Soil temperature prediction using measured atmospheric temperature in two high altitude regions of Kenya

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Abstract

Soil stores heat energy during the day, supplying it to its near surface at night. Soil temperature, an important environmental regulator for crop growth, is the function of heat flux in the soil and heat exchanges between soil and the atmosphere. Its determination however, is time-consuming, costly and is not suitable for wide range coverage. It was on this basis that on-site underground measurements were conducted with the main objective of investigating the correlation between air and soil temperature in two highland regions of Kenya. Two variables were investigated: atmospheric and soil temperatures as from the year 2000 to 2010 (11 years) at Timbilil (0^{O}22'S, 35^{O}21'E, 2200 metres above level), and for four years (2007-2010) at Kangaita (0^{O}30'S, 37^{O}16'E, elevation of 2100 metres). Measurements were done thrice daily, with soil temperature readings taken at a depth of 30cm. The coefficient correlation was determined using Pearson's distribution with atmospheric temperature being independent, while soil temperature was a dependent variable across the two locations at $p \leq 0.01$. The computed differences between soil and air temperatures for Kangaita and Timbilil were 4.6167^{O}C (SED ±1.2543) and 2.1636^{O}C (SED ±0.2838) respectively. Timbilil and Kangaita soil and air temperature differences subjected to two-way ANOVA (F pr ≤ 0.001) indicated sites are statistically different from each other. The outcome rejects the use of a universal air temperature to calculate soil temperature at *d*=30 cm for blanket highland regions of Kenya. The study concluded that empirical models are site specific. Soil temperature of each site should be determined independently.

Keywords: Air temperature, empirical models, soil temperature, tea (*Camellia sinensis*)

Introduction

Soil is a matrix of solids including sand, silt, clay, organic matter particles as well as aggregates of various sizes formed from them, and pore spaces, filled with either gases or water (Hillel, 1998 & Kenya Agricultural and Livestock Research Organization-Tea Research Institute [KALRO-TRI], 2018). Significant environmental variables impacting on life in soil includes humidity, precipitation, atmospheric temperature, pH, aeration, solar radiation, organic matter, inorganic nutrients and wind (Islam *et al*., 2015; Pouloupatis *et al*., 2011).

Soil is a reservoir of heat energy during the warm season, releasing it to air during the cold season (Onwuka, 2016; Geiger *et al.*, 2003). It stores energy during the day, supplying heat to the soil surface at night (Onwuka & Mang, 2018). Soil temperature, one of the most significant components of the life-containing soil climate (Mahilum, 2004), is defined by Elias *et al*. (2004) as the function of heat flux in the soil and heat exchanges between the soil and atmosphere. It is an important environmental regulator for plant growth because it determines the rates and directions of soil physical processes, microbial activity, energy and mass exchange with the atmosphere, evaporation, aeration (Hillel, 1998), seed germination, seedling emergence and growth by influencing water and nutrient uptake (Toselli *et. al*., 1999), soil water retention, transmission and availability to plants (Onwuka & Mang, 2018). Soil temperature fluctuation usually lags behind that of air temperature due to the relatively high heat capacity and low heat conductance of the soil (Göbel *et al*., 2019), varying seasonally at greater depths and is transmitted down through the earth at a rate dependent on thermal diffusivity of rocks within the soil (Nwankwo & Ogagarue, 2012). It is further documented that soil temperature influences soil-plant relationships, soil biophysical processes which serve as determinants of the chemical and mechanical processes, serves as a catalyst for most biological processes (Onwuka, 2016; Cochran, 2010; Ahmad and Rasul, 2008), planting design, soil respiration, vermin and pest growth (Islam *et al.*, 2015). Solar radiation is a major source of soil temperature at the deep and shallow zones (Pouloupatis *et al*., 2011), and is influenced by two main factors: the amount of heat made available to the soil surface, and that which is dissipated from soil surface down the profile (Onwuka, 2016).

