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A Predictive Approach to Simulate Possible Impacts of Climate Change on the Agricultural Sector

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Abstract

The aim of this paper is to investigate the possible implications of climate change of maize and beans crop in the country of Belize. The approach utilized PRECIS and observed input data in combination with the Food and Agriculture Organization (FAO) CROPWAT program. Six scenarios were predicted looking at Maximum Temperature (T_{max}), Minimum Temperature (T_{min}) and Rainfall for the years 2050-2055 along with observed data of similar climatic variables for the year 1998. The approach was use for three sites namely Towerhill which is located to the north of the country, Central Farm which is located at the center of the country and Toledo Research and Development Project Site (TRDP) which is located at the southernmost part of the country. The results showed that there was an increase in both maximum and minimum temperature at two of the three sites with the exception of the Towerhill site and there was a reduction in rainfall in all predicted scenario with the exception of Towerhill site in 2051 which exhibited a 4.28 % increase over the baseline scenario. The reference evapotranspiration ET_o value illustrated more precisely the possible impact of climate change as there was an increase in of all ET_o values at the three observation sites. In regards to yield percent reduction the scenarios determine that climate change would have an impact on crop yield. Where yield percent reduction was as high as 80.1% at the Central Farm site. The results determined that climate change will affect these crops, by validating this, more suitable strategies and mitigating programs can developed and established to assist Belize in the prevention of a future food crisis.

Keywords: Climate change; Developing countries; Yield reduction; Reference evapotranspiration; Agriculture; Adaptation

Introduction

Climate change is projected to increase global annual mean temperatures in the range of 1.8-4°C; increase the variability in rainfall; enhance frequency of extreme weather events such as heat waves, cold waves, droughts and floods [1]. Therefore there is concern about the impacts of climate change and its variability on agricultural production worldwide [2]. Two reasons were highlighted for this concern: Firstly food security which is notably on the list of human activities and ecosystem services under threat of dangerous anthropogenic interference on earth's climate and secondly each country is naturally concerned with the potential damages and benefits that may arise over the coming decades from climate change impacts on its territory as well as globally, since these will affect domestic and international policies, trading patterns, resource use, regional planning, and the welfare of its people.

Studies have shown that while there is a positive response of crops to and increased level of carbon dioxide in the absence of climate change [2-5] the associated impacts of high temperatures [6,7], altered patterns of precipitation, and possibly increased frequency of extreme events [8], such as drought and floods, will likely combine to depress yields and increase production risks in many world regions [2]. Of these regions the regions which are more vulnerable to the impact of climate change are developing countries. Due to the importance of agriculture to their economies, scarcity of capital for adaptation [9-12], their warmer baseline climates [1,3] and their heightened exposure to extreme events [13]. According to United Nations Food and Agriculture Organization [14], 870 million people of the 7.1 billion people in the world were suffering from chronic undernourishment in 2010-2012. Almost all of the 852 million hungry people live in developing countries. Developing countries which rely heavily on farming not only as a source of income at a national and local but more importantly these countries rely on farming as a food source for its growing population.

Understanding the impacts of climate change will help Belize determine, where, when and how adaptation should be undertaken. There are four sources of information about the sensitivity of farms to climate [1,15,16]. 1) Agronomists have conducted controlled experiments in greenhouses with different temperatures. 2) Agronomic crop simulations model key grains such as maize, wheat, soybeans, and rice. 3) Cross sectional studies of yields of specific grains have been conducted across different climate zones. 4) Cross sectional economic models have been estimated using land values and farm net revenues across climate zones. These studies revealed that crops are sensitive to changes in temperature [1,15,16] and precipitation [17,18]. The consistency of these findings suggests that there is high confidence that crops are potentially vulnerable to climate change [15].

Gohari et al. [8] stated temperature increases affect most plants leading the crop yield reduction and some complex growth responses. Nevertheless, the impact of increasing can vary widely between crops and regions. Acknowledging this the overall objective of this paper is to assess the impact of climate change on rain fed agriculture in Belize. It observes percent yield reduction in two staple crops (beans and maize) as a result of observed and future scenarios derived from Providing Regional Climates for Impact Studies (PRECIS) in combination with FAO's CROPWAT model.

