OPTIMIZED SUGARCANE MODELLING FOR SUGARCANE PRODUCTION IN THE NORTHEAST OF THAILAND

(東北タイにおけるサトウキビ生産についての最適モデル化)

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ABSTRACT

Agricultural systems are vulnerable to environmental changes, especially climate changes. These changes directly affected on crop production, in both spatially and temporally. To reduce these effects, alternative strategies of crop management must be used. Crop models are needed to use on the evaluation of crop production under changing climatic circumstances. It requires at least 2 groups of data input for the crop model. One group is considered conservative, in that the parameters should remain basically constant under different growing conditions and water regimes. The other group encompasses parameters that depend on location, crop cultivar, and management practices, and must be specified by the users. So the model needs local calibration and validation before being applied. The first study, two crop models were calibrated and validated for estimating sugarcane yields in North-eastern Thailand. On the calibration, parameters of both models were optimized and gave realistic predictions. On the validation, optimizing water demand gave good results in DNDC95, but overestimated yields in DSSAT-CANEGRO. When water balance specific to sugarcane were optimized, DSSAT-CANEGRO also simulated yields well. After that the CANEGRO model were selected to simulate the sugarcane yield of existing cultivation areas under both rainfed and irrigated conditions for identifying the highest priority areas for irrigation development. Then the benefit of the irrigation development was calculated using the simulation results and the actual data of groundwater well capacities, sugarcane prices, and irrigation development and running costs. And then the results of the benefit were analysed using ABC analysis and the decision tree method. The decision tree analysis confirmed that well capacity most influenced the benefit. Rainfed condition areas where rainfall was higher and had high cane yields, the benefit from irrigation was small. A notable finding showed that low soil available water content resulted in low yields in both rainfed and irrigated conditions. While high available water content resulted in high yields under rainfed conditions. Therefore, both low and high available water content resulted in low benefit from irrigation development. However, using the crop models, for the accuracy simulation in some locations are limited by the input data, especially weather data. In this study, the simple models were also developed for estimating sugarcane yield and evapotranspiration with minimum input data but giving high accuracy. The "*Cal Cane*" is the application for the estimation of sugarcane yield cultivar Khon Kaen 3 and LK92-11 with now available for downloading on the google play store. The technique for getting the good data using for the application have discussed in general discussion. The simple model for estimating evapotranspiration and the change of soil moisture in sugarcane fields also can be used with only the solar radiation and precipitation for data the input that available in all sub districts around Thailand. Both simple models were better used for the particular area. In conclusion, the crop parameters for sugarcane cultivar Khon Kaen 3, LK92-11, and 02-2-058 are available to be used for the CANEGRO model and DNDC model and gave the good estimation of sugarcane yield in both irrigated and rainfed condition. In the case of limitation of local input data, the simple models can estimate sugarcane yield, evapotranspiration, and soil moisture changes in each particular area.

Key words: Sugarcane, CANEGRO, DNDC, Simple model

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A	area
AI	agreement index
APFMX	maximum fraction of dry mass increments that can be allocated to aerial dry mass
as	available water capacity
AUIC	automatic irrigation condition
AWC	available water content
BD	Bulk density
BF	benefit
^oC	degree Celsius
CHTA	canopy high at harvest
CHUPIBASE	thermal time (base TTBASEEM) from emergence to start of stalk growth
cm	centimeter
cm/h	centimeter per hour
CS	cost
D	stalk circumference
D_p	depth percolation
DAP	day after planting
DNDC	De-Nitrification De- Composition
DSSAT	Decision Support System for Agrotechnology Transfer
ea	actual vapor pressure
es	the vapor pressure of the air at saturation
ET	evapotranspiration
ET_o	reference evapotranspiration
EORATIO	ratio of potential evapotranspiration from fully canopied unstressed sugarcane canopy to grass reference evapotranspiration
FC	water holding at field capacity
FC	fixed cost
G	soil heat flux
g/cm^3	gram per square centimeter
$g\ m^{-1}$	g per square meter
GP	yield gap
Grain CN	ratio of C/N for grain
H	stalk high
HIAM	harvest index [sucrose/ (stalk dry mass + sucrose)]
IC	income
Inf	infiltration rate
K	potassium
K_{FC}	coefficient for fixed cost
K_{VC}	coefficient for variable cost
KK3	sugarcane cultivar Khon Kaen 3
K-Sat	saturated hydraulic conductivity
K_s	allowing of soil for evaporation

