, 1959). Fireline intensity (energy release per unit length of flame front) is a principal driver of many important fire effects and varies greatly between fires and portions of fires. Fireline intensity is closely related to impacts on ecological attributes such as tree mortality as well as the controllability of fire On the other hand, fire line intensity depends not only on local conditions at the time the fire occurs (e.g., fire orientation which means the fire frond or heading direction and existing environmental conditions like fuel moisture level, wind speed and directions and fuel load are other variables that determine the fire intensity) (Catchpole et al., 1982). Even under the homogeneous landscape, fire intensity varies due to changing of the above mentioned factors (Catchpole et al., 1992). In order to find the spatial and temporal variations of fire size, intensity, burn probability with fuels, weather and ignitions the simulation models can be used (Finney et al. 2011).

1.3 Motivation of the study.

- Less priority has been given for forest fire mitigation and monitoring programs.
- Forest fire hazards has become a burning issue at present as well as in future.
- Forest fire models and forest fire vulnerable areas mapping for climate change still remain a gap.
- There is insufficient research on forest fire impacts and climate change related impacts.
- Policymakers should pay attention to fire controls and mitigations.

- Forest fire has become a crucial factor in deforestation and forest degradations.
- To achieve Sustainable Development Goals (SDG), Sri Lanka should maintain forest resources while improving natural recourses.
- , Deforestation contributes a significant amount to forest fires that in turn become one of the main causes of deforestation.
- To get carbon benefits and carbon neutralization forest cover should be maintained also to get REDD+(Reduce Emission from forest Degradation and Deforestation) benefit we should maintain and enhance the forest resources.

1.4 Goal of the project.

Main goal of the project is to identify the climate change impact on forest fire occurrence and distribution in different Sri Lankan Forest types and to predict future forest fire risk areas.

1.4.1 Objectives of the study:

The project will have four main objectives:

- Identify the relationship between forest fire and climate change in Sri Lanka.
- Develop fire model platform capable of simulating a library of plausible fire under current and future conditions.
- Identify and map forest fire vulnerable areas for climate change.
- Propose recommendation for preparation of forest fire management plan.

1.4.2 Key deliverables

- Prepare forest fire vulnerable areas maps.

- Develop future forest fire risk area maps.
- Develop maps that show the details of climate change impacted forested areas.
- Recommend documentation as an input for forest fire management plan preparation.

2. Methodology.

2.1 Overview of the study

From this study I have focused on the climate change impacts on forest fire occurrences and distribution with the identification of future risks. In this study, I have used a main forest fire simulator that has been developed by the US forest services to model the wildfire behaviors in the USA. Based on the weather scenario, landscape types and fuel load characteristics, I have done the simulation for the Sri Lankan context. A baseline scenario was matched with the climate change impacted projected scenario to find out the real climate change impact on forest fires. Fuel models (custom type) are very important in the preparation of landscape files.

2.2 Conceptual framework of the methods of the study.

As Figure 03 shows, six fuel model were developed for this study. After the LCP was prepared, to develop the baseline condition of the fire simulation, fire simulation was done several times by adjusting fuel moisture content and weather parameters slightly until they matched with the ground level fire information. This is the calibration of simulation model with the ground level conditions.

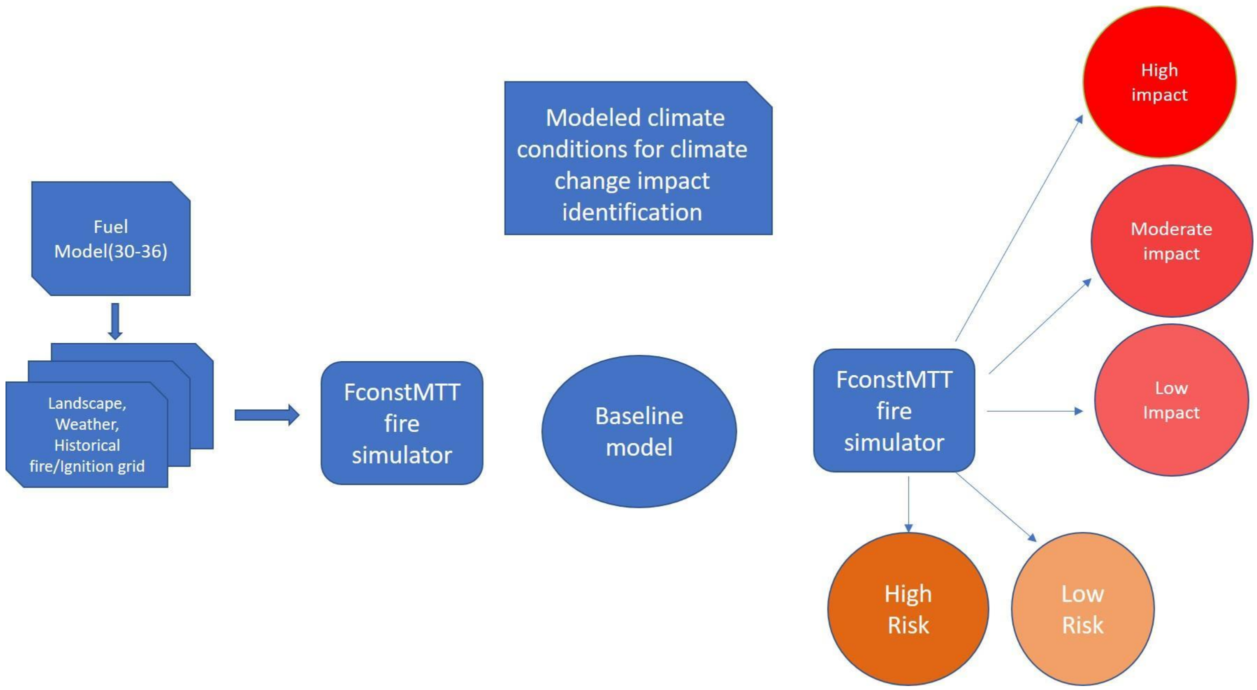


Figure 03: Methods for fire simulation under the baseline weather conditions and projected climate change impacted conditions. Two scenarios have five output results with maps. Climate change impacted scenarios have three levels of output with high, moderate and low risk areas while baseline scenarios have two levels of high and low risk areas.

2.3 Study area.

The total land area of Sri Lanka was selected for this study.

2.3.1 Location of Sri Lanka and Country information.

Sri Lanka is an island with a land extent of 65610Km2 and a tropical climate weather pattern. The island has a total land extent of 6.5 million hectares (ha) (65,610 km2), and is located between 5°55′–9°51′ N latitude and 79°52′–81°51′ E longitude. Sri Lanka is densely populated, with 21.8 million people who mostly reside in the southwestern portion of the island. Figure 04 shows the climatic zones and administrative districts of Sri Lanka. According to the weather pattern, annual rainfall and temperature, there are three climatic zones in Sri Lanka that determine the weather patterns of the island, namely, the wet zone, the intermediate zone and the dry zone. The dry zone has about 66% land mass (2/3) from the total land mass and is predominated by agricultural activities while having a remarkable extent of forest resources as well.

2.3.2 Administrative context in Sri Lanka

Sri Lanka has 25 main administrative districts that govern the government services (Figure 04) which are received by the citizens. Colombo is the main capital city of Sri Lanka. Agriculture is predominant in the economy and tea is the main export crop of Sri Lanka.

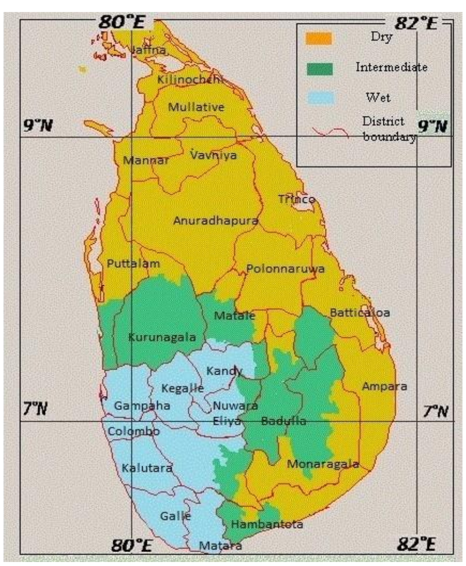


Figure 04: Climatic Zone of Sri Lanka with administrative district in Sri Lanka. (Source: Meteorological Department).

Given Sri Lanka's location, it is subject to the Indian Ocean (IO) monsoon system, which results in a systematic migration of intense rainfall across the region during the course of a year (Burt et al., 2014). Sri Lanka has four rainfall seasons (climate seasons), which are First Inter-monsoon (March to April), South-West Monsoon (May to September), Second inter-monsoon (October to November) and North East Monsoon (December to February). Out of the four climatic seasons, the strongest impact can be seen during the SIM (Second inter-monsoon) season when probability of receiving above-median rainfall over most parts of the Island is high during El Nino and low during La Nina events (Sumathipala, 2014). The western slope of the central hills has a considerable influence during ENSO (*El nino* Southern Oscillation) extremes with suppressed seasonal rainfall during *El Nino* events and enhanced seasonal rainfall during La Nina events in SWM (South-West Monsoon) season. Enhanced and suppressed rainfall activity is evident in the Northwestern parts of the island during La Nina and *El Nino* events respectively during NEM (North-East Monsoon) season. The weakest impact of ENSO extremes can be seen during the FIM (First Inner-monsoon) season (Hapuarachchi et al., 2015).

The forest resources in Sri Lanka are managed by the Forest Department and Department of Wildlife Conservations (Figure 01). Based on 2010 national forest inventory, the total forest cover is 2.1million of hectares and that covers 29.7% of the total land extent. Dry monsoon forest covers 2/3 of the total forest resources which are located in the dry zone of Sri Lanka (Figure 01) that receive less than 900mm total rainfall annually. Conservation forests, reserve forests, village forests and other state forests are the forest types which are managed by the Forest Department, while stick nature reserves, national reserves, and sanctuaries are the forest types managed by the Department of Wildlife Conservation.

2.4 Data Collected.

The main data needed for this analysis are weather and fire data. Weather data like rainfall, temperature, relative humidity, wind speed and direction were taken from the Meteorological Department of Sri Lanka. At the same time, the extent of forest fire damages in different forest types, forest fuel loads, canopy height, location of fire ignition, perimeter of damage, value for the fire damages, attempt to control the fire, how long from the near village or residential area were taken from the Forest Department. All weather data and fire data were collected from 2000 to 2020 (20 year period). Forest canopy cover, canopy height, canopy base height were taken from the National Forest Inventory data which were collected from 2017 and 2018 by the Forest Department. On the other hand, canopy bulk density, flue moisture content was taken from the same type of research that have been carried out in Brazil (White et al., 2012), Netherlands (Oswarl et al., 2017), USA (Scott et al., 2005) and India (Mondal et al., 2016). Because of not having field level data of the fuel moisture content on 1hr, 10hr, and 100hr time lag periods were taken from the above mentioned published information. Moreover, herbaceous and woody moisture content also were taken in similar manner.

2.4.1 Fire ignition location taken from MODIS/Aqua satellite.

Figure 05: FIRMS –NASA. Fire data

Fire ignition locations in Sri Lanka were taken from the FIRMS, NASA, fire information and resources management system. Ignition location data were taken from 2014 to 2019 (Figure 05).

2.4 Preparation of forest fire vulnerable area maps.

Forest cover data shapefiles were classified into forest type's categories. The attribute table of the forest cover layer contains forest areas, divisions, FFA (Forest Field Assistant) divisions, forest category, extent of the forest area. Meanwhile, the fire ignition location layer attributes consist of time, date, location (Lat/Log), and brightness of the ignition (significance level of damage). Separate layers were added to ArcGIS and some digitizing was done based on the fire locations. After overlaying each map layer and editing with ArcGIS, the vulnerable forest fire areas were identified in a sequential manner in each year. Forest fire ignition point layers from 2014 to 2019 were joined spatially to produce one layer by spatial joint method. After that, a forest cover layer was joined with the above composite layer via a spatial joint to make one final composite layer. From that layer based on the joint count forest fire, vulnerable forest types were selected. If the joint count was equal to or more than 20, then those areas were considered as the highest vulnerable areas. On the other hand, if the joint count was between 15 to 20, then these areas were taken as the moderate vulnerable forest type. Finally, if the joint count was less than 15 and higher than 5 then those areas were considered the forest fire vulnerable areas.

2.5 Identification of climate change impact for forest fire occurrence and distribution.

When carefully checking the weather data in the dry zone of Sri Lanka, the dry period and wind speed change significantly with time. As a result of increasing the dry weather patterns in Sri Lanka, fuel moisture content was reduced. So, to identify the climate change impact, reduced fuel moisture content and wind speed were used for fire simulations.

2.5.1 Preparation of Landscape Files (LCP).

Identification of current and future forest fire damage and risk areas are the most important part of a proper and effective forest fire management strategy. At the moment, the Sri Lankan Forest Department does not have any of the prepared

Landscape Files (LCP) that are need in the fire simulation activities. From my research, one of the most important outcomes is the landscape file for Sri Lankan forests that can be used for current and future forest fire simulations and other forestry related research activities.

Layers need to prepare an LCP file.

a) Elevation (meters)

b) Aspect (degress)

c) Slope (degress)

d) Fuel models (custom)

e) Canopy cover (percent)

f) Canopy height (meters)

g) Canopy base height (meters)

h) Canopy bulk density (kg/m^3).

A digital elevation model in Sri Lanka, which was taken from the Forest Department, was used to derive elevation, slope, and aspect raster layers in Sri Lanka, from ArcGIS pro. At the same time, a separate Excel spreadsheet was prepared with canopy cover, canopy bulk density, canopy base height, canopy bulk density, and fuel model, and listed the magnitude of those parameters in each forest type. Canopy cover, canopy base height, and canopy height were taken from the National Forest Inventory data that was carried out in 2017 and 2018 at the field level by the Forest Department. Custom fuel models were prepared to represent each forest type in Sri Lanka (30 to 36 except 33). Based on the available information on canopy bulk density from Brazil, Netherlands, and the United States that corresponds with Sri Lankan Forest types, canopy bulk density was used for the analysis with modification with the data from the national forest inventory that can be used for the Sri Lankan Forest types.

The data which was needed for the preparation of custom flue models such as flue moisture content (for 1hr, 10hr, and 100hr time lag period), woody and herbaceous moisture content were taken from the available literature from Brazil, Netherlands, United States, and India. The above mentioned Excel spreadsheet was made a table joint with a forest cover layer using ArcMap 10.4. Then other five relevant rasters layers which show the forest features were produced based on the joined attribute table with the Sri Lankan forest cover (canopy height, canopy base height, canopy cover, canopy bulk density). All layers have a spatial resolution (cell size) of 91.6m. Each spatial layer was projected into the projected coordinate system of Everest_1830_Transverse_Mercator. All raster layers were fed into ArcFuel which was the extension of the ArcMap 10.4 to produce Landscape files.

2.5.2 Custom Fuel models.

Based on Scott et at. (2005), custom fuel models were derived. On the basis of the elevation, rainfall pattern, Sri Lankan forest types were categorized as follows.

1. Dry Monsoon Forest

2. Forest Plantation

3. High elevation wet forest

4. Low elevation wet forest

5. Scrubland

6. Open and Sparse forest

The parameters that were needed to develop the custom fuel models were taken from the above mentioned references (White et al., 2012; Oswarl et al., 2017; Scott et al., 2005). The custom fuel models were numbered from 30 to 36 except 33 (See Appendix A Figure 01a to Figure 06a). Behaveplus application was used to develop custom fuel models. Almost all the time, we can see only surface forest fires in Sri Lanka while crown fires are very rare occurrences. The surface fuel load was from the tropical forests, which represented an average from of 12.5 t/ha- to 40t/ha in the forest (Ariyadasa, 2002). The forest plantations contained about 10t/ha- 15t/ha of fuel load. This amount in low elevation forest is between 13t/ha-17t/ha, scrublands presented an average of 9.18 t/ha, and the grass fields 3.7 t/ha. Correspondingly, fuel bed depth is about 2 to 3 feet in wet forest, 1.5 feet in dry forest and 1 feet in forest plantations.

2.5.3 Fire Simulation.

After preparation of the landscape file, fire simulation was done using FconstMTT fire simulation executive files. FConstMTT uses the Minimum Travel Time (MTT) algorithm (Finney, 2002), which is the most commonly used method to model fire spread and analyze burn probability because it has been incorporated into all fire simulation software applications recently developed by the USFS including FSim (Finney, et al. 2010b), FlamMap (Finney, 2006), and WFDSS (Finney et al., 2010a). FConstMTT, requires the same inputs. Spatial datasets representing topography, surface fuels, and canopy characteristics parameterize the fire behavior models at the pixel level. Wind direction and speed and fuel moisture parametrize the models for the whole simulated area. Each simulation run keeps these inputs constant, varying only the ignition location in FConstMTT.

Constant weather condition was used throughout the burn period (simulation period). Normally, in Sri Lanka, the forest fire season is from August to October when Sri Lanka faces the South West (SW)Monsoon and receives high rainfall in the wet zone and very little rainfall in the dry and intermediate zone of Sri Lanka. Specially, during those months the dry zone faces to dry wind conditions which accelerate the forest fire ignitions and fire damages. Since the dry zone and intermediate zone in Sri Lanka face dry wind conditions from the SW monsoon, this wind direction (direction of 225) was used to simulation input (based on the Meteorological Department data) with the wind speed of 4 miles per hour. Fuel moisture content was taken from the White et al,. (2013) study in Itabaiana National Park in Brazil.

