Development of Soil Moisture Index for Planning Water Management in the State of Sikkim (India)

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Research Paper

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ABSTRACT

Soil moisture and soil temperature are two important parameters that have a wider implication on crop production. The fluctuation in soil moisture and temperature has an impact involving climate, vegetation and drought. The presence of soil moisture does not ensure its availability to a crop but the force by which water is held by soil particles is important. The amount of work done to extract soil moisture is generally expressed as stress. It is necessary to understand the extent of stress for proper water resources management. The soil moisture index (SMI) is a criterion that denotes the extent of stress experienced by a crop. The temperature also has an impact on germination and production. In the present study, we developed an SMI for different locations in Sikkim. The index ranges from +5 to -5. The negative index indicates extreme stress. The study indicated during winter the index goes beyond-3. Considering wilting point stress as 500 and 700 kPa. The soil temperature was also observed to fall below 15^0C. Further, it was observed that soil temperature and moisture are strongly correlated. The SMI can play an important role in adopting suitable water management practices for improved crop production.

Keywords: Soil moisture index; Soil moisture; Soil temperature; Soil moisture stress; Soil moisture characteristics curve.

INTRODUCTION

Soil moisture is an important parameter that has a wider implication on crop production. It is highly dynamic that varies with respect to space and time (Korres et al., 2013). The variation of the parameters has an impact involving climate, vegetation and drought (Saha et al., 2018). It also plays an important role in hydrological balance and has a role in understanding land surface interactions (Hunt et al., 2009). Soil moisture plays an important role in the global water cycle by controlling the partitioning of water and energy fluxes at the earth's surface and may control the continental water distribution through land-surface atmosphere feedback mechanisms (Koster et al., 2003). Soil moisture variation is a function of several factors such as topography, soil properties, land use, vegetation cover, radiation and rainfall pattern (Korres et al., 2009; Rodriguez-Iturbe et al., 2006; Svetlitchnyi et al., 2003).

The presence of soil moisture does not signify its availability to the plant. The availability of soil moisture to the plant is dependent on soil and water interactions. Generally, the moisture content between field capacity and wilting point (lower limit of extractable water) is known as available water (Jensen et al., 1990). At field capacity, the water is held very loosely and the plant extracts it at ease. Many researchers have shown that at field capacity the water is held at a tension of around 33 kPa. However, as time passes the moisture content decreases and the forces that hold the water increase and reaches an extent when the plant is unable to extract any more. Under such a situation energy needed for getting water from soil becomes high (Kirkham, 2005). This state is known as wilting point. Literature shows a wide range of values from 700 to 1500 kPa to define a wilting point. The wilting point varies from crop to crop as per specific rhizospheric structures. However, in actual field conditions, the plants find difficulty in extracting water at 500 kPa and above. The amount of work done by a crop to extract water from the soil is generally termed soil moisture stress (Gingrich and Russel, 1957).In the management of irrigation, water effort is made to maintain soil moisture stress within 100 kPa for the best crop performance. Taylor (1952) has stated that water is not equally available between field capacity and wilting point. As the soil moisture reaches wilting point significant decline in physiological activities is observed. The decline in physiological activities during different growth stages may impact the yield of a crop. Baier (1969) reported that as available moisture in soil declines below 50%, the plant restricts its metabolic activities resulting in affecting the yield. The stressed condition is commonly expressed as agricultural drought. The drought-like situation negatively affects plant development and it arises due to the intermittent nature of precipitation and irrigation system (Suralta et al., 2010). This harms dry matter production as well. As the soil gets drier the hydraulic conductivity is affected and triggers stomatal closure (Carminati and Javaux, 2020) disrupting the process of Soil-Plant-Atmospheric Continuum (SPAC) and photosynthesis. However, measuring soil moisture stress on a real-time basis is cumbersome and involves cost. But it is possible to measure random soil moisture at a short interval. The soil moisture can be related to suitable soil moisture stress and it can be classified into different categories. Such classification can help in planning suitable water management strategies under water-stressed situations.

