Estimating Soil Loss in Upland Corn Production using the SWAT Model

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ABSTRACT

Soil erosion is a common problem worldwide. There are lots of models developed to estimate soil loss; however, most of them are location-specific. The study assessed the adaptability of the Soil and Water Assessment Tool (SWAT) model for estimating soil losses under different slopes and management practices in upland corn production from January 2015 to December 2016. The study included establishment of erosion plots with three management practices (as treatments) to include: T1 (conventional tillage), T2 (minimum tillage) and T3 (minimum tillage + hedgerow). The portable Automatic Weather Station (AWS) was also installed in the area to record the amount of rainfall. The coefficient of determination was used to compare the measured and simulated data while the Nash-Sutcliffe efficiency was used for determining the adaptability of the model. Sensitivity analysis of scenarios for various slopes and management practices were also done. The 86.95% coefficient of determination and 0.81 Nash-Sutcliffe efficiency revealed the statistical acceptability of the SWAT model. Results also have showed that a substantial reduction in annual soil loss of up to 40 percent and 27 percent is achieved when minimal tillage and minimum tillage plus hedgerows, respectively are performed in contrast with traditional tillage practices. Highest yield was observed in the treatment minimum tillage plus hedgerows. The findings of the study can be used in the formation of policies and decision-making support mechanisms for the conservation and utilization of agricultural resources for improved and sustainable corn farming in the upland areas of Quirino, Philippines.

INTRODUCTION

Quirino Province in the Philippines is generally mountainous with more than two-thirds of its area having a slope of more than 18%. Its economy is basically agriculture-base with rice, corn and banana as the major crops produced by the community residents. An estimated area of about 68,093.66 hectares or 22.27% of the total land area of the province is devoted to different agricultural activities. From the total area, rice land covers 12,650 hectares while 20,537 hectares is devoted for corn production (Provincial Government of Quirino, 2020). The upland areas of the province are being utilized to respond to the inadequacy of lowlands and the necessity to produce more food as there are more people and animals that need to be fed (Bruun *et al.*, 2016).

Along with the increasing areas used for agricultural production in the upland is the occurrence of issues and problems associated with corn-based farming. In Quirino, Philippines, for example, most of the corn production areas are situated in sloping areas and majority of the farmers are engaged into single crop or mono-cropping system. In addition, systemic herbicides are excessively used during land preparation. This farming practice is very alarming considering that the areas subjected to corn production are mostly sloping and devoid of vegetation. Extreme weather events have aggravated the situation. The prolonged exposure of soil to heat and water has resulted to the occurrence of soil erosion and landslides in steep slopes especially during the rainy season, affecting not just the corn farmers but also lowland farming communities due to river siltation and flash-floods.

The conventional farming systems and the lack of soil and water management initiatives have led to a significant amount of soil loss each year in the upland areas due to erosion. According to Duan *et al.* (2016), as soil erosion rose from mild towards moderate to extreme, organic matter content is reduced by 15.29%, 18.00% and 27.37%, respectively. This corresponds to a decreased of average corn seed of 1.56 %, 29.18 %, and 35.03% for mild, moderate, and severely eroded sites, respectively compared to sites with no erosion. Van Loo *et al.* (2017) pointed out that soil erosion is caused by more of anthropogenic actions rather than by climate change. If the field is transformed to cropland or disturbed by human activities, there will higher the rate of erosion (Marin & Jamis, 2016). In the Philippines, upland cultivation is the primary source of soil erosion (Elauria *et al.*, 2017). According to ADB (2009), twenty-one percent of the country's area devoted to agriculture and 36 percent of land devoted to other purposes are under moderate or severe erosion. Deforestation and poor farming methods have destroyed two billion hectares of the world's arable land. Despite global advances in land resource management, unsustainable land use activities result in net cropland production losses measured at an average of 0.2 percent per year (IWMI, 2010). Not only does it cause agricultural land to go out of demand, but it also needs increased inputs and investments to sustain a high level of productivity. Without appropriate intervention, the soil is washed away when it rains and the land becomes unusable. This suggests that the issue of the erosion crisis is severe and a threat to global food security (Zhang *et al.*, 2020).