FConstMTT, Wildfire simulation algorithm used mandatory switches as inputs for the simulation. Those switches are landscape files (LCP) as. lcp format, resolution of the simulations (cell size), grid distance unit (either meters or feet), wind speed (miles per hours), wind direction (if wind direction is southwest then used as 225), number of fire iterations (number of fires), fuel moisture file as, fms format, FConstMTT output file name and locations, and duration of fire (in hours). On the other hand, there are twenty options for switches that can used according to our requirement (FConst Input File Documentation). In order to find the fire damage extent, burn probability and fire line intensity (FLI), I simulated the fires using FConstMTT (Finney, 2002) with 1000 fire iterations . According to the Forest Department figures, the mean number of annual fires is around 75 (between 50 to 100). This average was then used to find the 10 to 20 years predicted impact from the forest fire under the both baseline and climate change conditions. These medium term future fire impacts under the climate change scenarios were compared with the baseline conditions and 1000 iterations were run in the simulations. These 1000 fire locations were based on an ignition grid(Figure 06) which was derived from historical fire data that was downloaded from MODIS satellite platform and weather data (Kalabokidis et al., 2014). FConstMTT is the algorithm used for minimum travel time to fire front to reach to closest burnable area. The algorithm was derived from long time field based research on fire behavior (Andrews, 2018) and it is also a type of semi-physical simulation approach. These methods are widely used in North America and other countries like Brazil to predict fire behaviors and quality of the fire (Ager et al., 2017).

Wind speed and direction were taken from the meteorological past weather data for the dry zone of Sri Lanka. A fire ignition density grid was produced from a downloaded MODIS ignition point shapefile feature by using a kernel density tool in ArcGIS pro

(Figure 06). I used 2016 fire ignition location data from MODIS satellite platform because that year had an outbreak of fire damages in Sri Lanka which resulted in the highest damage ever reported. After the ignition density raster layer was derived, the raster features were converted into ascii forms using ArcGIS pro which is compatible with the input switch in FconstMTT to fire simulations. The burn period was set to 180 minutes and 210 minutes for baseline scenario and climate change projected condition respectively, corresponding to the fire data from the fire outbreak year of 2016. In 2016, the average burn period was reported as 210 minutes (according to the Forest Department facts). Simulated fire size was matched to the size of the largest fire in the region, which burned at approximately 361 ha in 2016 (Nuwara Eliya District /Nuwara eliya range/ forest Plantation).

I executed FConstMTT for a total of 1000 simulated fires to find out the baseline information and other 1000 simulated fire with changing climatic conditions (moisture level as in Table 01, and wind speed of 5 miles per hour). After both simulations were done, I compared the baseline information with climate change altered simulation results. At the same time, baseline results were compared with the field level fire data which were taken from the Forest Department. If the ground level information was not compatible with the baseline simulated results, then I slightly altered the input variables and re-ran the simulation until the simulation results were comparable with ground level data. Fire perimeters, burn probabilities (BP) and fire line intensity (FLI) are the output results from the fire simulations. The burn probability in the coarse grain approach reflects the fire damages in the given districts or in a forest types per total forest area on that district or per total forest landscape area. The forest fire simulation used table forms of geospatial data of forest fuel, weather, ignitions, and topology data to produced geospatial output with burn probability and fire intensity (Scott et al., 2013). The simulation output result of the burn size and perimeter vector feature layer and burn probability raster layer does not have proper coordinate system (unknown coordinate system), so these layers were not aligned with the Sri Lankan boundary features. Therefore, I reprojected these two vector and raster layers using the define projection method in ArcGIS pro, to the projected coordinate system of Kandawala Sri Lankan grid. Based on the simulation results, I categorized the district by the extent of damage, number of ignitions, and the extent of damage per ignition.

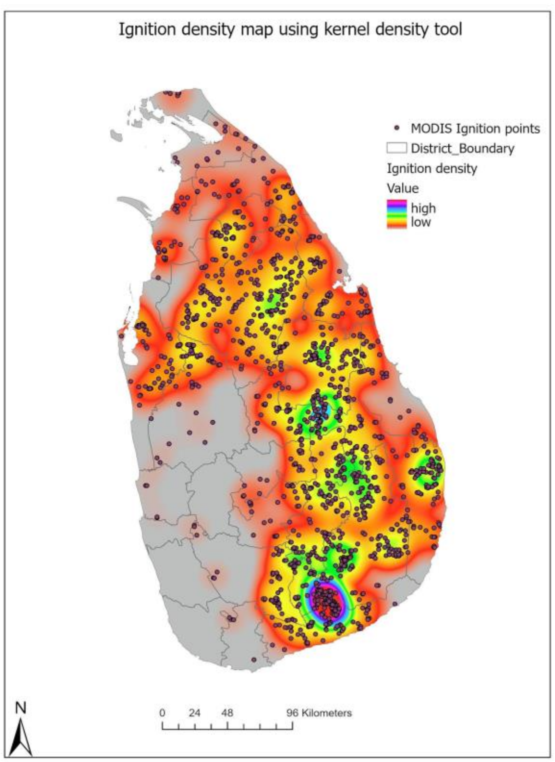


Figure 06: Ignition density map which was used to make an ascii grid file from ArcGIS pro to used as the input on FConstMTT fire simulation (as one of the switches in the simulation model).

In order to identify the climate change impact, I used the same simulation for 1000 fires under dry weather conditions with low level of fuel moisture content as in Table 1 (1hr, 10hr and 100hr time lag periods, woody and herbaceous). After that, the fire simulation output results under dry weather conditions (projected climate change impact scenarios) were compared with the baseline fire scenarios to find out the impact of climate change on forest fire occurrence and distribution in Sri Lanka. Moreover, the forest cover layer was overlaid with simulated fire output results to find out the most impacted forest types for forest fires under the climate change impact scenario. 4 miles/hr and 5miles/hr wind speed were used for throughout the fire simulations under the baseline and climate change scenario respectively. In order to get the exact figure of burn probability from the simulation output, 1000 fire iterations may not have been enough to saturate the forested landscape. In that case, I have calculated the burn probability by numerical equation as follow,

$$Burn\ Probability = \frac{Total\ Fire\ damege\ area(ha)}{Total\ forest\ land\ areas(ha)}$$

Table 01- Fuel moisture content used for fire simulation under both conditions. Fuel model represent the custom fuel models which were developed for six different forest categories (Appendix B). Fuel moisture represent for the 1hr,10hr, 100hr time lag period and woody and herbaceous materials.

Fuel model	Baseline (moisture content as %)					Climate change (moisture content as %)				
	time lag					time lag				
	1hr	10hr	100hr	woody	Herbaceous	1hr	10hr	100hr	woody	Herbaceous
0	8	9	11	40	60	4	6	8	30	55
30	8	9	11	40	70	4	6	8	30	55
31	13	15	16	55	70	10	12	14	40	55
32	11	13	15	70	60	10	12	14	40	55
34	6	8	10	35	45	4	6	8	30	50
35	7	9	10	38	55	4	6	8	30	50
36	7	9	11	38	55	4	6	8	30	50

Based on above equation, burn probability was calculated under the both baseline conditions and future climate change scenario, for the districts level and forest type categories. Then these results were plotted on a bar chart to get the clear clarification on changing of burn probability under both conditions.

The past twenty years of weather data of temperature, wind speed and direction, temperature and relative humidity in different districts were plotted (using Excel) to identify the weather variability in each district (especially the dry zone and the intermediate zone). I used Excel statistical results to get a better picture on whether temperature, rainfall and relative humidity variations were significant or not. Fire simulation results were matched with the weather variable results to find out the actual climate change impacted areas for forest fire occurrence. Finally, all results were prepared as ArcGIS maps, plotted grapes, and tables which are described in detail in the results and discussion sections. In order to validate the results, I have used the ground level fire data on Badulla, Puttalam, Anuradhapura and Monaragala. Those data were converted to percentage (based on the total damage area) and compared with the baseline and climate change scenario (percentage data) after plot with the Excel graph.

2.6 Make recommendations for preparation of fore forest fire management plan

In this study, the final deliverable is to propose some useful recommendations for future management plan preparation. To achieve this objective, I referred to relevant literature from India, USA, Brazil and Sri Lanka that includes information about the strategies on forest fire management. These strategies include mitigation, adaptation and controlling strategies. At the same time, I used my field level experience as a forest officer in Sri Lanka who is working with communities, government offices and other relevant stakeholders for forest management, conservation and forest fire management. These field level experiences are vital to propose better recommendations on preparation of forest fire management plans.

3. Results and Discussion.

3.1 Results.

This section includes main findings from the studies with several maps, tables, figures and graphs. One of the most important findings is the landscape file (Figure 06) that I have developed for the Sri Lankan forest types with customs fuel (see Appendix A, Figure 01a) model based on the Scott and Burger's (2005) guidelines of preparation of fuel models.

3.1.1 Landscape file (LCP).

Based on the forestry data and elevation data (Elevation, slope and aspect), a landscape file was derived to represent the whole Sri Lankan island (Figure 07). The LCP which includes all raster layers can be found in Figure 06a in Appendix A. The Dry monsoon forest which represents the close canopy has a canopy cover of 40% or more. Wet zone forests like wet monsoon forest, montane forests and submontane forests are categorized into the close canopy category. Historical fire data imply that most of the Sri Lankan forest fires are under the surface fire categories, with very rare occurrences of the crown fire. In that context of elevation, slope and aspect, fuel models play a major role in fire behaviors with the fuel load compared to the other forest characteristics (canopy characteristics). Forests which are located in East, North, South East and North East parts of Sri Lanka are mainly categorized as the forest fire vulnerable areas which have high dry burnable fuel loads.

Figure 07 shows the Landscape file derived from ArcFuel (Extension on ArcMap10.4) which has eight raster layers from the top left to the bottom right: elevation, slope, aspect, fuel model, canopy cover, canopy height, canopy base height, canopy bulk density. The LCP shows that most of the forest plantation, dry monsoon forest, and sub montane forest have high fuel loads (13-30mt/ha) which become more burnable under the dry weather conditions. As the climate change evets happen most of the dry zone of Sri Lanka faces to drastic drought condition that causes to dried up the forest fuel load. In that case I have used less fuel moisture level under the climate change condition for each time lag period and woody and herbaceous moisture level(Table 01).

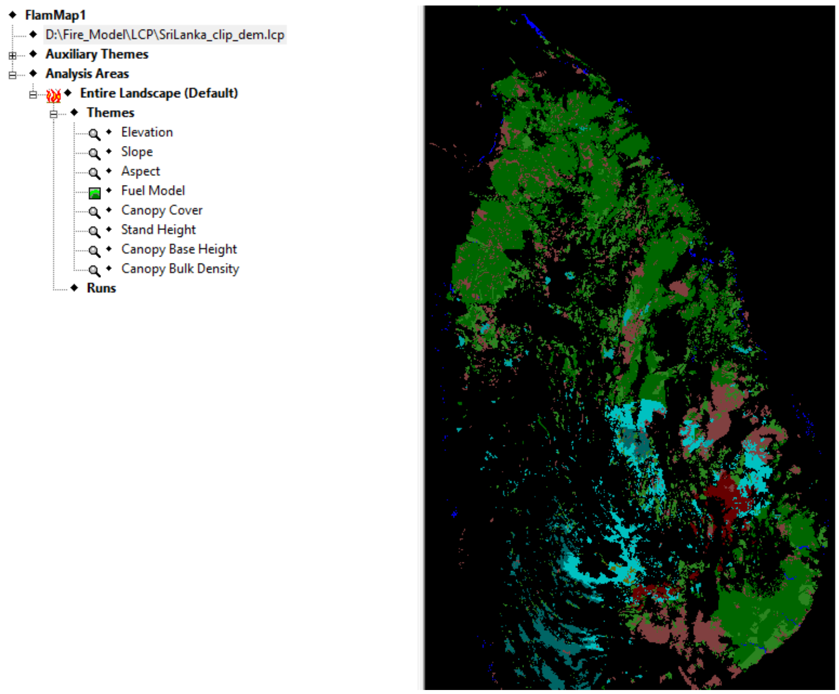


Figure 07: Landscape fire with eight Themes (raster layers). For more details see appendix A Figure 5a. (Data source: Forest Department of Sri Lanka).

The 1hr, 10hr, and 100hr time lag period fuel moisture content become less with less woody and herbaceous moisture content (for more details please see the details of the custom fuel model in Appendix I Figure 6a). Most of the rural people in Sri Lanka are dependent on forest resources for their livelihood by providing feed for the cattle by allowing them to enter the forest areas. Moreover, slash and burn cultivations, normally called as the chena cultivation, are done by the villages, creating more threats to the forest resources by opening more chances for forest fire.

3.1.2 Weather pattern changes.

Day time relative humidity changes.

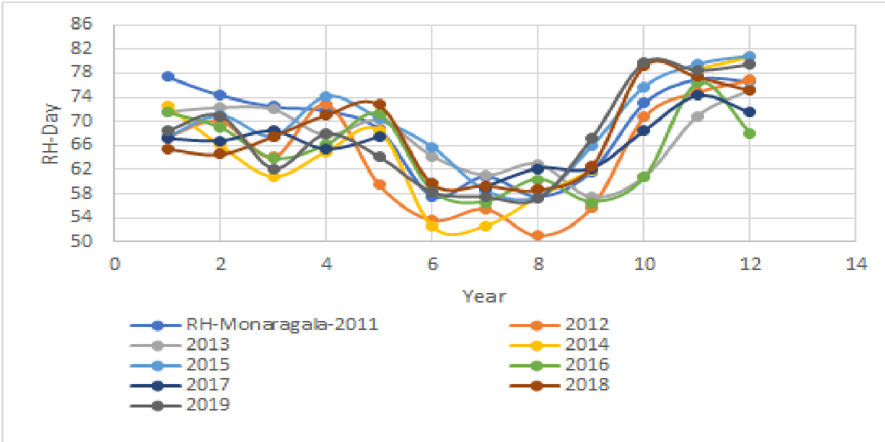


Figure 08: Day time relative humidity changes within the year in Monaragala districts. From 2011 to 2019 (Source: Meteorological Department of Sri Lanka).

Based on the Forest Department information, the Monaragala District was considered the one of the highest forest fire vulnerable districts. The months from June to September show the lowest day time RH from 2011 to 2019 (Figure 08). At the same time, the trends are almost the same as the Badulla (Figure 9) meaning that June to September represent the lowest RH compared to other months in the corresponding year. Furthermore, in 2016, September to October show the lowest values compared to other years analyzed, district which is also considered as the forest fire vulnerable district (Figure 08).

3.1.3 Rainfall fluctuation.

When we consider the rainfall pattern in the Dry Zone districts of Sri Lanka like Monaragala, Badulla, Anuradhapura, Polonnaruwa, and Hambantota, the average monthly rainfall varies significantly throughout the year.

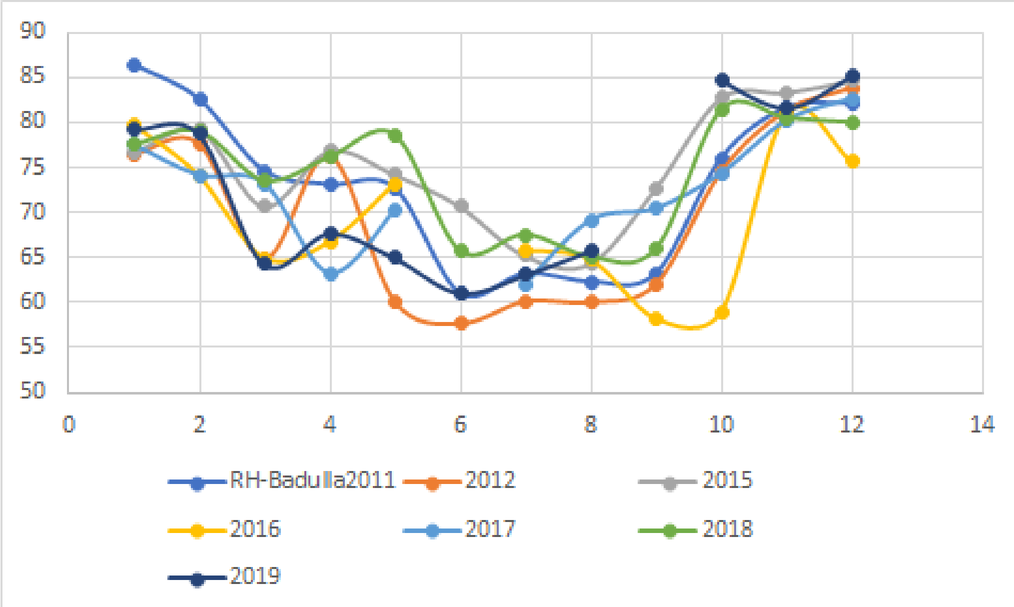


Figure 09: Day time Relative humidity in Badulla District from 2011 to 2019(except 2013 and 2014), (Data Source: Meteorological Department of Sri Lanka).

Figure 09 clearly implies that the monthly average rainfall received in 2016 is very low compared to other years. That was the year, Sri Lanka faced a fire outbreak which destroyed more than 2500ha of forest resources. Moreover, according to Figure 10, 2018 also received less rainfall compared to other years, except 2016. Figures 10, 11,12 and 13 provide data on monthly rainfall in mm for three districts in the dry zone of Sri Lanka which shows that rainfall amount received from June to September (on a monthly basis) is low compared to other months. This happened mainly because during that time period, Sri Lanka faced a South West monsoon which brought less rainfall than normal in the dry zone of Sri Lanka. On the other hand, from October to February, the same zone received higher rainfall (on a monthly basis) from the North East Monsoon and second inter-monsoon. So, in that time period, dry zone forest fuel had higher moisture content than in the June to September time period.