Soil moisture and soil temperatures are important parameters in seed germination and crop yield (Egley, 1989; Ramakrishna et al., 2006). The soil moisture influences the soil temperature as heating starts only when evaporative demand is met (Bristow, 1988). Kuroyanagi and Paulsen (1988) stated that soil temperature has a higher influence on photosynthesis and respiration in comparison to air temperature. Researchers have shown that a drop of soil temperature below certain levels affects the growth and yield of different crops (Fly and Huang, 2004; Tachibana, 1982). For example, temperature below 19^{0}C impacts the yield of rice (Nishiyami, 1985; Wada, 1992). It is a common perception that drought is generally experienced in arid and semi-arid regions only. However, it has been observed that such a stressed situation can be experienced in high rainfall areas too. Sikkim (India) is one such area that receives a very high annual rainfall to the tune of 3000 mm but experiences a drought-like situation during the non-rainy season due to the non-availability of soil moisture. Further, the soil texture in Sikkim, which is sandy loam (Kusre et al., 2018), aggravates the situation by its poor water holding capacity. In this study, an effort is made to categorize the stress level and suggest suitable measures to mitigate its impact. The present study is being taken up with the objective to (i) develop a soil moisture index to understand the extent of stress a crop experiences particularly during the winter season (ii) Study the relationship between soil moisture and soil temperature.

METHODOLOGY

Study area

Sikkim is a small Indian constituent state with an area of 7096 km^2. It lies between the coordinates of 27º5' N to 27º9' N latitude and 87º59' E to 88º56' E longitude (Fig. 1). It is located in the middle Himalayas and is characterized by a steep slope (average slope >15%). Administratively it is divided into 4 districts namely the North district (4,226 km^2) followed by West (1,166 km^2); East (954 km^2) and South (750 km^2). The state receives very high rainfall with average values of more than 3,000 mm annually. Around 85% of the rainfall is received from April to September and the remaining month receives around 15% only. The dominant soil of the state can be classified as a sandy loam (Kusre et al., 2018). Agriculture is the major economic activity in the state with around 11% of land under crops. Most of the agricultural area is rainfed with a meagre area of 8.9% of the total net cultivated area under irrigation. The major crops of the state are large cardamom, ginger, paddy, maize, wheat and other vegetables.

The methodology for developing soil moisture index included the following steps
  (a) Generation of soil moisture data and soil temperature and electrical conductivity at selected stations
  (b) Estimation of soil texture
  (c) Development of soil moisture characteristics curve
  (d) Development of soil moisture index.
The steps are shown in the flow chart in Fig 2.

Generation of soil moisture, soil temperature and electrical conductivity data

Five soil moisture sensors were installed at different locations for generating continuous data at every 1-hour interval (Fig. 1). The locations of the stations are shown in Table 1. Fig. 3 shows one of the soil moisture measurement stations along with the data logger. The extent of data collected at different stations is shown in Table 2. The data was aggregated every week and analysis was made to understand the soil moisture stress on a weekly aggregate basis. The weekly data was considered for planning an appropriate water management strategy.

Table 1. The details of the various monitoring station installed under the project area

Sl.No.	Station Name	Longitude	Latitude	Elevation (m)
1	Ravangla	88º21'12.33" E	27º17'24.44" N	1739
2	Geyzing	88º14'40.22" E	27º17'49.33" N	1509
3	Dalapchand	88º40'40.10" E	27º11'47.02" N	1067
4	Assam Lingzey	88º36'32.80" E	27º16'56.86" N	1068
5	CAEPHT	88º35'57.50" E	27º17'42.10" N	878

