OCCURRENCE, MANAGEMENT AND FORECASTED DISTRIBUTION OF PINE PITCH CANKER DISEASE ON PINE PLANTATIONS IN TANZANIA

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EXTENDED ABSTRACT

Pine Pitch Canker (PPC) is a disease of pine trees caused by *Fusarium circinatum.* The disease is reported to damage pine plantations and woodlots in Tanzania. Disease attack result in a reduction of productivity which causes significant loss of national income. The disease occurrence and distribution is influenced by various factors such as climate, topography, and management practices. Currently in Tanzania there is an increasing rate of PPC disease incidences on pine plantations and woodlots mostly affecting tree aged 5 – 6 years. The risk of disease spread in Tanzania is high due to the wide distribution of host range, as pine covers about 78% of planted trees in mono-culture plantations.

Numerous studies have been conducted to predict the suitable areas of PPC disease distribution to various parts of the world. The global prediction of climatic suitability to pitch canker disease by the CLIMEX model showed Tanzania as one of the areas suitable for disease establishment. However, the model was biased showing a larger portion of PPC establishment on water bodies in Tanzania, possibly due to limited occurrence records for Tanzania during model calibration. Furthermore, there is no records of PPC disease incidence and severity; and the pattern of suitable areas for disease establishment in Tanzania.

Therefore, the study aimed (i) to determine incidence and severity of PPC disease in pine plantations for different management regimes, (ii) to determine the influence of management practice and stand characteristics on PPC disease incidence and severity, and (iii) to predict the suitable areas for PPC disease distribution in Tanzania.

The study employed different sampling and data collection methods. To determine the incidence and severity of PPC disease in pine plantations, purposive sampling was used where three management regimes comprising of government managed plantation, large-scale private managed plantation, and small-scale private pine woodlots were selected. A total of 14 square plots of 20 x 20 meters were established, at an interval of at least 100 m apart in each selected plantation. Assessment of disease infestation was done to 25 individual trees near the plot center totaling 1050 trees for the whole study area. A Pine Pitch Canker severity ranking system was used to determine disease severity index (DSI), and a total number of symptomatic trees were used to determine disease incidence (DI). The management practices were obtained from compartment register and by interviewing key informant. Stand parameters including tree diameter at breast height (DBH) and height were measured.

Analysis of Variance (ANOVA) was used to compare means of disease incidence and severity index between management regimes. Then, Tukey's Honest Significant Difference (HSD) test was employed to separate the means within different management regimes. Pearson correlation coefficient was used to establish the association between disease incidences, severity index and stand parameters. The effect of management practices on PPC disease incidence and severity index was determined by using multiple linear regression model. The management practices comprise; land preparations techniques, seed source, weeding, spacing, pruning, and thinning.

Maximum Entropy (MaxEnt) was used to predict the suitable areas of PPC establishment. Pine Pitch Canker disease occurrence and environmental variables (climate and topographic) were used in prediction. The GPS coordinates for affected areas were obtained from the field survey, plantation managers, woodlots owners and various published and unpublished reports. A total of 70 affected points were used in prediction of the potential distribution of PPC disease in Tanzania.

The disease incidence was significantly higher in large-scale private plantations and woodlots ($p< 0.05$) than government-owned plantations. The results were similar to disease severity index which was significantly higher at large-scale private plantations than government managed plantations ($p< 0.05$). It was found that, the disease incidence and severity was significant negatively correlated with stand age, DBH and height regardless of the management regime. Among the practice that may cause a wound to tree stems, only pruning had a positive significant influence on disease incidence and severity.

Maximum Entropy model accurate predicted the suitable area for PPC disease establishment in Tanzania with area under the curve (AUC) value greater than 0.9. Bioclimatic variables related to temperature have a high percentage contribution to the model. The mean temperature of the coldest quarter (Bio11) and temperature seasonality (Bio4) contributed higher to the prediction with 68% and 32% respectively. The PPC disease establishment is much favored under scenario of low emission of Green House Gases (RCP 2.6). Since under RCP 2.6, the predicted suitable area for PPC disease occurrence will be stable in 2050 with a minor smaller decrease in 2070. But under scenario of high greenhouse gases emission (RCP 8.5) the model predicts a continuous decrease of suitable areas for PPC disease occurrence from the current climate condition to future (2070) climatic condition. The model predicts areas suitable for PPC disease will cover much on southern, southern highland, and northern zones of Tanzania.

The study conclude that PPC disease exist in all management regimes with a high occurrences on the private managed plantation in Tanzania. The disease incidence and severity correlated negatively with height, DBH and age. The management practices that are likely to cause a wound on tree stems especially pruning increase chance of PPC occurrence and severity. Bioclimatic variables related to temperature (mean temperature of

the coldest quarter (Bio11) and temperature seasonality (Bio4)) influence and limit the distribution of PPC disease. Southern highland, southern and northern zones of Tanzania were predicted to be high susceptible to PPC disease infestations. The PPC disease establishment is much favored with a low concentration of greenhouse gas that provides an intermediate warmer environment and high humidity level. Under current conditions, the area suitable for PPC disease establishment is much larger than that of future climate scenarios.

The study recommends development of holistic management approach to include all tree growers to reduce the spread of PPC disease to pine plantations. Pruning should be done during the dry season with minimum damage level, to reduce the chances of infections through wounds. Also effective screening of imported seeds should be done before planting. Furthermore, the study recommends the development of strict quarantine and monitoring system of the disease so as to prevent introductions of the pathogen to the predicted regions where PPC disease is not reported.

DECLARATION

I, **Cosmas John Emily** do hereby declare to the Senate of the Sokoine University of Agriculture that this dissertation is my original work and it has neither been, nor concurrently being submitted for higher degree awards in any other institution.

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LIST OF PAPER CHAPTERS

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LIST OF ABBREVIATION

ANOVA	Analysis of Variance
AUC	Area Under the Curve
Cm	Centimeters
DBH	Diameter at breast height
DI	Disease Incidence
DSI	Disease Severity Index
FAO	Food and Agriculture Organization of the United Nations
FDT	Forest Development Trust
GPS	Global Positioning System
GRL	Green Resources Limited
Ha	Hectare
HSD	Tukey’s Honest Significant Difference
IPCC	International Panel of Climate Change
MaxEnt	Maximum Entropy
MNRT	Ministry of Natural Resource and Tourism
PCS	Pitch Canker Severity
PFP	Private Forest Programme
PPC	Pine Pitch Canker
RCP	Representative Concentration Pathway
ROC	Receiver Operating Characteristic
SUA	Sokoine University of Agriculture
TaFF	Tanzania Forest Fund
TAFORI	Tanzania Forest Research Institute
TPRI	Tanzania Pesticide Research Institute

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Background information

Pine pitch canker is a serious disease in pine plantations globally (Fernández-Fernández *et al*., 2019). It is caused by the fungal pathogen *Fusarium circinatum* Nirenberg and O'Donnell belonging to class ascomycete (Zamora-Ballesteros *et al*., 2019a). Disease attacks result in a reduction of productivity which causes significant loss to national income. The control of pathogen is challenging due to the presence of sexual and asexual modes of reproduction (Bezos *et a*l., 2012). Sexual reproduction involves the recombination of genes, which can result in the development of strains with enhanced virulence (Bezos *et a*l., 2017).

The interaction of pathogen, host tree, and suitable environment results in the occurrence of PPC disease. Therefore, both biotic and abiotic factors influence the occurrence of the PPC disease in pine plantations Abiotic factors include forest management practices and environmental factors while biotic factors include the presence of pathogens (Coyle *et a*l., 2020). The pathogen can be spread from tree to tree by aerial dispersal of the conidia through wind, mist of water, or vectors (Zamora-Ballesteros *et a*l., 2019b). The movement of plant material like infested seeds as well as infected seedlings can serve as a vehicle for long-distance dissemination of *F. circinatum* (Gordon, 2011). Tree host selection also influences disease distribution. Worldwide, there about 60 species of pine which have been reported to be susceptible to PPC disease (Gordon *et al*., 2015).

The pine pitch canker disease occurrence, severity, and distribution tend to differ with stand characteristics and management variability (Drenkhan *et al*., 2020; Möykkynen *et a*l., 2015b). In Tanzania, forest plantations are managed under different management regimes such as; government-managed plantations, large scale private-managed plantations, and small-scale plantations/woodlots. Management regimes influence how various silvicultural practices are implemented due to several reasons including technical capacity, resource availability, and the objective of managing that plantation (Ankomah *et al*., 2020). Also, the management practices have been reported to affect stand structure and growth parameters in a plantation (Bryce, 2009).

For appropriate control of PPC disease, it is important to understand the incidence and severity level of disease and early identify the suitable areas for disease establishment and their influencing factors (Meentemeye*r et a*l., 2008). Early detection of the suitable areas will assist in planning and executing a rapid early response to fighting against the disease (Slater and Michael, 2012). Therefore, this study aimed (i) to determine incidence and severity of PPC disease in pine plantations for different management regimes, (ii) to determine the influence of management practice and stand characteristics on PPC disease incidence and severity, and (iii) to predict the suitable areas for PPC disease distribution in Tanzania.

1.2 Problem Statement and Justification

1.2.1 Problem Statement

There is a high risk of the spread of PPC disease in Tanzania due to the wide distribution of host trees species. A survey conducted by Petro *et al* in 2019 on private woodlots and plantations in Njombe and Iringa regions, southern highlands, has reported 60-70% death of trees aged 5 – 6 years due to PPC. The rate of incidence and severity are influenced by various factors such as environmental factors, management practices, and stand characteristics (Martín-Rodrigues *et a*l., 2013; Zamora-Ballesteros *et al*., 2019b). However, there is limited information on how these factors influence the PPC incidences and severity in Tanzania pine plantations and woodlots.

Numerous studies have been conducted to predict the suitable areas of PPC distribution to various parts of the world (Möykkyne*n et al*., 2015b). The global prediction of climatic suitability to PPC disease by the CLIMEX model showed Tanzania as one of the areas suitable for PPC establishment (Möykkyne*n et al*., 2015b). However, the model was biased showing a larger portion of PPC establishment on water bodies in Tanzania (Ganley *et a*l., 2009). This is possibly due to missing occurrence records for Tanzania (Ganley *et a*l., 2009; Drenkhan *et a*l., 2020) during model calibration. Furthermore, there is no information on the pattern of suitable areas for PPC disease establishment in Tanzania. Therefore, the study aimed to quantify disease incidence and severity, predict suitable areas for PPC distribution and investigate the influence of management practices and stand characteristics on PPC incidence and severity in Tanzania.

1.2.2 Justification of the study

The findings from this study will help in raising awareness to forest managers and owners on the management practice influencing PPC incidence and severity. The finding will provide the possible pattern of PPC spread which is crucial in the control and management of the disease. It will also expand the understanding of the risk of PPC spread in different parts of Tanzania. The information obtained will help plantation managers to develop proper plans for controlling and eradicating the diseases. Moreover, the study will provide baseline information for holistic management of PPC which is much required in reducing the spread of the disease.

1.3 Objectives

1.3.1 Main objective

The main objective is to assess the PPC disease incidence, severity, and suitable areas for disease distribution in Tanzania.