Mainly, rainfall, relative humidity, temperature and the wind speed with directions are the weather variables that govern the fire regime in Sri Lanka. On the other hand, ground level characteristics such as slope and elevation are the geographical factors that determine the fire regime. Population density and human impact also have significant contributions on fire vulnerability.

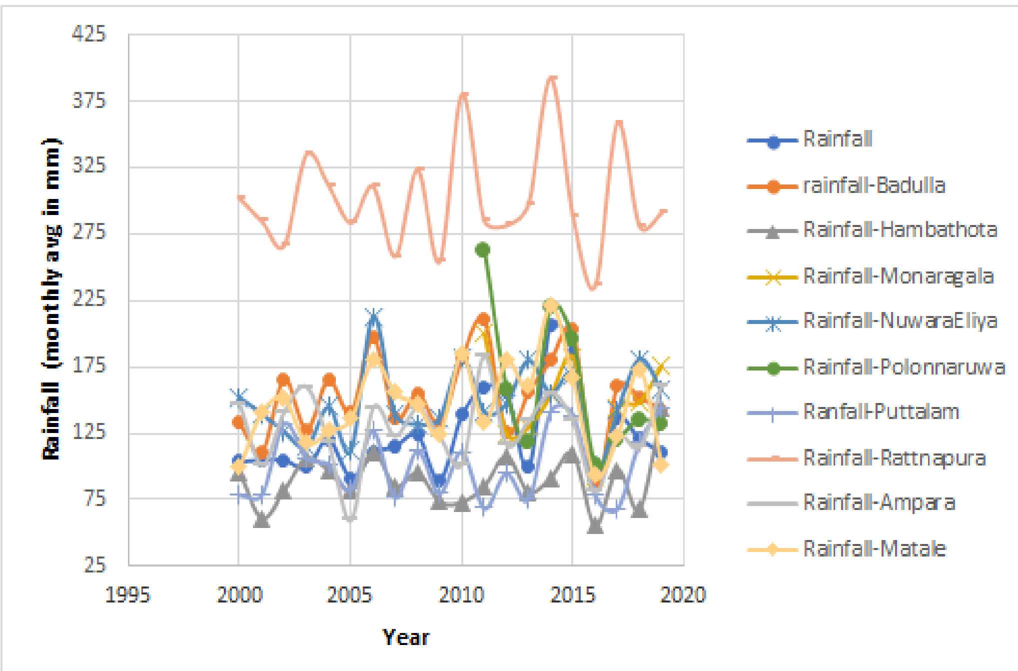


Figure 10. Monthly average rainfall distribution from 2000 to 2019, dry zone districts of Sri Lanka(Source: Meteorological Department).

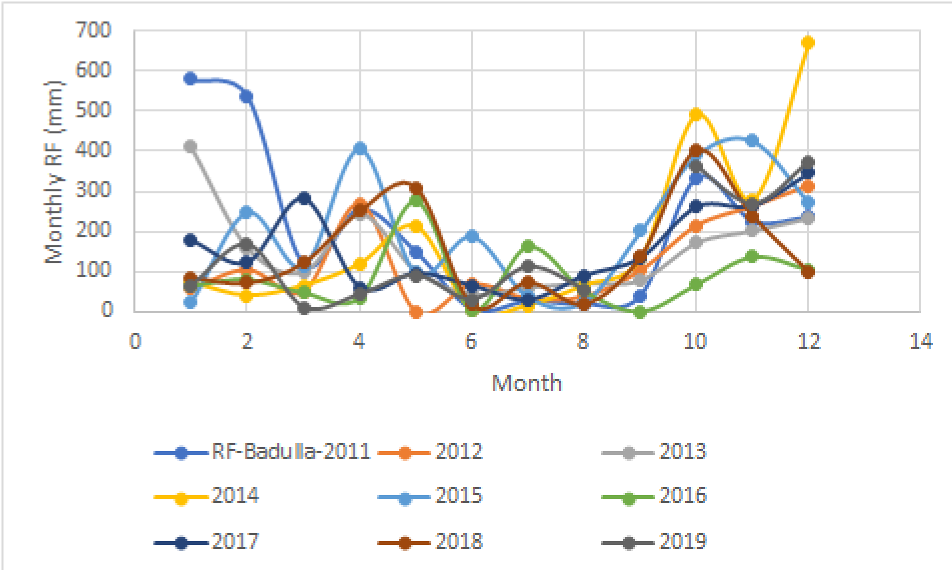


Figure 11: Monthly rainfall(mm) in Badulla district from 2011 to 2019(Source: Meteorological Department of Sri Lanka).

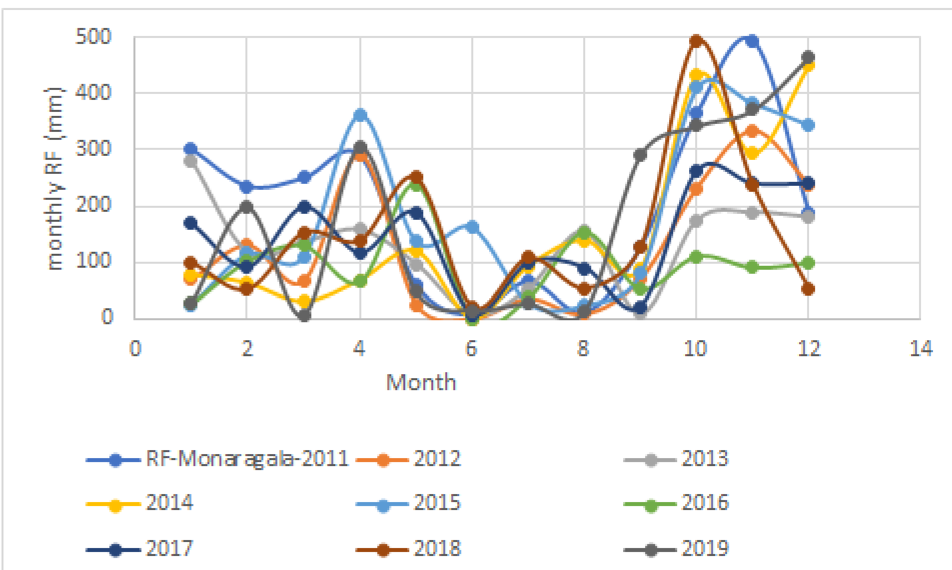


Figure 12: Monthly rainfall(mm) in Monaragala district from 2011 to 2019(Source: Meteorological Department of Sri Lanka).

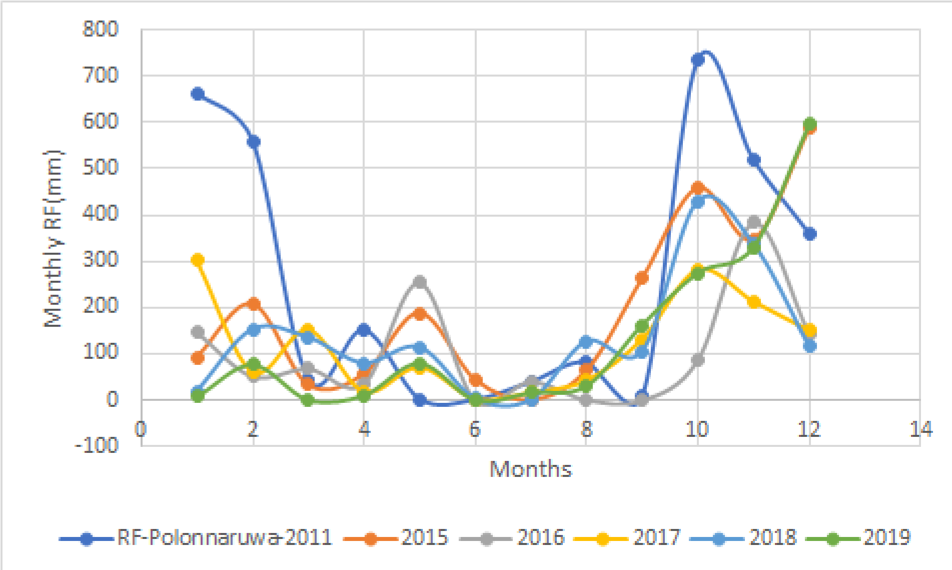


Figure 13: Monthly rainfall(mm) in Pollonnaruwa district from 2011 to 2019(Source: Meteorological Department of Sri Lanka).

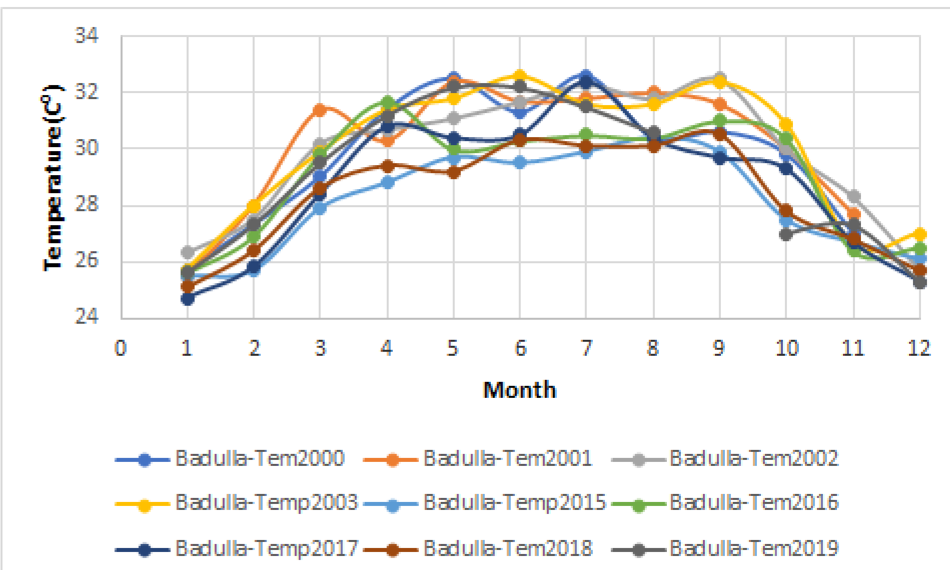


Figure 14: Monthly day time temperature in celsius, Badulla districts for several years. (Data source: Meteorological Department of Sri Lanka.)

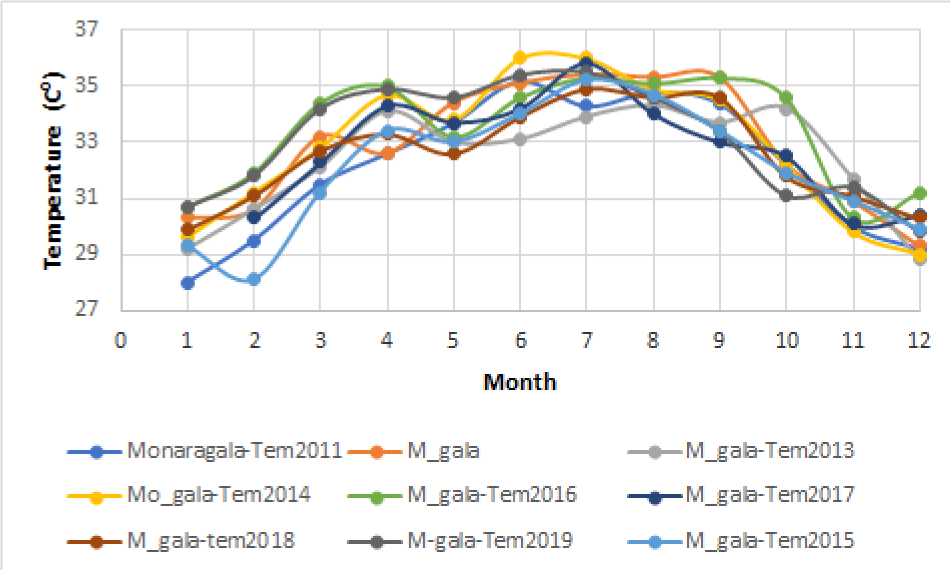


Figure 15: Daytime maximum temperature in Monaragala district. (Data Source: Meteorological Department of Sri Lanka)

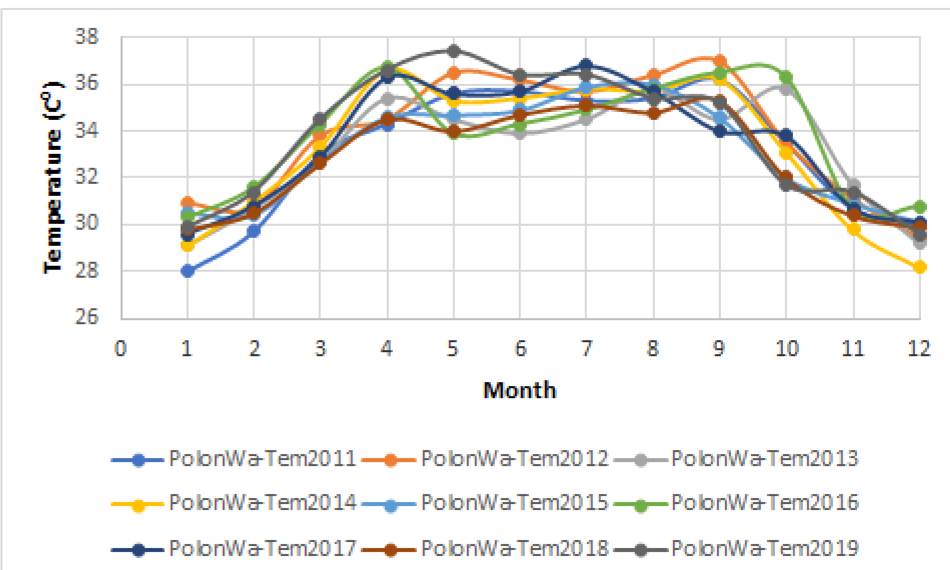


Figure 16: Daytime maximum temperature in Polonnaruwa district(data source: Meteorological Department of Sri Lanka).

Figure 14 to Figure 16 give clear evidence that every year from June to September, recorded the highest maximum day time temperature under any perspective. These months are the hottest months in the dry zone, which increase the frequency of forest fire damage and vulnerability to damage, as well as increase the extent of damage. Most of the districts in the dry zone recorded the day time maximum temperature of 35^{o}C. Furthermore, rainfall at the same time duration (from July to August) received in the dry zone are the lowest amounts compared to other months in the same year. This rainfall amount is below 25mm (monthly rainfall). At the same time, the relative humidity would be below 55% in the corresponding months. This RH amount is the lowest level compared to other months at the respective years.

3.1.5 Wildfire hazard under the projected climate change and baseline condition and Climate change projected scenario

Fire simulation was done under the existing condition (baseline condition) shown in Figure 03. The first set of the analyses examines the impact on climate change for forest fire occurrence and distribution as the objective number one. Figure 17 presents the summary of the simulation results under the baseline conditions and projected climate change conditions. Figure 17, shows the highest forest fire damage in one simulated occurrence is 726 acres (293.3ha) in projected climate change conditions. This figure shows 600 acres (242.4ha) in baseline weather and fuel moisture conditions.

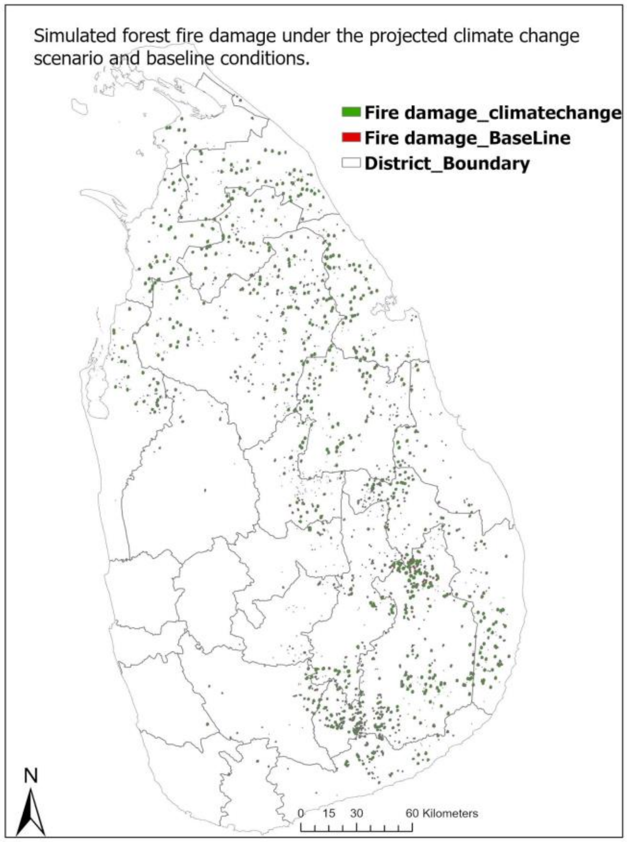


Figure 17: Fire simulation output result under the projected climate change and baseline scenario.

Statistical parameters like mean, median and standard deviations were derived for the climate change conditions for 293.758 acres, 326 acres and 144.45 acres respectively. These statistical figures for baseline scenarios are 36.61 acres, 37 acres and 59.44 acres respectively. Total simulated damages for the 1000 fire iterations are 293,758 acres and 56,617 acres on both projected climate change and baseline scenario.

Table 02: Statistical parameters on both simulated fire results under the baseline and projected climate change scenario.

Parameter	Baseline condition	Projected climate change scenario
Total Fire damage area(ac)	56617	293758
Maximum damage area(ac)	600	726
Mean damage area(ac)	56.61	293.75
Standard deviations (SD)	59.61	144.45

Table 03: Statistical parameters of Fire line intensity level in both projected and baseline condition

Parameter	Baseline condition	climate change scenario
Fire line Intensity (FIL3)	Mean- 0.001	Mean-0.001
Average Fire line intensity	Mean –0.00011 SD-0.0023 Sum-1136	Mean- 0.00055 SD-0.0052 Sum-5714

3.1.6 District level simulation result.

Table 04: Simulated fire damage statistical results under the baseline conditions in seven districts in dry and intermediate zone in Sri Lanka.