Fig 1: Map of Sikkim showing the location of measuring
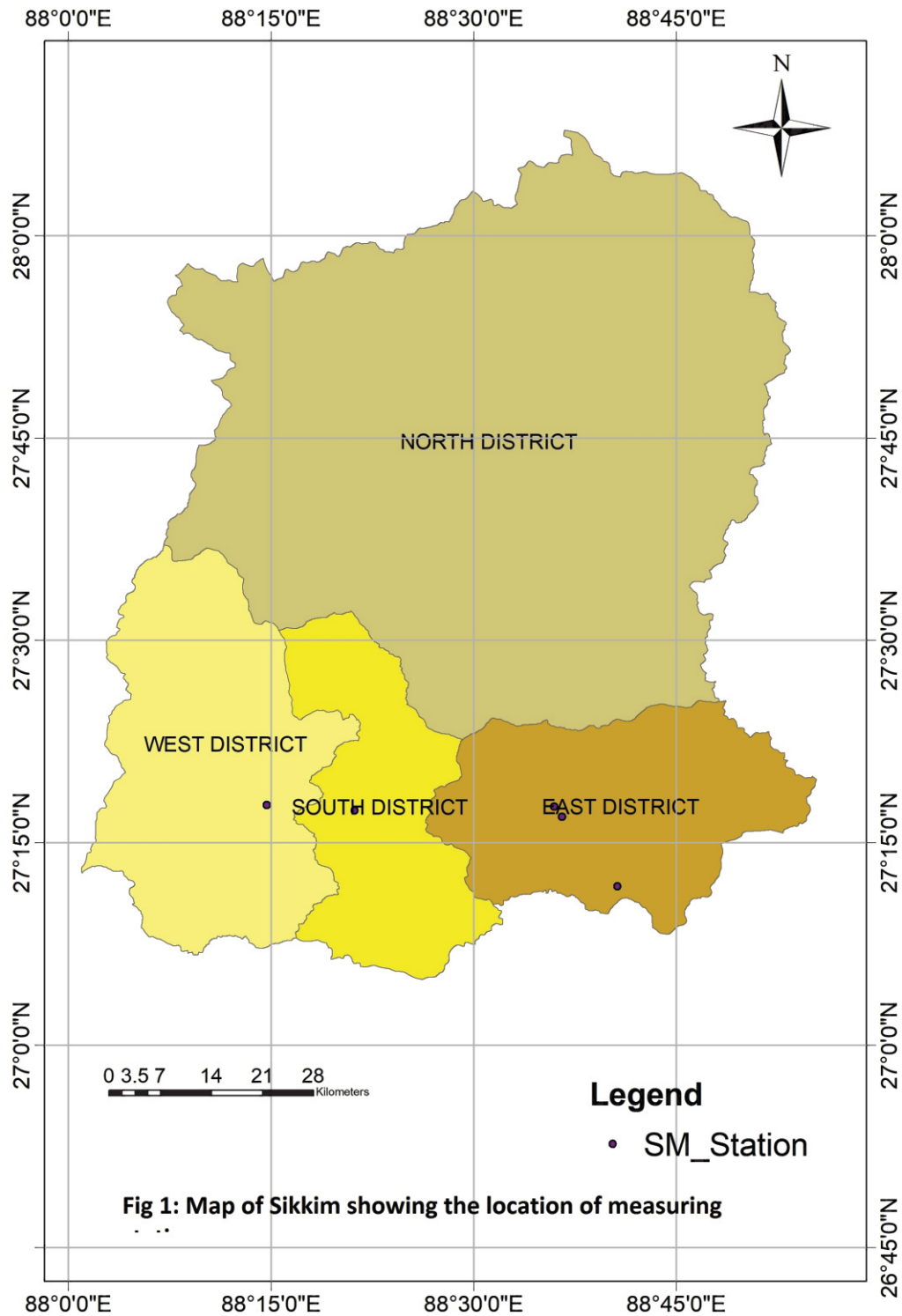
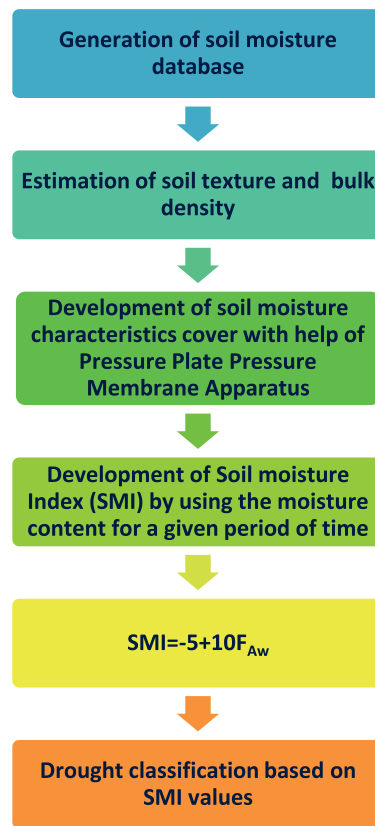**Fig. 1** 27º5' N to 27º9' N latitude and 87º59' E to 88º56' E longitude.

Fig 2 : Flow chart for Development of soil moisture index

Table 2. The length of data collected at different stations

Sl.No.	Station Name	Soil Moisture			Soil temperature	
		From	**To**	**Missing data**	**From**	**To**
1	Ravangla	May 2015	April 2018	April to June 2017		
2	Geyzing	May 2015	Sept 2018	Jul 16 to June 17		
3	Dalapchand	April 2015	Nov 2016			
4	Assam Lingzey	June 2015	Feb 2019	Jan 16 to June 17	June 2017	Feb 2019
5	CAEPHT*	Oct 2015	Aug-2019		June 2018	Aug 2019

