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Application of GIS and remote sensing techniques in frost risk mapping for mitigating agricultural losses in the Aberdare ecosystem, Kenya

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Frost is a perennial agricultural hazard that normally causes crop damage leading to huge agricultural losses within the Kenyan highlands; aggravated by inadequate information on frost. This research mapped frost hotspots within the Aberdare and Mount Kenya regions and identified the extent of arable land under frost risk while establishing the trend of minimum temperature occurrences between the years 2000 and 2013. Minimum temperature values were extracted from daily Moderate Resolution Imaging Spectroradiometer land surface temperature data-sets, and frost risk categorized into very severe frost (<250 K), severe frost (250–260 K), moderate frost (260–270 K), minor frost (270–280 K) and areas of no frost. Concentration of frost (<273 K) was mapped within regions above 1500 m asl and occasional occurrences within valleys lower than this altitude with recurrent occurrences in the months of April, May, July, August and November. Elevation, land surface convexity and humidity were found to influence frost occurrence. Improved agricultural practice to mitigate against losses is recommended.

Keywords: frost risk assessment; MODIS LST; land curvature; elevation; susceptibility

1. Introduction

Frost is the occurrence of an air temperature of 273 K or lower, measured at a height of between 1.25 and 2.0 m above ground, inside an appropriate weather shelter (Synder and De Melo-Abreu 2005). A study done by Chemung (1995) showed that frost is formed when surface temperature drops below 273 K and water vapour in the atmosphere condenses and freezes. Each plant has a threshold, beyond which it is damaged by the decreasing temperatures. Depending on the species and cultivar, frost damage to crops occurs below the threshold temperatures (Hijmans 1998). Based on its effect on plants, Koss et al. (1988) classifies freeze temperatures ranging from a light freeze of 29 F (271 K) to 32 F (273 K) where the tender plants and crops are killed. A moderate freeze ranging from 25 F (269 K) to 28 F (270 K), which is widely destructive to most plant species and heavily damages the tender fruit blossoms and semi-hardy plants. Severe freeze, on the other hand, is experienced at temperatures of 24 F (268 K) and less and damages most of the plants while freezing the ground. According to Synder and De Melo-Abreu (2005), frost damage is the leading weather hazard, on a planetary scale, to crops and forest resources. It damages leaves and or fruit, impact crop health

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and cause death of plants, depending on the severity of a frost and the susceptibility of a particular crop.

Agriculture dominates as the mainstay for the economies of many developing countries and is the single most important sector of the Kenyan economy, supporting over 80% of the total population (National Environment Management Authority – NEMA 2009). According to Geerts et al. (2006), recent advances in agricultural technologies may not mean much if agricultural production still depends on weather and climatic patterns. This is because climatic variability is now playing a greater role in limiting production to match the present population growth rates. A study done by the World Bank reveals widespread climate change in Europe and Central Asia manifesting in terms of increased disasters related to extreme weather; cold and heat waves, floods, drought and strong winds, thus, calling for disaster risk management plans as part of the climate change adaptation measures (Pollner et al. 2010). Lavalle et al. (2009) points out the importance of determining the duration of consecutive frost-free days when temperatures are above 273 K in the planning and integration of new species as well as planning of growing seasons to reduce on crop damage by frost especially to crops with long growing periods. To reduce agricultural losses, due to climate variability, decision-makers need up-to-date information on crop management and protection against natural agricultural hazards such as frost, drought and hailstorm among others. In the recent past, for example, Kenya has suffered from frost cases that led to huge losses to the farmers in the Kenyan highlands where most of the 20% arable land is located. The rest of the land in Kenya (80%) is arid and semi-arid (NEMA 2009). There is need, therefore, to limit losses that occur in the high agricultural potential areas, and cushion farmers through proper agricultural planning, provision of advisory services and or issuance of insurance against the increasingly recurrent frost incidences.

In the Aberdare and Mount Kenya regions, farmers in Nyeri, Nyandarua and Lari have in the past suffered losses amounting to millions of shilling as a result of an overnight frost. As a result, the United States Agency for International Development supported Kenya Horticultural Competiveness project, has taken management measures to assist the farmers at the foot of Mount Kenya and the Aberdare ecosystem area, by encouraging them to plant trees, diversify crops and adopt greenhouse technologies (USAID Kenya Horticultural Competitiveness project Monthly Bulletin January 2012 paper). These are among the management practices that involve modification of the crop's physical environment that farmers can adopt to mitigate against the losses.

The current paper illustrates the role satellite technologies can play in frost risk mapping. It identifies the predisposing factors that lead to frost occurrence and explains the trend of frost and probabilities of frost risk for mainstreaming resilient crop cultivars in the Aberdare region. It identifies the predisposing factors for frost occurrence and explains the trend of minimum temperature occurrences. Further, the study integrates useful information necessary to form a basis for the development and design of compensation products to the farmers for losses related to frost damage to high-valued crops like tea and coffee.

2. Background

Most frost events occur during clear and calm nights (Kalma et al. 1983). They are influenced by terrain aspects combined with meteorological factors such as wind, clouds and humidity. Research by Kalma et al. (1992) verified that cloud cover, wind and elevation, could be combined in an equation to give a good prediction of the expected minimum ground temperature at any particular site. In addition, Avissar and Mahrer (1988) developed a model that combines the factors that affect minimum night land surface temperature (LST) to include topography, humidity, land cover, soil moisture and wind velocity. Because cold air flow down slope, much like water, the valley floors and lower portions of the slopes are colder (Richards and Mandy 2003) and are at higher frost risk.

Varied methodologies have been applied in mapping temperature variations in the past (Richards and Mandy 2003). Long-term weather station temperature recordings have been used to produce frost risk maps of the Altiplano in Peru and in Israel as reported in Richards and Mandy (2003). Kalma et al. (1992) used mobile temperature surveys and elevation models to evaluate the relationship between frost characteristics and geographic variables. Recently, Moderate Resolution Imaging Spectroradiometer (MODIS) remotely sensed data were used by Pouteau et al. (2011) to estimate the probability of frost occurrence over the arid Andean Highlands of Bolivia. The research revealed the influence of elevation, altitude, slope, topographic convergence and insolation on LST variations. More so, Neteler (2010) presented a methodology for improvement of the MODIS data-sets for LST mapping at a regional scale by improving the resolution and reconstructing data gaps brought about by presence of clouds which obscure the land surface.

The current paper shows the role satellite imagery technologies can play in frost risk mapping. It evaluates factors that facilitate occurrence of frost within the Aberdare ecosystem and explains the trend of minimum temperature occurrences and probabilities of frost risk. This is useful in mainstreaming resilient crop cultivars in the region. It further establishes the implications of frost occurrence on crop production and therefore, impact on food security and economic development in the region.