	Total Forest cover in district(ha)		Baseline			
Distrcits		Dry monsoon forest(ha)	Total damage Area(ha)	Mean	SD	No of fire
Monaragala	300231.5	110490.62	7932.94	32.68	25.57	216
Badulla	89557.07	3685.1	2571.05	34.74	30.96	74
Anuradhapura	299515.1	173388.3	1934.75	22.21	13.39	136
Ampara	218844.7	96428.91	2455.10	25.73	24.00	95
Mulaitive	182475.36	155403.3	467.02	9.53	9.77	49
Polonnaruwa	157151.67	9499.98	1384.91	16.88	15.82	82
Mattale	88728.97	15702.06	1159.07	21.07	26.53	55

Table 05: Simulated fire damage statistical results under the future projected climate change scenario in seven districts in dry and intermediate zone of Sri Lanka.

	Total Forest cover in district(ha)	Dry monsoon forest(ha)	Climate Change			
Distrcits			Total damage Area(ha)	Mean	SD	No of fire
Monaragala	300231.5	110490.62	31253.44	130.76	56.95	239
Badulla	89557.07	3685.1	7593.98	99.91	72.81	76
Anuradhapura	299515.1	173388.3	16649.64	112.49	54.28	148
Ampara	218844.7	96428.91	1519.84	125.61	54.29	121
Mulaitive	182475.36	155403.3	8237.56	147.09	36.72	56
Polonnaruwa	157151.67	9499.98	9384.11	16.88	15.82	82
Mattale	88728.97	15702.06	3408.14	83.61	73.78	41

Monaragala districts show the highest forest fire damages under both baseline and climate change scenario. These amounts are 7932.94 and 31,253.44 respectively. At the same time Anuradhapura, Mulaitive and Polonnaruwa districts show a significant level of increasing of forest fire damages. In each district level, all parameters like fire intensity line, fire damage areas seem to increase considerable levels in climate change conditions compared to the baseline conditions (Table 02, Table 03, Table 04 and Table 05). As compared with the number of forest fires assigned in each district except Mattale and Pollonnaruwa, other districts inTable 04 and 05 increased in Climate change scenario compared to the baseline level. Moreover, Badulla districts show a slight increasing of the number of fires in climate change conditions. On the other hand, fire intensity levels inTable 03 clearly indicate that the effects of climate change increase fire hazards.

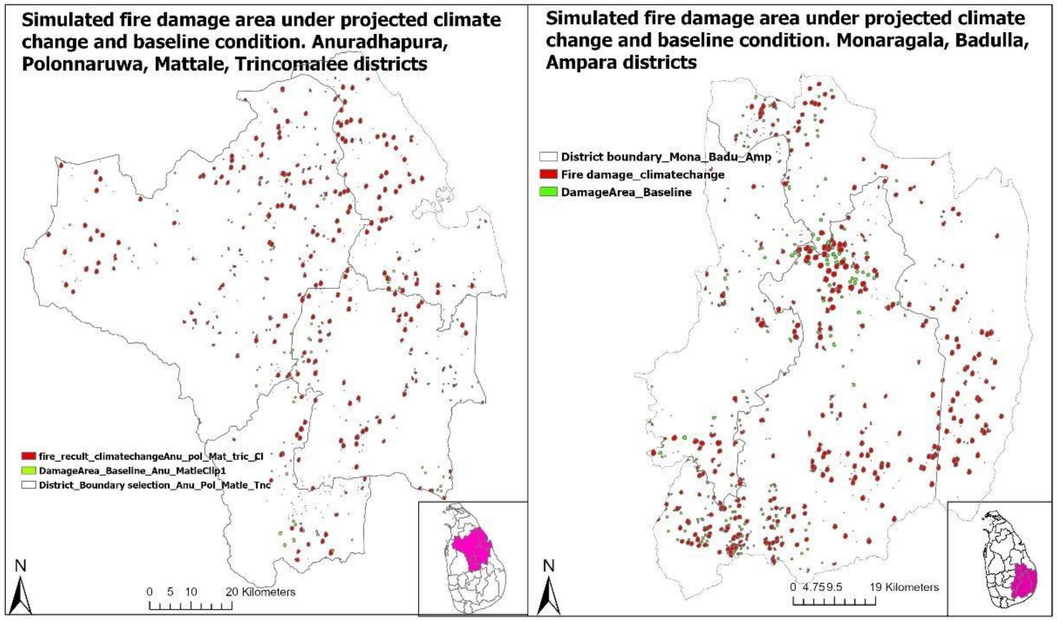


Figure 18: Simulated fire damage area under the projected climate change scenario and baseline conditions in Anuradhapura, Pollonnaruwa, Mattale and Trincomalee districts (left) and Monaragala, Badulla, Ampara districts(right).

The district-wise distribution of fire damages in climate change scenarios significantly increased the fire damage, especially in Monaragala, Ampara and Anuradhapura districts (Figure 18). The number of fire results that represent districts in Figure 18 (right) is 409 and 375 under climate change and baseline conditions, respectively. Those in districts in Figure 18 (left) are 324 and 316. The Monaragala district has the highest simulated forest fire damage under the projected climate change scenario and baseline conditions, which are about 726 acres and 387 acres respectively. On the other hand, this figure in the North central and North east part of the country (Figure 18 left) is 518 acres and 247 acres respectively under the both projected climate change and baseline scenario.

At the northern part of the island, Mulaitive and Vavuniya districts are the top forest fire vulnerable districts which have similar numbers of fires under the both simulated conditions. However, the projected climate change scenario shows the damage area of 452 acres and 155 acres under the baseline conditions. Under the baseline conditions, closer to 70% fire occurrences were found in the Vavuniya district, but these trends drastically changed under the projected climate change condition. This is because under the dry weather conditions (due to climate change impacts), considerable fire occurrence can now be seen in the Mullaitivu district as well (Figure 19).

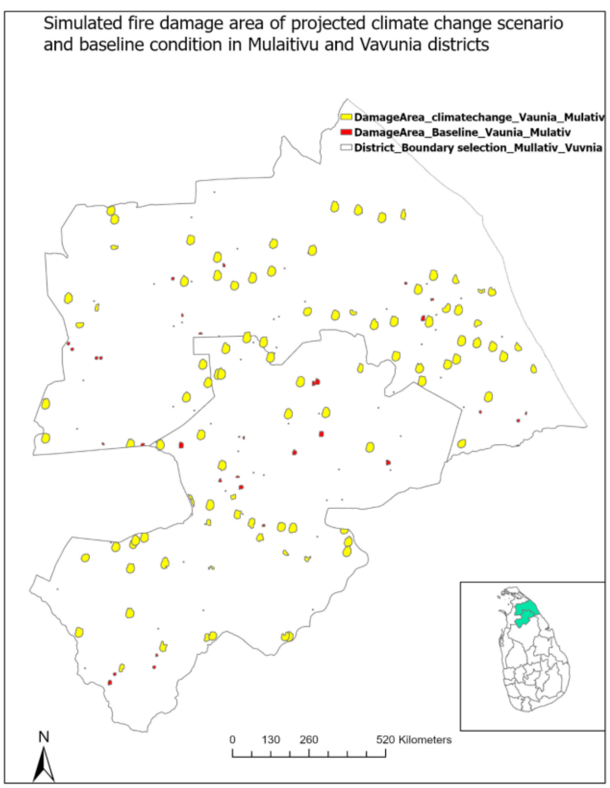


Figure 19: simulated forest fire damage areas (acres) in Mullaitivu and Vavuniya districts under both conditions.

3.1.7 Fire Intensity level (FIL).

The Fire Intensity level (FIL) is the rate of energy (heat) release per unit length of the fire front which depends (Byram, 1959; Scott, 2012) on flame rate of spread, forest fuel type, fuel load, and forest fuel moisture content (McEvoy et al. 2020). The fire intensity level (FIL) also slightly (not significantly) increased with the future projected climate change conditions compared to baseline scenarios, which means that the intensity of fire damage due to fire occurrence has increased to make the fire more hazardous for forest resources under the climate change impact. At the same time Monaragala, Badulla, Ratnapura districts level FIL1 to FIL20 is slightly higher in climate change conditions compared to the baseline level.

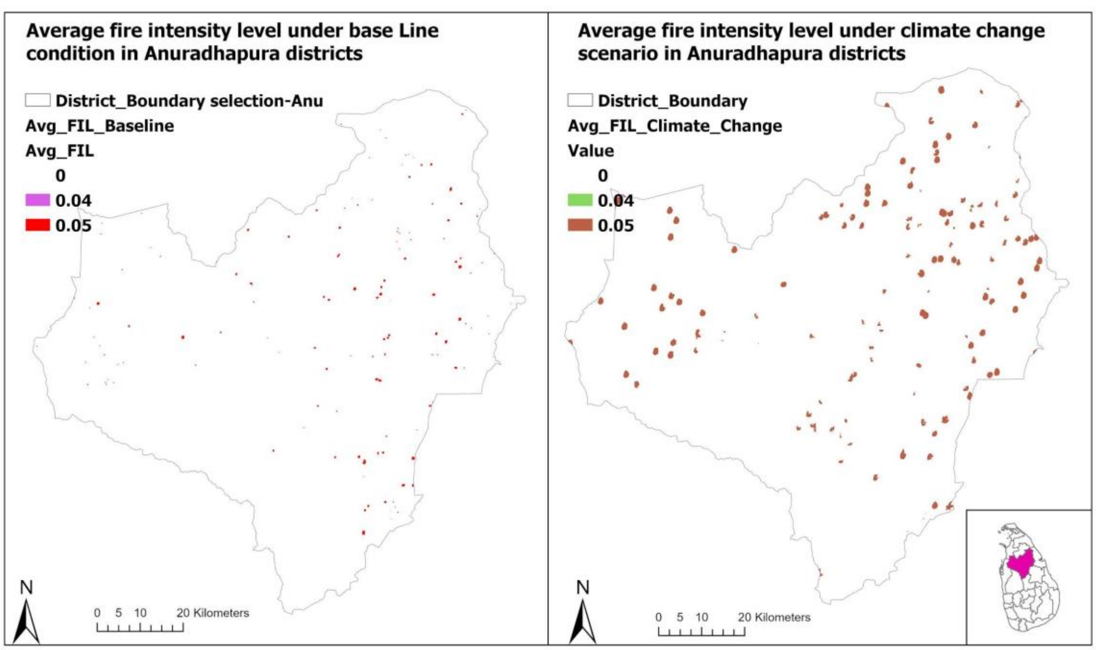


Figure 20: Average Fire intensity level (FIL) Under both baseline and projected climate change scenario in Anuradhapura district.

However, these figures are considerably higher in average FIL and FIL3, in climate change condition than the baseline level (Figures, 21,22, and Table 3) but the fire rate of spread (ROS), flame length (FL) and heat release per unit area which determine the fire severity, smoke production and crown scorch height (Scott, 2012) are increased significantly in projected climate change conditions compared to baseline levels which means that the fire hazards have increased significantly under the climate change scenarios. Moreover, in the Anuradhapura district (Figure 20 and 23) Fire intensity level increased slightly in climate change conditions compared to the baseline scenario. However as mentioned above, the ROS and flame length increased at significant level, meaning that the forest resources will be open to more fire vulnerability in future drier and hot weather conditions.

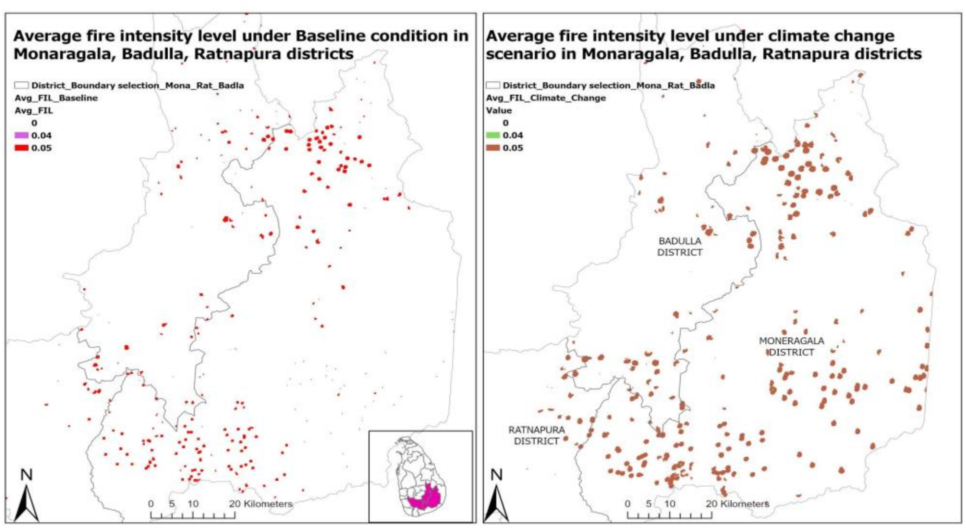


Figure 21: Average Fire intensity level in Monaragala, Badulla, Ratnapura districts under the baseline conditions and projected future climate change conditions.

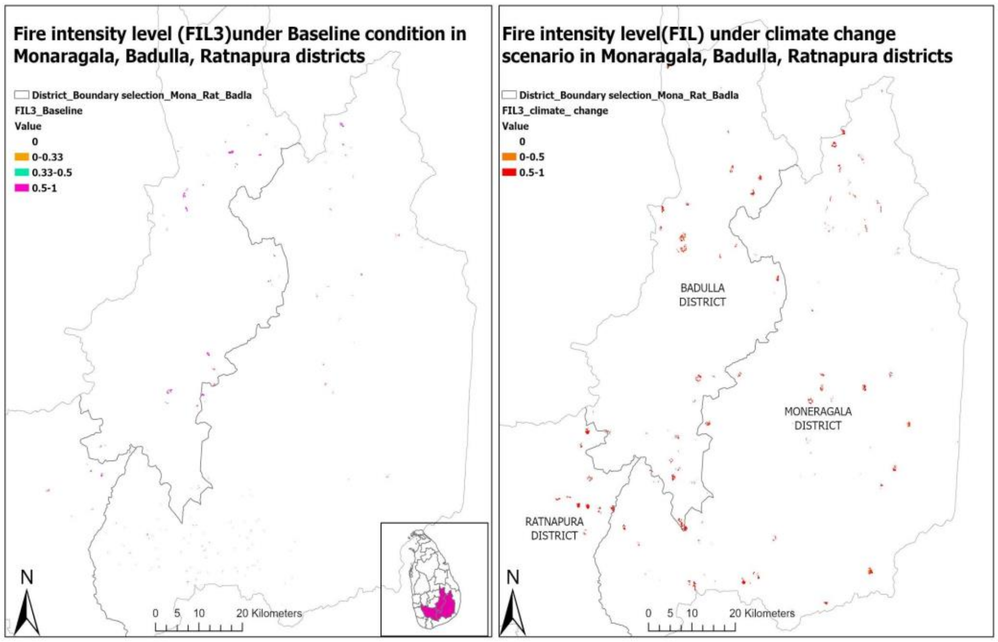


Figure 22: Fire intensity level 3(FIL3) in Monaragala, Badulla, Ratnapura districts under both conditions.

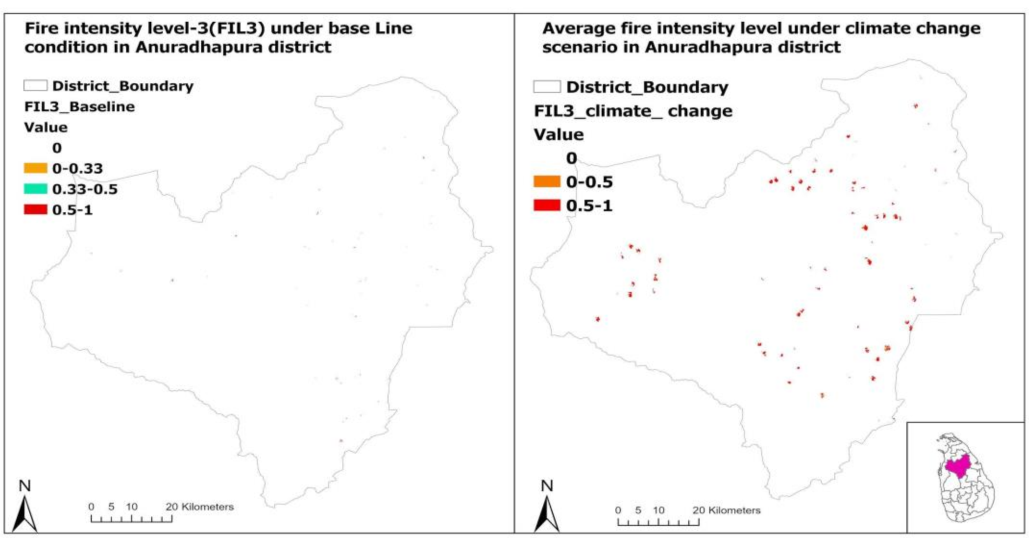


Figure 23: Fire intensity level 3 (FIL3) in Anuradhapura district under both baseline and projected climate change conditions.