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The specific objectives are the following:

- to generate future scenarios as input data for CROPWAT using PRECIS
- to compare both observed and modeled climatic parameters and resulting reference evapotranspiration
- to analyze model results in reference to percent yield reduction as a result of both simulated and observed climatic parameters.

Materials and Methods

Sites and cropping considerations

The crops chosen for the simulation were Dry Beans (*Phaseoulus vulgaris)* and Maize (*Zea mays*), primarily because of their importance as staple grains in Belize. Beans are grown in a very wide range of latitudes and the mean air temperature varies between 14ºC and 35ºC with an optimal range of 29-35ºC. The temperature of the air and the root determining, seed germination, root growth, taproot formation and flowering [19,20]. Extreme temperatures, that are lower than 10ºC and higher than 40ºC can result in poor germination rate which subsequently disrupt the plant growth cycle [21]. The water requirements for maximum production of a 60-120 day crop vary between 300-500 mm depending on the climate [22]. Red Kidney beans was the variety of choice but the crop coefficient for R. K. beans was not available, therefore the reference crop coefficient value for dry beans was utilized which is similar to that of R. K. beans. Maize crop performed best when grown under an optimal air temperature of 20-22ºC. For maximum production a medium maturity crop requires 500-800 mm of water. Both crops would suffer from low productivity/yield if the adequate growing conditions are not available.

Three sites were selected for the simulation, namely: Central Farm (Cayo District), Towerhill (Orange Walk District) and the Toledo Research and Development Project site (TRDP) near Blue Creek village. The main agronomic parameters considered in the simulation were soils: primarily light sandy, medium loam and heavy clay. The cropping system was assumed to be rainfed mechanized, and in the case of Maize, the simulation was run for early planting (one month before the normal planting period in June), normal and late (one month after the normal planting period in June). The normal planting period in December was use for the simulation for Dry Beans. The simulation was run for each year from 2050 to 2055.

Crop simulation

The crop model simulations for this study were conducted with CROPWAT 8.0 [23] for Windows computer program. The main functions of this model are: to calculate reference evapotranspiration; develop irrigation schedules under various management conditions and water supply schemes and to evaluate the efficiency of irrigation practices [24]. The model requires input data such as climatic (monthly rainfall data, monthly means of minimum temperature T_{min} (ºC), maximum temperature T_{max} (ºC), air relative humidity (%), sunshine duration (h), wind speed at 2 m high (m/s) and potential evapotranspiration ET_o), crop (planting date, crop coefficient (K_c), crop description and percent covered by the plant) and soil data (intial soil moisture condition, maximum root infiltration rate and maximum rooting depth).

CROPWAT is essential for this study being that it utilizes the Food and Agriculture Penman Monteith Method (FAO-PM) to determine reference evapotranspiration by the given equation [22]:

$$ET_0 = \frac{0.408\Delta(R_N - G) + \gamma(\frac{900}{T+273})u_2(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)}$$

where ET_o is the reference evapotranspiration (mm day^{-1}), R_N is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), γ is the psychometric constant (kPa $°C^{-1}$) and is the slope of the saturation vapor pressure–temperature curve (kPa $°C^{-1}$).

The FAO PM is the standard method for estimating ET_o [22], it is physically based and explicitly incorporates both physiological and aerodynamics [25] as seen in equation. Its ability to apply missing data approach was vital in the case of the areas under evaluation due to poor data availability.