1.3.2 Specific objectives

Specifically, the study aimed;

i. To determine incidence and severity of PPC in Pine plantations for different management regimes

ii. To determine the influence of management practice and stand characteristics on PPC incidence and severity

iii. To predict the suitable areas for pine pitch canker disease distribution in Tanzania

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CHAPTER TWO

2.0 INCIDENCE AND SEVERITY OF PINE PITCH CANKER DISEASE IN PINE PLANTATIONS AT MUFINDI DISTRICT, IRINGA, TANZANIA.

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Abstract

Forest plantations in Tanzania are managed under different management regimes such as government managed plantation, large scale private-managed plantations, and small scale plantations/woodlots. Management regimes influence how various practices are implemented and hence affect stand structure, growth parameters, and response to diseases. Currently, Tanzania is experiencing an increasing rate of PPC disease incidence in pine plantations under different management regimes. The disease incidence and severity among other factors are influenced by management practices. This study assessed the incidence and severity of PPC disease on the three mentioned management regimes. A total of 14 square plots of 20 x 20 meters were established at an interval of 100 m apart in each selected plantation in the three management regimes. Assessment of disease severity was done to 25 individual trees near the plot center. Pine pitch canker disease severity ranking system was used to determine the disease severity index, and a total number of symptomatic trees were used to determine disease incidence. The management practices were obtained from compartment register and key informant interview. Stand parameters including tree diameter at breast height (DBH) and height were measured. Results showed that out of 1050 trees assessed, 45% were found with PPC disease symptoms. The disease incidence was significantly higher at large-scale private plantations and woodlots ($p < 0.05$) than government-owned plantations. The results were similar to the disease severity index which was significantly higher at large-scale private plantations than government managed plantations ($p < 0.05$). It was found that the disease incidence and severity increase to young trees, shorter trees, and smaller DBH regardless of the management regime. Among the practice that may cause a wound to tree stems, only pruning had a positive significant influence on disease incidence and severity. This study recommends the development of the country's holistic plantation management practices approach as a means to reduce the spread of PPC disease. Also, silvicultural operations should be done carefully with minimum tree damage to avoid wounding of trees.

Keywords: Pine pitch canker, *Fusarium circinatum,* Severity, Incidence, Management regimes.

2.1 Introduction

Pine pitch canker disease is one of the serious diseases in pine plantations globally (Fernández-Fernández *et al*., 2019), caused by the fungal pathogen *Fusarium circinatum* Nirenberg and O’Donnell belonging to class ascomycete (Zamora-Ballesteros *et al*., 2019). It is a seed-borne pathogen that can survive both superficially and internally in the seeds (Muñoz-Adalia *et al*., 2018). It affects all stages of pine growth from seedling, young, mature, and old trees (Wingfield *et al*., 2008; Möykkynen *et al*., 2015; Blank *et al*., 2019).

The disease has diverse symptoms depending on the growth stages of pine (Zamora-Ballesteros et al., 2019), whereby for seedlings it results in necrosis, chlorosis, wilting of needles, dieback, and desiccation of the seedling tip (Vivas *et a*l., 2012; Bezo*s et a*l., 2012). For matured trees, the symptoms include the presence of pitch-soaked cankers in trunks and big branches which girdle both trunks and branches (Wikler *et al*., 2003; Blank *et al*., 2019). Trickles of resin can also be found on the trunks of diseased trees (Zamora-Ballesteros *et a*l., 2019). The disease can affect the crown in case of wounds suitable for infection (Gordon *et al*., 2015), causing dieback and eventual tree death.

The disease has a wide distribution range and is found throughout temperate and tropical regions (Ganley *et a*l., 2009; Martín-Rodrigues *et a*l., 2013). There is increasing evidence of widespread pine pitch canker on pine species planted in Tanzania (Petro, 2019). A survey conducted by Petro *et al* in 2019 on private woodlots at Kifanya in the Njombe region and Green Resources Limited in Iringa, southern highlands, reported 60-70% death of trees aged 5 – 6 years. The disease symptoms have been also noticed in Meru, Shume and West Kilimanjaro forest plantations.

Forest management practices like pruning, thinning and stand characteristics tend to differ with management regimes, also influencing the incidence and severity of PPC disease (Bezos *et al*., 2017; Blank *et al*., 2019; Fernández-Fernández *et al*., 2019; Bezos *et al*., 2012). The differences in forest management practices and stand characteristics across management regimes are caused by the objective of managing that plantation, resource availability and technical capacity (Ankomah *et a*l., 2020). In Tanzania, the government managed plantations are required to follow an updated technical order number 1 of 2021 and other government guidelines in managing plantations (MNRT, 2021). Woodlots owners are also advised to follow the technical orders and guidelines issued by the forest and beekeeping division in the Ministry of Natural Resources and Tourism. But the adherence is rarely due to various reasons such as budget constraints. Large-scale private plantations are mainly owned by larger investors outside the country with different management practices mostly oriented to commercial forestry but they are also required to follow the government guidlines.

This study aimed to determine the PPC disease incidence and severity in government plantations, large private-owned plantations, and small private-owned plantations and/or woodlots. Specifically, the study seeks to (i) quantify the incidence of the disease (ii) to determine the disease severity (iii) to assess the management practice and stand characteristics influencing the PPC disease incidence and severity. The findings from this study are useful in raising awareness to forest managers and owners on PPC disease incidence and severity. The information obtained is useful for developing proper plans for controlling and eradicating the diseases.

2.2 Methodology

2.2.1 Description of Study Area

The study was conducted in three pine plantations named SAO Hill Forest plantation, Green Resource forest plantations (GRL), and individual woodlots/plantations in Mufindi district, Iringa Tanzania (Figure 2.1). Mufindi district experience an average rainfall of 600 – 1500 mm and temperatures ranging between 10℃ and 28℃ per annum. The eastern zone lies between 1600 and 1800 m from sea level whereas the western zone lies between 1000 and 1600 m above sea level. The Sao Hill forest plantation area is found in the area of the rolling plateau with low hills and wide flat-bottomed valleys, within Ihalimba, Luhunga, Makungu, and Mafinga Wards whereas Green resource forest plantations lie at an altitude between 1400 m and 1760 m, (GRL, 2012). Green resource manages two main plantations of Mapanda and Uchindile forest projects. The current study was conducted at Mapanda forest projects. It is located on the lower elevation of Mufindi escarpment, within latitudes 8° 24′ - 8° 33′ S and longitudes 35˚ 39' - 35˚ 44' 5'' E. The altitude varies from 1400 m to 1753 m above sea level. The external boundaries are rivers and Sao Hill forest plantation in the western. Sao Hill plantation areas receive the mean annual rainfall of 1300 mm, starting from November to April and the corresponding average air temperature is 14℃. Green resource plantation receives a mean annual rainfall of 1050 mm with the rainy season from December to April with an average temperature of 14℃. The private-owned woodlots were located at Wami village surrounded by Sao Hill forest plantation with similar climate and topographic conditions.

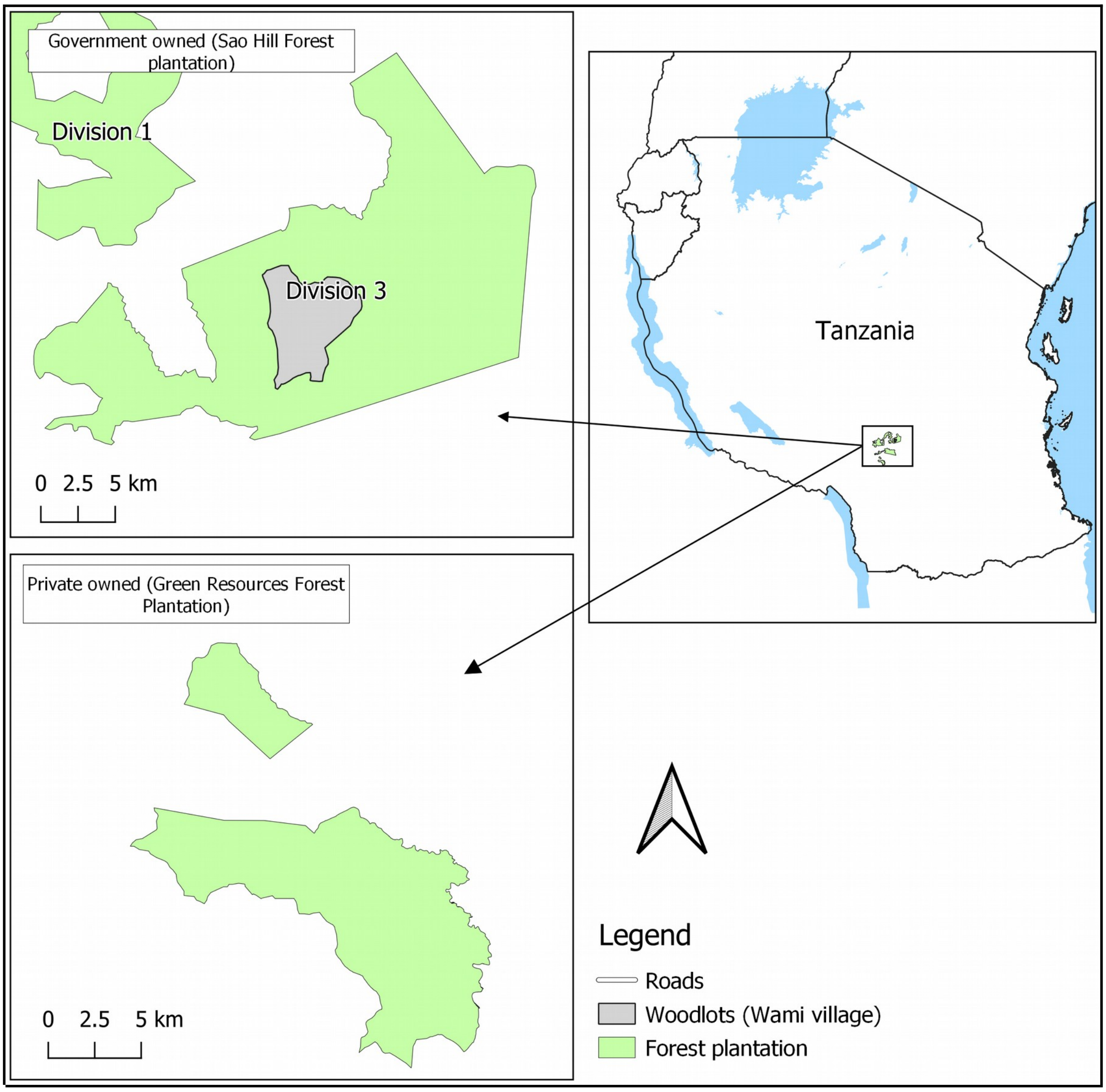

Figure 2.1: Map showing the study area in Mufindi District at Iringa Region, Tanzania

2.2.2 Sampling design

Three plantations of different management regimes named Government managed plantation, large scale private managed plantation and small scale private managed woodlots were purposively selected based on PPC disease symptoms reported. Plantation managers, village leaders and woodlots owners were interviewed to identify all the compartments and site with any tree disease symptoms. Then, reconnaissance survey was conducted to all mentioned sites to confirm the presence of PPC disease symptoms. Thereafter, in each regime, all sites or compartments with PPC symptoms were marked and used for data collection (Appendix 1)**.** Data on PPC occurrence and stand parameters were recorded in a square plot of 20 m x 20 m established randomly and an interval of 100 to 150 meters in each site. A total of 14 plots were measured in each management regime totaling 42 plots for the entire study area. A tree health assessment was done on 25 trees per plot located near the plot's center (Blank *et a*l., 2019).