3. Study area characteristics

The study area is located within the Kenyan highlands, one of the major water towers in Kenya and consists of the Aberdare Forest and National Park. Spatially, the area covers four administrative counties, Nyandarua, Kiambu, Murang'a and Nyeri shown in Figure 1. A 15 km buffer was, however, introduced in order to include variations in altitude and topography beyond the high-altitude Aberdare ranges and the county boundaries. The area is located between the latitudes: 0°16′53.51″N and 01°27′44.71″S and longitudes: 36°3′25.51′E and 37°33′24.90″E. The study area is approximately 21,399 km^2. The altitudes of the study area range from 948 m in the lowlands of Murang'a to 5065 m in Mount Kenya and 3900 m in the Aberdares. The topography is characterized by mountain ranges, strong local variations and feature elevations resulting in an undulating topography including deep valleys. This makes the region suitable for frost risk assessment since altitude is an important factor as far as choice of crops, temperature variations, rainfall and wind patterns is concerned (Oludhe 2008).

The general wind direction in the Aberdare ranges area is from east to west. South-east monsoon dominate from April to October and the north-east winds from October to March (Petiot 1997). The distribution of rainfall is typically bimodal with two distinct rainy seasons; the first with its peak in April and the second with its peak in November. Average annual rainfall varies from 400 mm in the low eastern plains to 2200 mm on the south-eastern windward side of the Aberdare range (Jaetzold et al. 2007).

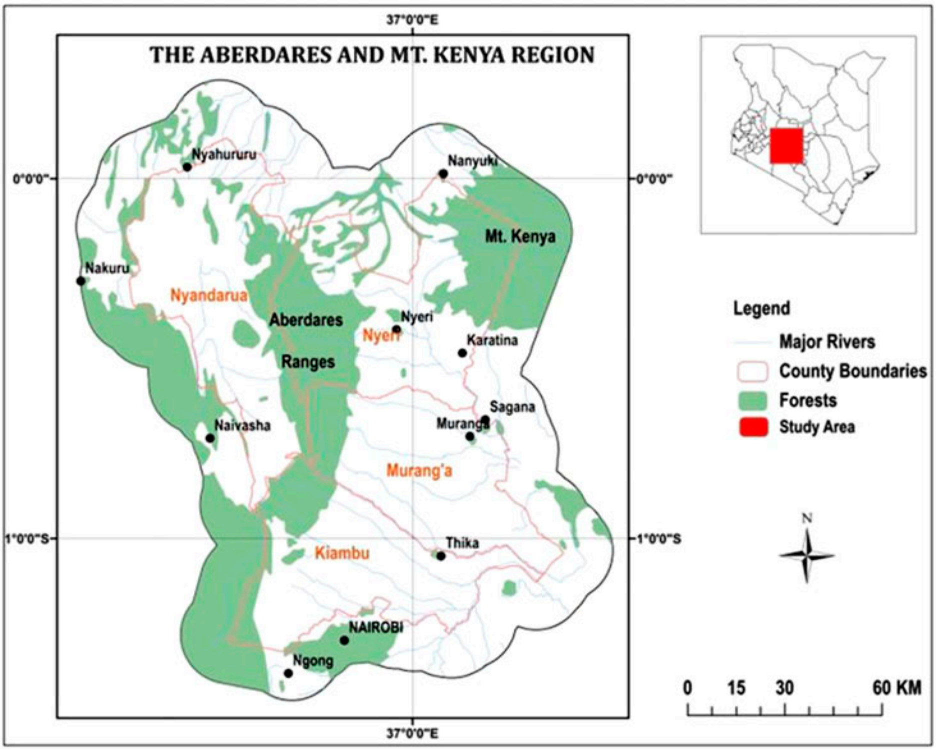

Figure 1. Study area map showing forested areas, major rivers and administrative boundaries.

Because of its geographical characteristics and complex terrain, frost is a constant occurrence and the most pressing atmospheric phenomenon affecting the local population because of its negative effects on agriculture, the region's main economic activity (Synder and De Melo-Abreu 2005). The main crops grown include maize, beans, peas, bananas and potatoes for subsistence and tea and coffee for cash crop.

3.1. Materials and methods

MODIS LST satellite data were used in the study. The MODIS sensor is onboard the Terra and Aqua satellites and provides twice daily observations; daytime and night-time (Zhengming 1999). Night-time data-sets for year 2000–2013 were used. In addition to the MODIS LST, meteorological temperature data records and rainfall data were collected from weather stations within and around the study area to calibrate the LST and investigate the influence of available ground moisture on frost occurrence. Other data-sets collected included Landsat imagery from the United States Geological Survey (USGS), Aster 30 m Digital Elevation Models (DEM) and frost occurrence data.

3.2. Delineation of frost hotspots

Using ENVI 5 software, minimum temperatures per pixel was extracted from the daily night-time data-sets to create continuous coverage of monthly data-sets in order to fill up potential data gaps on the daily acquisitions. The frequency of occurrence for minimum temperatures below 273 K was computed through time–frequency analysis to obtain a frequency map. The probability of occurrence for temperatures below 273 K was computed according to Pouteau et al. (2011). Further classification of the data-sets was done using ENVI 5 decision tree classifiers to discriminate various levels of frost risk; very severe frost (<250 K), severe frost (250–260 K), moderate frost (260–270 K), minor frost (270–280 K) and regions of no frost (>280 K). These are the levels used by the Kenyan meteorological department to classify frost levels. The determination of frost category threshold was based on the frequency and level of minimum temperature occurrence evaluated since the year 2000–2013.

3.3. Time series analysis

Average minimum LST within agricultural land for each month of the year was computed across all the years from 2000 to 2013. This was used to perform time series analysis of LST in order to establish the trend and existing patterns of minimum LST occurrences. Minimum LST was computed for each month across all the years in order to generate monthly frost hotspot maps. The trend of frost was compared with rainfall trends to deduce the influence of humidity and available moisture on frost occurrence. Rainfall trends were compared with the trends of monthly minimum temperatures to establish the influence of rainfall and humidity on LSTs.

3.4. Land cover mapping

A land cover map was developed using maximum likelihood classifiers of Landsat imagery and was used to identify cropland and pasture areas that fell within frost prone areas. Using the land cover maps and frost risk maps, crop-specific risk was evaluated for the major crop cultivars in the four counties depending on the critical temperatures for damage.

3.5. Elevation and land surface curvature

In order to establish and illustrate the relationship between elevation and LSTs, the frost delineated map was draped on an Aster 30 m 3D DEM model. A correlation analysis between the land surface curvature values and slope, profile convexity, longitudinal and cross-sectional curvatures with corresponding LST values was performed in SPSS software to determine the relationship between aspect, convexity/concavity with LST.