Relationship exists between mean daily air temperature and observed daily soil temperature at 10 cm depth mainly due to energy balance at the ground surface (Zheng *et al*., 1993) than with humidity, precipitation, wind speed and solar radiation (Salamene *et al*., 2010). The latter authors postulated that the correlation between soil and air temperature reduces with increased soil depth since air temperature is in direct contact with the soil surface. A study at a site having summer mean air temperature of 14.1^{O}C by Smith *et al*. (1998) reported annual mean air temperatures of 2.0 to 2.5^{O}C below soil temperatures at 50 cm, and a range of 1.0 to 2.0^{O}C below soil temperatures at 150 cm.

While soil is a major factor that affects the quality and quantity of crops, soil temperature affects the growth, yield and quality of agricultural crops directly, as it significantly impact on budding and growth rates of plants (Ahmad & Rasul, 2008). Studies show that tea (*Camellia sinensis*) clones differ in their response to air temperature through base temperature for shoot extension ($\boldsymbol{T_{be}}$). This factor can be exploited for cultivation of tea clones in suitable environments. Similarly, dry matter production and partition, hence yield, is dependent on both air and soil temperature. Plants growing in warm environments produce higher amounts of dry matter compared to those in cooler areas (Ngétich, 2002).

Soil temperature prediction using air temperature minimizes time, cost and maintenance of equipment necessary for on-site monitoring of soil temperature measurements (Ahmad & Rasul, 2008), provided reliable data is used (Pouloupatis *et al*., 2011). Soil temperature fluctuates annually and daily, mainly affected by variations in air temperature and solar radiation. The daily amplitude of soil temperature at the surface is greater than the daily amplitude of air temperature for clear days and is less for cloudy days. Most soil ecosystem processes occur within the top layers of soil (Zheng *et al.*, 1993). The annual variation of daily average soil temperature at different depths can be estimated using a sinusoidal function (*Equation 1*) (Hillel, 1998; Marshall and Holmes, 1988; Wu and Nofziger, 1999).

$$T(z,t) = T_a + A_O e^{-\frac{z}{d}} \sin[\frac{2\pi(t-t_0)}{365} - \frac{z}{d} - \frac{\pi}{2}] \qquad \textit{Equation 1}$$

Where: T(z,t) = soil temperature at time *t(d)*; depth *z(m)*; T_a = mean soil temperature (^{O}C); A_O = annual amplitude of the surface soil temperature (^{O}C); *d* = damping depth (*m*) of annual fluctuation; t_O = time lag (*days*) from an arbitrary starting date, e.g. January 1st to the occurrence of the minimum temperature in a year. $d = \sqrt{\left(\frac{2D_T}{\omega}\right)}$, where D_T = thermal diffusivity; $\omega = \left(\frac{2\pi}{365}\right) day^{-1}$, which is the radial frequency, in the case of annual variation the period is 365 days. Kochanowski *et al*. (2014) defines thermal diffusivity, also called the temperature conductivity as a material parameter describing the movement of the isothermal surface during the heat flow through the material, while damping depth is the depth in soil profile at which soil temperature is within 5% of average annual air temperature based on long-term data of soil surface temperature on the current day.

On sunny mornings after clear nights, air temperature may exceed soil temperature substantially (Göbel *et al*., 2019). During daytime, surface soil is hotter (longer amplitude) than the sub-horizon since it is exposed to direct solar radiation. At a depth of ≥50 cm, soil temperature is constant and is much lower (shorter amplitude) than that of the surface horizon (Mahilum, 2004). After repeated air and soil temperature measurements using sinusoidal function, Wu and Nofziger (1999) further reported that air temperatures can be used to estimate soil temperature. The model developed by these two authors consistently under-estimates soil temperatures by about 2^{O}C on bare soils.