CAEPHT: College of Agricultural Engineering and Post Harvest Technology

Fig 3 : Photograph of a soil moisture measuring stations

Estimation of soil texture and bulk density

The soil texture is an important physical parameter that determines the water holding capacity of the soil (Vengadaramana and Jashothan, 2012). For obtaining soil texture, soil samples were collected from areas near the soil moisture measurement stations. The texture was determined using the United States Department of Agriculture (USDA) soil classification method (Arora, 2003). Soil texture was assessed from the USDA soil texture triangle (Fig. 4).
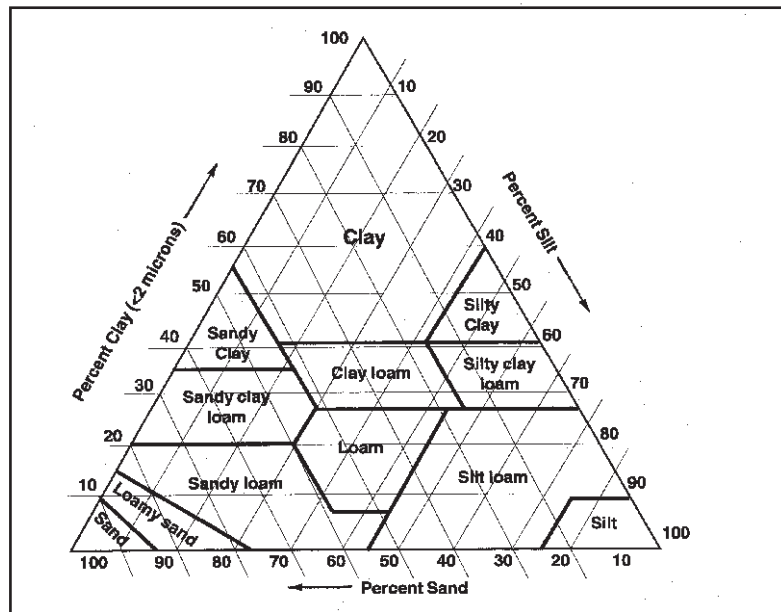
Fig 4 : Soil texture triangle

Soil moisture characteristics curve

The soil moisture characteristics curve is defined as the relationship between the water content and stress potential for the soil (Williams, 1982) where the water content is the amount of water present in the soil pores and stress indicates the matric potential or capillary pressure. In the present study, the soil moisture characteristics curve was developed to observe the soil moisture tension at different moisture content during different parts of the year for a selected soil type. The soil moisture curve was developed using pressure plate pressure membrane apparatus available at Biswanath College of Agriculture, Assam Agricultural University, Jorhat using standard procedure.

Soil moisture index

Soil moisture Index (SMI) was developed using the method suggested by Hunt et al. (2009). They suggested the following relationship to estimate the index

$$SMI = -5 + 10F_{AW} \qquad \qquad \text{… (1)}$$

where, SMI is a soil moisture index, F_{aw} is a fraction of available water and is calculated by the given Equ.2 shown below.

$$F_{AW} = \frac{(\theta - \theta_{WP})}{(\theta_{FC} - \theta_{WP})} \qquad \qquad \text{… (2)}$$

where, θ is the measured volumetric soil moisture content of the soil, θ_{WP} is the volumetric soil moisture content at the wilting point and θ_{FC} is the volumetric soil moisture content at field capacity. The factor -5 and 10 given in Eq. 1 are the intercept and slope developed from the relationship between SMI and F_{aw} (Hunt et al., 2009) and is shown in Eq. 3 and 4

$$a = -5 \qquad \dots (3)$$

and the slope is:

$$b = \{5 - 5(-5)/(1-0)\} = 10 \qquad \dots (4)$$

Fraction of available water varies from 0 to 1 as volumetric moisture content varies from wilting point to field capacity (Hunt et al., 2009). The soil moisture index value is scaled from 5 to -5, representing 5.0 as a wet condition and -5.0 as extremely dry conditions and 0.0 as in a neutral condition. The SMI value of 0.0 defined the stress and non-stress situation. However, the SMI value may cross the value of 5.0and -5.0 depending on the moisture condition. The classification of the Soil moisture index is proposed by Sridhar et al. (2008) and is shown in Table 3.

Table 3. Drought classification based on SMI values

Category	SMI
Less intense	-1 or more
Moderate	-2 to <-1
High Intense	-3 to <-2
Severe	-4 to <-3
Extreme	-5 or less

RESULTS AND DISCUSSION

Soil Texture classification

The soil texture w4as obtained from the methods described earlier. The soil texture classification is shown in Table 4. From the table, it is evident that almost all the soils fall under the sandy loam category. In the entire soil sample, the sand concentration is more than 60%. Such soils are characterized by low water holding capacity and moisture content depletes rapidly.