The ability to predict the amount of soil erosion can be valuable in understanding both the likelihood of soil loss and its effects (Borrelli *et al.*, 2017). This will also offer a catalyst to develop innovative and improved methods for analyzing, synthesizing and simplifying data that will provide us the opportunity to predict the effect of soil erosion on different landuses and management earlier before the implemention. In addition, predictive technology may be utilized to screen viable options and to remove those activities with the greatest unacceptable rate of erosion or to enable farmers to choose the most effective alternatives to avoid or control / reduce soil erosion.

Models have been an extremely valuable instrument for hydrological processes analysis and current anthropogenic influences effect on the hydrological system (Dwarakish & Ganasri, 2015). The Soil and Water Assessment Tool (SWAT) is a physically-dependent, distributed parameter model built to successfully predict runoff, erosion, sediment (Bouslihim *et al.*, 2016; Tyagi *et al.*, 2014; Ayana *et al.*, 2012; Ndomba & van Griensven, 2011); nutrient transport (Malunjkar *et al.*, 2020); stream flows (Teshome *et al.*, 2020; Bayazit *et al.*, 2019; Daramola *et al.*, 2019); land use change (Anaba *et al.*, 2017; Tadesse *et al.*, 2015); impacts of climate change to water resources (Abbasa *et al.*, 2016) and agricultural productivity (Mueller-Warrant *et al.*, 2019). However, despite promising results in many fields, most models are location-specific. It is therefore very important to perform the actual experiment in order to gauge the model's suitability for a particular field. The study assessed the efficiency and suitability of the SWAT model in upland corn production in Quirino, Philippines as there was no experiments conducted yet in the province.

MATERIALS AND METHODS

The Study Area

The study is conducted in San Manuel, Aglipay, Quirino, Philippines at 16023’28.7”N latitude and 121^{o}37’23.8”E longitude (Figure 1). The site has a steepness of 33%, precipitation ranging from less than 1,500 mm to more than 2,100 mm per year, mean annual temperature of 26.60^{o}C and elevation of 901-1100 m above mean sea level.

Figure 1. Site map of the sudy area

Erosion Plots and Experimental Treatments

Erosion plots were planted with corn and prepared using Randomized Complete Block Design (RCBD) with three treatments repeated twice. Treatments are: T1 (conventional tillage), T2 (minimum tillage) and T3 (minimum tillage with pigeon pea as hedgegrow) (Figure 2). The erosion plots are 22 meters long and 4 meters wide (Figure 3). At the end of each plot, 100-L capacity drums were used to collect runoff and sediments. The plots were framed on the side with plywood (hardiflex) to restrict soil movement and runoff of water and sediment to each plant. According to Paulin and Amplayo (2015), establishing soil erosion plots is an important technique for quantifying soil losses at field level.

After each rainfall occurrence, the collected run-off from each drum was properly stirred, from which 250 ml samples were taken using plastic bottles. Samples were stored for one day to allow soil particles to settle down. The water from each sample was drained and the soil particles were wrapped in foil paper and sundried for two hours to extract some of the water before being oven-dried at 105^{o}C for 72 hours. The weights of the oven-dried samples were taken and proportioned on the depth of runoff collected from each drum to determine the actual soil loss from each treatment.

The portable Automatic Weather Station (AWS) was used to record the amount of rainfall while the length of each rainfall was manually timed. The amount of erosion from experimental plots was estimated and compared to a given rainfall intensity.