4. Research results and products

4.1. Frost hotspots

Frost hotspots were found to be concentrated within the Aberdare and Mount Kenya regions above 1700 m asl. Only a few speckles of very severe frost are experienced in the study area. Severe frost occurrences are considerably high, while the moderate frost risk areas cover much of the highland areas. 48.35% of the study area is at risk of frost with probabilities of minimum temperatures below 270 K (−3 °C). Since the crops are grown up to a maximum altitude of 3000 m asl more than 50% the crop area is exposed to frost risk.

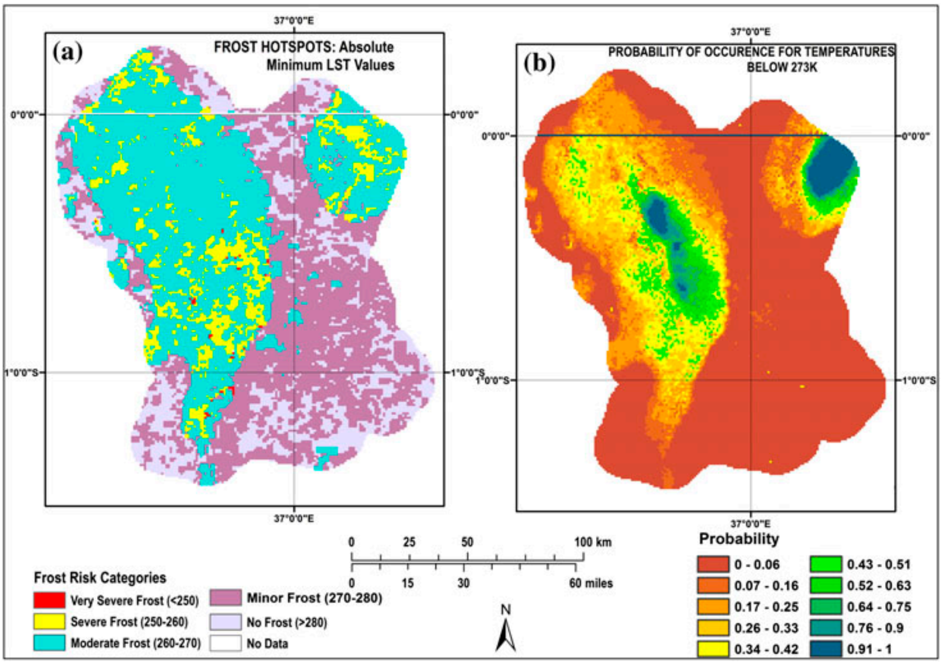

Figure 2. Frost hotspots map (a) showing categories of frost risk and a probability map (b) showing the probability of occurrence for temperatures below 270 K at least once in a month.

The frost hotspot map (Figure 2(a)) represents occurrence and distribution of minimum temperatures while the probability map (Figure 2(b)) represents the probability of occurrence of temperatures below 0 °C. The relationship shows that the extent of the region most frequented by low temperatures corresponds to the frost hotspots. There is a region above 3500 m asl where temperatures are constantly low enough to form frost. These areas coincide with the peaks of Mount Kenya and the Aberdare which are covered by snow for most of the year.

4.2. Trends and patterns of minimum temperature occurrences

From a comparison of the time series analysis for 2000–2013 and as interpreted from Figure 3, the temperatures are lower in the months of April, May and November. The lowest night temperatures occur more frequently in the months of April–May and November where monthly average minimum temperatures can get as low as less than 276 K. In the months of February–March, frost occurrences are minimal with monthly average minimum temperatures going not lower than 279 K. Occasionally, minimum temperatures are experienced in the months of December and January and in two occasions (2006 and 2007) in the month of August. The statistics displayed in the graph indicate average minimum night temperature dynamics within cropland areas in the Aberdare and Mount Kenya region.

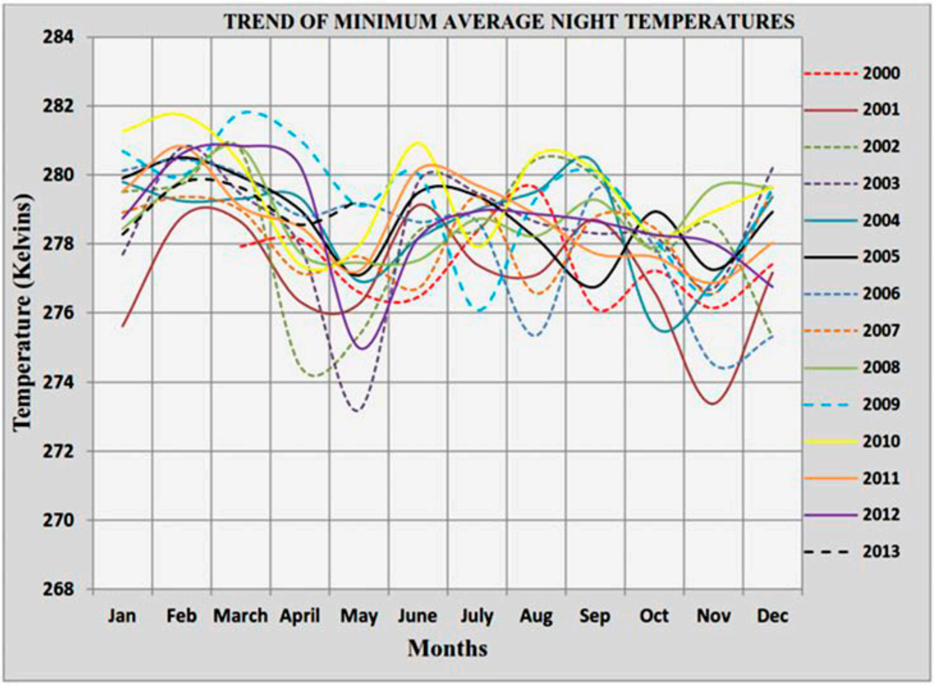

Figure 3. Time series analysis of monthly minimum average night temperatures from 2000 to 2013 in the Aberdare and Mount Kenya region.

Different months of the year experience variations in temperature that are unevenly distributed across the terrain (Figures 4–7).