Table 4. Soil textural classification of Sikkim at the selected location

Sl. No.	Stations	Sand (%)	Silt (%)	Clay (%)	Classes
1	Assam lingzey	84.02	9.66	6.32	Loamy sand
2	CAEPHT	66.12	19.34	14.54	Sandy loam
3	Dalapchand	66.34	17.68	15.98	Loamy sand
4	Geyzing	67.68	20.40	11.92	Sandy loam
5	Ravangla	64.68	19.38	15.94	Sandy loam

Soil moisture characteristics curve

The soil moisture characteristics curves were plotted for the soils adjoining the given installed stations. A sample soil moisture characteristics curve is shown in Fig 5. The equations were developed for moisture content and soil moisture stress to extrapolate the readings (Table 5). The equations were used to obtain soil moisture stress for any given moisture content for the given soil types. In this present study, we considered 500 kPa and 700 kPa as a wilting point. It is because some plants may start to wilt early and some late. However, majority of crop displays wilting condition at 700 kPa and beyond depending upon the type of crop and variety.
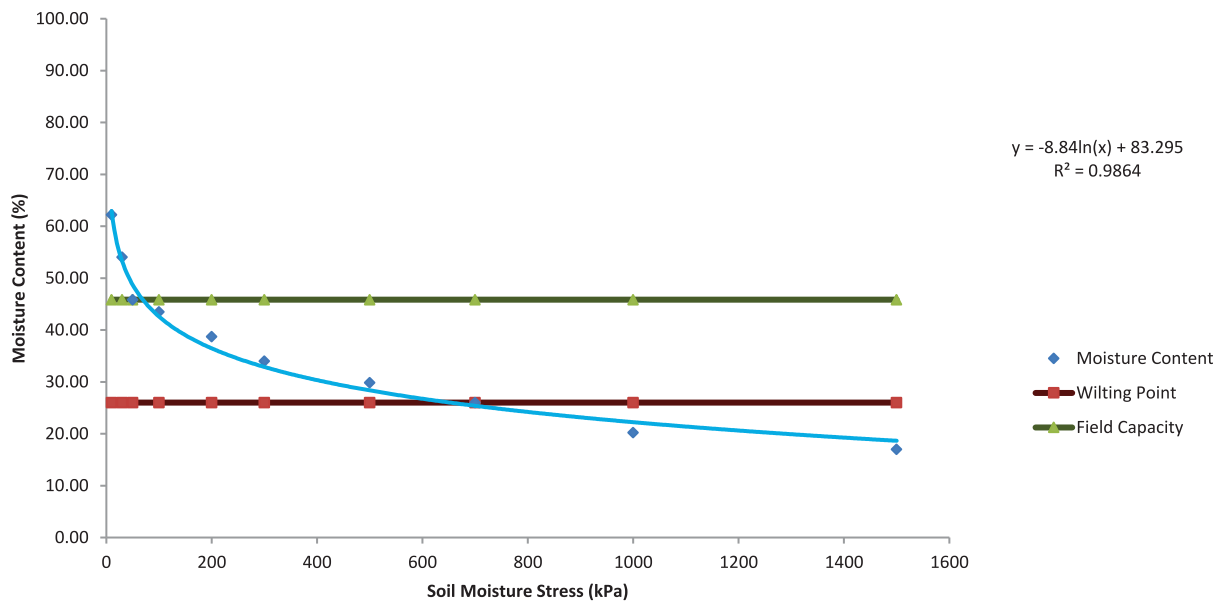

Fig. 5 : Soil Moisture Characteristics Curve of Assam Lingzey

Table 5. Soil moisture content at a critical moisture stress level

Sl No	Stations	Moisture content			Equation
		At field capacity (50 kPa)	At 700 kPa	At permanent wilting point (1500 kPa)	
1	Assam lingzey	45.85	25.34	17	y = -8.84ln(x) + 83.29 R^2 = 0.986
2	CAEPHT	36.97	21.21	10.58	y = -6.62ln(x) + 63.98 R^2 = 0.885
3	Dalapchand	49.10	28.28	15.41	y = -8.48ln(x) + 77.88 R^2 = 0.931
4	Geyzing	73.65	23.65	16.62	y = -16.6ln(x) + 129.4 R^2 = 0.895
5	Ravangla	52.32	23.37	15.21	y = -8.87ln(x) + 81.02 R^2 = 0.946