A study on thermal homogeneity of soil at Kericho, Kenya in which tea was grown under different mulch treatments on bare and thin soil covers by Stigter *et al.* (1984) showed temperatures at any depth within varied coloured homogeneous soils with identical or low evaporation are related to each other via soil temperature ratio (R), given by *Equation 2*.

$$R = \frac{1-\rho_1}{1-\rho_2} = \frac{\theta_1(z,t)-\theta_{1z}}{\theta_1(z,t)-\theta_{2z}} \qquad \textit{Equation 2}$$

Where R = soil temperature ratio; *t* = time, *ρ* (rho) = reflection coefficient for solar radiation of the respective soils, *θ(z,t)* = temperature pattern at depth *z*; θ_z = average temperature at that depth. The applicability of this equation is to facilitate interpretation and forecasting of soil temperature patterns. Stigter *et al.* 1984 asserts that for the underlying theory to be valid, the soil should be thermally homogenous with respect to thermal properties. Unit *θ* is approximately constant with depth, or be a linear function of depth. These theory-based models may provide accurate estimates of soil temperature at small scales, but may not be practical for estimation of soil temperature at continental and global scale. The many parameters required may depend on topography, soil texture, and soil water content, all of which may vary over short distances (Zheng *et al.*, 1993).

Deep volcanic, well-drained, red, brownish-red or dark red soil is a key factor in tea farming (KALRO-TRI, 2018). The rate at which tea flushes has been shown to be largely controlled by temperature, other factors such as dry air and soil nutrients not limiting. While Tanton (1982) gives the optimum range of 18-20^{O}C, Carr and Stephens (1992) proposed a wider range between 18 and 30^{O}C, stating that there is a base (minimum) temperature for *shoot extension* (T_{be}), i.e. unfolding of leaves (12-13^{O}C for most tea cultivars), below which the rates of growth (shoot expansion) are very slow, and the *optimum* temperature (T_{oe}),-18-30^{O}C, above which growth rates decline reaching zero at *maximum* temperature (T_{me}).

In high-elevation regions, plants can experience periods of high air temperature while the soil remains cold as a result of thick canopy cover, leading to temporary mismatch in the physiological activity of leaves and roots. Göbel *et al*. (2019) documented that there are several direct and indirect pathways by which low soil temperature can impair plant metabolism hence growth, first through reduced root growth and decreased root nutrient and water uptake, and secondly indirectly through reduced photosynthetic carbon gain due to stomatal closure in the course of cold-induced drought stress. Soil temperature data status informs agriculturalists on the most suitable crops to cultivate where measurements are done, or areas sharing similar temperatures. It is for this reason that air and soil temperature relations studies were carried out for 11 years (2000-2010) at KALRO-TRI Timbilil Agromet station in Kericho County, Kenya, (0^{O}22'S, 35^{O}21'E, 2200 metres above sea level, and for four years (2007-2010) at KALRO TRI Kangaita station, Kirinyaga County, Kenya, located in 0^{O}30'S, 37^{O}16'E, with elevation of 2100 metres. The main objective was to investigate the relationship between air and soil temperature in wet, highland regions of Kenya. The outcome will enable use of processed atmospheric temperature data to predict soil temperatures in similar ecological regions of Africa, since repeated measurement of soil temperature in the field is laborious, time-consuming and is not suitable for wide scale coverage. The study is projected to save on time and costs of buying and maintaining soil temperature measurement gadgets.

Materials and methods

Air temperature measurements

Air temperature, also called shade temperature or dry bulb temperature, was measured using dry-bulb thermometer, housed in a Stevenson screen to shield it against precipitation and direct solar radiation from outside sources while allowing free air circulation around them. The mercury-in-glass thermometer was mounted on a moveable wooden stand within a stand of about 1.5 m height over a neat short grass surface in each site. To reflect as much direct radiation as possible, the whole structure was painted white, with sloping roof covered with aluminium. The stand sites were large, open areas with free air circulation with no buildings, trees or other obstructions in the vicinity as recommended by Mwebesa (1970). Daily maximum and minimum temperatures at Kangaita and Timbilil research sites were measured using dry-bulb thermometers.

Soil temperature measurements

Figure 1: Symons-pattern earth thermometer ≥30 cm

Symons-pattern earth thermometer (Figure 1), designed to measure temperatures at depths of ≥ 30 cm, was used to measure soil temperature at Timbilil and Kangaita experimental sites. This instrument was suspended inside a stout metal tube closed at the bottom by a cone of solid metal and sunk in the soil. The metal cap prevents water collecting in the tube (Mwebesa, 1970). Soil temperature readings were taken between 0800 and 1900 hours daily by raising the thermometer to the eye-level to prevent parallax error, data recorded within 30 seconds to the nearest 0.1^{O}C. The bulb of the thermometer was embedded in a micro-crystalline paraffin wax to prevent it from the effects of temperature change when drawn to the surface to take readings, reducing significant error margins.