Climate change scenario

Quantification of changes in climate variation such as temperature and precipitation is the first step in climate change impact assessment [8]. With the global climate models (GCMs) being known as the most credible tools for the projection of future global climate change. GCMs simulate the physics of the atmosphere and various climate scenarios (SRES) [1,3]. The input climate data for CROPWAT as seen in Figure 1 was taken from observed data and from modeled data. Modeled data being taken from the Regional Climate Model (RCM), Providing Regional climates for impact studies (PRECIS). PRECIS is an atmospheric and land surface model of limited are locatable over any part of the world with spatial resolution of 0.44º×0.44º [6]. Jones et al. [26] claimed that it accounts for meteorologic dynamic flow atmospheric sulfur cycle, formation of clouds and precipitation, radiative processes, land surface vegetation, incoming radiation, heat fluxes, soil temperature and lateral boundary conditions, and is more suitable for high resolution impact assessments. The future climate projection for the period 2050-2055 was derived from the output of the Caribbean Community Climate Change Center (CCCCC) PRECIS-Echam5 A2 (25 km resolution) experiment conducted for the western Caribbean. The PRECIS-Echam5 A2 describes a heterogenous world with strong population growth, slow economic development and slow technological change [1]. Whereas the baseline climatic data used in this study for the year 1998 was acquired from Belize's National Meteorological Service.

Model performance evaluation

A single statistical measure was used to compare the ET_o generated from the baseline or observed data with that generated from PRECIS.

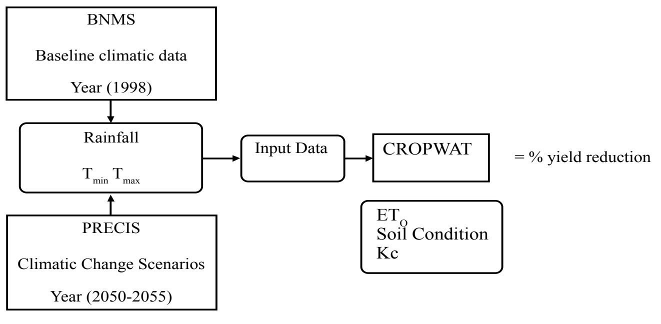

Figure 1: Flowchart of the proposed modeling framework.