LIST OF ABBREVIATIONS (Cont.)

kg C/ha/y	kilogram carbon per hectare per year
L_{ro}	row spacing
L#SM	green leaf number at harvest
LAIH	leaf area index at harvest
Leaf CN	ratio of C/N for leaf
LFMAX	maximum number of green leaves a healthy, adequately watered plant will have after it is old enough to lose some leaves.
LG_AMBASE	aerial mass (fresh mass of stalk, leaf, and water attached to them) at which lodging starts
ln	long wave
m	meter
m^2	square meter
$m^3\ hr^{-1}$	cubic meter per hour
MAX_POP	maximum tiller population
MJ $m^{-1}d^{-1}$	megajoule per square meter per day
mm	millimeter
mm d^{-1}	millimeter per day
mm yr^{-1}	millimeter per year
MWH	maximum water holding
MXLFAREA	maximum leaf area assigned to all leaves above leaf number MXLFARNO
MXLFARNO	leaf number above which leaf area is limited to MXLFAREA
N	nitrogen
nRMSE	normalize root mean square error
P	phosphorus
P	precipitation
P_s	price
PARCEmax	maximum (no stress) radiation conversion efficiency expressed as assimilate produced before respiration, per unit PAR
PI1	phyllochron interval 1 (for leaf numbers below PSWITCH)
PI2	phyllochron interval 2 (for leaf numbers above PSWITCH)
PM-56	Penman-Monteith (FAO-56) equation
POPTT16	stalk population at/after 1600 ^oC.d
PT	Priestley and Taylor equation
PSWITCH	leaf number at which the phyllochron changes
PWP	water holding at permanent wilting point
R^2	coefficient of determination
R_f	rainfall
R_n	net radiation
R_o	run off
RFC	rainfed condition
RMSE	root mean square error
Root CN	ratio of C/N for root
RWUEP1	soil water supply/potential evaporation ratio threshold below which evaporation and photosynthesis are limited.

LIST OF ABBREVIATIONS (Cont.)

RWUEP2	soil water supply/potential evaporation ratio threshold below which expansive growth is limited.
RWUMX	maximum root water uptake per unit length of root
S	solar radiation
S_{10}	stalk number in the row with 10 m long
S_{no}	stalk number peer rai
S#AH	stalk population at harvest
SD	standard deviation
SDW	stalk dry weight
SE	simple equation
SG	soil group
SMFMH	millable cane fresh weight at harvest
Stem CN	ratio of C/N for stem
STKH	stalk dry mass at harvest
STKPFMAX	fraction of daily aerial dry mass increments partitioned to stalk at high temperatures in a mature crop
SUCA	Sucrose partitioning parameter: maximum sucrose content in stalk base
SUCH	sucrose dry mass at harvest
t	ton
T	air temperature
t ha^{-1}	ton per hectare
T_I	hour of pump operation
Tbase	base temperature for canopy development
TBFT	sucrose partitioning: temperature at which partitioning of unstressed stalk mass increments to sucrose is 50% of the maximum value
TDW	total dry weight
Tthalfo	thermal time to half canopy
TTPLNTEM	thermal time to emergence for a plant crop
TTPOPGROWTH	thermal time to peak tiller population
TTRATNEM	thermal time to emergence for a ratoon crop
VC	wind speed
u_2	variable cost
W	stalk weight
W_{kk}	stalk weight for sugarcane cultivar Khon Kaen 3
W_{lk}	stalk weight for sugarcane cultivar LK92-11
WC	well capacity
WS	weather station
Y	yield
Y_I	simulated yield under irrigation condition
Y_{kk}	sugarcane yield for cultivar Khon Kaen 3
Y_{lk}	sugarcane yield for cultivar LK92-11
Y_R	simulated yield under rainfed condition
z	soil depth