Soil temperature estimation using air temperature

This 11-(2000-2010) and 4-year (2007-2010) air and soil temperature study at Timbilil and Kangaita respectively was aimed at improving the work done by Smith *et al*. (1998) and Wu and Nofziger (1999), but specifically targeting wet, highland regions of Africa. The outcome is proposed to model estimation of soil temperature at 30 cm-depth in the tea growing areas having similar climatic conditions with Timbilil and Kangaita using measured atmospheric temperature. *Equation 3* was used to come up with a modified soil temperature estimation model, which can be used to estimate soil temperature in similar sites using known air temperature.

$$T_{est-canopy} = (dT_{mb} - dT_{mm}) \qquad \textit{Equation 3}$$

Where $T_{est-canopy}$ = Hillel's (1998) modified estimated soil temperature at 30 cm in canopy-covered areas (e.g. tea); dT_{mb} = Mean measured soil temperature on a daily basis at a depth of 30 cm in areas covered by canopy, e.g. tea bushes; dT_{mm} = Mean recorded or estimated mean daily air temperature in tea growing zone.

Statistical model and analysis

Statistical comparison of soil temperature results of the two sites were done for the purpose of applying findings elsewhere. G×E analysis was done using split plot design following the model: Xjklm = ì + xj + åjk + ôij + ëil + åjklm; Where: *Xjklm* = experimental observation; *ì* = mean of observation; *xj* = main treatment effect (sites); *åjk* = error (1); *ôij* = sub-treatment effect (environmental factors -E, i.e. soil temperature, air temperature); *ëil* = interaction between main treatment (sites), and the sub-treatment (E); *åjklm* = error (2).

Two-way ANOVA (p=0.05) for split plot design (GenStat, 2012 and Stern *et al*., 2001) was used to determine significance of soil and air temperature between and within sites, and across locations (spatial) and years (temporal). Correlation ANOVA (Pearson) was used to compare the relative strength of parameters and determine significance/ interrelationships (SPSS, 2011 and Pallant, 2011).

Results and discussions

Kangaita air and soil temperature results

Table 1 and Figure 2 presents mean air and soil (*d*=30cm) temperature measured between January 2007 and December 2010 at Kangaita site.

Table 1: Kangaita mean air T^{O}C (T_{mm}), soil T^{O}C at 0.3m (T_{est}), difference between (a) and (b): ($T_{est} - T_{mm}$), and SPSS descriptive statistics (Jan. 2007 to Dec. 2010)

Temp. ^{O}C	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean	S. Dev
T_{mm}	15.8	15.9	16.7	15.9	16.0	14.5	13.2	13.3	15.2	16.3	15.7	15.7	15.35	±1.1188
$T_{est}d$=30cm	22.3	23.5	22.4	20.3	19.2	18.8	17.1	16.5	18.7	18.9	20.4	21.5	19.97	±2.1622
$T_{est} - T_{mm}$	6.5	7.6	5.7	4.4	3.2	4.3	3.9	3.2	3.5	2.6	4.7	5.8	4.617	±1.5081