2.2.3 Data collection

The sampled sites were visited between April and May 2021. Different attributes were collected including the number of trees with PPC disease symptoms, GPS coordinates of affected areas, stand age, tree height, diameter at breast height (DBH) and pitch canker infection severity. Severity infection levels of the individual tree was classified using a pitch canker severity (PCS) ranking system adapted from Owen and Adams, (2001) and Wikler *et al*. (2003). Pitch canker severity of each symptomatic tree was assessed based on three categories: branch tips, stem cankers and 'top kill' as summarized in Table 1.1. The branch tips (BT) were considered infected if symptoms of browning and loss of needles on the terminal end were present, rating depended on the number of infected needles. Stem cankers (SC) were measured by counting the number of cankers in the stem and top kill (TK) was measured as the percent of crown killed by the disease.

Table 2.1: Pine pitch canker disease severity ranking system used to assess severity level of individual tree in Mufindi district, Iringa, Tanzania.

Branch Tips (BT)[1]		**Stem Cankers (SC)[2]**		**Top Kill (TK)[3]**	
Rating	**Quantity**	**Rating**	**Quantity**	**Rating**	**Quantity**
0	0	0	0	0	0
1	0-2	1	1	1	<10%
2	3-10	2	2-3	2	10-50%
3	>10	3	>3	3	>50%

Source: Owen and Adams (2001) and Wikler *et al*., (2003).

After assessing each tree and assigning rating scores to each of the three categories, the rating scores were summed to a final severity score value. Severity score values classify trees as having no (1), low (2-4), moderate (5-7), or high (8-12) signs of PCS (Table 1.2). To improve rating accuracy, each tree sample was viewed from numerous ground vantage points. The management practices starting from land preparation, weeding, pruning, and thinning were obtained from compartment register and through interviews with plantation managers and woodlots owners.

Table 2.2: Severity score values of PPC used in Mufindi district, Iringa, Tanzania

Pitch canker severity (PCS)	**Total score value**
Healthy	0
Low	1-3
Medium	4-6
High	7-9

1.2.3 Statistical analysis

Pine pitch canker incidence was expressed by a percent of symptomatic trees in a plot. Disease damage scores were used to compute disease severity indices on each plot by using equation 1.

$$DSI\ (\%) = \frac{\sum(C.f\,x\,SR)}{TNTR\ x\ MDI}\ \text{X}\ 100\ldots\ldots \text{ Equation 1}$$

Where; *DSI= Disease severity index, C.F= Class frequency, SR = Score rating, TNTR = Total number of tree rated per plot, MDI = Maximal disease index*

The disease incidence and severity results obtained were tested for normality by using Shapiro–Wilk test. Then, analysis of variance (ANOVA) was used to compare means of disease incidence and severity index between management regimes. Thereafter, Tukey's honest significant difference (HSD) test was employed to separate the mean difference within different management regimes. The Pearson's correlation was used to establish the relationship between disease incidence and severity index with stand parameters. Multiple linear regression was performed to determine the effect of PPC disease incidence and severity index based on management practices comprising of land preparations techniques, seed source, weeding, spacing, pruning and thinning.

2.3 Results

2.3.1 Occurrence of PPC disease

Out of 1050 trees assessed in all sites, 475 (45%) trees were found with PPC infections. A total of 106 trees were found dead, out of those 51 (48%) were from government plantation 46 (43%) at large-scale private plantation and 9 (8%) at small-scale woodlots. One-way Analysis of Variance (ANOVA) reveals that disease incidence was significantly different between the three management regimes ($p < 0.001$). Honest significance difference test showed that disease incidence within large scale private plantation and woodlots were significantly higher than government plantation ($p <0.05$). While there was no significant difference in disease incidence between large-scale private plantation and Woodlots ($p > 0.05$) (Figure 2.2).

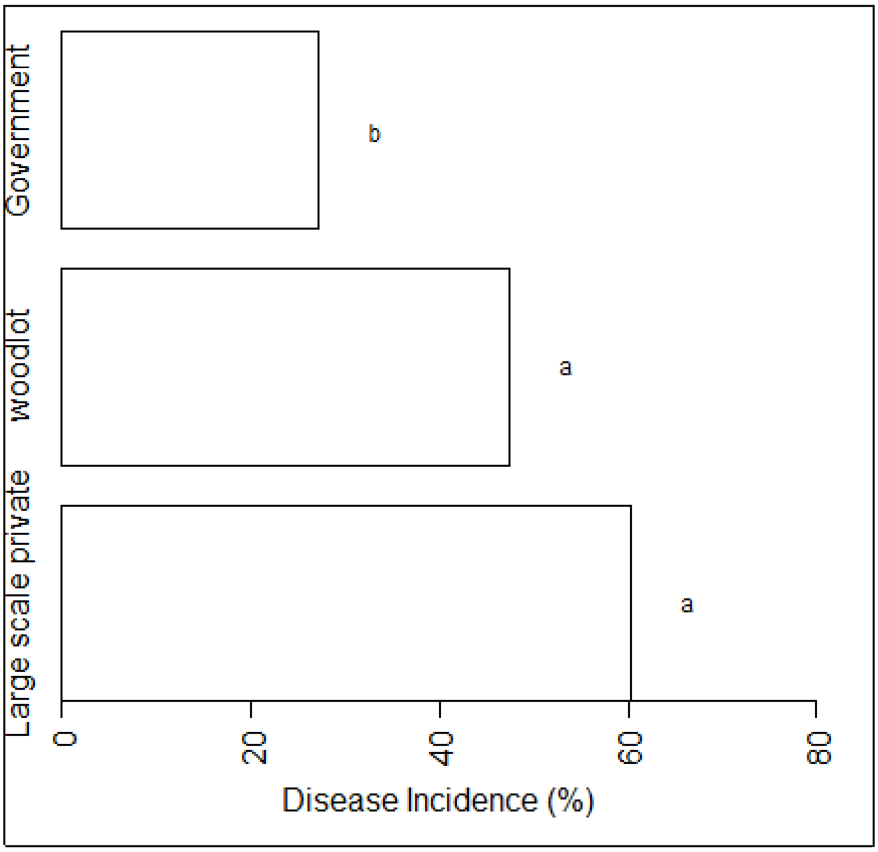

Figure 2.2: Disease incidence for different management regimes in Mufindi district, Iringa, Tanzania (Different letters mean significant different).

2.3.2 Severity of PPC disease

Out of 1050 trees assessed, the majority (54.76%) were healthy while 45% were affected at different infection levels (Table 2.3).

Table 2.3: PPC severity level of assessed trees in Mufindi district, Iringa, Tanzania

Pitch Canker Severity (PCS)	Total Score Value	Number of Symptomatic trees	Percentage
Healthy	0	575	54.76%
Low	1-3	63	6.00%
Medium	4-6	311	29.62%
High	7-9	101	9.62%
Total		**1050**	**100%**

The PPC disease severity of individual trees differs between three management regimes. Many trees ranked with high disease severity were observed at large scale private plantation (52) followed by individual woodlots (39) and least at Government managed plantation (10) (Table 2.4).

Table 2.4: PPC disease severity of the individual tree within and between management regimes in Mufindi district, Iringa, Tanzania

Pitch Canker Severity (PCS)	Total Score Value	Government	Large scale private	Woodlot	Total
Healthy	0	254	136	185	575
Low	1-3	10	30	23	63
Medium	4-6	76	132	103	311
High	7-9	10	52	39	101
Total		**350**	**350**	**350**	**1050**

Analysis of variance revealed that disease severity indices were significantly higher at large scale private plantation ($p<0.001$). Honest significance difference test revealed that DSI within large scale private plantation was significantly different from that of government plantation ($p <0.05$), while that of woodlots didn't vary significantly from large-scale private plantation and government ($p >0.05$) (Figure 2.3).

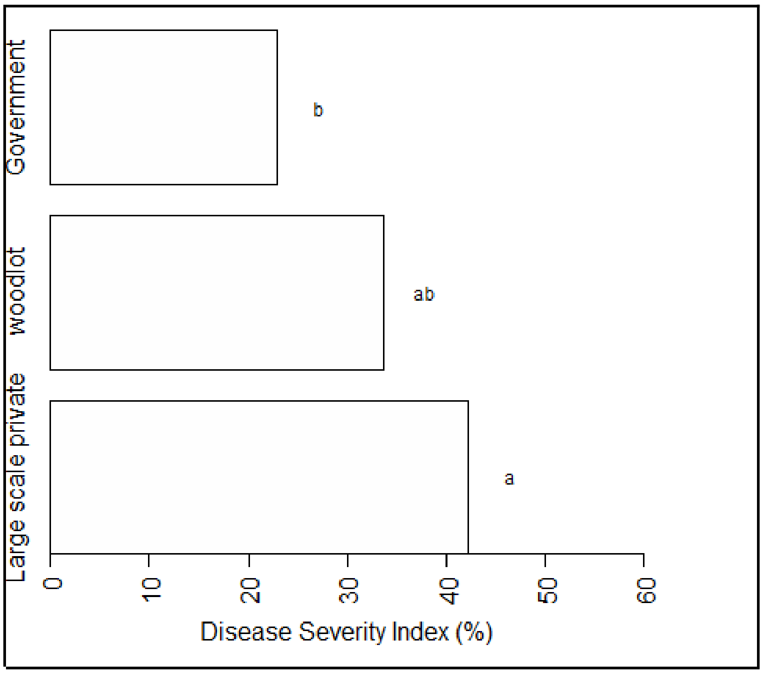

Figure 2.3: Disease severity indices for different management regimes in Mufindi district, Iringa, Tanzania.

2.3.3 Association of stand parameters with PPC disease Incidence and severity

Most of the affected pine stands were below 15 years in age with stands of 5 years *Pinus patula* having higher disease incidence compared to other age class (Figure 2.4). A negative correlation was observed between disease Incidence and stand age with a Pearson's correlation coefficient of -0.58 and p-value (<0.001) (Figure 2.5). The severity indices also varied with stand age whereby stands with 5 years was noticed to have high disease severity index followed by stand with 7 years and lastly of 11 years (Figure 2.4). A moderate negative correlation was observed between disease severity index and stand age with a Pearson's correlation coefficient of -0.48 and p-value (<0.001) (Figure 2.5).

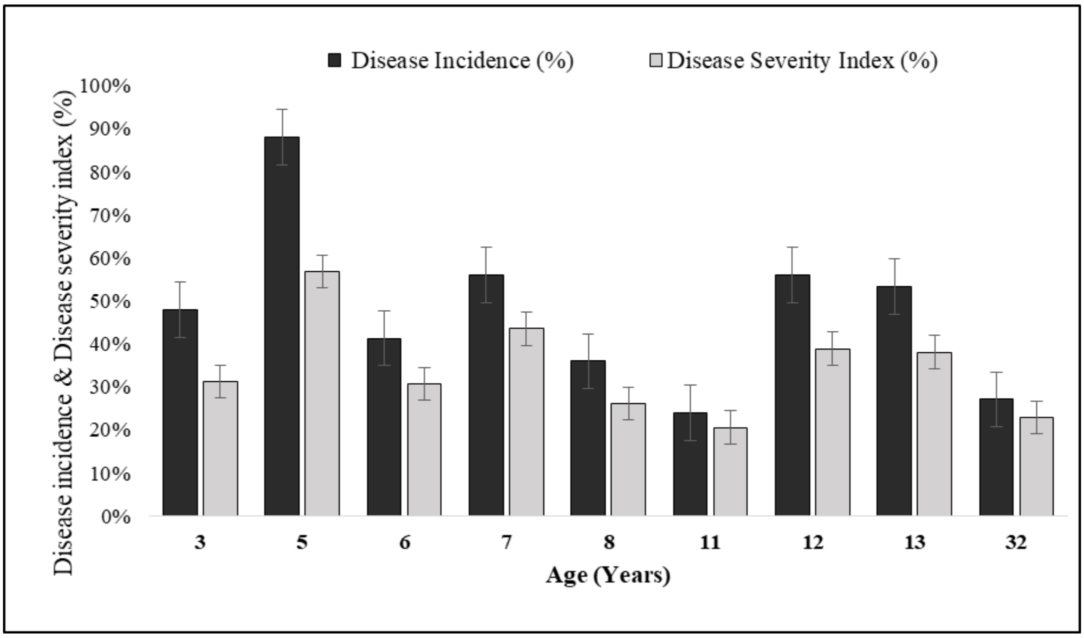

Figure 2.4: Disease incidence and disease severity indices for different age class in Mufindi district, Iringa Tanzania

Also, a significant negative correlation was observed between disease incidence and stand mean height (r = 0.61, p < 0.01) and mean DBH (r = -0.57, p <0 .001). Likewise, negative correlation was also observed between disease severity index mean height (r = 0.51, p<0.001) and mean DBH (r = -0.49, p<0.001) (Figure 2.5). Among all three stand parameter tree height was showing strong negative correction to both DI and DSI.