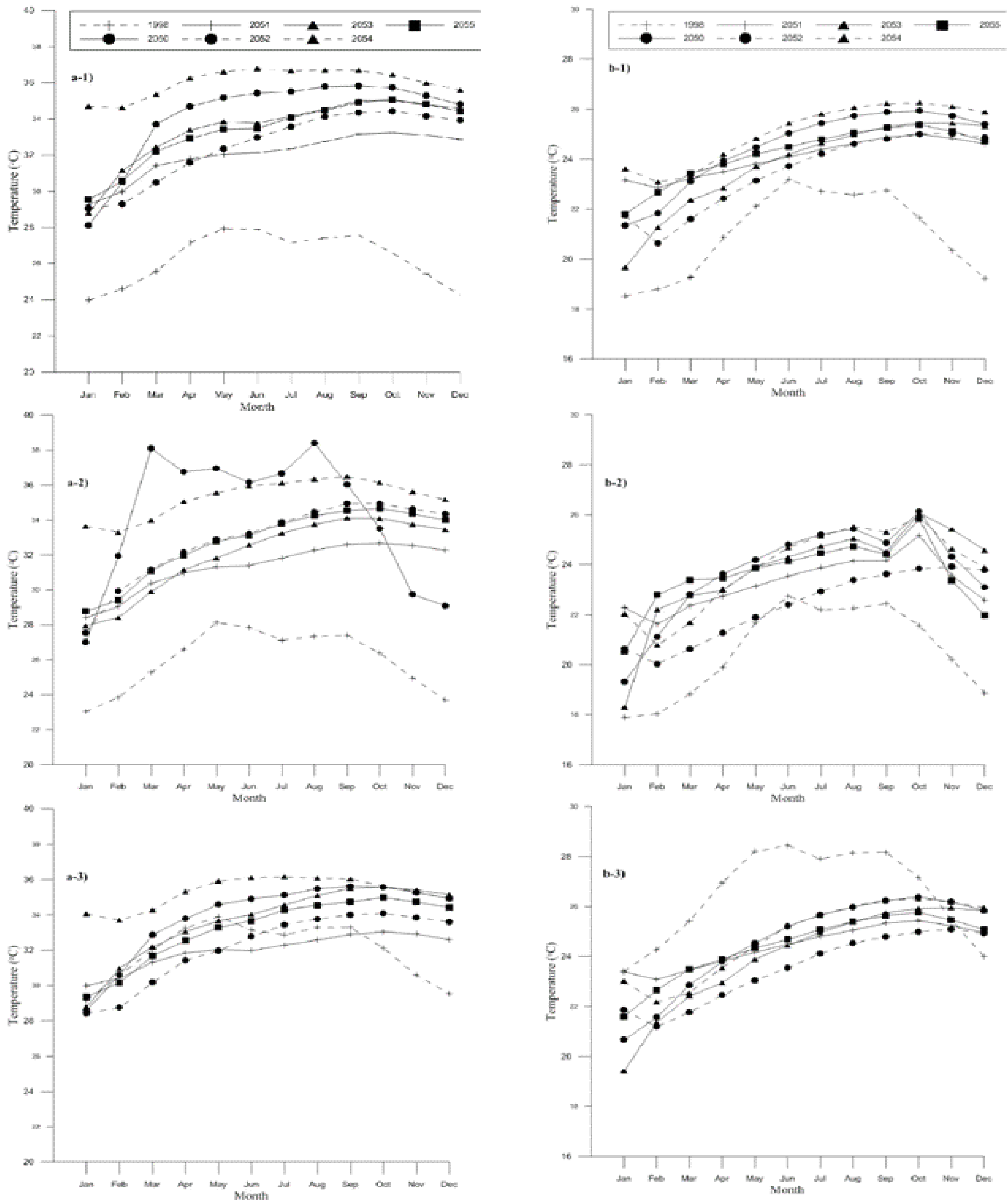

Figure 2: Comparison of the observed and modeled maximum (a-1) – (a-3) and the minimum temperatures (b-1) – (b-3) of the three sites under observation, (TRDP, Central Farm and Towerhill) respectively.

For each of the locations the statistical criteria of Percentage Error of Estimate (PE) was used to evaluate if there would be change in ET_o in the year 1998 and in the future scenarios of the years 2050-2055. If there is a change what would be the extent at which the ET_o values as a result climate change would differ from the baseline ET_o values. The PE is defined as:

$$PE = \left| \frac{\bar{P} - \bar{O}}{\bar{O}} \right| \times 100\%$$

Where $\bar{P}$ and $\bar{O}$ are averages of P_i and O_i which are the ith predicted data using PRECIS input data to generate future ET_o values and observed input data to generate baseline ET_o values respectively.

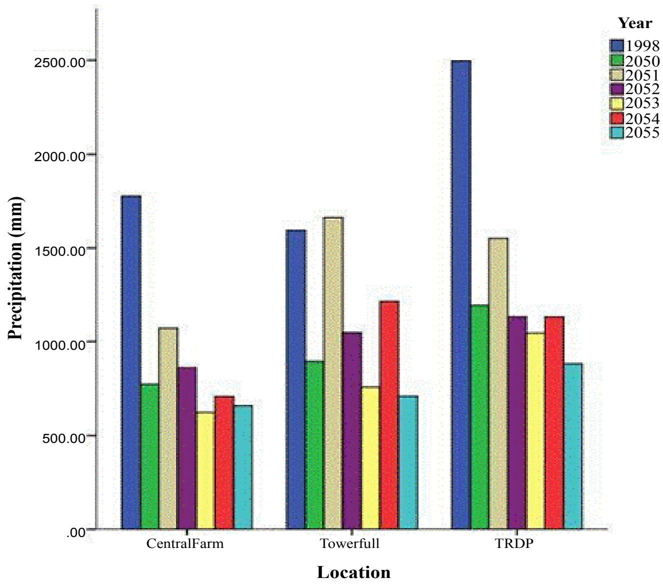

Figure 3: Comparison of observed precipitation data and modeled precipitation data.