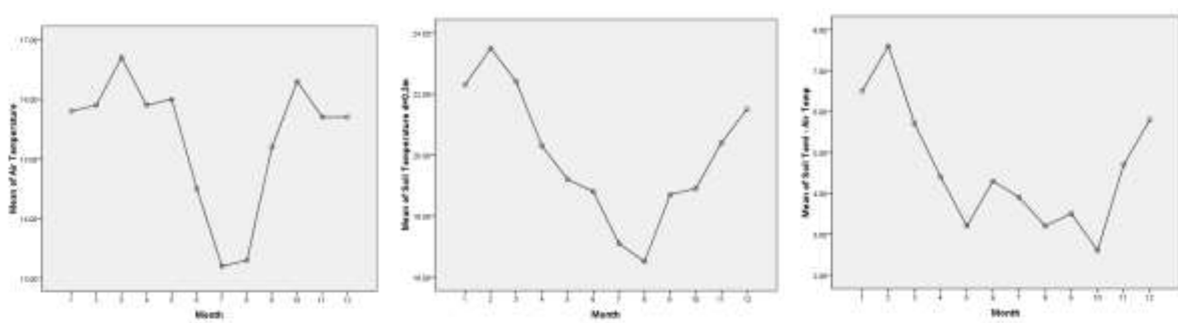


Figure 2: Line graph analysis means for Kangaita site showing (a) Air temperature (T_{mm}); (b) Soil ($T_{est}d$=30cm); and (c) difference between (a) and (b)- ($T_{est} - T_{mm} = T_{est-canopy}$)

Kangaita temperature measurements recorded minimum $T_{est-canopy}$ of 2.6^{O}C in the month of October, and maximum of 7.6^{O}C in February. The atmospheric temperature was below soil temperature in all the months of the year. Mean $T_{est} - T_{mm}$ was 4.617, SED of ±1.5081.

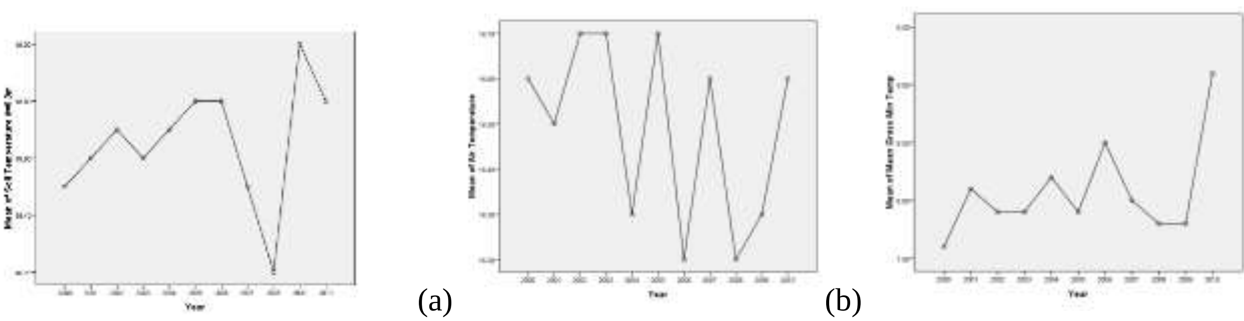
Timbilil air and soil temperature results

The 11-year Timbilil $T_{est}d = 0.3m$ and T_{mm}, their differences and T_{dgm} (Table 2) were calculated for the purpose of comparing and contrasting with those of Kangaita (Table 1).

Table 2: Timbilil yearly means of soil temperature (T_{est} ^{O}C) at d=0.3m, air temperature (T_{mm} ^{O}C), grass minimum temperature (T_{dgm}), recorded from the year 2000 to 2010, and ANOVA descriptive statistics

Temperature (^{O}C)	**Year**											**Descriptive statistics**	
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	**Means**	**SED**
$T_{est}d$=0.3m	18.5	18.6	18.7	18.6	18.7	18.8	18.8	18.5	18.2	19.0	18.8	18.6545	±0.21149
T_{mm}	16.6	16.5	16.7	16.7	16.3	16.7	16.2	16.6	16.2	16.3	16.6	16.4909	±0.20226
$T_{est} - T_{mm}$	1.9	2.1	2.0	1.9	2.4	2.1	2.6	1.9	2.0	2.7	2.2	2.1636	±0.28381
T_{dgm}	7.6	8.1	7.9	7.9	8.2	7.9	8.5	8.0	7.8	7.8	9.1	8.0727	±0.41495

From the Timbilil data presented in Table 2, analytical line graph was plotted using descriptive one-way ANOVA, the outcome presented in Figure 3.