4.3. Influence of land surface curvature

From theory, the occurrence of minimum temperatures corresponds to valley bottoms while that of warmer temperatures corresponds to hill slopes. This is attributed to the fact that cold air is denser than warm air and hence tends to sink to lower regions in the landscape. This knowledge is paramount providing knowledge and information to aid in planning for planting locations. In order to determine the effects of land surface curvature on LST and consequently frost occurrences, a correlation analysis was performed between LSTs obtained from the MODIS data-sets and topographic parameters; slope, profile convexity, cross-sectional curvature and longitudinal curvature obtained from a 30 m USGS DEM; slope in this case is measured in degrees with the convention of 0° for a horizontal plane, profile convexity is the rate of change of slope which translates to the rate at which the slope steepness changes along the profile. For the measures of curvature, convex surfaces have positive values while concave surfaces have negative values.

The correlation coefficient, r ranges from −1 to +1. A correlation coefficient quite close to 0, but either positive or negative implies little or no relationship between the two variables. A correlation coefficient close to plus 1 means a positive relationship between the two variables, with increases in one of the variables being associated with increases in the other variable. A correlation coefficient close to −1 indicates a negative

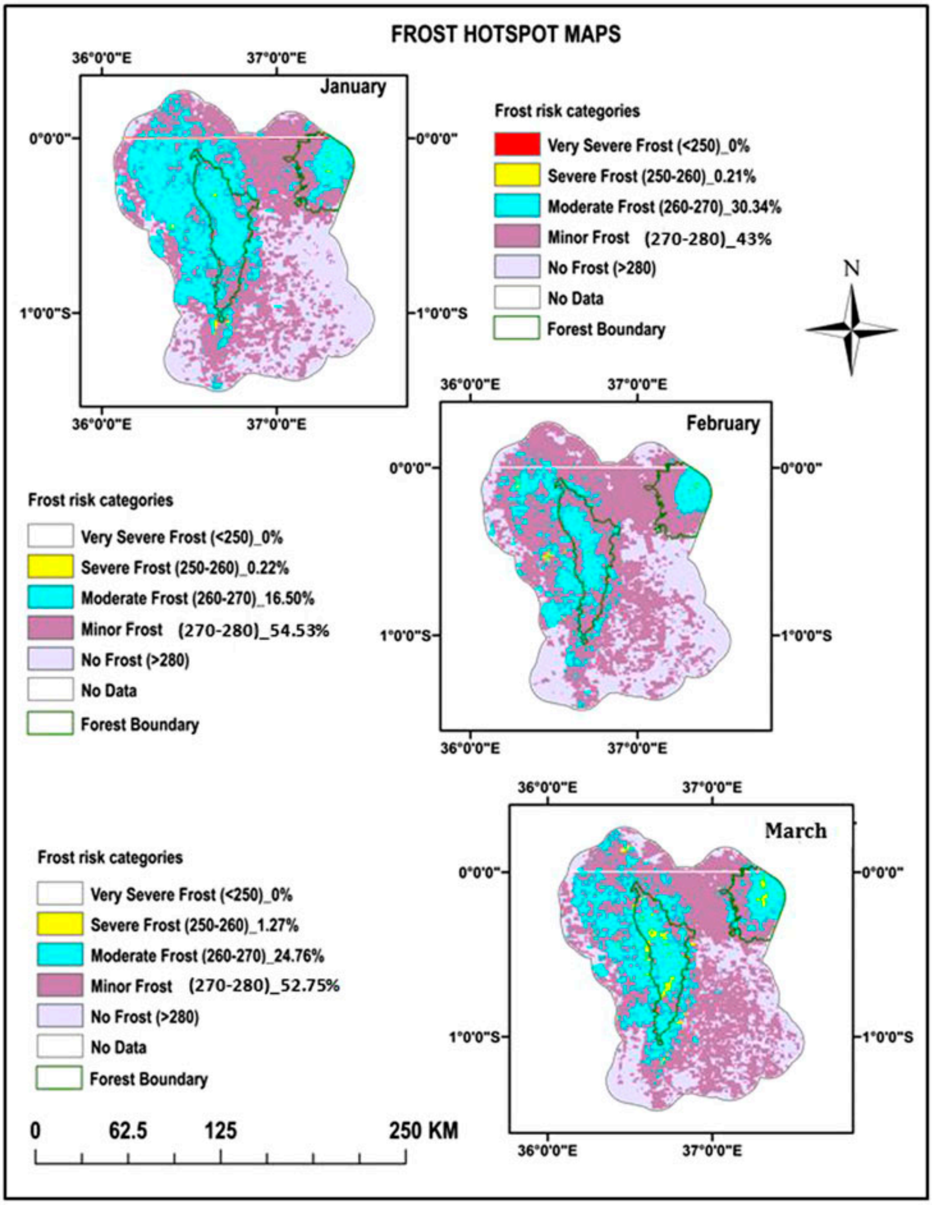

Figure 4. Average monthly minimum LST representing frost hotspots for January, February and March.

relationship between two variables, with an increase in one of the variables being associated with a decrease in the other variable.

A significantly consistent negative correlation was indicated between surface temperature values with land profile convexity, slope, cross-sectional curvature and longitudinal curvature. LST thus decreases with increasing surface convexity. This is indicated by the negative r values within the profile convexity, cross-sectional curvature and longitudinal curvature rows of Table 1. Depressions are therefore cooler than slopes and