3.1.8 Impact on forest fire damages on Dry monsoon forest and other forest

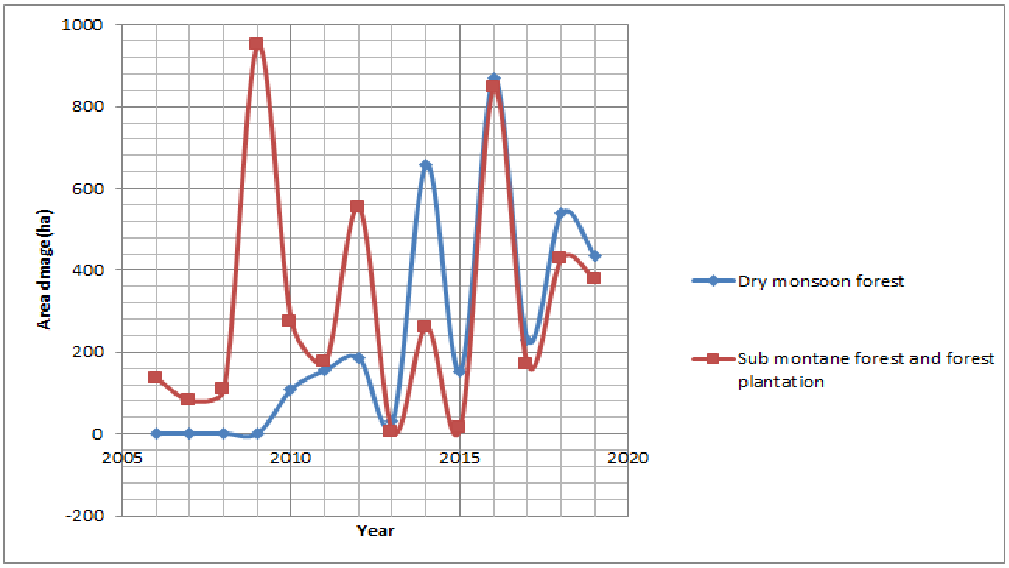


Figure 24: Forest fire damages from 2006 to 2019 on dry monsoon forest, forest plantation plus sub montane forest. (Source: Forest Department).

Figure 24 shows that from 2006 to 2009, no records were found which reported damages to the dry monsoon forest due to forest fires. At that time the highest vulnerable forest category would be the forest plantation. On the other hand, after 2009 we can see a significant increase of forest fire damages to the dry monsoon forests. As mentioned at the introduction, dry monsoon forests cover 2/3 of the total forest resources in Sri Lanka. Because these forests provide more ecosystem services in Sri Lanka, it is important to take good management actions to control forest fires to protect these valuable forest resources. These forest areas act as the catchment for Mahawelli, Menik, Walawe River which nourish the dry zone agricultural lands.

Burn probability was calculated from ratios between total burn area and total forested area in a particular district. As Figure 25 shows, the Badulla district shows the highest burn probability of 0.7, under the baseline condition while with the projected climate change scenario of these values is 0.08 meaning that future risk for fire vulnerability under the climate change scenario in Badulla district is significantly reduced. As fire simulation results imply, the Monaragala, Anuradhapura, and Mulaitive districts show the burn probability of 0.071, 0.01 and 0.003 respectively (Figure 25), but under the future climate change conditions those values are 0.1, 0.055 and 0.04 respectively. This means that the Moneragala, Anuradhapura and Mulaitive district will have the most vulnerable forests for the future climate change impacted forest fires. As Figure 25 shows, in other districts like Mattale and Ampara, the burn probability under the climate change scenario is less severe compared with the baseline conditions. At the existing condition, the Mattale district is considered a moderate forest fire vulnerable district. On the other hand, it becomes less vulnerable under the future climate change scenario.

When we compare burn probability in different forest types, dry monsoon forest, open and sparse forest and forest plantations show the values of 0.003, 0.01, and 0.005 correspondingly under the baseline conditions (Figure 26). Furthermore, those figures under climate change conditions are 0.06, 0.08 and 0.033 respectively.

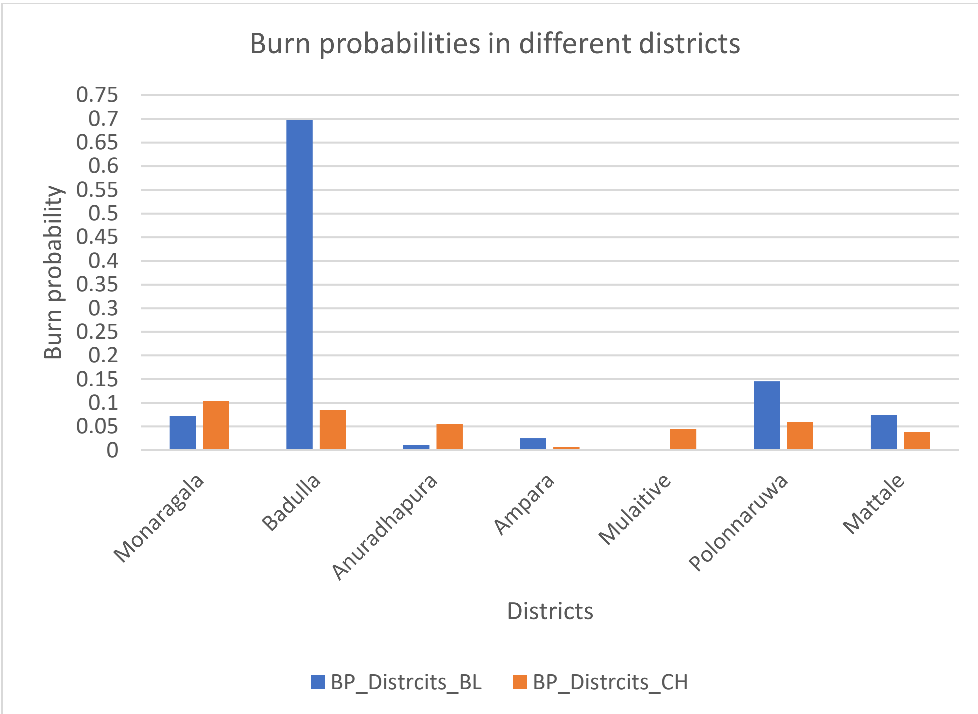


Figure 25: Burn probability under projected climate change future scenario and baseline scenario in Monaragala, Badulla, Anuradhapura, Ampara, Mulaitive, Polonnaruwa and Mattele districts.

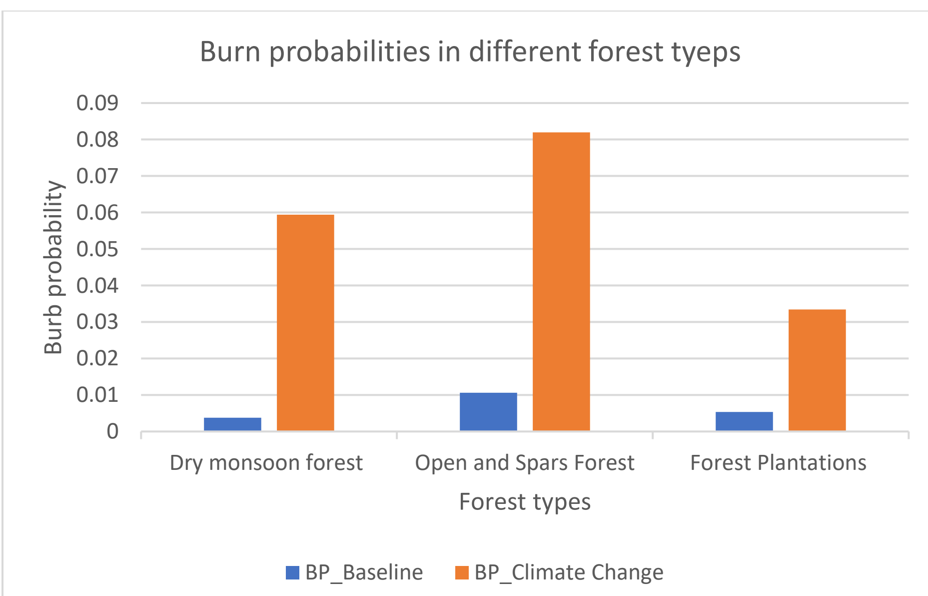
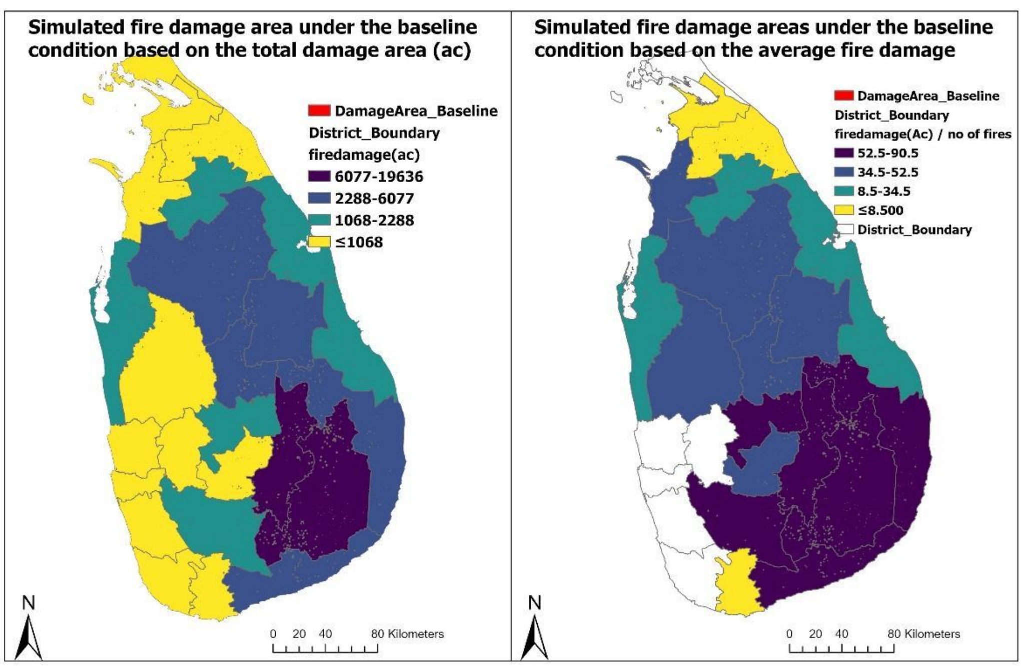


Figure 26: Burn Probability of simulated fire under the both projected climate change and baseline condition in Dry monsoon forest, Open and spare forest and forest plantations.

On the basis of the initial baseline values, Dry Monsoon Forest shows the highest increasing of burn probability followed by open and sparse forests and forest plantations. However, open and sparse forests show the highest level of increasing burn probability under the future climate change scenario. So based on the burn probability values, dry monsoon forests, and open and sparse forests show the highest vulnerability for future forest fire damage under the climate change events (Figure 26).



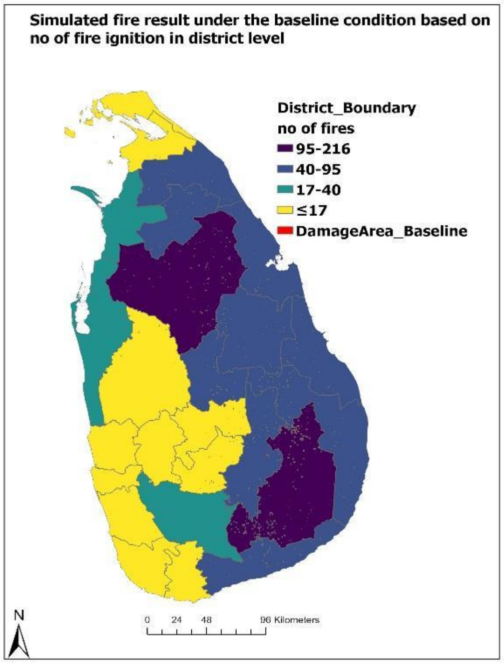


Figure 27: Simulated fire scenario under baseline condition, Fire damage area per ignitionI(right) and total fire damage areas (left). The extent in acres. simulated no of fire occurrence (bottom left).

Based on the baseline scenario, the Monaragala district has the highest fire damage among other districts with the highest fire damage per one fire incidence followed by Badulla and Anuradhapura districts. The total simulated fire damage areas is 56,617 acres. The percentage of fire damaged areas in Monaragala districts is about 51% from the total simulated fire damage areas (Figure 27, top left). At the same time, Monaragala and Badulla districts show the highest areas damaged in one incidence (Figure 27, top right). On the other hand, Anuradhapura and Monaragala districts show the highest number of fire occurrence under the simulated fire (Figure 27, bottom).

3.1.9 Fire simulation results under the baseline and projected climate change scenario (dry weather and fuel moisture conditions)

Fire simulation with baseline conditions.

The districts like Monaragala, Ratnapura, Pollonnaruwa, Baddulla have a high risk for forest fire damages, and dry monsoon forests, scrubland, open and sparse forest have a high risk for forest fire damages (based on 1000 fire simulation results). Mean forest fire damage extents in baseline conditions is about 56 acres (22.6 ha). The biggest damage is 600 acres (242.4ha) and the minimum extent of damage is 2 acres (0.8ha). Test statistics show that the standard deviation of forest fire damage is 59.44 acres (24ha). The simulated results are properly tallied with the annual forest fire spatial and temporal data (extent of damage, district and forest types) (Table 04)

3.1.10 Risks Categories (districts) under the projected Climate change scenarios.

Based on the future projected climate change conditions, the severity of fire damage and fire hazardous increased drastically in Monaragala districts. The total fire damage on island is 293,758 acres with the mean damage of 293.75 acres , Standard deviation (SD) is 144.45 acres.

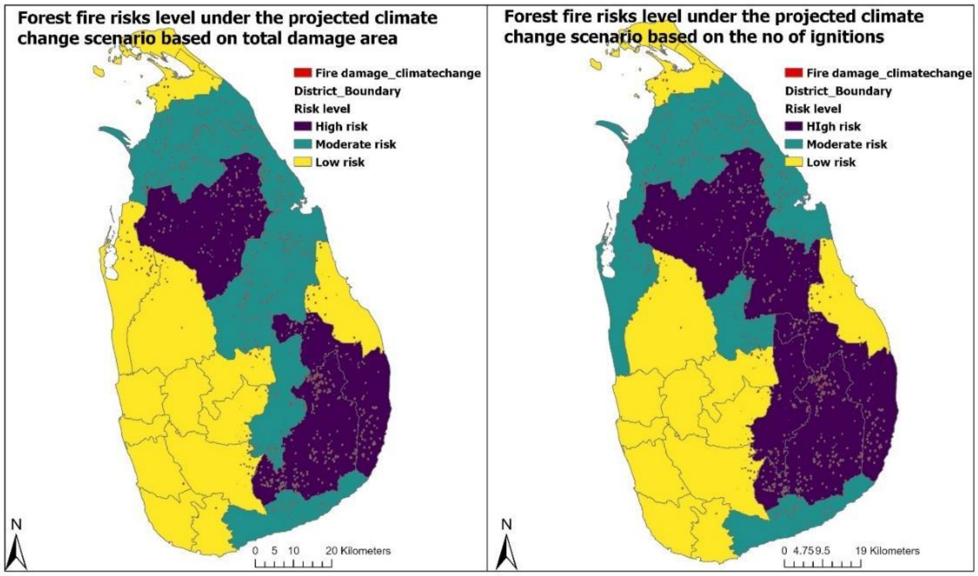


Figure 28: Risk areas for fire simulation under the projected climate change scenarios. based on the total damage area(ac) (left). Based on the fire damage areas(ac) per one incidence (right).

One of the objectives of this study is to categorize the fire damage area under three groups of low, medium, and high fire risks areas. Risk areas were categorized based on the total area damage, number of fire ignitions, and damage area per one incidence. The threshold level was decided based on total damage area and number of fire ignitions. Total damage areas that have equal to or less than 12,585 acres are considered the low forest fire risk areas, districts that show fire damage areas between 12,585 acres and 36,380 acres are considered moderate risks areas and other areas are high risk areas. On the other hand, the districts which show the number of fire ignitions equal to or less than 21, categorized as the low risk areas, number of fire ignitions are between 21 to 60 areas consider as the moderate risk areas and other areas are the highest forest fire risks area. As the Figure 28 (right) shows, based on the number of fires (fire number) Monaragala, Ampara, Anuradhapura, Polonnaruwa, Trincomalee, and Mullaitive are under the high risk category in the projected climate change scenario. However, based on the only fire damage area (ac) Monaragala, Anuradhapura, districts are the high risks area for future climate change impact from forest fires (Figure 28 right). On the other hand, in Figure 28a, Ratanpura, Hambantota, Mattale, Anuradhapura, Trincomalee, Batticaloa, Kandy, Vavuniya are the risk areas for fire damage on the basis of fire damage areas per incidence. Total simulated fire damage area under the projected climate change scenario is approximately 293,758 acres and 41% from the total damage represented in the Monaragala district.