Description and Validation of SWAT Model

SWAT is a graphical user interface program for the public domain. According to Gassman *et al.* (2007), SWAT model has become a globally accepted tool for modeling watershed processes in the various applications throughout this period. Physical-

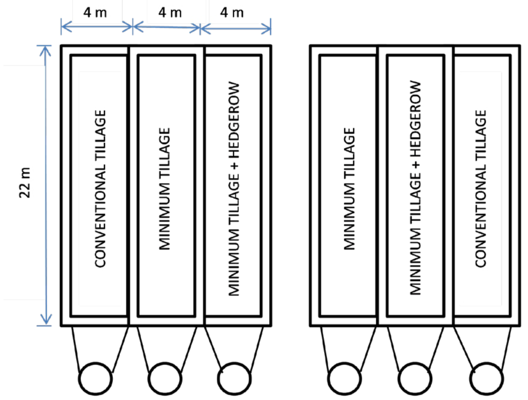

Figure 2. Layout of the erosion plots and experimental treatments

Figure 3. Actual picture while establishing the erosion plots

based continuous-event hydrological model built to forecast the effect of land management activities on water, agricultural chemical, and sediment yields over a long period of time in large, intricate watersheds with variable soils, management conditions, and land use. The SWAT model is limited in that it does not specifically allow spatial data to be used as input to the model. The data should be stored in a way that can be used by the model. Processing these data is time-consuming even with the help of GIS because of the huge quantity of model parameters needed to run SWAT.

Before the SWAT model was used, it was validated using the actual rainfall data of the experimental time and other input parameters of the model. Actual/measured rainfall data were collected utilizing the AWS mounted in the study area. Individual storms were recorded, analyzed and used as inputs in the model from the start to the end of the study.

Building of Input Data

The Aglipay watershed was delineated by combining potential sub-basins that drain into a common point to create the largest potential catch basin that captures the experimental region. The land use factor map was generated on the basis of updated land cover taken from the PhilGIS website, which was then reclassified to meet the model requirement. Figure 4 indicates that the majority of the region is dedicated to agricultural production, while only a small area is a forest area.

The soil map was created using a modified soil shape file downloaded from the PhilGIS website, which was reclassified and appended to create new soil characteristics in the current SWAT database. The predominant soil type in the area is Rugao clay (Figure 5).

The digital slope classes (Figure 6) were created from SRTM DEM 2013-vs (2011) with spatial resolution mosaic of 90 m for the entire area. Weather files have been

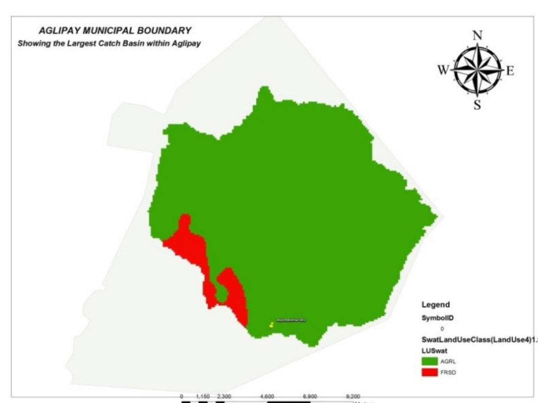

Figure 4. Landuse map of the study area

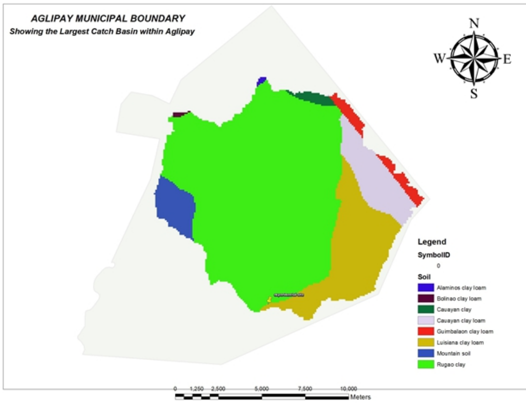

Figure 5. Soil map of the study area

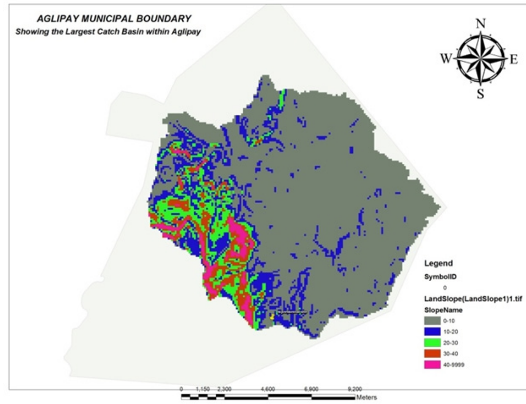

Figure 6. Slope map of the study area

prepared which have made it compliant with the specifications of the SWAT model.