Temporal variation of soil moisture

Temporal variation of soil moisture was analysed for the selected station. The plots of temporal variations are shown in Fig 6. The plots indicate that the soil moisture depletes rapidly after the rainfall recedes after September and continues till March. The soil moisture is observed to be minimum in December and January. These months coincides with the cultivation of major rabi crops, horticultural crops and vegetables that are economically potential crops for the farmers. The variation of the respective stations and their moisture content is shown in Table 5. As the moisture recedes during the period October to March, we concentrated the development of soil moisture index during these 6 months only.
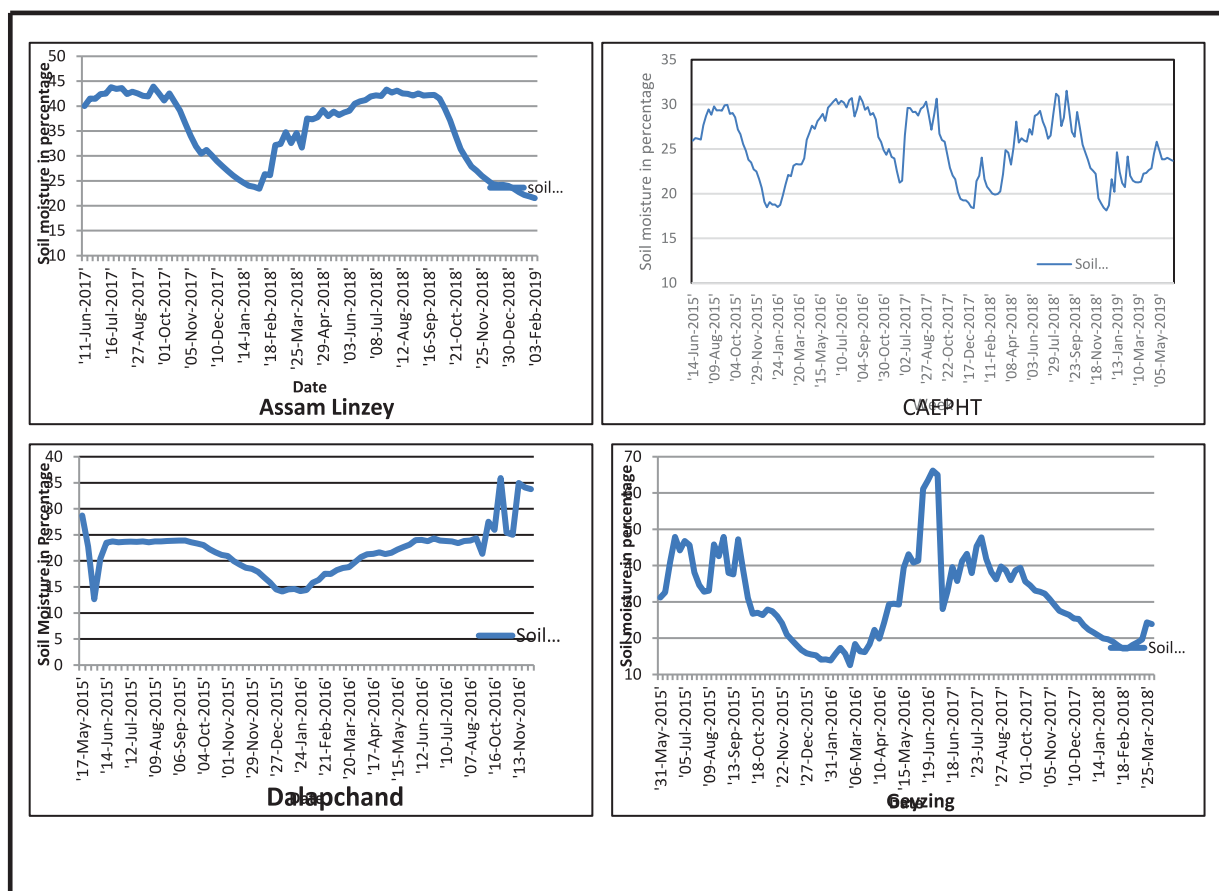

Fig. 6 : Temporal Variation of Soil Moisture at different locations in the Study area.