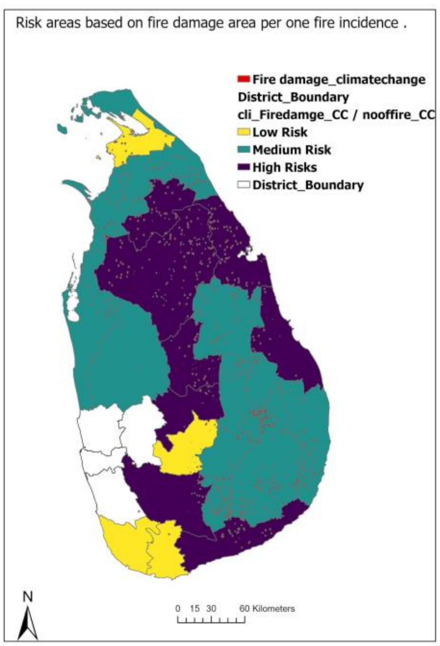
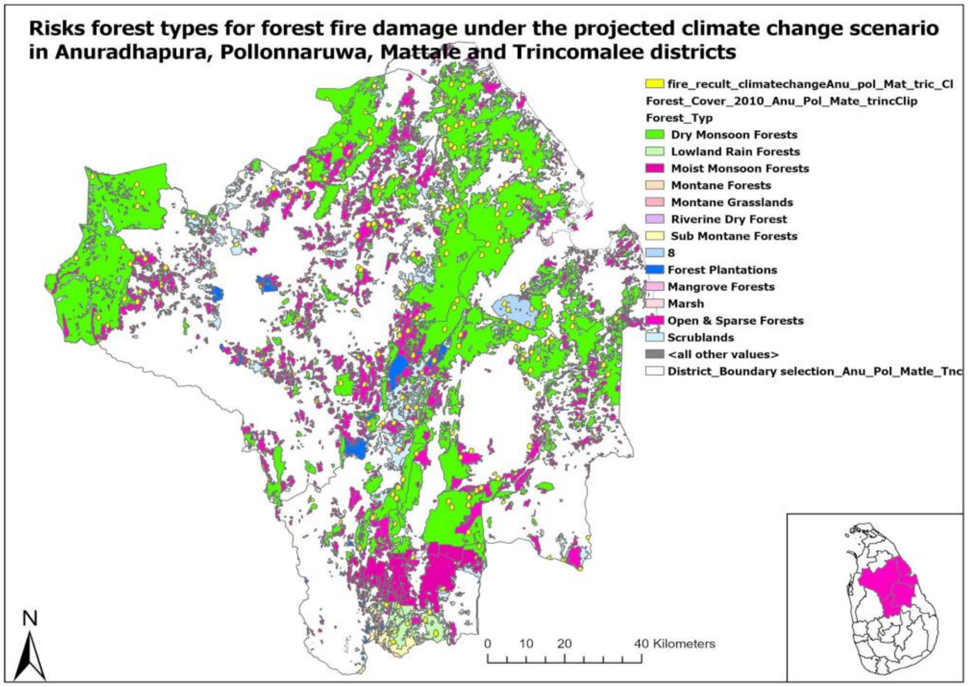


Figure28a: Risk areas based on the fire damage areas(ac) per one fire incidence under the projected climate change conditions.

3.1.11 Risk forest types for fire damages under the projected climate change scenario.



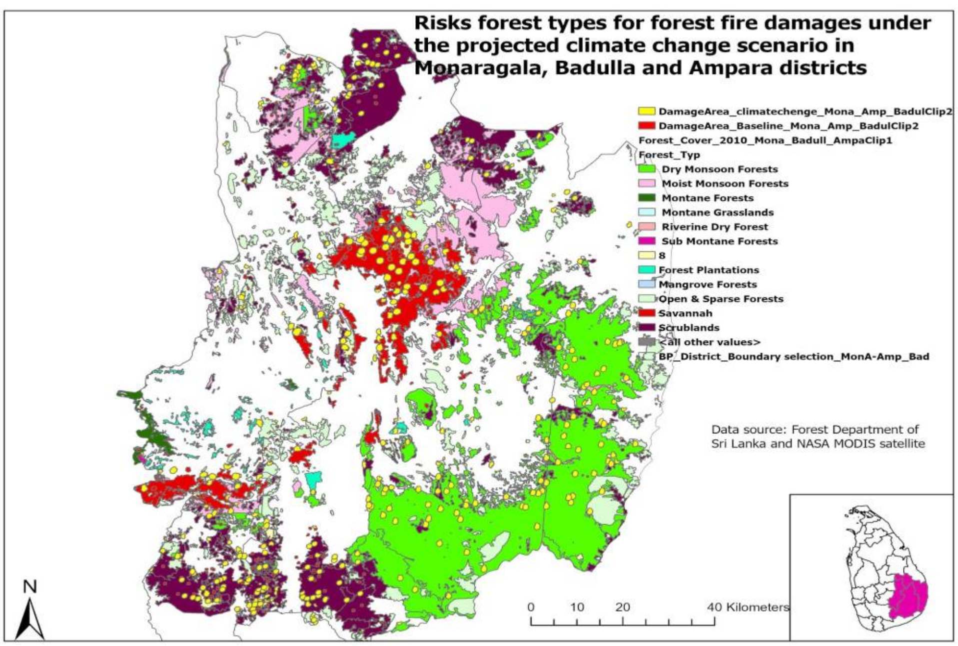
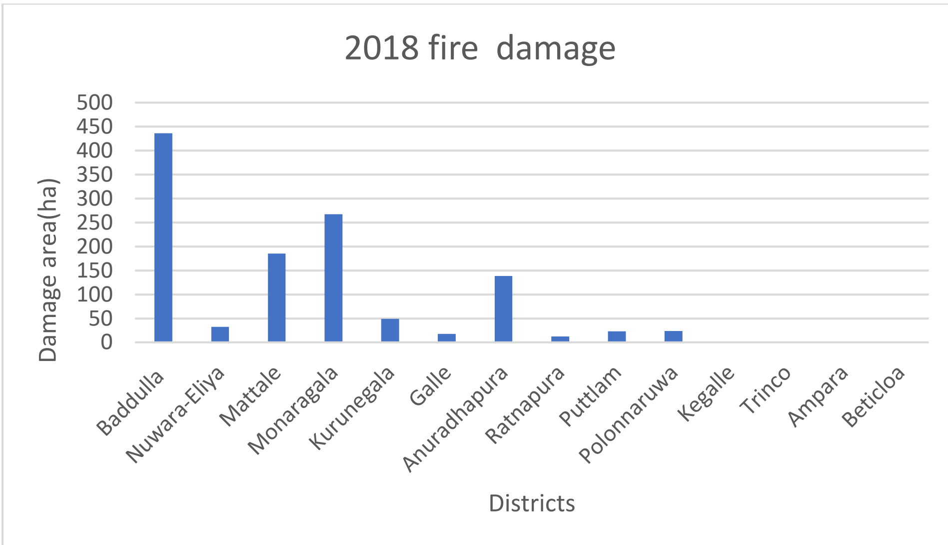


Figure 29: Risk forest types for forest fire damages under the projected climate change conditions. Anuradhapura, Mattale, Polonnaruwa and Trincomalee districts (top figure). Monaragala, Badulla, Ampara districts (bottom figure).

As discussed before, the ground level figure in the past few years implies that the dry monsoon forest has the highest forest fire damages. Of the forest types found in the districts in Figure 29 (top), dry monsoon and open and spare forests are the highest forest fire damages under the projected climate change conditions. On the other hand, districts in Figure 29 (bottom), including dry monsoon forests, scrubland and savannah, open and sparse forest and forest plantations are the forest types with the highest vulnerability for forest fire damages under climate change.

3.2 Validation of results.

The Forest Department figures on forest fire imply that the higher forest fire damages were recorded in Badulla districts in both 2016 and 2018 (Figure 30) which are about 805.9ha and 436ha respectively. As mentioned earlier, 2016 is the out-break year that showed the higher forest fire damage ever reported. At the same time, 2018 (Figure 30) also reported considerably higher forest fire damages compared to other years except 2016. Puttalam district shows the minimum extent of forest fire damages in 2016 which is about 11.5ha and Ratnapura district in 2018 is about 12.5ha. For that reason, I have used the filed level forest fire data on 2016 and 2018 to validate the simulated baseline results. In order to validate the data, the Badulla district was used as the highest fire damage district and Puttalam district was considered the lowest forest fire damage district (Figure 30).



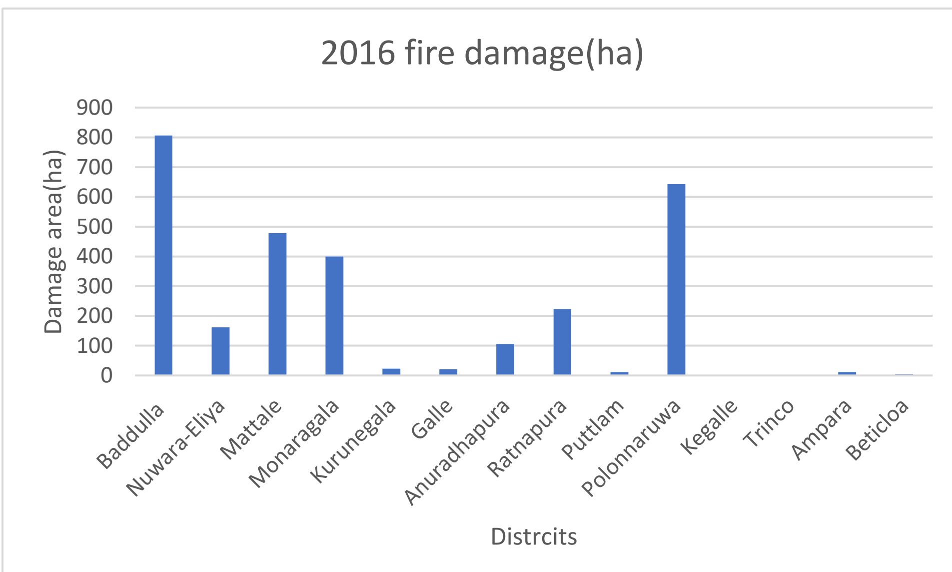
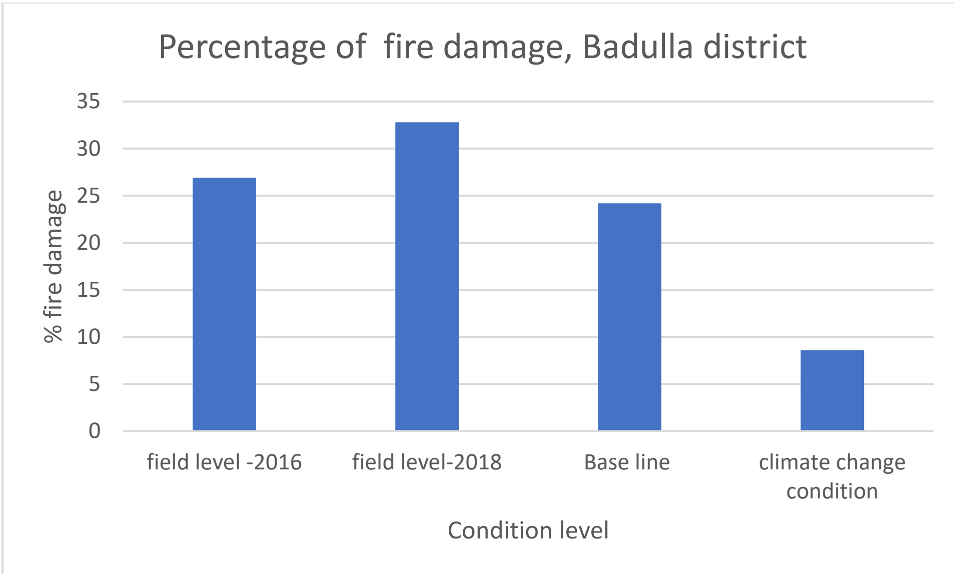


Figure 30: District level forest fire damage in hectors(ha) in 2018(upper) and 2016(bottom). Source: Forest Department.



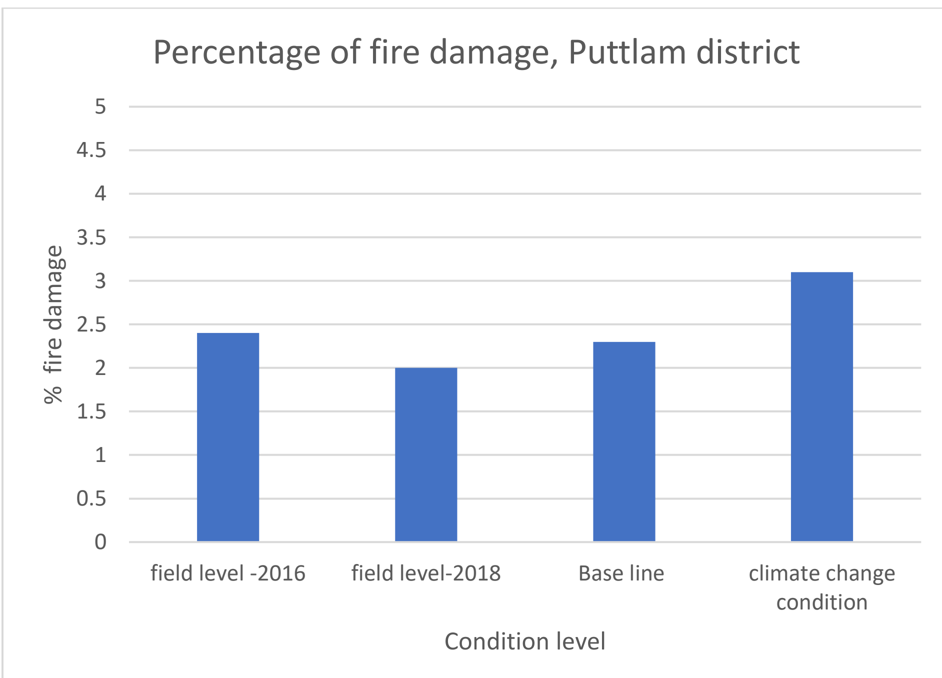
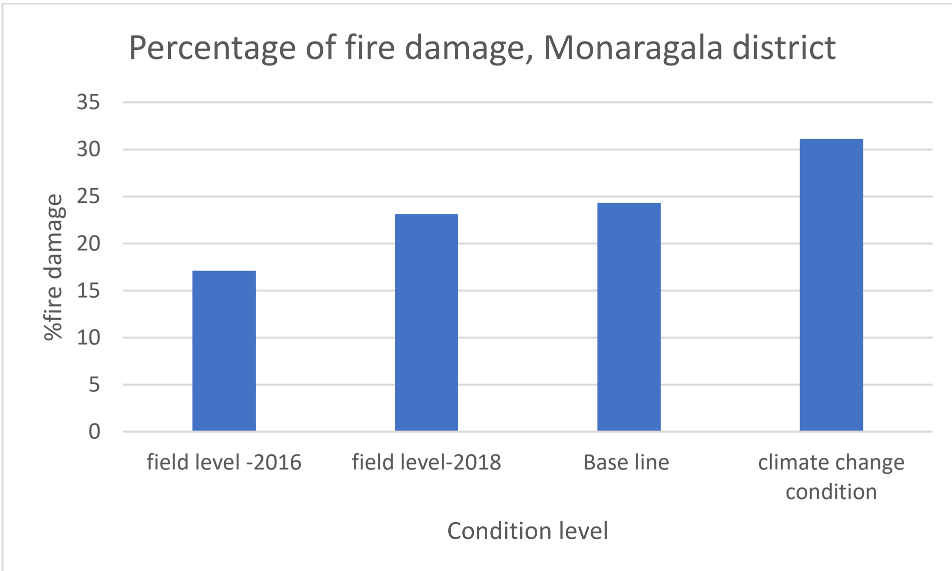


Figure 31: Percentage of forest fire damages (from the total fire damage) in Baddulla district(upper) and Puttalam district (bottom). Source: Forest Department.

As Figure 31(Upper), 2016 field level forest fire percentage of damage (from the total damage) in Badulla districts is more or less similarly comparable with the simulated baseline results.



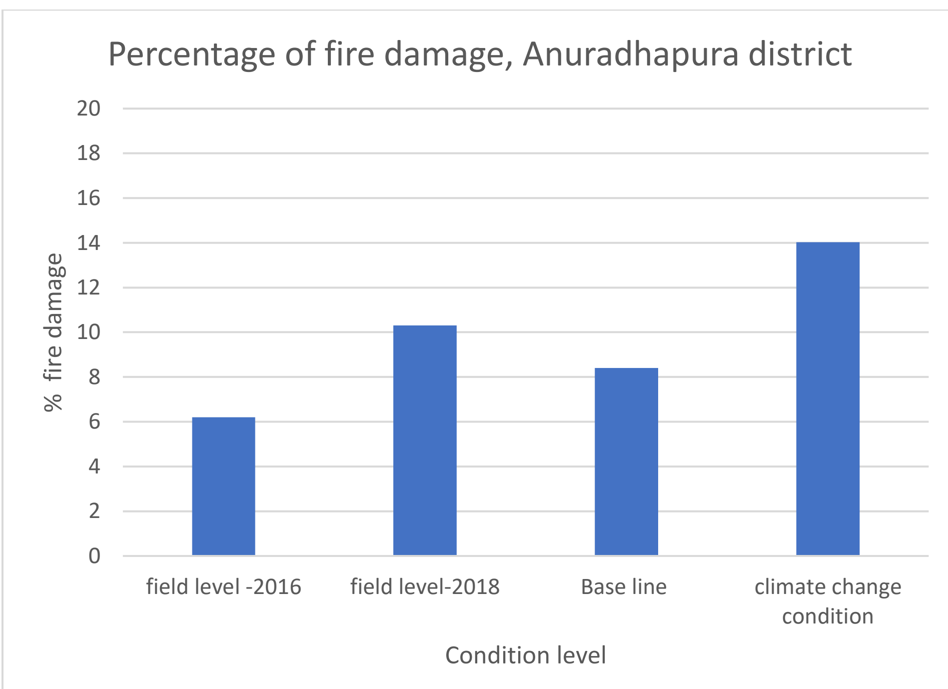


Figure 32: Percentage of forest fire damage in hectors(ha) in Monaragala districts(upper) and Anuradhapura districts(bottom). Source: Forest Department.