(a) (b) (c)

Figure 3: Line graph means (a) $T_{est}d$=0.3m; (b) T_{mm} (^{O}C); (c) T_{dgm} (^{O}C) between years 2000 and 2010 at Timbilil site

The outcome as carried in Figure 3 reflects a close, consistent relationship between air and soil temperature parameters, with air temperature recording a uniform, constant figure below soil temperature.

Analysis of variance (ANOVA)

The Timbilil and Kangaita soil and air temperature differences were subjected to ANOVA (GenStat, 2012) to determine whether either of the two findings could be used to estimate soil temperature using measured air temperature of another tea canopy-covered site of scientific importance- Kipkebe (0^{O}17'S and 35^{O}3'E, elevation of 1740 metres). The T_{est} ^{O}C analysis across sites and different periods of measurement is depicted in Table 3.

Table 3: ANOVA of T_{est} ^{O}C between Kangaita and Timbilil measurements (Variate: T_{est} ^{O}C)

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Period stratum	10	10.491	1.049	0.73	
Site	1	31.680	31.680	22.06	<0.001**
Residual	10	14.360	1.436		
Total	**21**	**56.531**			

**: *Statistical significant difference exists at $F \leq 0.001$; SED=0.511.*

Analysis showed that soil and air temperature measurements across the two sites: Kangaita and Timbilil, was statistically different from each other at F pr ≤ 0.001. The analysis outcome, therefore, rejects use of a universal air temperature to calculate $[dT_{mb} - dT_{mm}]$ at *d*=30 cm for blanket tea growing zones.

Estimation of soil temperature (T_{est}) at Timbilil and Kangaita using air temperature, modifying Hillel's model

ANOVA analysis outcome of the two study sites as presented in Table 3 discounted the general use of a single formula to calculate soil temperature in all the tea canopy-covered areas using measured air temperature. Further, data reflected a close, consistent relationship between air and soil temperature parameters, with air temperature recording a uniform, constant figure below soil temperature. Arising from this finding, the study came up with a modified scheme given by Figure 4, backing up *Equation 3* and published works by Hillel (1998), Wu and Nofziger (1999), Salamene *et al*., (2010); Smith *et al.* (1998). The latter authors applied their models on soil extensively devoid of vegetation in contrast to the current study where data was generated from canopy-covered soil. This study is specifically developed for Timbilil and Kangaita at *d*=30 cm, and applies only when measured air temperature is available. It can also be applied to estimate air temperature for any of these two locations when soil temperature is measured.