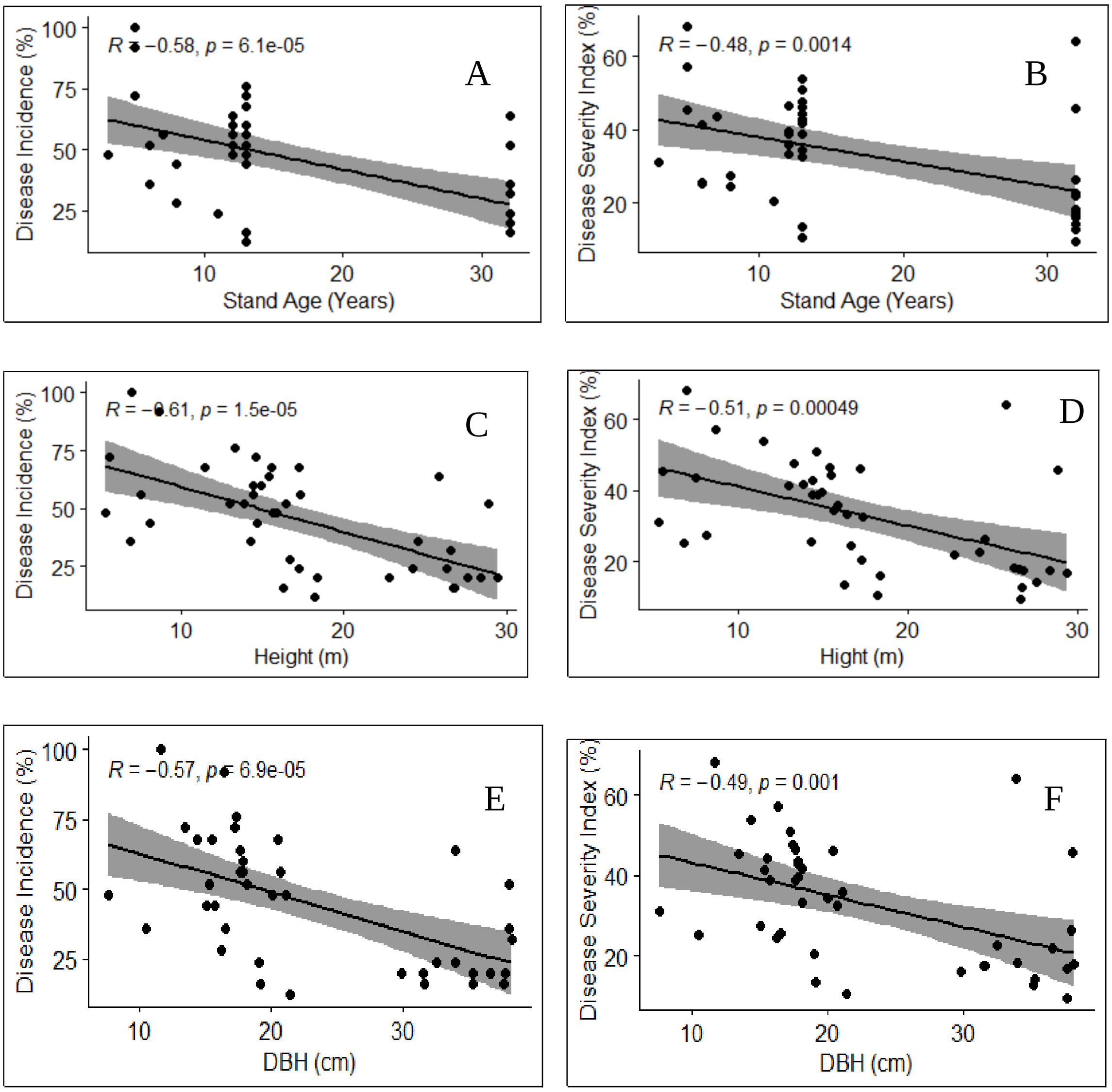

Figure 2.5: Correlation between Age and (a) disease incidence (b) disease severity Index; Height and (c) Disease incidence (d) disease severity index; DBH and (e) disease incidence (f) disease severity index

2.3.4 Effect of management practices on PPC disease incidence and severity

Results shows that, management practice have a significant effect on DI ($F_{(8, 32)} = 8.02$, $p< 0.001$) with an $R^2 = 0.69$ and on DSI ($F_{(8, 32)} = 4.369$, $p< 0.001$) with an $R^2 = 0.55$. However, pruning was the only significant independent predictor of DI and DSI ($P<0.001$) (Figure 2.6 and 2.7). The relationship was positive for pruning implying that increased pruning activities are related to an increase in DI and DSI.

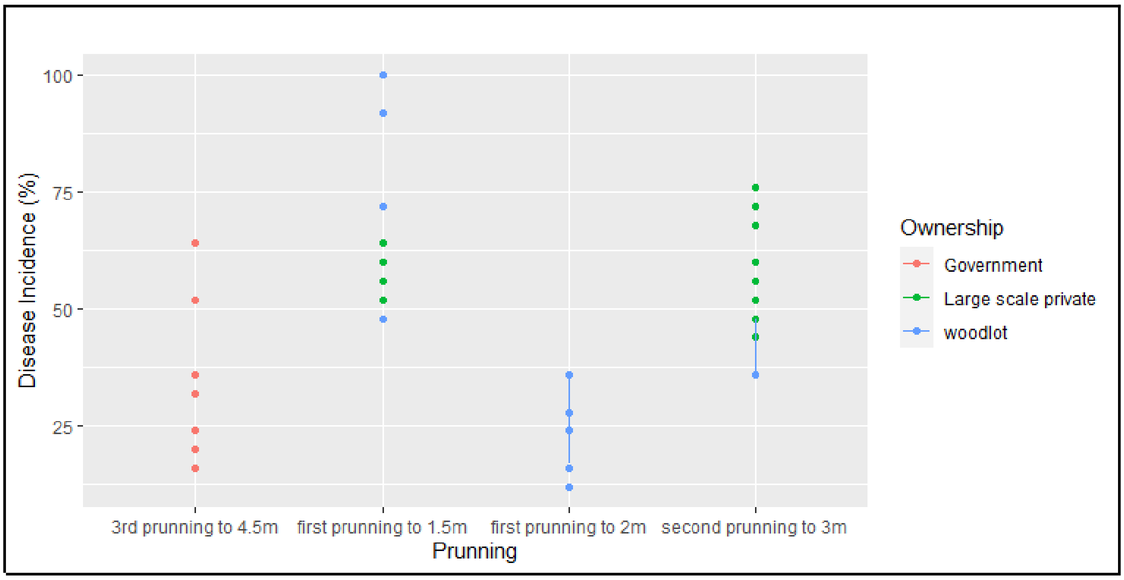

Figure 2.6: Disease incidence for different pruning levels in a pine plantation at Mufindi District, Iringa, Tanzania

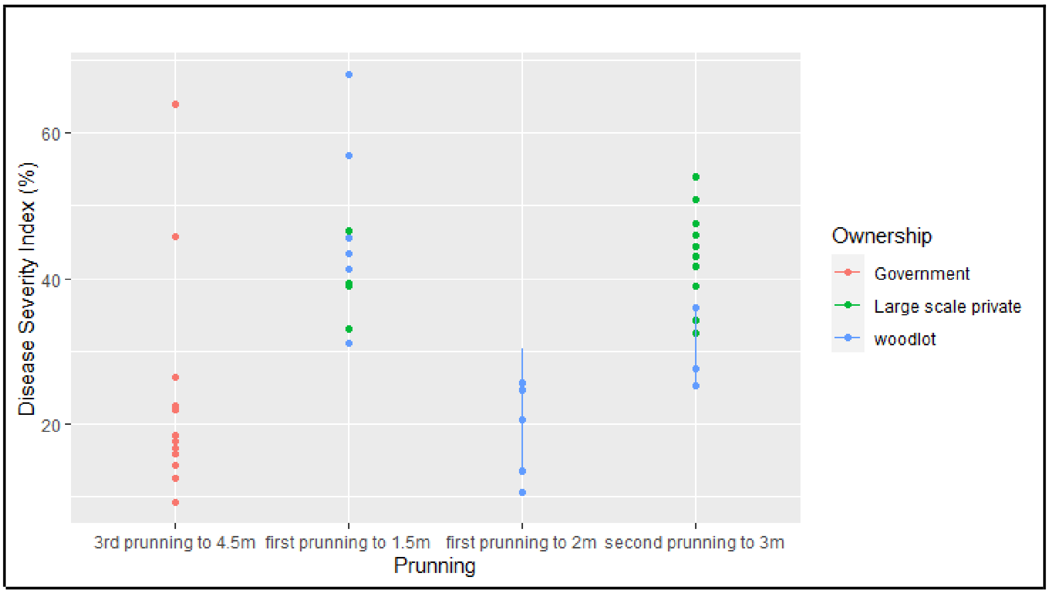

Figure 2.7: Disease Severity index for different pruning levels in pine plantations at Mufindi district, Iringa, Tanzania

2. 4 Discussion

The study reported a high level of diseases incidence on the private managed plantation, followed by woodlots and government managed plantation. The high level of disease incidences in privately managed plantation could primarily be explained by seed source since all affected areas were planted with imported seeds from the same source. However, there is not much evidence to confirm that seed source are the cause as it was not possible to assess the seeds that were planted. Other models of transimmison such as wind, vectors and splash water could play a vital role of transmitting the pathogen within the plantations. *Fusarium circinatum* can pass to seed directly from the affected tree or during seed storage (Evira-recuenco *et a*l., 2015). Most of the government-managed plantations were planted with internal seed sources collected from the old pine stands. Similar to woodlots owners obtained their seeds from internal seed sources mainly from old pine trees within the villages and old government pine plantations.

In this study, all three measured stand parameters (age, DBH, and height) had a negative correlation to PPC disease incidence and severity index. The disease prevalence was mostly observed in the tree with age less than 15 years. The incidence and severity noticed to increase in younger stands, this suggests that the disease was present in newly established plantations and woodlots. However, most of the dead trees were found at the older stand this indicated that aging affects the capacity of trees to recover following disease damages. The young, vigorous tree replaces damaged tissues and resumes growth, while the older tree has a slower metabolism and a slower rate of wound recovery, which increases the tree's susceptibility to pathogens (Maid and Ratnam, 2014).