Results and Discussion

Climate change scenarios

Six predicted monthly trends in T_{max}, T_{min} and precipitation were compared in three different sites in the southern part of the Belize the second in the central part of the country and the third in the northern part of the country. At these locations as seen in Figure 2 the model value of T_{max} and T_{min} are fairly higher than the observed values. The highest T_{max} value was in 2050 at Central Farm with a high of 38.4°C in the month of August and likewise the lowest T_{min} value was at the same site in 2053 with a low of 18.3°C. In Figure a-1, a-2 and b-1 a clear distinction is possible between the observed and the modeled temperature values. Also Figure 2 b-2 can be considered as having a clear distinction since only in the month of May and June in the year 2052 does the T_{min} value exceed or overlap the observed T_{min} value. The Towerhill site however showed a different result in comparison to the previous sites whereby Figure 2 a-3 and b-3 showed observed T_{max} similar to modeled T_{max} temperature, which is similar to findings made by [27] and observed T_{min} values higher than modeled T_{min} values. The observation between validates the effect of climate change on temperature.

Precipitation scenario

The rainfall for the sites were compared using the observed data for the year 1998 and the predicted data for the years 2050 thru 2055 as illustrated in Figure 3. Where it can be observed that the site with the highest precipitation is TRDP and the site with the lowest precipitation is Towerhill. Figure 3 shows that with the exception of Towerhill in the year 2051 the remaining two sites are in general agreement with [27,28] whom in their studies documented that climate change will not only bring about variation in rainfall but the more common occurrence would be a reduction from the present volume falling on the earth's surface. This was observed in this study where in the future scenarios during the 2050 to 2055 where significantly lower in comparison the observed precipitation value as seen in Table 1.

Where the reduction range from a low of 37.89% in 2051 to a high of 64.63% in 2055 at the TRDP site, a low of 39.57 % in 2051 to a high of 64.93% at the Central Farm site and a low of 23.87% in 2054 and a high of 55.45% at the Towerhill site. As stated by [28] and further