Soil Moisture Index

The soil moisture index was developed and the value of critical moisture content (θ_c) was at 500 kPa and 700 kPa. Although the permanent wilting point for most of the crops is considered as 1500 kPa as per standard literature it has been observed that many crops particularly shallow rooted experience stress at 500 kPa onwards. The plot of soil moisture indexes is shown in Fig.7. The figure indicates that during winters the soil moisture exceeds -5.0 SMI and at times it had crossed -7.0 indicating severe stress conditions. On average the SMI during the winter

season is -3.0 and more. It was observed that barring Ravangla station in all other stations the SMI values crosses - 3 after October and it continues to February and has recorded an extreme stress level of -5.0. The Ravangla station is an exception due to its typical location at the bottom of high hills the origin of several rivers from glaciers. However, in Ravangla also stress conditions were experienced although for short period. The value of - 5.0 is a critical situation and have an impact on taking up winter season crops.

Lack of rainfall during the winter season in the state of Sikkim meant that the soil profile could not be recharged from the dry condition. Therefore, the SMI values were observed to vary between (-) 1 to (-) 5. Hunt et al. (2009) stated that an increase in negative SMI values can be directly correlated with decreasing the evapotranspiration process. They have termed such decline as flash droughts. Senay et al., (2008) defined flash drought as severe short term moisture deficit and abnormally high temperature. But in Sikkim conditions, it is associated with low temperature. The condition can be associated with continuous moisture deficit conditions for 3 or more weeks where the available moisture is below 50%.

Soil moisture and soil temperature

The soil temperature was measured at two locations viz., Assam Linzey and CAEPHT. The observation indicated that the average temperature varied from 22.06 ^{0}C in the month of December-January to a maximum of 25.15 ^{0}C in July-August and the minimum temperature varied from 13.63 ^{0}C in December to January to 24.74 ^{0}C in the month of July-August. The observations indicate that the temperature remains below 15 ^{0}C from December to sometimes till February (Fig 8 and 9). These months coincides with vegetable production as well as other rabi crops. A relationship was also established between soil moisture, soil temperature (average and minimum). It was observed that the parameters of soil moisture and the average temperature have a correlation of 0.82 for Assam Linzey and 0.89 for CAEPHT stations respectively whereas with minimum temperature the correlation is 0.81.
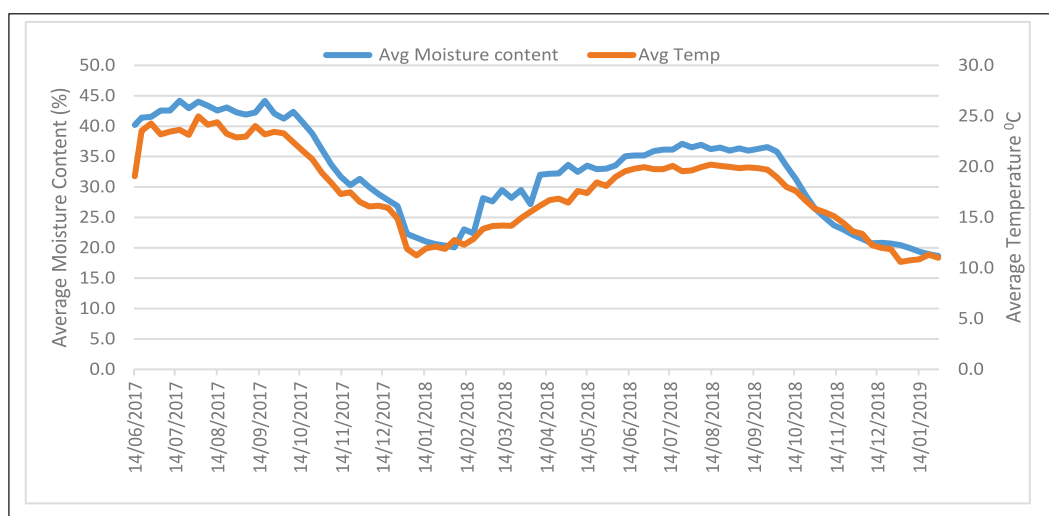