The negative correlation of tree height indicates that the disease increase to the shorter tree than tall trees. This explains that poor tree height growth associated with a shortage of light, water, or soil may stress the tree and become easily attacked by PPC disease. Since the pathogen can leave on dead tissues on the soil surface the splash of spores from surface to top of tall tree might be more difficult than to top of short trees. Tree height had a higher degree of correlation with DI and DSI compared to all predictors this implies that the PPC is affected by light availability and crown cover. Similarly Blank *et al*., 2019 observed a low canopy cover to have high level of the PPC dieback symptoms.

The significant positive effect of pruning activity indicates that disease incidence and severity increases on pruning sites. Pruning is a practice that ensured lower branches are removed in young stands to create longer clear bole and to avoid large knots (Víquez and Pérez, 2005). However, this created entry wounds for the *Fusarium circinatum* (Bezos *e*t *a*l., 2012) and affect the PPC disease incidence and severity. Other management practices such as weeding and thinning can cause wound if not carefully practiced but their effect was not significant on this study as most of the affected areas, weeding and thinning were not performed. In the current study, spacing was reported to have no significant effect on disease incidence and severity, though other studies have been reported as the factor influencing dieback symptoms of PPC disease (Blank *et a*l., 2019). The issue of land preparations was similar to most of the surveyed plots and did not show any signs on PPC incidence and severity.

2.5 Conclusions

This study revealed that, the PPC disease occurred in all management regimes with a high incidence to the private-managed plantations. Disease incidence and severity noted to be negatively correlated with height, DBH and age. The disease was attacking mostly younger stands of not more than 15 years. A young tree can recover quickly from PPC infections while older trees recover slowly which leads to the death of many old trees. The management practices that are likely to cause the wound on tree stems especially pruning have been reported to increasing PPC incidence and severity.

2.6 Recommendations

Based on the findings of this study and experience from another study, the following are recommended;

i. The government should develop a holistic management approach to include all tree growers to reduce the spread of PPC disease to pine plantations.

ii. Pruning should be done during the dry season with minimum damage level, to reduce the chances of infestation through wounds.

iii. There is a need to perform effective screening of imported seeds before planting.

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CHAPTER THREE

3.0 PREDICTION OF SUITABLE AREAS FOR PINE PITCH CANKER DISEASE UNDER DIFFERENT CLIMATE CHANGE SCENARIOS USING MAXENT MODEL IN TANZANIA MAINLAND

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Abstract

Pine pitch canker (PPC) disease caused by *Fusarium circinatum* has resulted to serious damage in forests worldwide. Climate and topography has been reported to influence the habitat suitability for PPC establishment. However, the interaction of this factors and pattern of PPC spread has not been studied in Tanzania. Seventy points of with PPC incidence were used to model the current and future habitat suitability of PPC disease in pine plantations based on two representative concentration pathways (RCP 2.6 and RCP 8.5) for 2050s and 2070s using MaxEnt. The PPC occurrence points were obtained from field survey, plantation managers, woodlot owners and various published and unpublished reports. The climatic data consist of 19 bioclimatic variables obtained from the world climatic database and topographic variables obtained from U.S. geological survey (USGS). Pearson correlation was employed to determine multicollinearity between variables and only 13 variables considered non-collinear were used in the model. The area under the receiver operating characteristic (ROC) curve (AUC) was used to evaluate the performance of the model and jackknife was used to assess variable importance. The AUCs were greater than 0.9, thereby placing the models was accurate. Jackknife results show bioclimatic variables related to temperature have a high percentage contribution to the model. The mean temperature of the coldest quarter (Bio 11) and temperature seasonality (Bio 4) contributed higher than other bioclimatic variables and topographic variable with percent contribution of 68% and 32% respectively. The PPC disease establishment was much favored with a low concentration of greenhouse gases emission. Since under RCP 2.6, the suitable area predicted was stable in 2050 with smaller decrease in 2070. But under RCP 8.5 the model predicts a continuous decrease of PPC disease occurrence from current distribution to 2070. The model predicts areas suitable for PPC will cover much on southern, southern highland, and northern zones of Tanzania. The study recommends establishment of quarantine and monitoring system of the disease so as to prevent introductions of the pathogen to the predicted regions where cases are not yet reported.

Keywords: Pine Pitch Canker, MaxeEnt model, Climate change, Habitat suitability, Climate change scenarios.

3.1 Introduction

Pines are commercial trees with high economic importance in Tanzania (Ngaga, 2011). They are primarily used for timber production and indirectly play roles in soil conservation and climate regulation. Pine pitch canker caused by *Fusarium circinatum* is a substantial threat to areas where *Pinus spp* are grown (Wingfield *et a*l., 2008). The disease results in an economic loss since it turns plantations into standing timber of low potential value for future production (Blank *et al.*, 2019). The disease is predominantly found in warm and moist areas and at present time its occurrence has been reported in more than 42 countries in the world (Drenkhan *et a*l., 2020).

Environmental factors such as climate, elevation, wind, rainfall, soil properties, and human activities, and other vectors influence the spread and infestation rate of PPC disease (Blank et al., 2019). The global rise in the emission of greenhouse gases associated with increased temperature has affected our natural ecosystems (Abdelaal *et a*l., 2019). Among others including the correlation between trees and pathogens (Sturrock *et a*l., 2011). *Fusarium circinatum* occurrence, virulence, and distribution have also been mentioned to differ with climate variability (Drenkhan *et al*., 2020; Martín-Rodrigue*s et a*l., 2013; Möykkynen *et al*., 2015). Moderate temperatures of 25 ℃ influence rapid growth and spore production of *F. circinatum* (Carlucci *et al*., 2007). Other microclimatic conditions such as humidity, precipitation, and wind tend to influence the spread of pathogens by the vector insects (Möykkynen *et al.*, 2015; Wingfield *et al*., 2008). Topographic factors such as elevation may affect the disease intensity mainly due to progressively variations of temperatures along elevation (Wingfield *et al.*, 2008).

For appropriate control of PPC disease, it is important to early detect the potential areas for disease establishment (Meentemeyer *et a*l., 2008). Early detection of the suitable areas will assist in planning and executing a rapid early response to fighting against the disease (Hanna *et al*., 2016). Recently, in Tanzania, the disease occurrence was reported from various regions in southern highland and northern Tanzania. The risk of disease spread is high due to the broad host range, as pine covers about 74% of planted trees in government and private plantations (Ngaga, 2011). Numerous studies have been conducted to predict the risk of PPC disease distribution to various parts of the world (Möykkynen *et al*., 2015). The global prediction of climatic risk of pitch canker disease by CLIMEX identify Tanzania as one of the areas suitable to PPC establishment, however, the model predicts a larger portion of water bodies as a suitable area (Ganley *et a*l., 2009a). This may be due to missing occurrence records in Tanzania (Drenkhan *et a*l., 2020; Ganley *et al*., 2009a). Furthermore, there is no study conducted to predict PPC disease distribution by using MaxEnt in Tanzania.

With the advancement in technologies, various prediction models have been developed for forecasting disease epidemics. Commonly applied including global geographic information system for a medicinal plant (GMPGIS), bioclimatic modeling (BIOCLIM), genetic algorithm for rule-set production (GARP), and maximum entropy (MaxEnt) (Manyangadze *et a*l., 2016; Tang *et a*l., 2021). The MaxEnt model is widely used due to its capability of accurately supporting multiple variables, small sample requirements, high flexibility, and easy result interpretations (Tang *et a*l., 2021). The MaxEnt is used in various ecological and medical research like plant species suitability, risk assessment of invasive species, endangered species survey, and climate change impact (Abdelaa*l et al*., 2019; Pablo *et a*l., 2019; Shukla *et a*l., 2020).

Therefore, this study aims at predicting the potential areas for pine pitch canker disease under the different scenarios of climate change. This will facilitate the development of better management strategies to limit the expansion of a pathogen in new areas.

3.2 Materials and Methods

3.2.1 Description of the study area

The study was conducted in Tanzania mainland located at the East coast of Africa between latitudes 1°S and 12°S and longitudes 29°E to 41°E (Luhunga *et a*l., 2018) (Figure 3.1). It covers about 885,800 square kilometers of land area. The country has a tropical type of climate that varies across the country. It experiences two types of rainfall patterns, bimodal and unimodal rainfall patterns. The annual rainfall total also varies from 200 to 1000 mm over most of the country. A higher amount of annual rainfall total is recorded over Southwestern and Northeastern highlands. Central Tanzania is a semi-arid region that receives an annual rainfall of less than 400 mm. The annual average temperature over Tanzania ranges from 25 to 32°C. However, over the highland temperatures are slightly lower, for example, during the hot month (February) and the coldest month (July) temperature is 20°C and 10°C respectively.

Tanzania mainland has a total forest area of 48.1 million hectares (ha), which is 55% of the total land area. Forest plantations cover a total area of 554 500 ha (1.2%) of the total forest. Out of this, the government owns about 95 000 ha, private industrial plantations 40 000 ha and the total area of private woodlots is about 419 500 ha (Ngaga, 2011). The main species planted throughout the country include *Pinus patula, P. elliott, P. caribaea, P. kesiya, Eucalyptus species, Cupressus lusitanica, Tectona grandis, Acacia mearnsii, Cedrela odorata, Grevillea robusta,* and *Juniperus procera*. Pines are the dominant species in most of the government, private plantations and woodlots with about 78% of the total area planted and the remaining 22% are shared among hardwoods and other softwood species (Ngaga, 2011).

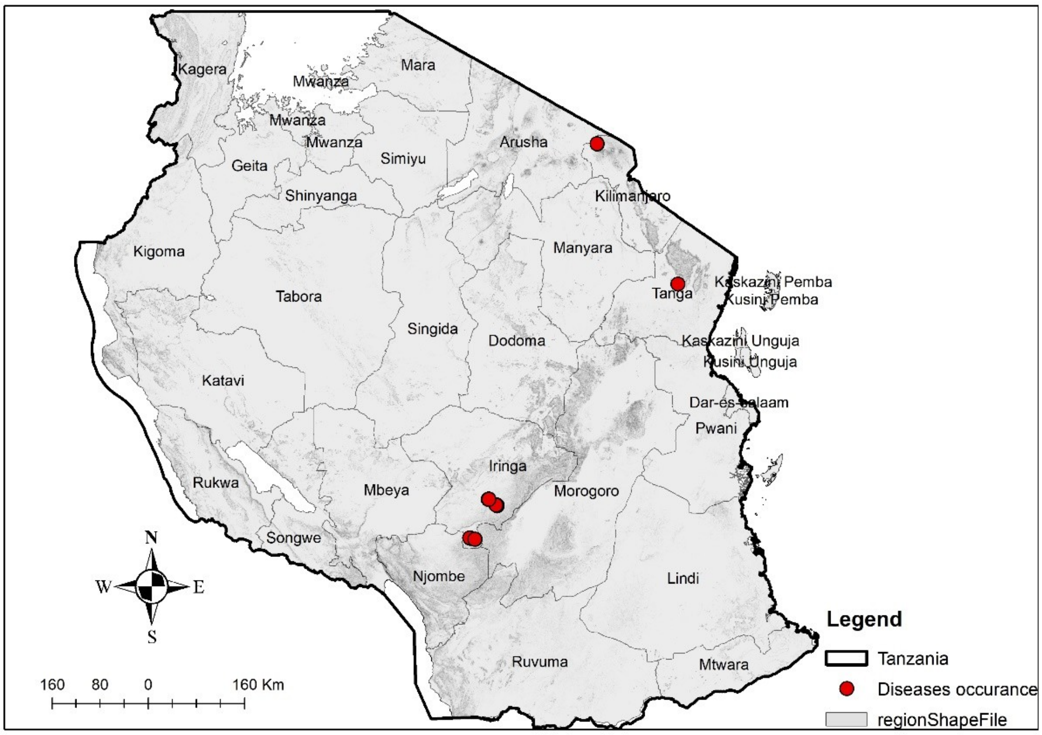

Figure 3.1: Map showing regions of Tanzania and areas with PPC disease occurrence

3.2.2 Occurrence data of PPC disease to pine plantations in Tanzania

The GPS coordinates of affected areas were primarily obtained through a survey conducted between January and May 2021 at the southern highlands of Tanzania where several cases of PPC disease symptoms were previously reported. A total of 50 points of affected areas comes from government and private-owned pine plantations were recorded during the survey. Other 20 epidemic records of PPC disease were obtained from the respective plantation managers and woodlots owners. Various published and unpublished reports developed by various institutions like Tanzania Forest Research Institute (TAFORI), Private Forest Program (PFP) and Forest Development Trust (FDT) were used in this study. Google Earth software was used to extract coordinates from the records/reports lacking GPS coordinates. A total of 70 affected points was used in MaxEnt prediction of the potential distribution of PPC in Tanzania (Figure 3.1).