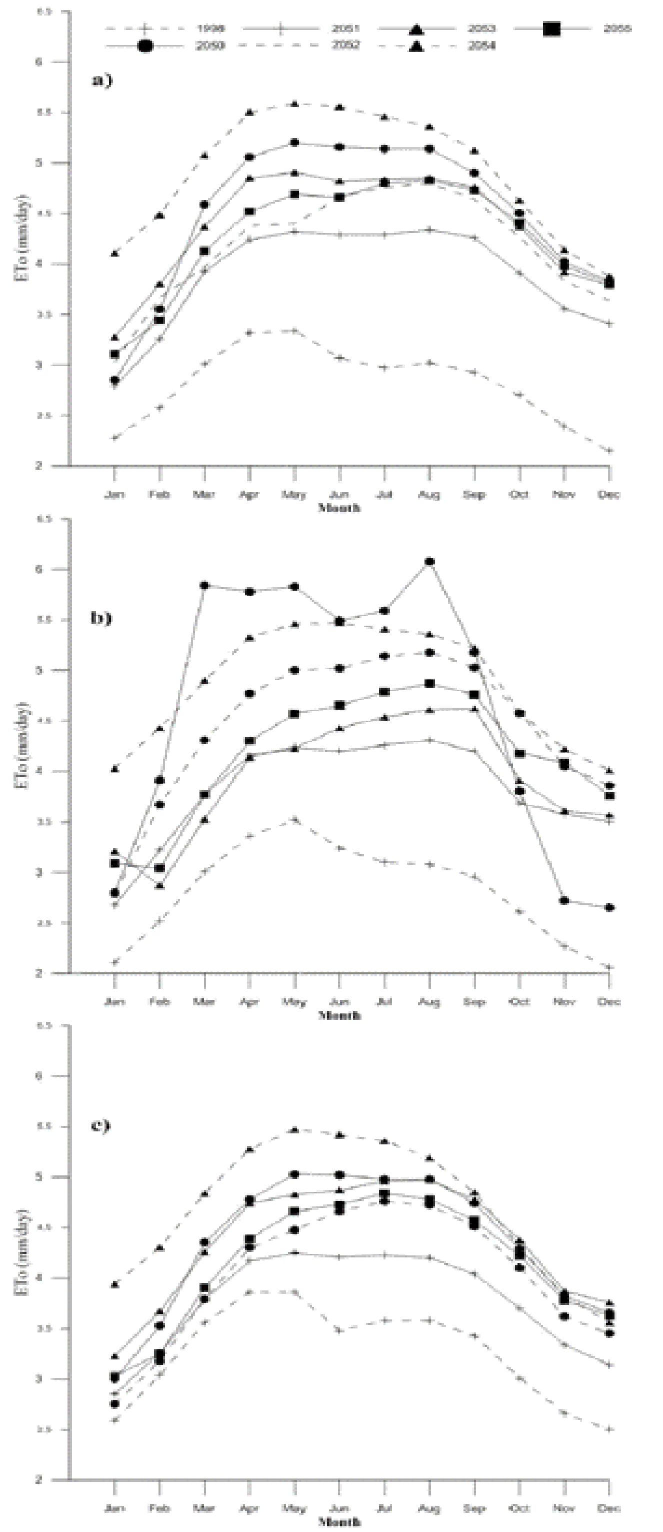

Figure 4: Comparison of ET_o values computed by CROPWAT using observed input data and modeled input data from PRECIS at TRDP (a), Central Farm (b) and Towerhill (c).

Variable	Location			Year			
		2050	2051	2052	2053	2054	2055
	Trdp	59.77	38.03	48.25	55.69	74.56	51.39
ET_o	Central Farm	64.51	35.37	57.8	39.69	72.64	47.37
	Towerhill	33.28	15.4	23.42	33.64	43.91	27.15
	Trdp	-52.22	-37.89	-54.6	-58.08	-54.63	-64.63
Rainfall	Central Farm	-56.42	-39.57	-51.41	-64.93	-60.09	-62.98
	Towerhill	-43.82	4.28	-34.17	-52.49	-23.87	-55.45
	Trdp	30.14	21.75	23.7	27.25	37.09	26.76
T_{max}	Central Farm	31.66	20.57	26.43	23.28	35.85	26.04
	Towerhill	6.15	0.04	0.65	5.27	10.36	3.81
	Trdp	16.6	14.69	11.84	13.17	19.38	15.38
T_{min}	Central Farm	15.56	13.22	8.82	15.5	16.17	14.74
	Towerhill	-7.15	-7.68	-11.11	-9.24	-6.41	-7.74

(+) Shows an increase and (-) a decrease with respect to the value of the variable

Table 1: Difference of future scenarios (2050-2055) to that of observed conditions (1998) (PE).

documented by [29] there is an overall trend in regards to precipitation when observing climate change which is the general decrease however there exist the possibility that in a given year rather than a reduction an increase of precipitation can occur. This was observed in the year 2051 at the Towerhill site where rather than a reduction in precipitation the value was 4.28 % greater than the observed value of 1998.

Scenario comparison

The results of the model performance evaluation are seen below in Table 1, where it can be observed that in the year 2051 the least amount of increase or decrease with respect to ET_o, Rainfall, T_{max} and T_{min} will occur. The maximum increase and maximum decrease however is not confined to a single modeled year. The maximum increase in ET_o amongst the three sites occurred in 2054 at TRDP, the maximum decrease in precipitation was at Central Farm in 2053, the maximum increase in T_{max} and T_{min} was at TRDP in 2054.

The overall results of Table 1 are in agreement with several studies [2,6,15,16,18,23,24,29-33] which highlight there will be changes made to the various climatic variables listed which in turn will increase the vulnerability of agricultural production [7] especially crop production [10,17,27].

Reference evapotranspiration (ET_o)

The ET_o values generated from CROPWAT are presented in Figure 4 where it can be seen that firstly all ET_o values in the future scenarios are higher than that of the observed ET_o values at all three sites under observation and secondly the increase in ET_o values from the months of

February to late May early June coincides with the country's dry season which peaks in the month of May. In Figure 4-b which is representative of the Central Farm site both the highest and the lowest ET_o values were calculated. The highest was 6.08 mm/day in the month of August which also coincides with the highest T_{max} value of the same year and the lowest ET_o value was 2.65 mm/day for January of the same year.