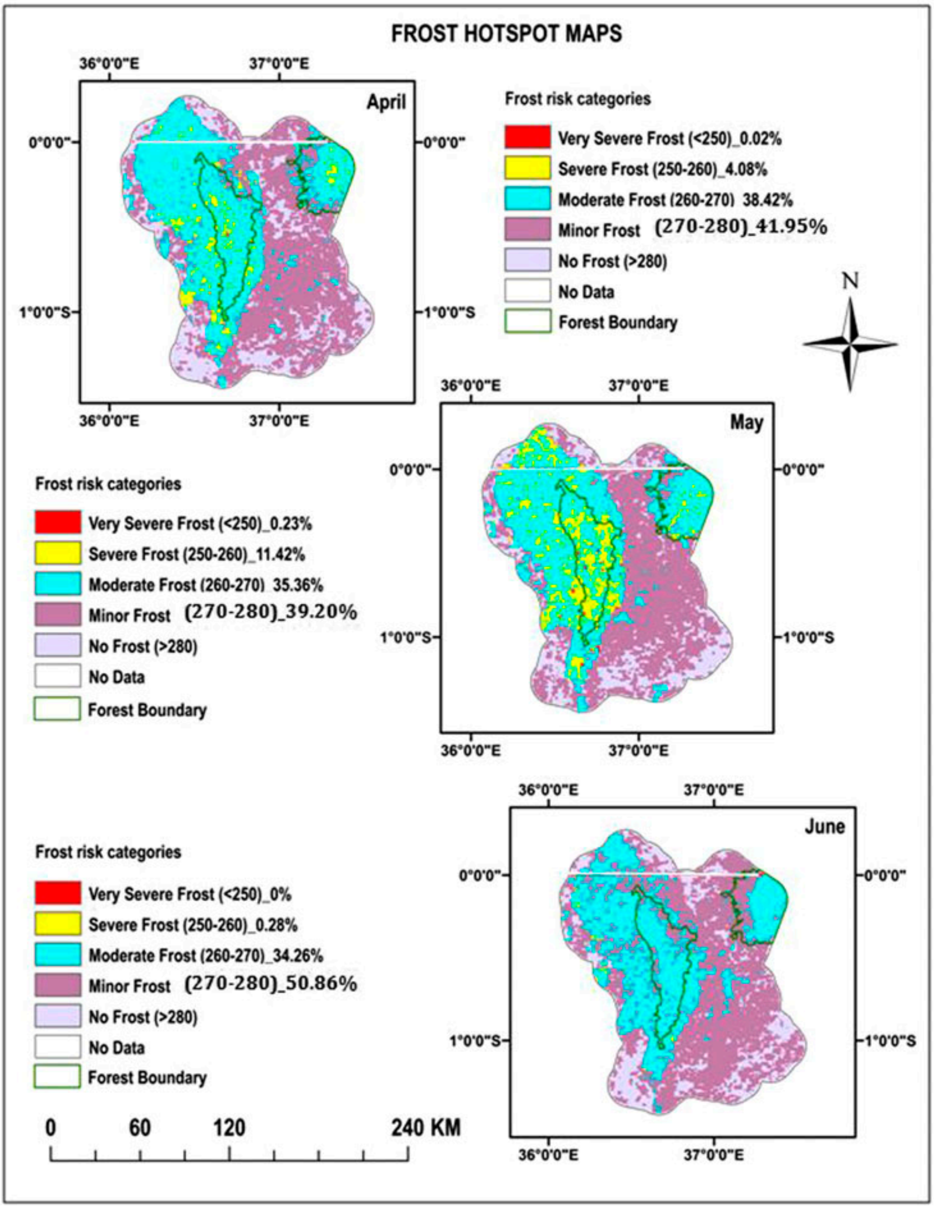

Figure 5. Average monthly minimum LST representing frost hotspots for April, May and June.

hilltops. This may be attributed to the fact that cold air is denser than warm air and therefore flows down slope and settles in valleys and depressions within the land surface. Since the slope angle increases from west to east, the positive correlation between LST and aspect as observed in Table 1 shows that slopes facing east are warmer than those facing west. This may be due to interference by winds that blow from east to west affecting the settlement of dense cold air. Table 1 illustrates the analysis results.

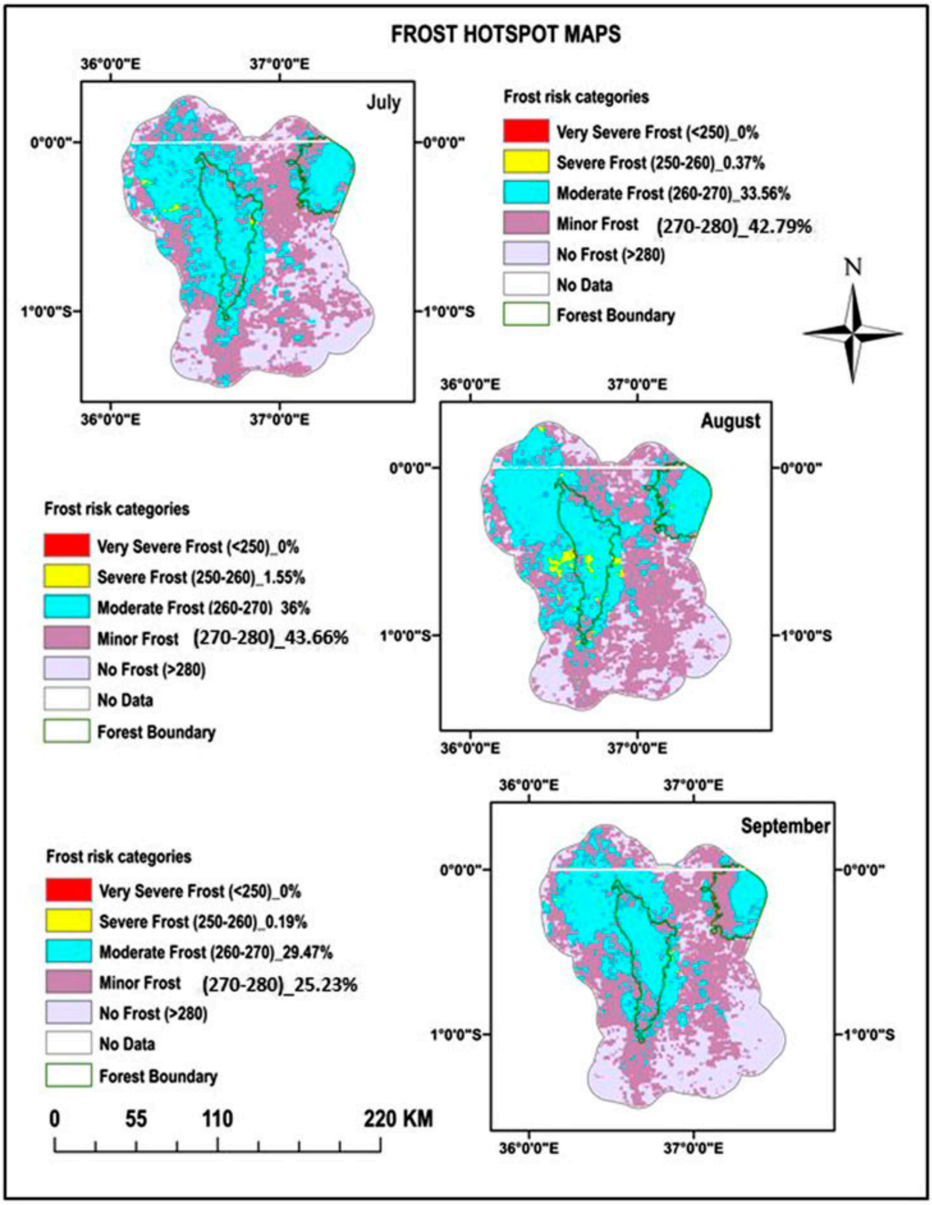

Figure 6. Average monthly minimum LST representing frost hotspots for July, August and September.

4.4. Influence of rainfall/humidity

Differing patterns of rainfall were observed within the study area. The eastern side of the Aberdare ranges where Nyeri, Murang'a and parts of Kiambu are located register the highest peak rainfall in the month of April. The peak of the short rainy season is between October and November for the three counties. Rainfall amounts are lowest in the months of December to February and from June to the beginning of September.