Data Analysis

The simulation results were compared with the measured soil loss recorded in the experimental plots. The validation method involved the use of the coefficient of determination (R2) to evaluate the degree of fitness between the measured and simulated amount of soil loss. Model performance was also evaluated using the model efficiency developed by Nash and Sutcliffe (1970) as follows:

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean}\right)^2} \right] \qquad \text{Eq. 1}$$

Where NSE is the efficiency of the model, Yiobs and Yisim are the measured and predicted values, and (Ymean) is the mean of the measured values. NSE value of 1.0 shows perfect prediction, while the negative value indicates that the prediction is less consistent than the mean of the sample.

On the other hand, sensitivity analysis is performed to explore the unknown relationship between input and output in mathematical models (Liu & Yan, 2019). In this study, sensitivity analysis was done to determine the influence of rainfall and management practices on the rate of annual soil loss on varying slopes.

RESULTS AND DISCUSSION

The relation between measured and simulated annual soil losses has a high coefficient of determination of 0.8695 (Figure 7). This means that 86.95 percent of differences in soil loss in the area can be explained by the SWAT model developed.

On the other hand, the Nash-Sutcliffe efficiency value of 0.81 suggests that the model correctly estimated the annual soil loss in the study area. The result is supported by the outputs of Ali *et al.* (2020) and Swami and Kulkarni (2016) proving the ability of SWAT model to accurately predict soil loss. This means that the SWAT model can reliably estimate the real soil loss in the upland corn areas of Quirino, Philippines.

Application for Upland Agriculture

Sensitivity analysis was carried out using the model to predict soil losses under various management activities at different slopes (Figure 8). The figure demonstrated the ability of the model to simulate the rate of soil loss when upland farming takes place on a range of slopes and various management practices. The graph also showed that, in the farming practice (conventional farming), the rate of soil loss was more than 140 tha-1yr-1 at a 40 percent slope at a length of 22 m. However, the practice of minimum tillage and minimum tillage plus pigeon pea as hedgerow minimized soil losses by 27 percent and 40 percent, respectively. The result is similar to the study of Melaku *et al.* (2018) which revealed that managing soil and water using structures substantially reduced soil losses by as much as 25–38%. The results only proved the significance of using conservation structures to manage soil and water. In the study of Wolka *et al.* (2018), cross slope minimized surface runoff by 50%. Moreover, Adimassu *et al.* (2017) also attested that most activities on agronomic soil and water management minimized runoff and soil losses. Bugonovic *et al.* (2018) found out that higher soil loss is obtained in conventional tillage than in no tillage. The result is also in consonance with the result of Paulin and Amplayo (2015) that higher soil loss was derived from conventional tillage than in reduced tillage.

The simulation results of soil loss at various management practices and on different slopes (Table 1) showed that in a severe agricultural scenario of 40 percent and 22 m of slope length, the estimated annual soil loss was 144,723 tha^{-1}yr^{-1}; however, the practiced of minimal tillage + pigeon pea as hedgerow substantially decreased the soil loss to 90,737 tha-1yr-1. These soil loss figured may be due to the interrupting effect of the hedgerow on the surface runoff velocity by shortening the length of the slope and thereby reducing the erosive potential of the surface runoff. According to Nepf (2012), vegetation is delaying the erosive energy from overland flow by disrupting the flow of water across various obstacles. Moreover, the planting of side crops between the main crops will mitigate this impact and also increase yields (Islami *et al.*, 2011). The map of soil loss formed for upland corn areas along the Aglipay, Quirino watershed is shown in Figure 9.