Any change in ET_o as seen in the results will likely have a profound effect on agriculture more specifically crop production. The effect of which according to [34] can impact agriculture mainly in two ways increasing crop water needs (water demand) and modifying crop patterns and growing seasons. To understand how an increase in ET_o influence water demand the procedure used to determine crop water requirement (ET_c) needs to be taken into consideration. ET_c refers to the crop water requirement and reflects the maximum crop water demand in a given growing period [22,35]. It can be simply estimated by multiplying the reference evapotranspiration by crop coefficient or crop factor [22-24,31]. Therefore a shift in meterological variables as seen in Figure 2 and presented in Table 1 resulted in changes in ET_o which would subsequently change the ET_c and if the resulting values in Figure 3 are unable to meet the crop demand it would result reduction in crop productivity.

Simulated yield reduction results

Figure 5 presents the comparison of percent yield reduction as computed by the CROPWAT model for TRDP, Central Farm and Towerhill. The simulation was done for two crops namely beans and maize which are known as staple crops for Belize. The simulation consider three default soil types (light, medium and heavy) and to evaluate another possible adaptation strategy the planting date simulated for maize was both early and late in addition to the crops normal planting date.

The results show that the soil which would result in the highest yield reduction percentage for both crops at all the sites evaluated would be the light soil. The highest value being 80.1% yield reduction in Central Farm when maize was planted a month earlier in 2052. The site least affected by climate change with respect to yield reduction was TRDP. A reason would be that although there was an increase in ET_o and a reduction in precipitation (Table 1). The rainfall was sufficient and met the crop water requirements and thus not impacting the yield. The rainfall based on the results was not sufficient in 2053 where it impacted yields at most of the sites. The response was explained by [36] whom mentioned the major factor which influence the yield of rain fed crops is rainfall therefore the yield would naturally vary according to rainfall level. Their study along with research conducted by other scholars [6,17,37,38] validated the yield reduction in response to climate change. Whereby some results which included sorghum, groundnut [37], onion, wheat [36,37] and maize [35,37-39] all showed a reduction in yield of in a rain fed system due to climate change scenarios.

The site impacted the most due to the climate change scenarios was Central Farm where the percent yield reduction was generated for both beans and corn in all three soil types and even by planting the crop earlier or later a reduction in yield still occurred. Shifting of cropping periods for maize was conducted to determine if the approach could be used as an adaptive strategy to mitigate the effect of climate change of this staple crop in Belize as in a previous study [28]. As shown in Figure