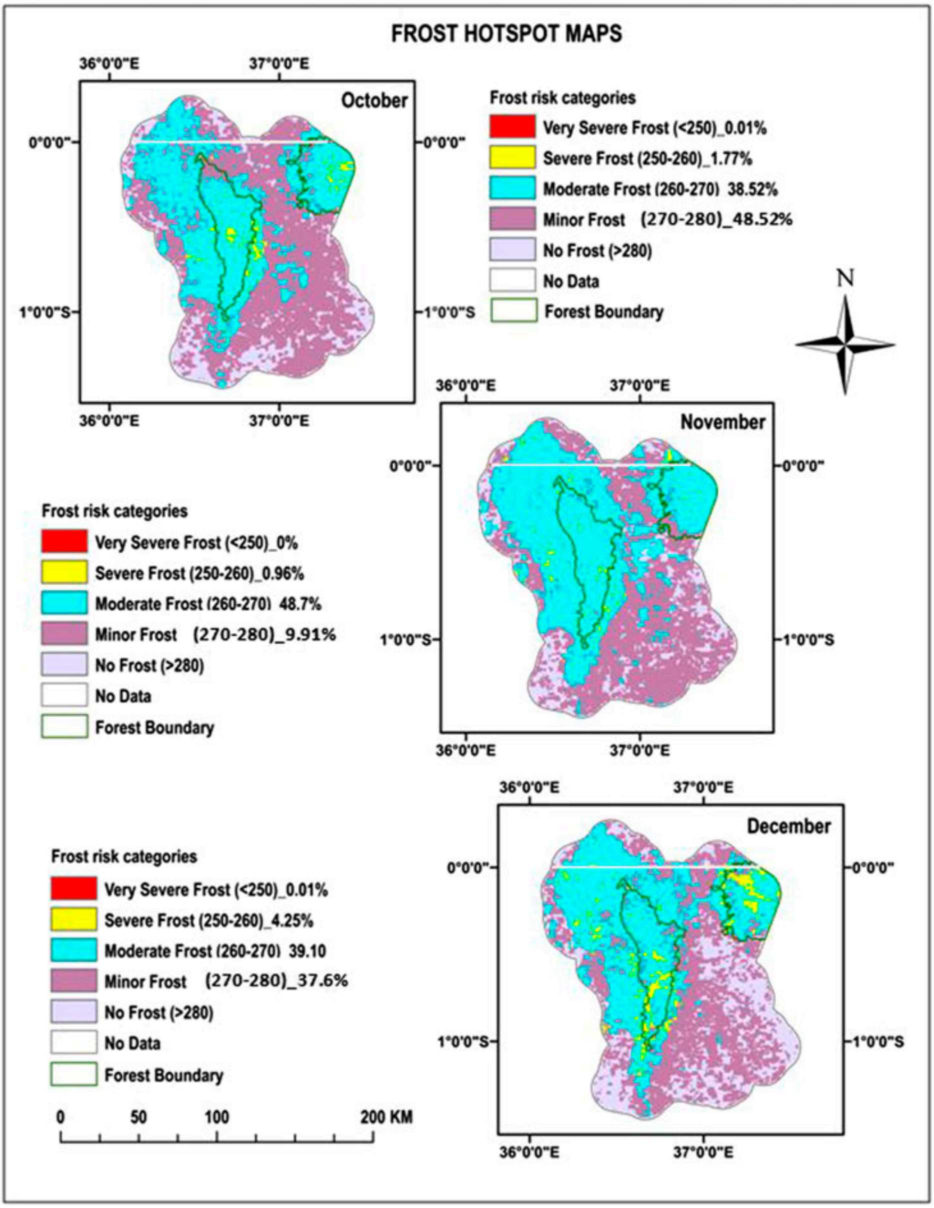

Figure 7. Average monthly minimum LST representing frost hotspots for October, November and December.

In Nyandarua County which falls on the western side of the Aberdare ranges, rainfall amounts vary considerably between the months with higher monthly averages in all the years. The peak rainfall period in Nyandarua is between July and August.

Comparing Figures 3 and 8, monthly minimum average land surface temperatures are lowest when rainfall amounts start to reduce in the month of May and end of November. As Garriott (1899) stated in his research in the United States, favourable conditions for the occurrence of frost require moderately moist soils. Favourable conditions for severe

Table 1. Pearson's correlation matrix between monthly LST and land surface curvature (months represent LST in those months for the year 2012).

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
PC	−.262**	−.234**	−.258**	−.237**	−.246**	−.276**	−.232**	−.256**	−.265**	−.246**	−.242**	−.268**
S	−.226**	−.240**	−.210**	−.188**	−.234**	−.239**	−.199**	−.224**	−.222**	−.206**	−.240**	−.202**
CC	−.089**	−.087**	−.096**	−.086**	−.072**	−.098**	−.091**	−.113**	−.102**	−.093**	−.081**	−.092**
LC	−.053**	−.054**	−.054**	−.052**	−.050**	−.058**	−.050**	−.040**	−.054**	−.052**	−.041**	−.060**
A	.002	.033	.001	.008	.001	.004	.032	.009	.008	.019	−.002	.005

Note: Two tailed.
**Sig. at the level 0.01 (PC – profile convexity, S – Slope, CC – cross-sectional convexity, LC – longitudinal curvature, A – aspect).

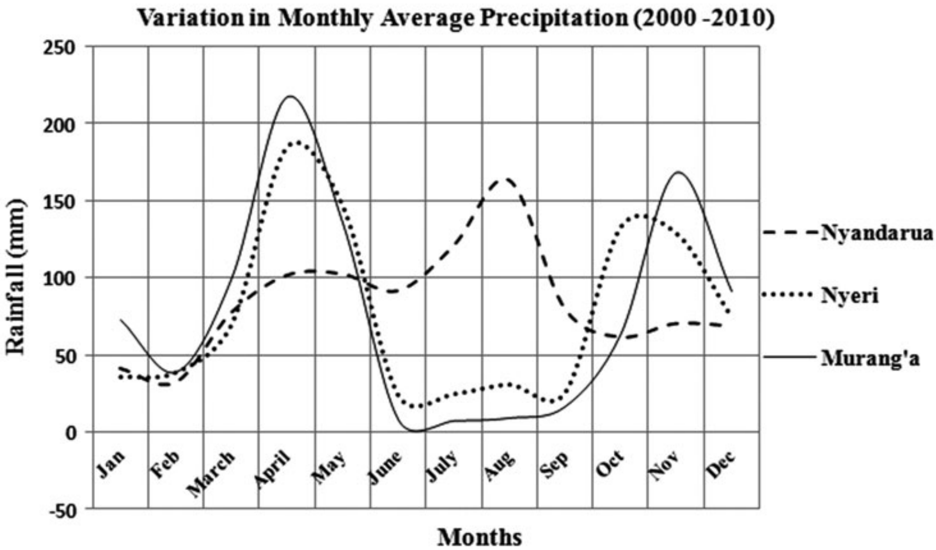

Figure 8. Time series analysis of average monthly rainfall for Nyandarua, Nyeri and Murang'a Counties for the years 2000–2010.

frost occurrences in the United States usually follow the rains of spring and autumn (Garriott 1899). His findings concur with the findings of this research where extreme low LST is experienced in the month of May when the long rains are subsiding and the month of November and December as the short rains come to an end and the soils are still moist. However, between the months of July and August, low temperatures were experienced in several years (Figure 3). This may be attributed to the high rainfalls experienced in Nyandarua.