3.2.3 Environmental variables

The environmental variables consist of climate and topographic data. The current climatic data were collected from the World Climate database, version 1.4 (http://www.worldclim.org/) at a spatial resolution of 2.5 min. About 19 bioclimatic variables (Bio1~19) were obtained (Table 3.1). The bioclimatic variables of future climate included two representative concentration paths (RCP 2.6 and 8.5). The RCP 2.6 (the minimum scenario for GHG emissions) and RCP 8.5 (the highest scenario for GHG emissions) were selected in this study to test PPC suitability ranges in the 2050s and 2070s respectively. In total, 19 bioclimatic variables (Bio1–Bio19) and 3 topographical factors (elevation, slope and aspect) were used to identify factors with the highest influences on the distribution of PPC disease. The topographic variables included were derived from 30 m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) obtained from U.S. Geological Survey (USGS).

Table 3.1: Bioclimatic variables used in PPC habitat suitability in Tanzania

Variable	Description	Unit
BIO1	Annual Mean Temperature	°C
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	°C
BIO3	Isothermality (BIO2/BIO7) (×100)	%
BIO4	Temperature Seasonality (standard deviation ×100)	°C
BIO5	Max Temperature of Warmest Month	°C
BIO6	Min Temperature of Coldest Month	°C
BIO7	Temperature Annual Range (BIO5-BIO6)	°C
BIO8	Mean Temperature of Wettest Quarter	°C
BIO9	Mean Temperature of Driest Quarter	°C
BIO10	Mean Temperature of Warmest Quarter	°C
BIO11	Mean Temperature of Coldest Quarter	°C
BIO12	Annual Precipitation	mm
BIO13	Precipitation of Wettest Month	mm
BIO14	Precipitation of Driest Month	mm
BIO15	Precipitation Seasonality (Coefficient of Variation)	%
BIO16	Precipitation of Wettest Quarter	mm
BIO17	Precipitation of Driest Quarter	mm
BIO18	Precipitation of Warmest Quarter	mm
BIO19	Precipitation of Coldest Quarter.	mm

Source: Phillips *et al.,* 2006.

3.2.4 Maximum Entropy model development, calibration and validation

The Pearson correlation coefficient was used to account for multicollinearity between the bioclimatic (Bio1– Bio19) and topographic (elevation, slope and aspect) variables (Graham, 2003). Two variables with a correlation coefficient of greater than 0.8 or -0.8 were considered highly correlated and omitted for further analysis (Tang *et a*l., 2021; Yan *et al*., 2020). The MaxEnt software (version 3.4.1) based on the occurrence point of the PPC disease and the environment variables, was used for analysis and predict the distribution of suitable habitats of the disease. The selected environmental variables and occurrence data of PPC were uploaded to MaxEnt for modeling and predicting the distribution. Seventy-five percent of the occurrence records were used to train the model, and the remaining 25% were used to test the model’s predictive ability. The model ran 1000 iterations with the default parameter settings, and the prediction output was saved in ".asc" format (Phillips *et al*., 2006). A Jackknife test was used to estimate the relative importance of each of the selected variables to the model development. The model performance was tested using the Area under the Curve (AUC) of the receiver operating characteristic (ROC). The area under the curve values in a model output range from 0 to 1 (unsuitable to highly suitable). When AUC shows the values below 0.5 then it can be interpreted as a random prediction. An AUC value between 0.5 and 0.7 indicates poor model performance, 0.7 to 0.9 indicates reasonable performance, and > 0.9 indicates high model performance (Peterson and Soberón, 2012; Phillips *et a*l., 2006). Response curves were used to study the relationships between bioclimatic variables and the predicted probability of the presence of PPC disease. The final MaxEnt model was projected into a spatial map for each of the selected climate scenarios to visualize current and future habitat suitability for PPC disease. The occurrence probabilities were classified as low (0 – 0.2) medium (0.2 – 0.45) high (> 0.45). Q-GIS, version 3.4 to produce suitability maps.

3.0 Results

3.1 Model accuracy and variables contribution

The calibration of the model for PPC was satisfactory (AUC= 0.935) indicating the model prediction being accurate and credible (Figure 3.2). The model performed well in matching the distribution of the PPC disease occurrence records.

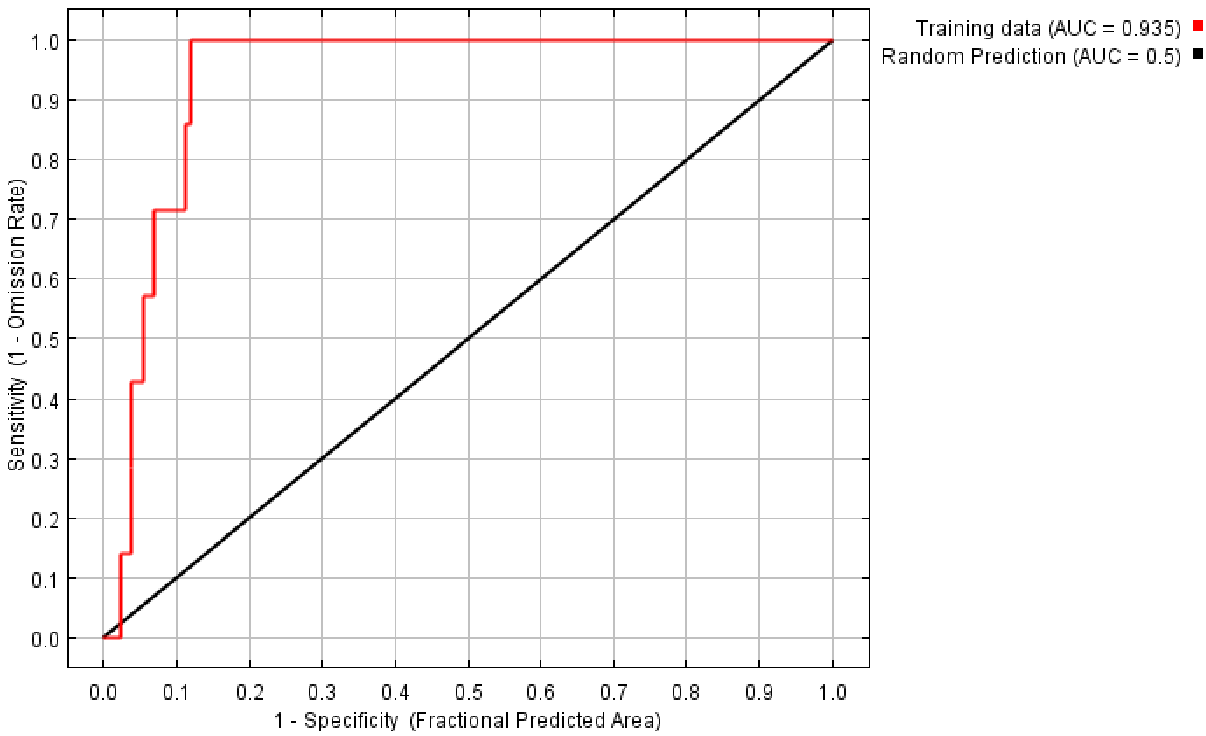

Figure 3.2: Receiver operating characteristic curve and Area under the curve value of prediction model in Tanzania

Out of 23 variables, only 13 variables were identified to be non-collinear and used in prediction. These were mean diurnal range (Bio 2), isothermally (Bio 3), temperature seasonality (Bio 4), temperature annual range (Bio 7), precipitation of wettest quarter (Bio 16), precipitation of driest quarter (Bio 17), precipitation of warmest quarter (Bio 18), precipitation of coldest quarter (Bio 19), slope, aspect and elevation.

Among all variables used in predicting PPC disease distribution, mean temperature of coldest quarter (Bio 11), temperature seasonality (Bio 4), mean diurnal range (Bio 2) and slope were found to be essential in the model. Mean temperature of coldest quarter (Bio 11) was the most important variable in predicting the probability distribution of PPC disease with the total percentage contribution of 68.2%. Temperature seasonality (Bio 4) was the second important variable with a percentage contribution of 30%. So the two variables Bio 4 and Bio 11 contributed to 90%. Mean diurnal range (Bio 2) and the slope was having a very little contribution to the model with 0.7% and 0.6% contribution respectively. The response curve reveals the inverse relationship between the mean temperature of coldest quarter and PPC disease distribution probabilities (Figure 3.3). On the other hand, temperature seasonality was found to have a positive relationship with PPC distribution probabilities (Figure 3.4).