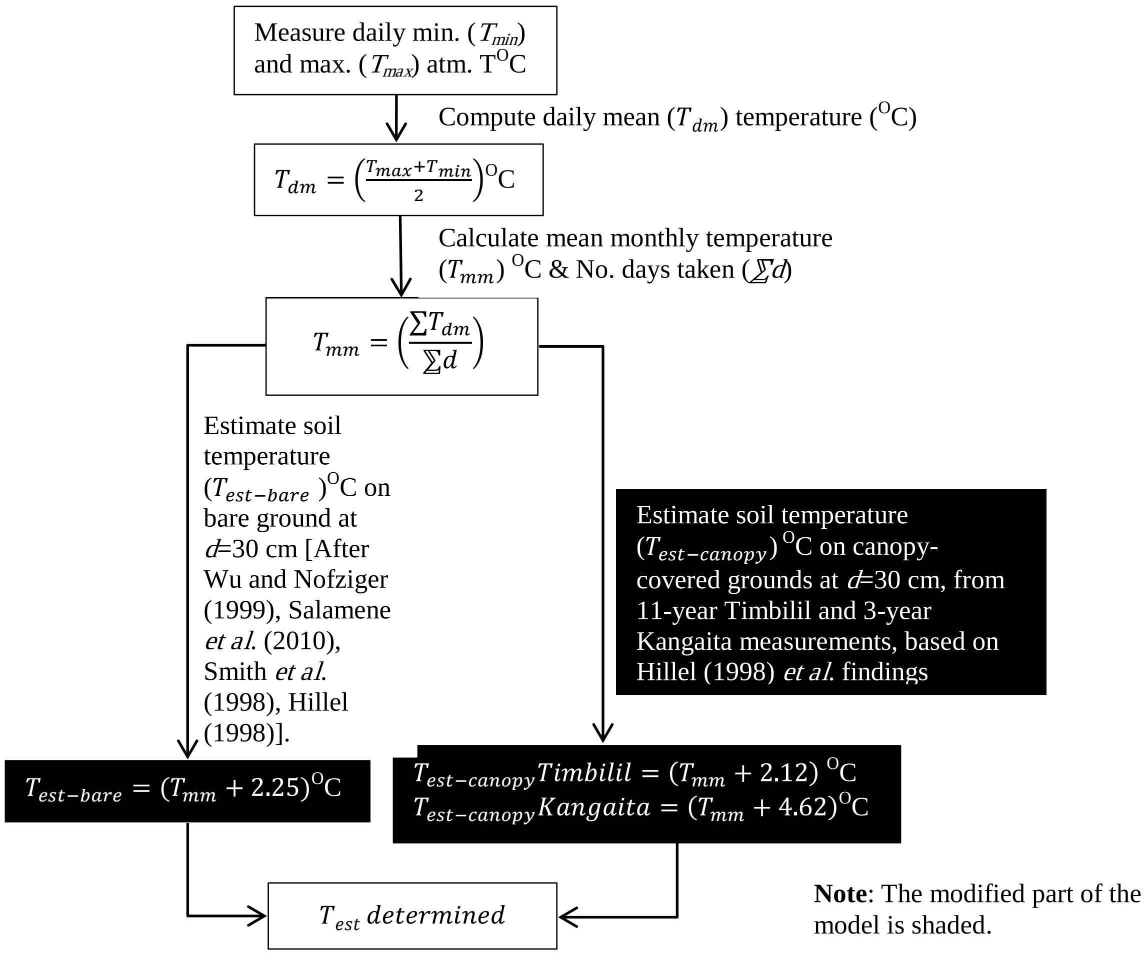


Figure 4: A model used to estimate soil temperature at *d*=30 cm on grounds covered by canopy at Kenya's Timbilil and Kangaita experimental sites.

The difference between air and soil temperatures was higher, i.e. by 0.15-0.45^{O}C, for bare grounds compared to canopy-covered Timbilil fields (Figure 4). This air-soil temperature difference was far much higher at Kangaita, where over 2.50^{O}C was computed. The modified part of this model is given by the shaded region in Figure 4.

Computed soil temperature using air temperature for tea growing areas

From Figure 4 and *Equation 3*, it is deduced that:

$$T_{est-canopy} = (T_{mm} + T_{mm}[dT_{mb} - dT_{mm}]) \qquad \textit{Equation 4}$$

The study, therefore deduced mean air temperature for Timbilil to be 2.2^{O}C $[dT_{mb} - dT_{mm}]$ below soil temperature at *d*=30cm, while that for Kangaita was 4.6^{O}C, making it impossible to generalize soil temperature estimation at different sites as the difference between these two values is huge. The

Timbilil findings compares favourably with work carried out by Smith *et al*. (1998) where annual mean air temperature remained about 2.0-2.5^{O}C uniformly below soil temperature at 50cm depth, and 1.0-2.0^{O}C below soil temperature at 150cm depth, and Wu and Nofziger (1999) whose model consistently underestimated soil temperatures by about 2^{O}C. The 4.6^{O}C Kangaita average finding however, was at variance not only with the Timbilil measurements, but with work carried out by authors on bare soil as well.

Conclusions

Modification of Hillel model in tea growing, canopy-covered areas using T_{est}^{O}C results of Kangaita and Timbilil were statistically different from each other. The original idea of blanket application of Hillel model to estimate soil temperature at *d*=30 cm using air temperature in the tea growing areas did not work. The study concluded that empirical soil temperature models are site specific, and therefore each site has to be calculated independently.

Recommendation

Using many years of measured air temperature, this study computed the differences between soil temperature and air temperature for Kangaita to be 4.6^{O}C (soil temperature higher than air temperature) and 2.2^{O}C for Timbilil. When either of the two measurements is known, the findings are recommended for use in specific sites.

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