4.5. *The effect of elevation on LST*

Widespread occurrences of minimum temperatures are a consequence of the region's elevation. A clear cutline on the western side of the Aberdare ranges follow the face of the Sattima escarpment at 2000 m asl. This can be observed from Figure 9, both from the elevation map that delineates the elevation levels (Figure 9(a)), and from the three-dimensional representation of the frost hotspots map (Figure 9(b)). The landforms of the Aberdare influence the patterns of temperatures within the area. The elongate plateau west of the Aberdare ranges is affected because it is a depression from the Aberdares. Cold air flows down from the Aberdare to settle on the plateau causing frost.

4.6. *Extent of agricultural land under frost risk*

While most of the area affected by frost fall within the protected forests of Aberdare Ranges and Mount Kenya area, minimum temperatures occur on the western side of the Aberdares where most food crops are cultivated. Besides the regions delineated as intensive cash crop zones, intense cultivation of food crops is practiced within the rest of the agricultural land. It is from this region that most food supplies to the surrounding

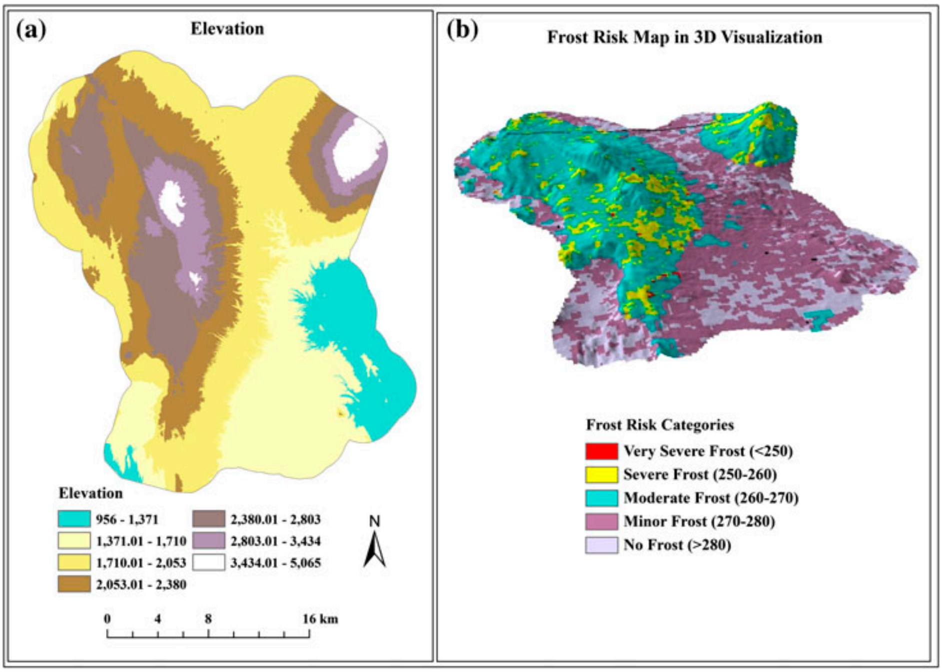

Figure 9. Elevation map (a) and a three-dimensional visualization of frost risk map (b) Showing the relationship between elevation and frost risk.

regions originate. These include maize, potatoes, beans, peas and vegetables which constitute the staple and main food crops in the country. Within the plantations zone, coffee, pineapples and sisal are intertwined with small-scale cultivation of millet, sorghum and fodder while other lands remain rangelands.

As seen from Figure 10(a), there is a stretch of land along the eastern side of the Aberdare where there is a tea-growing zone followed by a coffee-growing zone and pineapple plantations, all intertwined with subsistence cropland. As observed from Figure 10(b), most of the tea-growing zone experience or is at risk of severe frost bites with temperature occurrences below 260 K. This indicates the risk of economic losses that the tea farmers are exposed to. With the huge agricultural land, west of the Aberdare falling within a region of high frost risk, frost occurrences remain a threat to food security in the region in particular and the country in general considering that this is a high-potential food crop zone. The dependence of the people on agriculture means slow economic development, hunger and poor nutrition in the event of frost occurrence.

4.7. Susceptibility weighting of the main crops

According to Synder and De Melo-Abreu (2005), plants fall under four freeze sensitivity categories. Tender plants (e.g. potatoes, beans, tomatoes, bananas, sweet potatoes) which have not developed avoidance of intracellular freezing and slightly hardy plants are sensitive at about 268 K. Moderately hardy plants (e.g. carrots, onions, spinach) resist freeze injury to temperatures as low as 263 K. Very hardy plants (e.g. cabbages, kales) on the other hand avoid damage through cell desiccation. These freeze sensitivity