These figures are 26.8% and 24.8%. At the same time percentage of forest fire damages in Puttalam districts (lowest reported) is 2.4% in 2016 and 2% in 2018 (Figure 31 - bottom). Moreover, this percentage is 2.3% under the simulated results in the baseline scenario. So, the field level data are clearly validated with the fire results on simulation under the baseline conditions. As Figure 32 (upper) shows, Monaragala districts' 2018 filed level data clearly validate the simulated baseline condition. Those figures are 23.1% and 24.3% in both 2018 and simulated base line results correspondently. At the same time in Anuradhapura districts (Figure 32 bottom) those figures are 6.2%, 10.3% and 8.4% in 2016, 2018 and simulated baseline scenario respectively. So, field level data are more or less validated with the simulated baseline condition. On the other hand, the Figure 31 (upper) clearly imply that the climate change scenario the percentage of forest fire damage in Badulla district reduced compared to the baseline condition. However, this trend in completely inversed in the Monaragala district, meaning that the future climate change condition of the Monaragala district shows the highest impacts on forest fire damage. As Figure 32 (upper) shows, the percentage of fire damage in the Monaragala district has significantly increased under the climate change conditions compared to the baseline condition. This fluctuation is more less similar to other districts (Figure 32) except Badulla district.

3.3 Discussion.

In Sri Lanka, one of the main causes for forest fire damage is human involvement and there are no natural occurrences of forest fire like heavy winds and lightning. In places where the human activities are high, there will be a high risk of the forest fire damages. As mentioned earlier, July to September is the forest fire season in Sri Lanka. At that time, most of the schools and high level education institutes give vacation for the students. Therefore, this is the good season for picnics and most of the people are visiting scenic places which have forest resources. Most of the nature parks and reserves get fully loaded with visitors at that time. As a result of careless behavior of such visitors, sometimes fire ignitions may happen. Also, open and sparse forests are located adjacent to rural living areas and most of the village residents' daily routines are within the open and sparse forests. Most of the chena cultivations (slash and burn) are done in these forested areas which is also elephant habitat. As a result, human-elephant conflict can also be found in those areas. To move elephants out from the agricultural areas and to get fresh grass from the old vegetation for their cattle herd, people intentionally and accidentally ignite forest fires. Most of the fires start from the places where people's actions are. Open and sparse forest types are located very near villages and rural areas where the people live and have their activities. So, most of the forest fires start from the open and sparse forest and disperse into the dry monsoon forest types being that the dry monsoon forest types are often adjacent to the open and sparse forest. That is the main reason why the dry monsoon forests have the highest forest fire damages under both climate change and baseline scenario. As mentioned earlier, most of the forest fire ignitions arise from the open and sparse forests and then disperse in to the dense forest so we assume that from other land use categories such as agricultural lands fire burning not happen. This assumption seems to be more correct as the main causes of forest fires in Sri Lanka is the human impact that may happen with the chena cultivation areas which are next to the open and spare forest types.

When we carefully analyze the ignition location with roads, it can be clearly seen that most of the ignition locations are very near to the roads (may be rideable or walkable). When we calculate the Euclidean distance to the ignition point from the nearest road, most of the ignition points have less Euclidean distance, which indicates that most of the ignition may start due to human involvements. Fire simulation can also be used to evaluate how fire is expected to spread across the landscape including the likelihood and intensity of expected fires (Steven, 2017).

3.1.1 Climate change impact on forest fire occurrence and distributions

Weather data like rainfall, temperature and relative humidity (Figure 08 to Figure 16) are highly varied among the dry and intermediate zones, which are enhanced by the dry and warm weather patterns in the northern, north-east , north-central and south-eastern part of Sri Lanka. When we carefully analyze the weather scenarios, the frequency of the dry conditions occurring over the past few years seems to have increased. For example, as Figure 08 indicates, low rainfall was received in 2016 and this has happened again in 2018, which means that the variability of rainfall received from the North-East Monsoon has increased, suggesting that the average annual and monthly average rainfall has reduced drastically in several years. This variability of such reduction (frequency) has increased significantly. This variability directly relates to the climate change impact, which is mainly due to global warming and changing the sea surface temperatures. As a result of changing the sea surface temperatures in the Indian Ocean, rainfall wind currents blowing through the Indian Ocean may vary (Abeysekera, 2019). As a result of this variance, the time duration and moisture that is carried by the North East Monsoon has changed and this fluctuation has increased with time due to climate change and global warming. At the same time, day time temperatures have increased with the dry weather patterns and reduced the relative humidity with increase of wind speed. These weather pattern changes create fuel load, more dry material, and increase the possibility of ignitions.

My results suggest that the forest fire hazards in the dry zone of Sri Lanka could significantly increase for the near future under projected climate change conditions. Most interestingly, as Figure 19 shows, there are few fire occurrences in Mulaitive districts under the baseline condition. However, the projected climate change scenario shows the significant increase of fire damage as the number of occurrences, damage areas and burn probability as well. Fire damage areas over the whole island drastically increased under the projected future climate change condition when compared with the baseline condition. This is a 3.8 fold increase from the baseline conditions. In this analysis, the burn period of the baseline condition set to 180 minutes, which tallies with the 2016 fire information from the Forest Department and projected climate change burn period set to 210 minutes with a slight increase of wind speed. Burn probability in the Monaragala district also increased significantly under the projected future climate change condition. Furthermore, districts like Anuradhapura, Mulaitive showed an enhancement of burn probability with future climate change projections.

In addition to increase of forest fire hazards under the future climate change projections, the fire size also increased significantly in almost all districts in the dry zone of Sri Lanka. Distribution of fire ignitions are influenced by several factors like climate factors (rainfall and temperature) and vegetation types that determine the continuity of fire, significant level, fuel characteristics, and population density and level of human activities (Holz et al., 2018). During extreme fire conditions, hot, dry and windy conditions can lead to large fires in dry monsoon forests, scrubland, forest plantation, including savannah forest that can be found in Badulla and Monaragala districts. Warming and drying trends that are projected to continue into the future for much of the dry zone of Sri Lanka will further promote fires in these fuel-rich forests, such as dry monsoon and forest plantations.

These findings are more useful for making forest fire mitigation and adaptation decisions, which can be used to manage forest fire damages. When allocating funds and resources for forest fire prevention and management, it is better to give high priority to those areas which will have high risk for forest fires under the climate change scenario. As these findings suggest, the future climate change scenario will create more damage to the forest ecosystem especially and Monaragala, Anuradhapura, Polonnaruwa, Mulaitive, Districts which need to take immediate action to protect natural resources from the forest fires. Therefore, we need proper scientific approaches to fire management with active engagement with people and other stakeholders. As wildfire affects the wide range of ecosystem services at present and future, that will give the uncertainty for every sector which opens the doors for robust adaptation plans (McEvoy et al., 2020).

This research gives practical and valuable information for the Forest Department officers and other local and national level government, as well as managers, policy makers, planners to guide decisions around climate adaptation in land use management, wildfire management, forest management, water provision and other fields which would be effected by forest fires.

According to Table 6, the rainfall receiving variability is very high in North-East Monsoon season. Dry weather conditions enhanced the ignition probability of fuel load and dry matter content on the fuel load contributes to high burn probability. As Figure 31 shows,the percentage of fire damage under the climate change scenario in Baddulla district is likely significantly reduced due to the increase of fuel moisture condition under the climate change scenario because other than the South West monsoonal changes, from the second inter-monsoon Badulla districts may receive higher rainfall than the present level compared to other districts.

Table 6 shows the annual rainfall receiving variability (there is more variability on rainfall in recent time). According to those figures, North East monsoon receiving variability is the higher variability, which received more rainfall in the dry zone of Sri Lanka. Considerably dry periods increase and sudden rainfall (very high intensity for a shorter period) also happens, which creates a dry zone natural forest and forest plantation more at risk for fires

Table 6: Variability of Rainfall pattern under 30 year period (Source: Department of Agriculture, Sri Lanka)

Monsoon	1931 to 1960(30-year period)	1961 to 1990 (30 yr)
1st Intermonsoon (March – April)	23%	27%
South West Monsoon (May – September)	21%	16%
2nd Intermonsoon (Oct – Nov)	22%	23%
North East Monsoon (Dec – Feb)	31%	42%
Total	11%	14%

The Agriculture Department in Sri Lanka has identified Districts in the dry zone as climate change vulnerable districts in Sri Lanka. According to this identification, the dry zone is more vulnerable to climate change. According to Meteorological Department data on temperature and rainfall in the last few years, the dry zone of Sri Lanka receives less rainfall than comparable months in the 30 year before. That causes increased dry weather conditions and drought which contribute to increase the vulnerability for the forest fire on dry zone forest of Sri Lanka (Figure 08).

There are many researchers who suggest that sea surface temperature fluctuation directly the influences the *El-Nino* and *La-Nino* oscillation patterns and duration (McPhaden, 2004; Philander, 1980). Sea surface temperature is greatly influenced by climate change and global warming. Sri Lanka as an island directly influenced by the changing weather pattens due to climate change. According to the research of Costa (2008), there is a direct link of climate change with global warming that influences the Sri Lankan climate under the global weather pattern changes. As a result of global warming the *El Nino* Southern oscillation has changed which extremely effects the island's weather and climate pattern. Moreover, the island's level variations of latitude, topography, atmospheric circulation, vegetation modify the global scale impacts. Costa's analysis of long-term air temperature data provides strong evidence that significant and systematic warming of the atmosphere has occurred in all climatic zones of Sri Lanka. This paper also highlighted that most parts of Sri Lanka, including dry and wet zones, are faced with increasing rates of warming with increasing daily mean temperatures and reductions in rainfall accompanied by the warming of the lower atmosphere. That happens mainly due to global warming and climate change (Costa, 2008).

3.4 Applicability of this findings for forest policy and forest management programs.

The national forest sector target is to improve the existing forest cover from 29.7% to 32% at the end of 2030. In order to achieve that target, we need to conserve the existing forest cover. This finding gives more reliable data that future climate change impacted forest types and districts need to be given more priority in conservation activities. For those districts such as Monaragala, Anuradhapura, Mulaitive, there needs to be more financial and human resources allocated to protect the existing forest cover, especially dry monsoon and open and sparse forests. In the dry zone and intermediate zone of Sri Lanka, there are considerable quantities of abundant land which are not considered forest can be used to improve the forest cover through forest restoration and reforestations. My findings are vital to identify the suitability of those lands for forestry activities. This is because if there are future forest fire vulnerable lands (forest) near to those areas or within abundant areas, we need to apply more control measures with forestry activities like opening fire belts, planting fire resistance forest plants, conducting awareness programs, developing fire protection mechanisms with villages and other stakeholders, and establishing some alert mechanisms and coordination mechanisms.

Sri Lanka as a nation is legally bound with international communities and countries through the Paris Agreement in United Nation Framework Convention on Climate Change (UNFCCC) to reduce the greenhouse gas emission (to reduce the global warming) and to mitigate the impact of climate change. As my findings suggest, if the forest resources are destroyed due to forest fires under the baseline conditions, at an annual rate of 4220 acres (If we assumed the average number of fires as 75 and total number of fires is 1000, then to complete 1000 fires at the rate of 75, takes about 13 years). Moreover, under the climate change condition to complete the total burn areas of 294000 acres if it takes 13 year that means that annual forest damage areas could be about 22615 acres. This means that if we do not take proper measures to control the forest fire within the next decade, up to 100,000 hectares of forest resources may be damaged. In order to achieve the Paris Agreement target, we need to protect the existing forest cover. In addition, to reach the Sustainable Development Goals (SDG), we need to conserve the forest resources while enhancing the quality of the forests.

My findings clearly indicate the future forest fire risk areas and forest types that need to be given high priority for the conservations in future climate change conditions. With this knowledge, policy makers should develop climate change mitigation and adaptation plans that mainly focus on those vulnerable areas. At the same time, when preparing our new forest sector master plan for enhancing the forest resources, this finding can be useful to propose mitigations and adaptation strategies for climate change and forest fire damages. To increase the forest over 1%, we need about 60,000 hectares of abundant lands. As my findings suggest, due to climate change events our forest resources will be degraded by 100,000 hectares within 13 years at the rate of 9136 (294000/13) hectares per year, meaning that we cannot achieve our targets if we do not adapt proper measures to control and manage the forest fire with the climate change and baseline level.

Not only do we need to protect existing lands, in order to increase the forest cover, we need a total of 138,000 hectors of additional lands (2.3% increase of forest cover at the end of 2030). If We do not adapt proper mechanisms to control forest fires, we need to find additional forest land of 100000ha to improve the forest cover other than the 138000 hectares. Those figures can be used by the policy makers, forest officers, companies and other relevant stakeholders to prepare proper forest cover enhancement programs while managing the future forest fire damage by the climate change occurrences.

3.5 Assumptions, Limitations, and Future Research

3.5.1 Limitation of the Study.

There are several limitations to this study. In this study, Sri Lankan Forest types were categorized into 6 types. However, dry monsoon forests are dispersed in several geographical districts which may have different rainfall patterns. In that case, the fuel moisture content may vary in dry monsoon forests within different districts. So, one fuel model not be applicable for the same forest types in different districts. For the sake of time and to identify the medium term climate change impact such as 10 to 20 years future impacts, 1000 fire iterations were done. Therefore, we cannot obtain good results of burn probability in different forest types. However, In order to get more saturated landscape from the process, at least 10000 or more fire iterations need to be done. In that case we can get the more reliable burn probability which determines accurate output on a given landscape under burn probability. In the simulation process, wind speed and wind direction are the mandatory switches in the FConstMTT algorithm. Althoughy study used constant wind direction of the South-Went wind direction of 225. However, with the climate change and inter-monsoonal impact wind direction may change over the fire simulation period.

3.5.2 Future research and fallow on works.

As future follow up works, it would be better to develop fuel models that correspond to the forest type within each district level. In this study, only forest type landscapes were analyzed under the fire simulation and non forested areas like agricultural lands, plantation crops land (rubber, tea) and some grasslands were not considered. Therefore, future research should focus on those areas to identify the burnability under future climate change scenarios. Moreover, in order to get more reliable burn probability output, fire iterations need at least more than 10,000. Future research should therefore run the same statistics with more iterations. Finally, future fire simulations should use a weather grid as an input on FConstMTT to account for the fluctuating wind directions.

3.5.3 Assumptions.

In this study only focused on the forested landscape where fuel models were produced. In this research, I assumed that most of the forest fires occur in forested landscape and non forested landscapes like agricultural, plantation lands may not contribute to fire ignitions. Throughout the simulation process, wind direction and speed remain constant. Also I assumed that forest fuel characteristics in a given forest type (eg. dry monsoon forest) are similar in different districts withthe same forest categories.

4. Conclusions.

Under the projected climate change scenario, reduced rainfall, increased temperature, low relative humidity and high dry wind speed will increase in the dry and intermediate zones of Sri Lanka, which will cause increased ignition of forest fuel leading to significantly increased forest fire damages.

Dry monsoon forests have the highest vulnerability for forest fires under the projected climate change conditions, followed by open and sparse forest and scrublands. This is because those forests consist of greater fuel load which may get a full dryer under the drought conditions. Monaragala, Anuradhapura, districts show higher vulnerability for the climate change impact. Burn probability of future climate change conditions increased significantly in these districts compared to baseline conditions. Places where the human impact are high fire vulnerability get increased due to human involvement. Most of the time ignition starts near the road and spreads to the forest. First, village type forests like open and sparse forests get damaged and this damage spreads into near dry forest, scrublands and forest plantations. Burn probability, damage area and fire intensity are significantly increased under the projected future climate change condition that will create more fire hazardous in the dry zone.

5. Recommendation and future implications

As a recommendation, these findings should be incorporated with the forest fire mitigation and management programs. Forests which are more vulnerable for forest fires with the future climate change need to be identified properly. This study gave clear directions to identify those future risk areas for forest fires under the future climate change impacts.

Forest fire management strategies could include maintaining the existing fire belt and making new fire belts, establishing fire protection units from the communities who are more vulnerable to the forest fires, maintaining good networks with stakeholder agencies, increasing the awareness among the peoples by field activities, and increased training on forest fire prevention and management. Furthermore, human resources at the departmental level in future forest fire risk areas should be strengthened to take precautionary measures to forest fire management while establishing the directives of forest ordinances by taking actions to punish people who are involved in starting forest fires.

On the other hand, areas which have high risks for forest fires can form forest fire protection units with volunteers for youth groups to control fires (university students, school children’s, youth senanka, etc.), to build a strong and effective fire prevention campaign. Prevention implies public awareness, equipment and infrastructure preparation, enforcement and fire fuel management. Institutions should also improve capacity and capability to prepare for forest fires that have gaps in these attributes such as laws, policy, plans, practices and monitoring.

The Ecosystem and conservation and management project (ESCAMP), which is the World Bank funded project that contributes to our studies was mainly focused on improving the forest resources while enhancing the people's livelihood who are living near to the forest areas. This project provides immense amounts of resources (funding) to forest resources improvement with the considerable amount of findings to control the forest fire damage to forest resources. When properly identifying the future risk areas for forest fires and vulnerable communities the resources allocation would be more productive. Findings of this study can provide (ESCAM projects) direction for proper resources allocation. This project suggests allocating funds and resources for opening fire belts, strengthening the fire protection organizations, for forest restoration programs, providing incentives for the people who are directly involved with forest fire prevention, providing equipment's to forest offices and villages for forest fire control, and conducting training and awareness programs to control forest fires. Therefore, this project provides valuable resources for the Forest Department to improve the forest resources while controlling forest fire damages.

Information which was gathered from this research can be used for many applications. Specially, Sri Lanka's national policy is to improve forest cover up to 32% within the next five years, so forest fire damages need to be controlled. These findings are more vital to give better suggestions and recommendations when preparation of forest fire management plans which includes the strategies of fire damage mitigation and adaptation. At the same time forest enhancement programs like reforestation and forest restoration (ANR-Assisted Natural Regeneration) which are done by the Forest Department and other entities would obtain more productive results from their investment.