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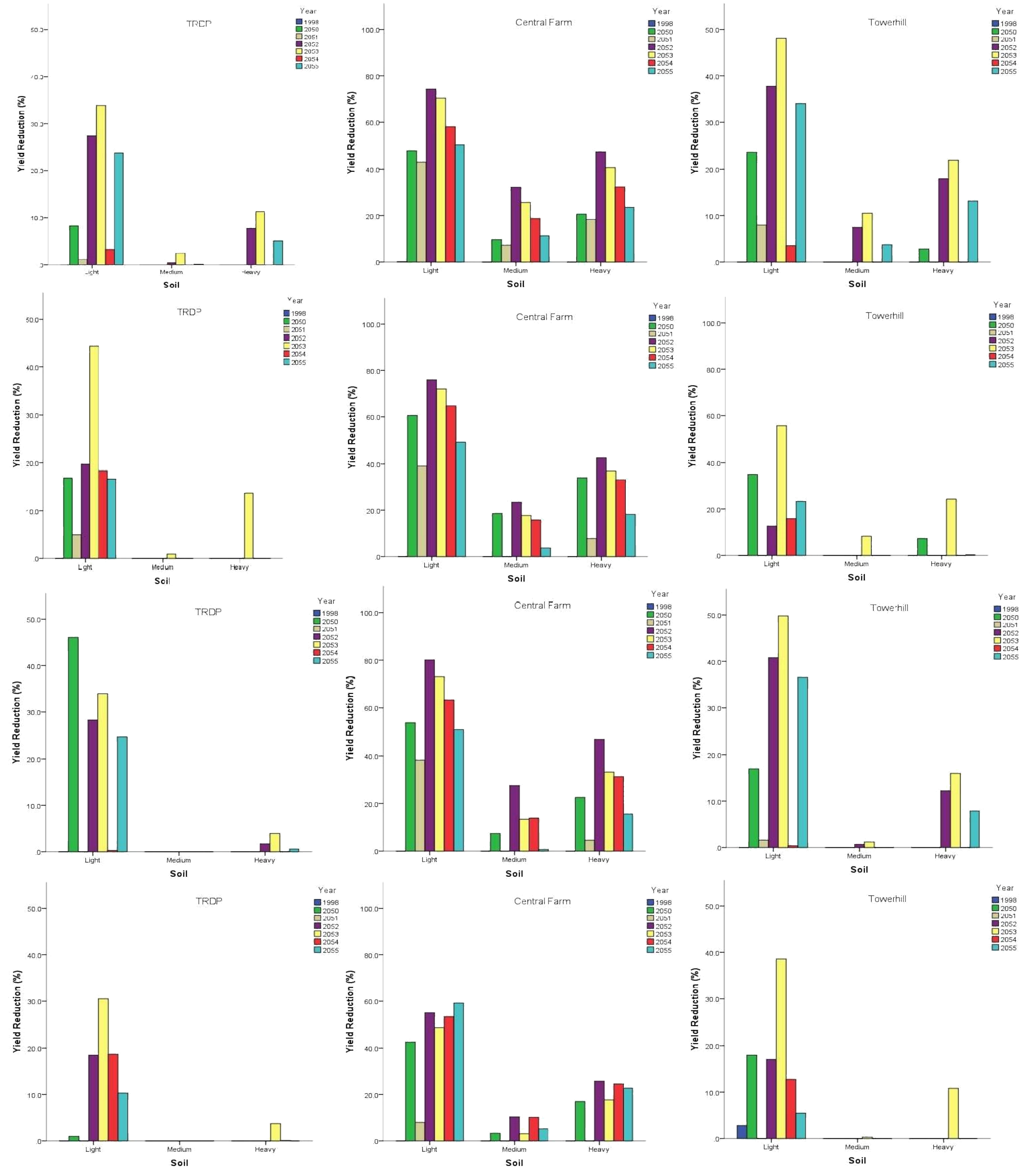

Figure 5: Percent yield reduction of dry beans (a)(b)(c) and maize (d)(e)(f) normal planting (g)(h) early planting (i)(j)(k)(l) late planting under a rain fed system.

5 shifting cropping period can be utilized as a mitigating strategy. As it is more clearly depicted in at the Central Farm site (Figure 5 e-h-k) where later planting season resulted in a lower percentage of yield reduction of the maize crop planted.

Conclusions

There is a need for a fundamental shift in water and land policy in Belize to avert a food crisis in the future due to climate change. This study investigated the use of PRECIS in combination with CROPWAT to determine the possible implications of climate change on two staple crops in the country of Belize. The approach is simple method to predict the effect of climate change and thus providing the stakeholders and agricultural practitioners with the data required to formulate adaptation and mitigation programs for water and land use on an annual basis. More the former since water availability is known to be the most striking consequences of climate change for the agricultural sector. Furthermore since it is the mandate of the country to enhance agriculture production currently and in the future additional research is needed to encompass more crops. Before doing so as a recommendation, due to data unavailability at certain meteorological sites the first step would require a sensitivity analysis to observe the various climatic variables on ET_o and the variation of ET_o across the country. With the objective being to improve the input data since climatic variables vary not only between regions but locally as well. Therefore the impact to the sector as seen in the study will also vary. Although some limitations with data availability were encountered the approach was able to reveal possible impact of climate change.

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