Fig. 8 : Comparision between soil moisture and soil temperature at Assam Linzey
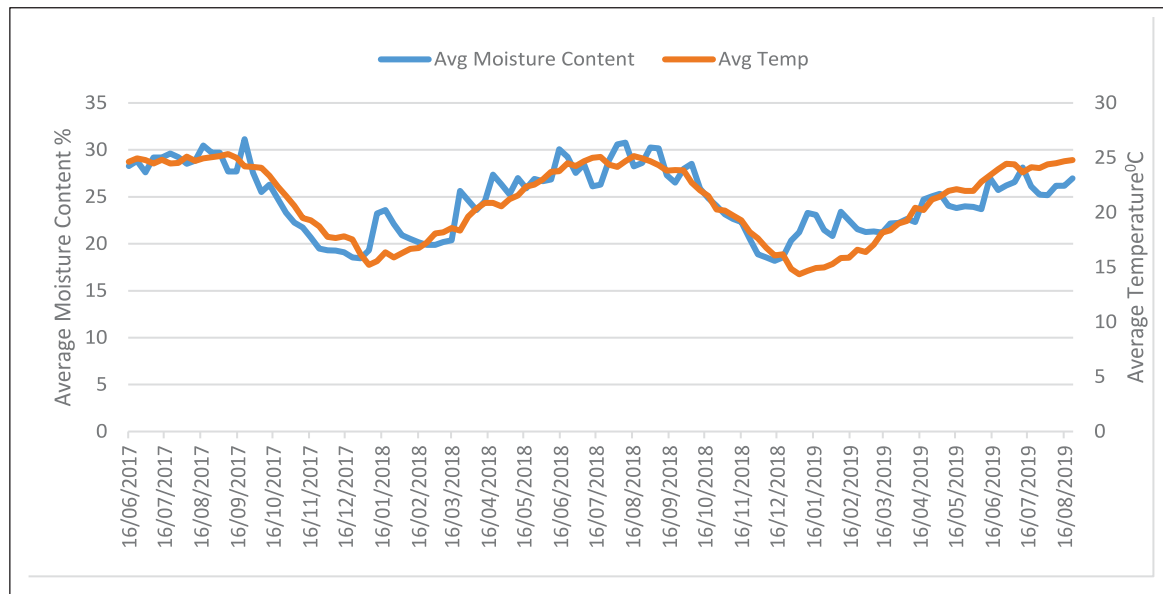
Fig. 9 : Comparision between soil moisture and soil temperature at CAEPHT

Management Strategy

As per the irrigation management principles the moisture stress should not exceeds 100 kPa for the best crop growth. However, in the case of Sikkim, during winter the moisture conditions continually remain below 100 kPa. The reasons for such extreme stress can be associated with the soil texture, steep terrain and shallow depth of the soil profile. To overcome such stressful conditions suitable management techniques, need to be adopted. Of various methods drip irrigation, mulching and selection of suitable variety are important. Drip irrigation can help in saving water by providing a low amount of water within the root zone on regular basis. Such application of water will reduce the loss of water due to a reduction in evaporation or deep infiltration or runoff. It will help the plant from experiencing a drought-like situation. A study conducted by Koehler et al. (1982) observed that the application of drip irrigation could improve stalk elongation, plant sugar, K, and amino acid concentrations in sugarcane cultivation. Similar findings were reported byAdekoya et al. (2014) on the application of drip in paddy cultivation. They reported that drip irrigation could maintain competitive grain yield and also indicated reduced pollution risk due to reduction in emission of methane gas. As in Sikkim, the weather is favourable during the season, crop productivity can be enhanced by making available the necessary water regime.

Similarly, mulching can also improve water conservation and productivity. The studies have reported that mulching can improve soil moisture availability resulting in a higher photosynthetic rate, water use efficiency, flag leaf area, number of tillers and drought tolerance efficiency (Thakur et al., 2000; Qin et al., 2010). The mulches have been reported to regulate and maintain favourable soil temperature (Iqbal et al., 2020). The maintenance of soil temperature is beneficial for crop growth. The studies have reported the beneficial impact of straw mulch, plastic mulch and a combination of both (Hu et al., 2019). Drought resistant varieties can also improve productivity. Ahloowalia et al. (2004) reported a synergetic effect on increasing yield and quality of crop and consumer acceptance due to improvement of variety.

Conclusions

The state of Sikkim although categorized under high rainfall zone but experiences a drought, particularly during the non-rainy season. The non-rainy or winter season coincides with some high value and important crops that help in the economy of the state and individual farmers. Under such a situation, soil moisture index becomes a handy indicator for expressing the onset of drought and its intensity. The SMI on a weekly time scale can help forecast potential flash droughts and also taking up suitable management strategies. The soil temperature also drops below 15^0C during the same period. It may affect production and productivity. Improvement in soil water potential in the root zone has an impact on the yield and quality of production apart from improving environmental conditions within the root zone. In the present study, we have developed the methods of developing soil moisture index and it could be obtained by simply measuring the soil moisture content on the given day.

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