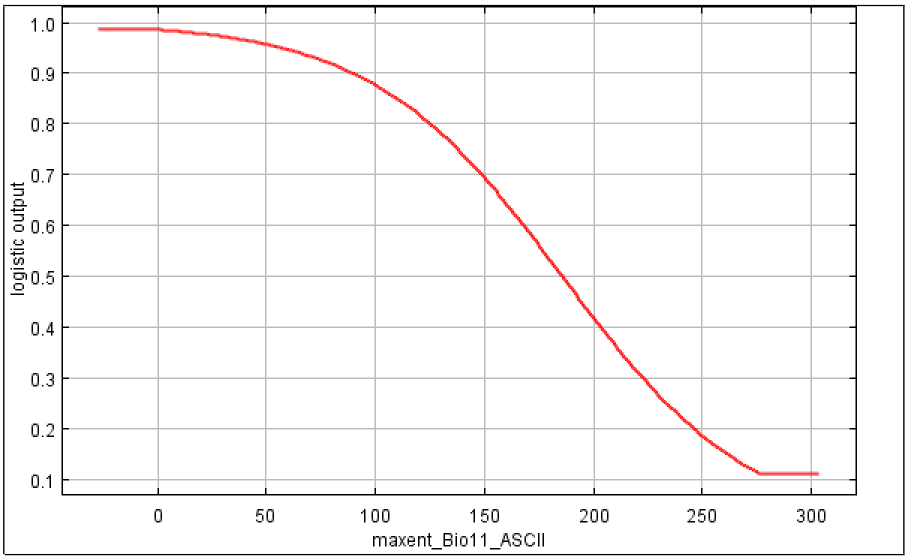

Figure 3.3: Response curve showing the variation of mean temperature of coldest quarter with the probabilities of PPC disease distribution

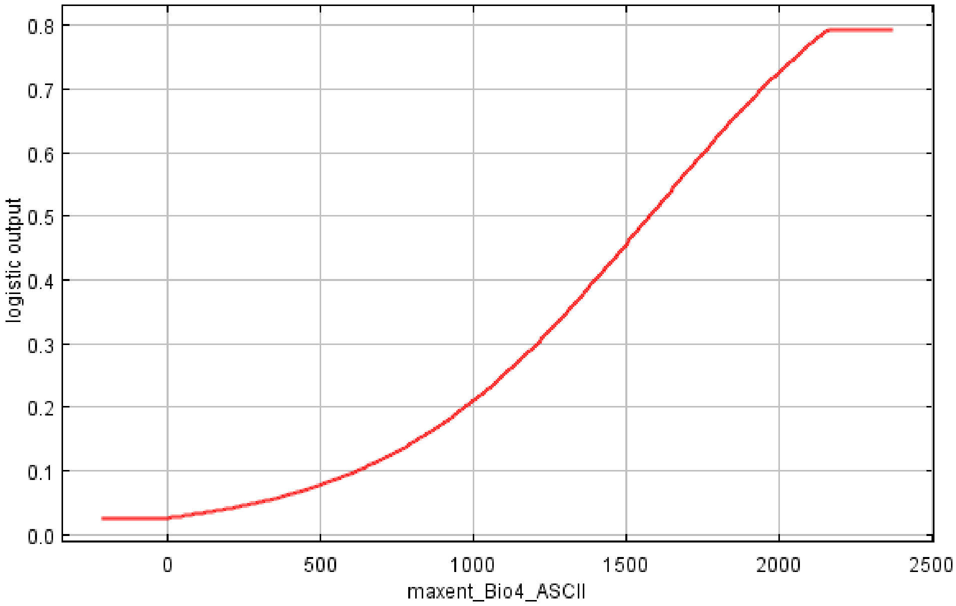

Figure 3.4: Response curve showing the variation of temperature seasonality with the probabilities of PPC disease distribution

3.2 Current PPC disease prediction

In the current scenario, the MaxEnt model predicted the high level of suitability for PPC establishment on the southern highland, southern and northern highland zone of Tanzania. The area suitable for PPC disease establishment was mostly predicted in the Southern highland to the regions of Iringa, Njombe, and Mbeya; southern zone to the region of Ruvuma and northern Tanzania to the regions of Arusha, Moshi and Tanga regions (Figure 3.5). The central and eastern zones was noticed to have a very small area with medium suitability for PPC establishment. Other zones like Western and Lake Zone were predicted to have a very low probability of having PPC disease. Under current climate conditions areas predicted to have a high probability of PPC was about 5 649 600 ha, medium 10 572 800 ha, and low 78 246 930 ha (Figure 3.7).

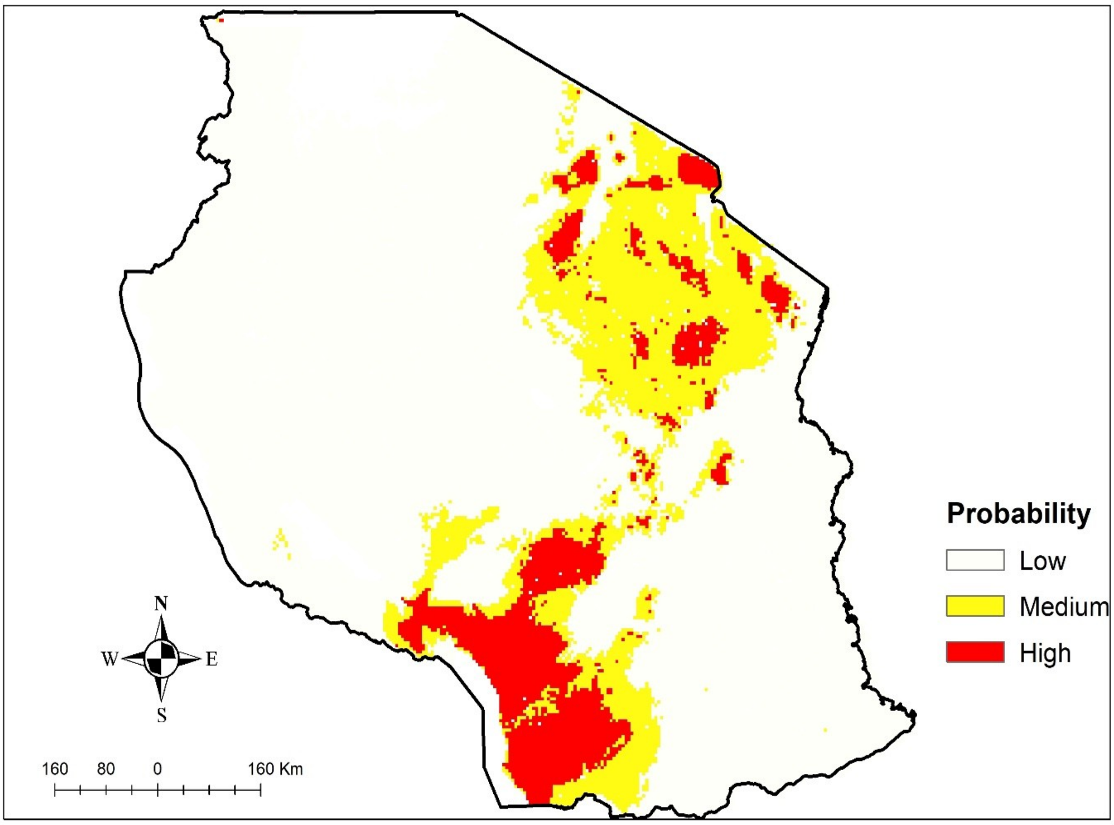

Figure 3.5: Habitat suitability maps showing the occurrence of PPC disease under current climatic condition in Tanzania

3.3 Future prediction potential distribution of PPC disease

The model predicts climate change will increase or reduce the spread of PPC disease. Under scenario RCP 2.6 the model predicts an initial increase of PPC disease occurrence in 2050 then decrease in 2070, while scenario R.C.P 8.5 predicts a continuously rapid decrease of PPC disease spread (Figure 3.6 and 3.7). In the future with an increase in greenhouse gas emission , the spread of PPC will significant decrease to the northern and central zone of Tanzania and the risk will only exist to small part of the Southern and Northern part of Tanzania.

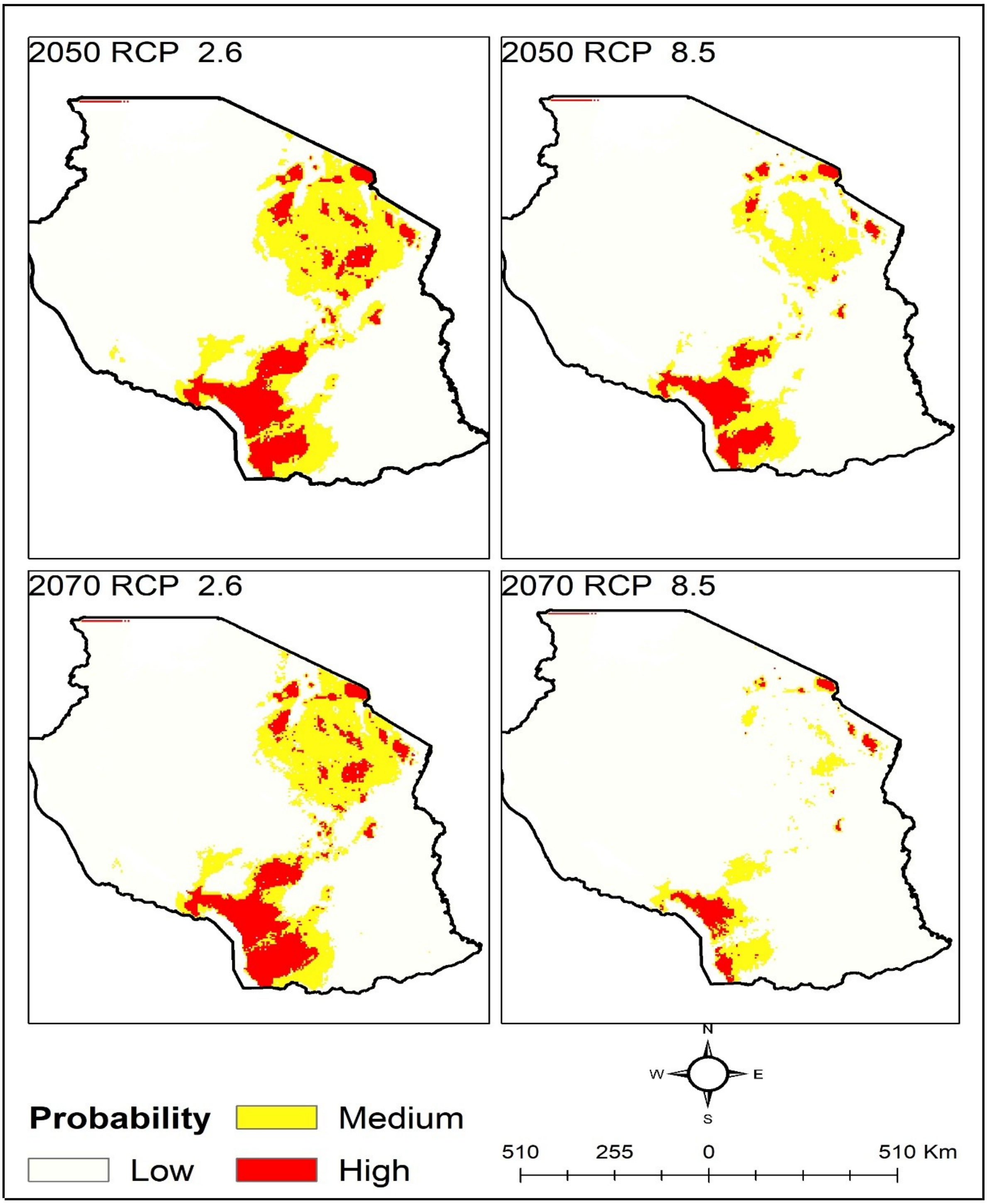

Figure 3.6: Habitat suitability maps showing the occurrence of PPC disease by 2050 and 2070 under R.C.P 2.6 and R.C.P 8.5 in Tanzania mainland