At the policy level, when making the decisions on rural poverty alleviation, management of Human-Elephant conflict, habitat restoration, this information is even more vital. After identifying the future climate change risk areas, it is easier to implement forest control mechanisms such as opening fire belts and establishing fire protection units with villages, officers and other stakeholders. With this information, the relevant institute can give priorities under the limited budget for fire prevention activities. Landscape files and simulation results can be used for other field applications like ecosystem valuations. Existing fire data have many weaknesses which cannot be used for proper scientific approaches. However, my findings would be helpful to fill these gaps of data deficiencies and inappropriateness for forest fire databases.

Finally, it is important to maintain good networks with the stakeholder agencies such as the Forest Department, the Department of Wildlife Conservation, the Disaster Management Center, the Armed Forces (Army, Air Force), Pradeshiya Shaba, Divisional Secretariats, Non-Government organizations, and Village Organizations. Such networks may be helpful for early detections of forest fires, uses for control measures, and finally to minimize the damages to forest, human beings and other resources like households, animal husbandry, and infrastructure which will conserve the ecosystem services provided by the forest resources.

6. Suggestion.

It would be better to developed better inter governmental networks on forest fire data collection. Because some developed countries has (USA, Australia, Netherlands) proper mechanism to forest fire data collection and alert system with the satellite based technologies. So If we can make good connection with government in those countries, research organizations and relevant entities then we can build good network for fire data collection while making forest fire alert systems which will helpful to forest fire control advance level.

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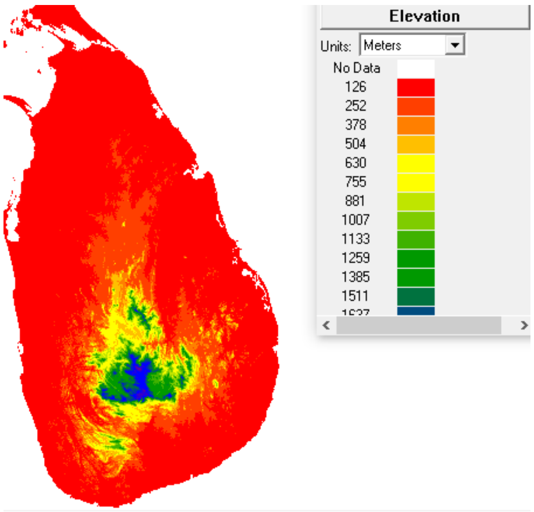
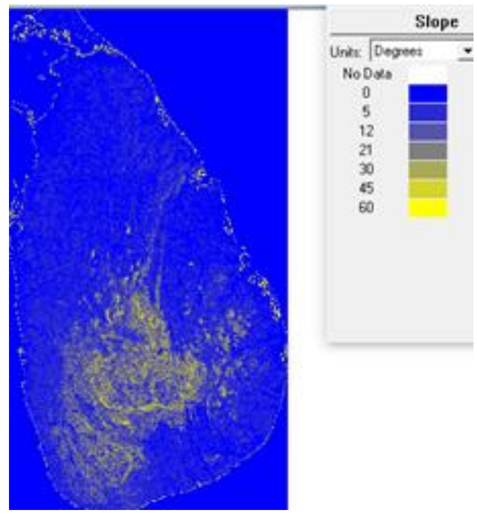
Appendix A: Layers of Landscape file

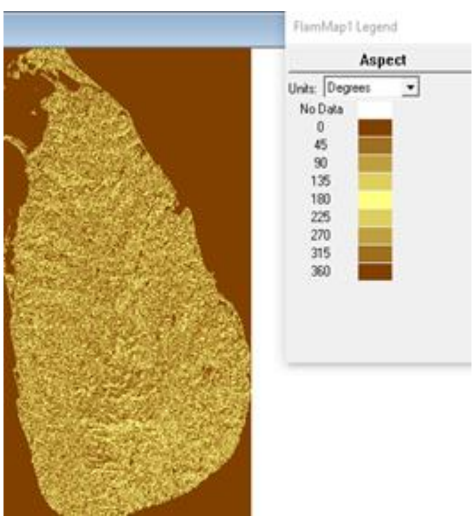
Elevation



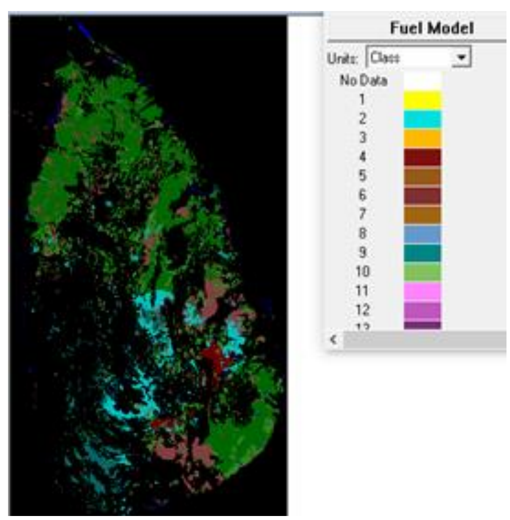
Slope



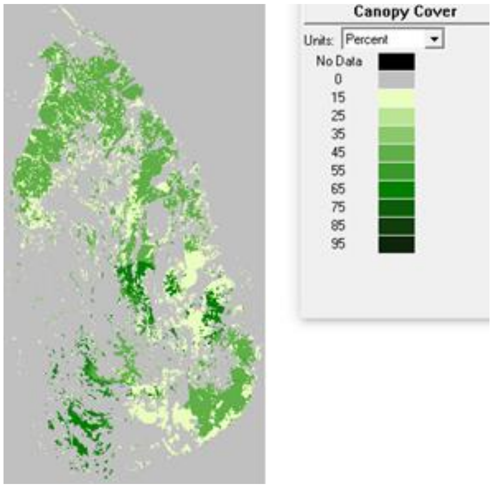
Aspect



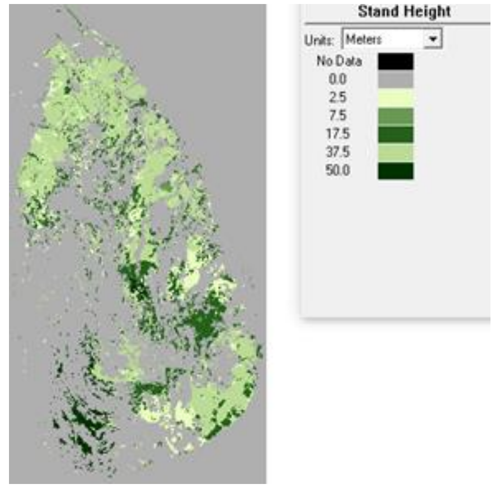
Fuel model



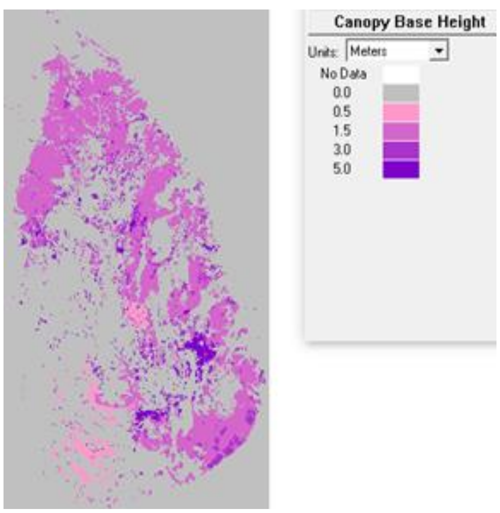
Canopy cover



Stand Height



Canopy Base Height



Canopy Bulk density

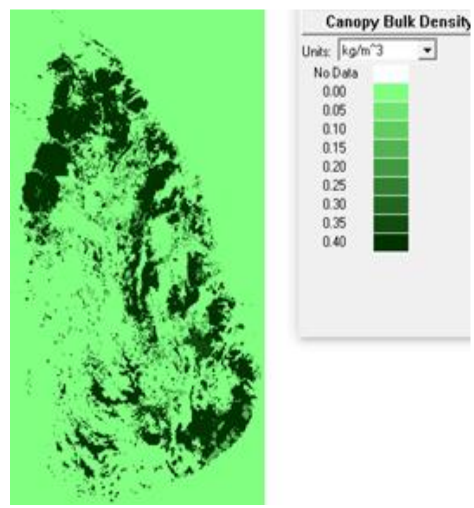


Figure 06a: Eight raster layer that represent the LCP in Sri Lankan forest types.

Appendix B- Custom fuel model

Custom fuel model for dry monsoon forest(30)

Description: DryMonsoon Forest

Parameter	Units	Initialize from a Fuel Model
Fuel/Vegetation, Surface/Understory		
Fuel Model Number		30
Fuel Model Code		TM
Fuel Load Transfer Portion	%	75
Fuel Model Type		D
1-h Fuel Load	tonne/ha	8.7
10-h Fuel Load	tonne/ha	0.65
100-h Fuel Load	tonne/ha	1.85
Live Herbaceous Fuel Load	tonne/ha	0.62
Live Woody Fuel Load	tonne/ha	0.85
1-h Fuel SA/V	m2/m3	5906
Live Herbaceous Fuel SA/V	m2/m3	5906
Live Woody Fuel SA/V	m2/m3	5249
Fuel Bed Depth	m	0.22
Dead Fuel Moisture of Extinction	%	25
Dead Fuel Heat Content	kJ/kg	18622
Live Fuel Heat Content	kJ/kg	18622
Fuel Moisture		
Dead Fuel Moisture	%	8
Live Fuel Moisture	%	53
Weather		
Midflame Wind Speed (upslope)	km/h	3.5
Terrain		
Slope Steepness	%	15

Custom fuel model for High elevation forest(31)

Inputs: SURFACE

Description: High Elevation Forest

Fuel/Vegetation, Surface/Understory		Initialize from a Fuel Model
Fuel Model Number		31
Fuel Model Code		TM
Fuel Load Transfer Portion	%	66.7
Fuel Model Type		D
1-h Fuel Load	tonne/ha	18.7
10-h Fuel Load	tonne/ha	3.44
100-h Fuel Load	tonne/ha	4.02
Live Herbaceous Fuel Load	tonne/ha	1.55
Live Woody Fuel Load	tonne/ha	1.87
1-h Fuel SA/V	m2/m3	5906
Live Herbaceous Fuel SA/V	m2/m3	5906
Live Woody Fuel SA/V	m2/m3	5440
Fuel Bed Depth	m	0.5
Dead Fuel Moisture of Extinction	%	40
Dead Fuel Heat Content	kJ/kg	18622
Live Fuel Heat Content	kJ/kg	18622
Fuel Moisture		
Dead Fuel Moisture	%	13
Live Herbaceous Fuel Moisture	%	60
Live Woody Fuel Moisture	%	55
Weather		
Midflame Wind Speed (upslope)	km/h	12
Terrain		
Slope Steepness	%	50

Custom fuel model for Low elevation forest(32)

Inputs: SURFACE

Description: Low Elevation Forest

Fuel/Vegetation, Surface/Understory		Initialize from a Fuel Model
Fuel Model Number		32
Fuel Model Code		TM
Fuel Load Transfer Portion	%	50
Fuel Model Type		D
1-h Fuel Load	tonne/ha	22
10-h Fuel Load	tonne/ha	5.2
100-h Fuel Load	tonne/ha	5.5
Live Herbaceous Fuel Load	tonne/ha	2.35
Live Woody Fuel Load	tonne/ha	2.15
1-h Fuel SA/V	m2/m3	5906
Live Herbaceous Fuel SA/V	m2/m3	5906
Live Woody Fuel SA/V	m2/m3	5249
Fuel Bed Depth	m	0.85
Dead Fuel Moisture of Extinction	%	45
Dead Fuel Heat Content	kJ/kg	18622
Live Fuel Heat Content	kJ/kg	18622
Fuel Moisture		
Dead Fuel Moisture	%	11
Live Herbaceous Fuel Moisture	%	70
Live Woody Fuel Moisture	%	60
Weather		
Midflame Wind Speed (upslope)	mi/h	5
Terrain		
Slope Steepness	deg	7

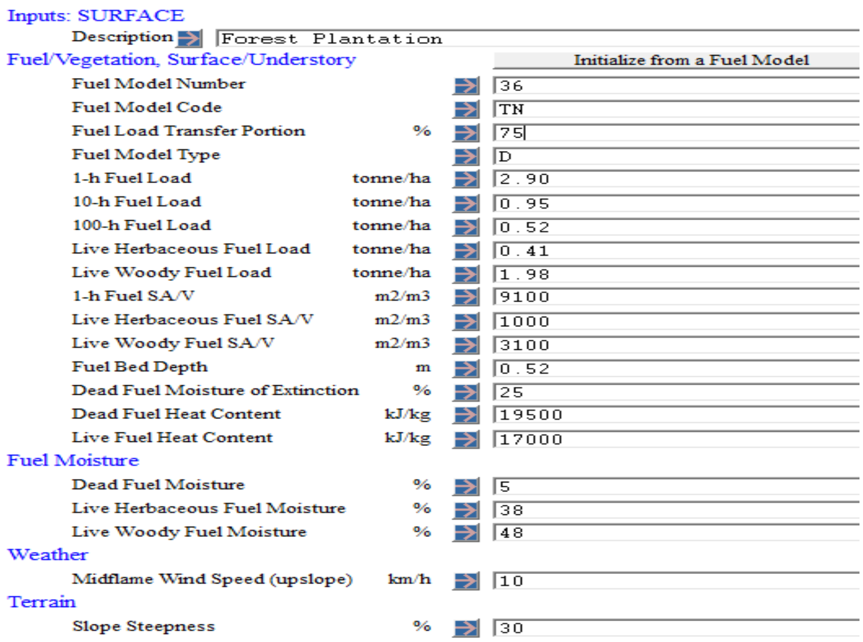
Custom fuel model for Open and sparse forest(34)

Inputs: SURFACE		
Description		Open and Sparse Forest
Fuel/Vegetation, Surface/Understory		Initialize from a Fuel Model
Fuel Model Number		34
Fuel Model Code		TM
Fuel Load Transfer Portion	%	75
Fuel Model Type		D
1-h Fuel Load	tonne/ha	8.4
10-h Fuel Load	tonne/ha	1.22
100-h Fuel Load	tonne/ha	1.11
Live Herbaceous Fuel Load	tonne/ha	1.58
Live Woody Fuel Load	tonne/ha	2.35
1-h Fuel SA/V	m2/m3	2461
Live Herbaceous Fuel SA/V	m2/m3	5227
Live Woody Fuel SA/V	m2/m3	4998
Fuel Bed Depth	m	0.21
Dead Fuel Moisture of Extinction	%	25
Dead Fuel Heat Content	kJ/kg	18622
Live Fuel Heat Content	kJ/kg	18622
Fuel Moisture		
Dead Fuel Moisture	%	6
Live Herbaceous Fuel Moisture	%	35
Live Woody Fuel Moisture	%	32
Weather		
Midflame Wind Speed (upslope)	mi/h	6
Terrain		
Slope Steepness	deg	5

Custom fuel model for Scrublands(35)

Inputs: SURFACE		
Description		Scrubland
Fuel/Vegetation, Surface/Understory		Initialize from a Fuel Model
Fuel Model Number		35
Fuel Model Code		sb
Fuel Load Transfer Portion	%	75
Fuel Model Type		D
1-h Fuel Load	tonne/ha	5.54
10-h Fuel Load	tonne/ha	0.77
100-h Fuel Load	tonne/ha	0.65
Live Herbaceous Fuel Load	tonne/ha	0.41
Live Woody Fuel Load	tonne/ha	1.54
1-h Fuel SA/V	m2/m3	2461
Live Herbaceous Fuel SA/V	m2/m3	5906
Live Woody Fuel SA/V	m2/m3	5249
Fuel Bed Depth	m	0.77
Dead Fuel Moisture of Extinction	%	40
Dead Fuel Heat Content	kJ/kg	18622
Live Fuel Heat Content	kJ/kg	18622
Fuel Moisture		
Dead Fuel Moisture	%	7
Live Herbaceous Fuel Moisture	%	38
Live Woody Fuel Moisture	%	48
Weather		
Midflame Wind Speed (upslope)	mi/h	5
Terrain		
Slope Steepness	%	35

Custom fuel model for Forest plantation(36)



Inputs: SURFACE

Description: Forest Plantation

Fuel/Vegetation, Surface/Understory		Initialize from a Fuel Model
Fuel Model Number		36
Fuel Model Code		TN
Fuel Load Transfer Portion	%	75
Fuel Model Type		D
1-h Fuel Load	tonne/ha	2.90
10-h Fuel Load	tonne/ha	0.95
100-h Fuel Load	tonne/ha	0.52
Live Herbaceous Fuel Load	tonne/ha	0.41
Live Woody Fuel Load	tonne/ha	1.98
1-h Fuel SA/V	m2/m3	9100
Live Herbaceous Fuel SA/V	m2/m3	1000
Live Woody Fuel SA/V	m2/m3	3100
Fuel Bed Depth	m	0.52
Dead Fuel Moisture of Extinction	%	25
Dead Fuel Heat Content	kJ/kg	19500
Live Fuel Heat Content	kJ/kg	17000
Fuel Moisture		
Dead Fuel Moisture	%	5
Live Herbaceous Fuel Moisture	%	38
Live Woody Fuel Moisture	%	48
Weather		
Midflame Wind Speed (upslope)	km/h	10
Terrain		
Slope Steepness	%	30

Figure 07aCustom fuel model for forest types numbered from 30 to 36 except 33.