Table 2 displayed the average yield of the plot of corn at various management activities. Average mean plot yield obtained from minimum tillage plus pigeon pea as hedgerows was significantly higher over treatments minimum tillage and conventional tillage. The results confirmed the study of Adimassu *et al.* (2017) that the use of soil and water conservation activities had increased crop yield. This also conforms to the study of Bugonovic *et al.* (2018) who found that higher crop yields obtained are higher in no tillage than in conventional tillage.

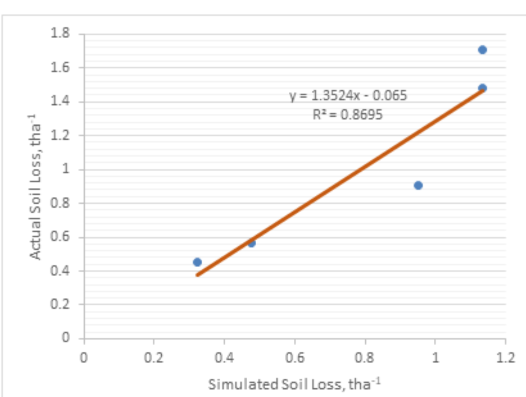

Figure 7. Comparison of actual and simulated soil loss

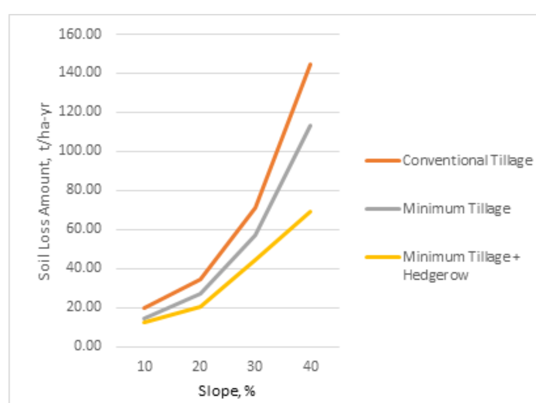

Figure 8. Projected soil loss (t ha^{-1}yr^{-1}) under different management practices and slopes

Table 1. Soil loss at different management practices and various slopes, t $ha^{-1}yr^{-1}$

Slope	Treatment		
	Conventional Tillage	Minimum Tillage	Minimum Tillage + Hedgrow
10	19.794	14.426	12.312
20	34.327	27.374	20.642
30	71.034	57.027	44.229
40	144.723	115.336	90.737

Table 2. Mean plot yield of corn under different management practices

Treatment	Mean Plot Yield (kg)	F-value	p-value
Conventional tillage	37.25[b]		
Minimum tillage	37.90[b]	43.00*	.0227
Minimum tillage plus hedgerow	41.80[a]		

CONCLUSION AND RECOMMENDATION

The practiced of minimal tillage plus pigeon pea as hedgerow gave the highest yield and greatly decreased the amount of soil losses. This proved the capacity of pigeon pea as hedgerow to limit soil losses under upland corn cultivation. The results also demonstrated the good performance and suitability of the SWAT model in estimating soil loss. The SWAT model can therefore be used for agricultural planning in the upland areas of Quirino, Philippines, for sustainable corn farming.

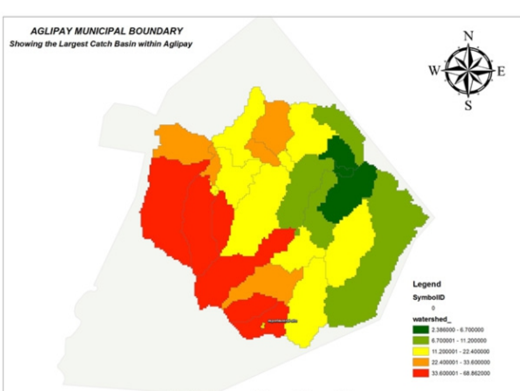

Figure 9. Developed soil loss map of Aglipay watershed

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