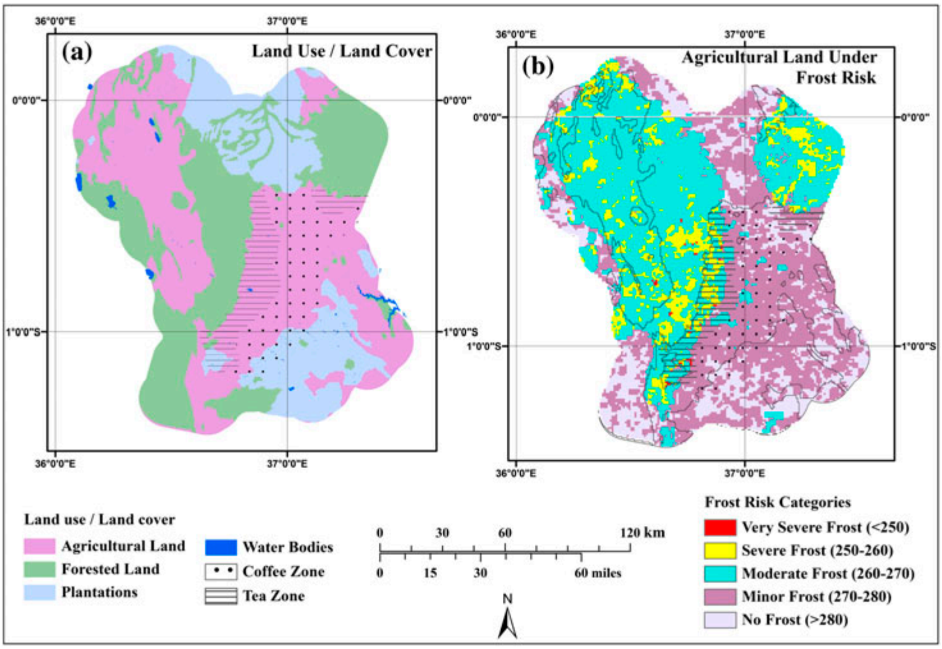

Figure 10. Land cover map (a) showing major land uses/land cover and frost hotspot map with the extent of major agricultural land illustrated (b).

categories provide a general conclusion on the minimum temperatures that a plant can endure before damage by frost can occur. Also important is the hardening and damage threshold of the growth stage of the plant. Plants have different damage thresholds depending on the stage of its development as much as the intensity and duration of the frost (Das 2005). There are critical temperatures beyond which specific crops get affected by frost; maize 272.55 K (−0.6 °C), tomatoes 272.65 K (−0.5 °C), potatoes 272.35 K (−0.8 °C), beans 272.45 K (−0.7 °C), peas 272.55 K (−0.6 °C), bananas 272.35 K (−0.8 °C) and kales 272.65 K (−0.5 °C). According to agro-climatic zonation in Kenya, these crops are well suited for Nyandarua County and the higher parts of Nyeri, Kiambu and Murang'a most of which is at risk of moderate (250–260 K) to severe (243–250 K) frost occurrences. Complete damage becomes inevitable in case of an intense frost event. Given that this area falls within the high-potential agricultural zones, this means limited extent for productive agricultural activities.

4.8. Discussion

Apart from the possible influence of vegetation within the Aberdare and Mount Kenya regions and the effects of altitude, land forms have a role in determining where frost forms (Synder and De Melo-Abreu 2005). Valleys and ridges experience different temperatures. Results from the correlation analysis indicated that slopes facing west are cooler than those facing east, while areas lying low on the landscape are at high risk of minimum temperature occurrences than raised grounds and hill slopes. The relationship between land surface curvature and minimum temperatures is that valley bottoms and low areas experience lower temperatures on a wind-free condition (Richards and Mandy 2003). From the correlation results obtained, it was deduced that temperatures

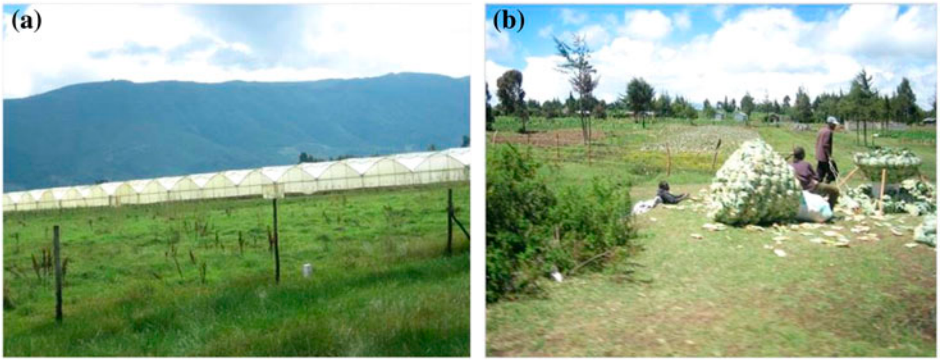

Figure 11. Increasing adoption of green houses (a) in cultivation of vegetables and fruits and switch to cultivation of cabbage (b) which has high tolerance for low temperatures (mist can be observed at the background of Figure 11(a)).

decrease with increasing land surface convexity, meaning depressions are cooler than hilltops and steep slopes.

The landforms of the Aberdares and Mount Kenya have also influenced the occurrence of frost on their western sides. The formation of the Aberdare ranges is such that the eastern slopes are gentler while the western side of it is an escarpment that slopes into an extensive plateau (Thomson 1964). As winds blow from east to west, they bring with them cold air into the region. This cold air settles at the western sides of these mountains leading to frost. It is on this plateau that much of the frost occurs. Consequently, farmers within this region have resorted to use of green houses for vegetables and fruit crops and cultivation of cabbages as they have high tolerance for low temperatures (Synder and De Melo-Abreu 2005) (Figure 11(a) and (b), respectively).

Depending on the crop specie, there are altitudes within which the production of a crop would be optimum. These favourable altitudes as documented by the Kenyan Ministry of agriculture considering the crops-growing season include 1800–2900 for potatoes, 0–1500 for pigeon peas, 800–2000 for cabbages, 0–2000 for beans, 1000–2300 for tea, 500–2500 for tomatoes, 1200–2000 for coffee and 0–1900 for onions (Jaetzold et al. 2007). Factoring in agro-climatic suitability of each crop based on the elements of climate that affect the growth of vegetation, there is need to take caution and limit agricultural losses related to hazards like frost. Adoption of frost-tolerant crop cultivars like cabbages and kales would optimize this. Other ways would be to avoid risky areas such as low-lying depressions and west-facing slopes when dealing with susceptible crops. Other management practices to avert losses would be to modify the physical environment of the crop following the methods suggested by Synder and De Melo-Abreu (2005), Kalma et al. (1992) and Wratt et al. (2006). These methods include wind induction, sprinkler irrigation, smoky fires on the farm, mulching and adoption of green house technologies.

5. Conclusion

Frost risk assessment is important in agricultural hazard mapping and in making crop productivity evaluation within the Kenyan highlands. Negative effects of frost can be attenuated through systematic assessment of frost occurrence probability in order to provide useful and informative information to farmers and agricultural decision-makers.

Mapping is also important to inform on the seasons to expect frost, the basic conditions for frost occurrence and the locations most likely to be affected by frost. In order to limit on the losses from frost damage to crops, considerations need to be made on the planting season, altitude as well as choice of crop cultivars and species suitable for the various locations. In addition, it becomes possible for the insurance providers to come up with compensation products for farmers for the high-valued crops like tea and coffee according to the levels of frost risk exposure. However, more research on local characteristics of soil moisture, vegetation cover and specific crop phenology stage is necessary if maximum benefits are to be accrued.

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