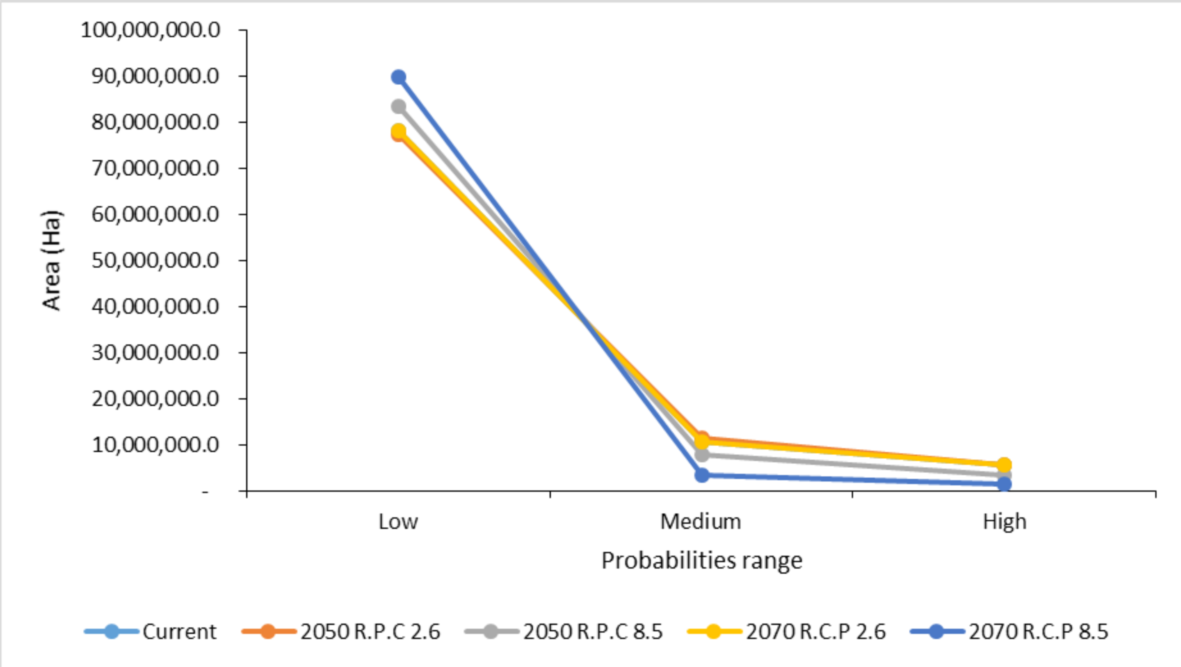

Figure 3.7: Changes in potentially suitable habitats for PPC disease in current, 2050 and 2070 under R.C.P 2.6 and R.C.P 8.5 in Tanzania Mainland

3.4 Discussion

Climate modeling of fungi species distribution has shown that future global climate change will have important effects on forest plantations (Ganley *et a*l., 2009a; Drenkhan *et a*l., 2020; Wei *et a*l., 2021). The present study aimed at modeling and predicting the potential area for PPC disease infestation at the national level. The model used the environmental variables to identify similar localities where PPC disease has the potential to occur. Among the 13 environmental variables used in the model, mean temperature of coldest quarter (Bio 11) and temperature seasonality (Bio 4) were the most important contributors to habitat suitability distribution of PPC disease as indicated by their high percentage. The mean temperature of coldest quarter was inversely related with PPC disease probability meaning that an increase in the mean temperature of coldest quarter reduces the suitability of PPC disease establishment. While temperature seasonality was having a positive relationship with PPC disease probability meaning that PPC suitability increase with an increase in temperature seasonality. Temperature is closely related to humidity, according to Lafarie, 2005 and Lawrence, 2005, humidity levels increase with a decrease in temperature.

For PPC disease development, the optimal temperature of (20 – 25 ℃) and high humidity level are key factors for a pathogen to develop (Bezos *et al*., 2017). So the decrease in mean temperature of the coldest quarter increases the humidity level and favors the PPC disease establishment and development. This is in line with other findings that revealed PPC infections may not occur even where temperatures are within the optimum range if sufficient moisture is not available (Wikler *et a*l., 2003; Wingfield *et a*l., 2008a). The positive relation of temperature seasonality and PPC suitability supports the fact that mating of a fungal pathogen is favored by low temperatures (Covert *et a*l., 1999), whereas disease outbreaks occur during relatively warm periods (Wingfield *et a*l., 2008a). So as the temperature change over the year it creates favorable conditions for mating, growth, and spread of the causative agent.

Under current climate conditions, the probability was high at the southern highland, southern and northern zones of Tanzania. The average mean temperature of these areas were ranging (10 – 28℃), (16 – 29℃) and (16 - 28℃) respectively, which favored the reproduction and infection of the causative agent. These areas are also characterized by a high amount of relative humidity ranging from (60 – 80%) which is suitable for *F. circinatum* growth. The low occurrence possibility of western and lake zone disease is due to excessive temperature reaching up to 35 ℃ and low amount of humidity. Under scenario RCP 2.6 representing low greenhouse gases concentration, the PPC probabilities are relatively stable with a minor increase in 2050 and decreasing in 2070. This might be due to a small increase in global temperature of not than 2℃ that will increase the mean temperature of the coldest quarter favorable for *F. circinatum* establishment and survival. According to IPPC targets, under RCP 2.6 the carbon dioxide (CO_2) emissions are expected to start declining by 2020 and go to zero by 2100 (van Vuuren *et al*., 2011) (Figure 3.8).

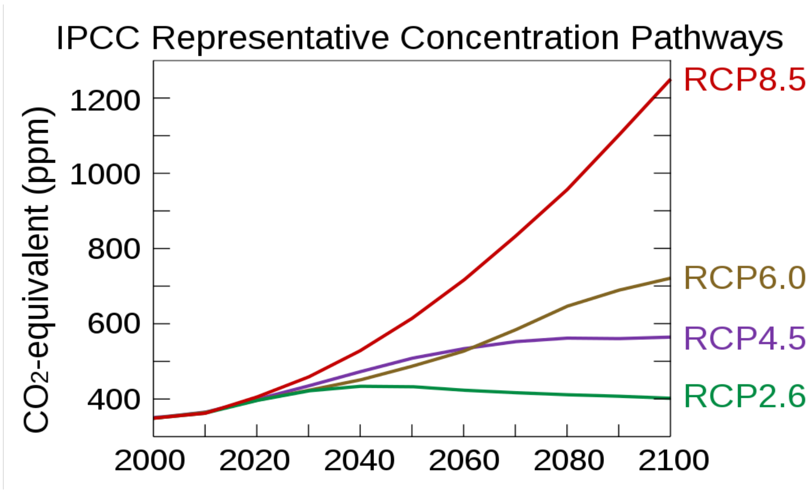

Figure 3.8: Graph showing the variation of CO_2 concentration under IPPC representative concentration pathways (RCP 2.6, 4.5, 6.0 and 8.5), Source (van Vuuren *et al*., 2011).

Under scenario R.C.P 8.5 representing the high concentration of GHG (Figure 3.6), the model predicted a continuous decline in PPC disease occurrence. This can be firstly explained by the rise in global temperature higher than optimum temperature for *F. circinatum*. Secondly is by lowering the amount of humidity through increased temperature and reducing moisture content required for *F. circinatum* growth. Lastly, the rise in temperature seasonality might lead to reduced pathogen capability to adapt to their environment. Furthermore, the high concentration of GHG could affect direct and indirect the host tree ability to resist attack as the growth of pines species are favored by a low amount of temperature.

The model predicted the areas with environmental conditions favoring the PPC pathogen establishment but didn't take into account the severity level when the incidence occurred. However, it is most likely the severity to be high to the suitable environment than other areas. It is important also to note other biotic factors like insect vector, host availability and resistance, and silvicultural practice can influence the incidence and severity of the disease (Ganley *et al*., 2009a).

3.5 Conclusion

This study efficiently predicted the area suitable for PPC disease on current and future climate change scenarios using MaxEnt. The study found that bioclimatic variables related to temperature (Bio 11 and Bio 4) affect and limit the distribution of PPC disease. The establishment of PPC pathogen is much favored with a low concentration of greenhouse gas that provides an intermediate warmer environment and high humidity level. Southern highland, southern and northern zones of Tanzania were predicted to be highly susceptible to PPC disease infestations. Under current conditions, the area favorable for disease establishment is much larger than that of future climate scenarios.

3.6 Recommendations

The MaxEnt model predicted some pine areas of the high susceptibilities to PPC disease establishment for regions in southern, southern highland, and northern zones. This should be of concern for pine-growing industries in the country. Therefore, it is recommended to develop a quarantine and monitoring system of the disease to prevent the introduction of the PPC pathogen to the predicted regions where cases are not yet reported.

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CHAPTER FOUR

4.0 CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

Generally, the study shows the prevelance of PPC disease in all management regimes assessed. The disease incidence and severity was higher in the large scale private-managed plantation followed by small scale private managed woodlots and lastly to government managed plantation. Disease incidence and severity was negatively correlated with height, DBH and age. The disease was attacking mostly younger stands of not more than 15 years. The management practices that are likely to cause the wound on tree stems especially pruning have been reported to increasing PPC incidence and severity.

On predicting suitable areas for PPC disease establishment bioclimatic variables related to temperature (Bio11 and Bio4) had higher percent contribution to the MaxEnt model. The establishment of PPC pathogen was favored with low concentration of greenhouse gas that provides an intermediate warmer environment and high humidity level. Southern highland, southern and northern zones of Tanzania were predicted to be highly susceptible to PPC disease infestations. Under current conditions (RCP 2.6), the area favorable for disease establishment was larger than that of future climate scenarios (RCP 2.8).

4.2 Recommendations

The study recommended the following;

i. The government should develop a holistic management approach that includes all tree growers to reduce the spread of PPC disease in pine plantations.

ii. Pruning should be done during the dry season with minimum damage level, so as to reduce the chances of infestation through wounds.

iii. There is a need to perform effective screening of imported seeds before planting.

iv. There is a need to establish local inoculum pressure and the influence of their dispersal mechanism under local conditions.

v. Developing strict quarantine and monitoring system of the disease so as to prevent introductions of the pathogen to the predicted regions where PPC disease is not reported.

APPENDICES

Appendix 1: Stand parameters and management practices conducted in the study sites in Mufindi district, Iringa, Tanzania.

Site	Compartment	Species	No. of Plots	Seed source	Spacing (m)	Pruning	Thinning	Age (Years)	Mean DBH (cm)	Mean Height (m)
Large scale private managed plantation (Green Resource Forest Company)	Compartment No. B55	*P. patula*	4	Imported	3 x 3	Second pruning to 3m	First thinning	13	18.11	14.489
	Compartment No. B56	*P. patula*	6	Imported	3 x 3	Second pruning to 3m	First thinning	13	17.47	15.03
	Compartment No. E1b	*P. patula*	4	Imported	3 x 3	First pruning to 1.5m	No thinning	12	21.12	15.84
Woodlots	Woodlot 1	*P. patula*	2	Sao Hill	3x4	Second pruning to 3m	No Thinning	12	21.12	15.84
	Woodlot 2	*P. patula*	1	Sao Hill	2.5x2.5	Second pruning to 3m	No Thinning	6	10.51	6.86
	Woodlot 3	*P. patula*	1	Sao Hill	3x3	First pruning to 1.5m	No Thinning	12	17.8	15.28
	Woodlot 4	*P. patula*	3	Sao Hill	3x3	First pruning to 1.5m	No Thinning	7	17.87	7.49
	Woodlot 5	*P. patula*	1	Sao Hill	3x3	First pruning to 2m	No Thinning	11	19.03	17.28
	Woodlot 6	*P. patula*	1	Sao Hill	3x3	First pruning to 1.5m	No Thinning	5	13.82	7.06
	Woodlot 7	*P. patula*	2	Sao Hill	3x3	Second pruning to 3m	No Thinning	8	15.09	8.12
	Woodlot 8	*P. patula*	1	Sao Hill	2X2	First pruning to 2m	No Thinning	8	16.22	16.68
	Woodlot 9	*P. patula*	2	Sao Hill	3x3	First pruning to 2m	No Thinning	13	20.25	17.22
Government managed plantation	Comp 3-2 (Division 3)	*P. patula*	14	Imported	3 x 3m	3rd pruning to 4.5m	First thinning	32	34.98	25.92