Chapter I

General Introduction

Thailand is an agricultural country. The economics of the country as a whole depends on crop production. In 2011-2013, Thailand had an agricultural area occupied about 46 percent of the country (OAE, 2015). Sugarcane is important economic crop of Thailand. Besides using as raw material for sugarcane and sugar industries, it plays an important role as raw materials for producing ethanol. Each year, there are 1.5-1.7 million hectares for planting sugarcane, and produce 95-100 million tons of sugarcane per a year. (OCSB, 2015). Presently there are 51 sugar mills with total capacity of producing sugar more than 100 million tons per year. In addition, sugar industry provided jobs for more than 60,000 people, and the export worth of more than 88,000 million baht. Although, Thailand is the fourth biggest sugarcane producing country and the second biggest sugar exporter in the world, however the area of plantation is varying between the year. Some year was decreased due to drought as well as the epidemic disease and insects in some areas, especially sugarcane borer and the area of plantation is rebound back due to in incentive from higher price. The increases of the areas can come from cassava planting area which is having problems with aphids, and other from upper paddy areas that cannot grow rice because of drought.

The Northeast of Thailand is a major crop production region of the country. Crop production area in 2011-2013 is around 10.2 million hectares, or 60 percent of the whole agricultural area of the country. This comprises 0.76 million hectares, or 44 percent of sugarcane plantation and can produce 51 million tons of sugarcane. In 2010-2015 the overall area of crop production is almost changed with the tendency to increase, the area for planting each crop can vary, especially for the areas of sugarcane and cassava plantation. Change in the proportion allocated to each crops depends on price of the input, price of the crop, and environment and natural disaster. For the large area, crop production must have effect by environmental variability. Previous study of the impact of climate change effect on rice, sugarcane, cassava and maize (Boonpradub *et al.,* 2009) indicated that production of these crops in northeast Thailand would be most affected.

Agricultural systems are vulnerable to environmental change, especially climate change. These changes directly affected crop production, both spatially and temporally. In Thailand, Boonpradub *et al.,* (2009) investigated the impact of climate change on sugarcane production using DSSAT crop model linked with weather data from 2000-2100 obtained from ECHAM4-PRECIS climate model. The results showed that the long term yield of sugarcane on average of the whole country was not substantially changed by the climate change projections. The most notable impact of climate change was on temporal and spatial variability of yield that could increase by 23 percent. The most pronounced impact was in the North East region. To reduce these effects new management strategies must be identified. Such management strategies under climate change needs to be evaluated using crop models (Jones *et al*., 2003) that also include effects of the soil water balance (Gassman *et al.,* 2007).

Dynamic crop simulation models are now advanced that they can be used as a multipurpose tool for various applications in agricultural research and policy formulation. Process-based crop growth model, such as the CANEGRO model (Singels and Bezuidenhout, 2002) in the Decision Support System for Agrotechnology Transfer (DSSAT) program, can simulate sugarcane growth, development and yield for specific cultivars base on the effect of weather, soil characteristics and sugarcane management practices (Jones *et al.,* 2003). The other one is the Denitrification-Decomposition (DNDC) model (Zhang *et.al.,* 2002). This model is a process-oriented computer simulation model of carbon and nitrogen biogeochemistry in agroecosystem. In crops production, several applications of crop simulation models have been evaluated, including simulated yield and profitability of crops (Saseendran *et al.,* 2013), the impacts of film mulching on crop yield (Han *et al.,* 2014), growth and development of sugarcane under high input condition (Muchow *et al.,* 1996; Robertson *et al.,* 1996), the effect of climate change to crop production (Boonpradub *et al.,* 2009; Biggs *et al.,* 2013; Carvalho *et al.,* 2015) and the strategies for water management (O'Brien *et al.*, 2001; Singels *et al*., 2010).

Many crop models, including the CANEGRO model and DNDC model use the concept of cultivar coefficients to characterize genotypes or cultivars (Hunt *et al*., 1993; Ritchie, 1993; Jame and Cutforth, 1996; Boote *et al*., 1998, 2003). The cultivar coefficients or cultivar–specific traits are crop characters that define the development, vegetative growth and reproductive growth of individual genotypes (Hunt *et al*., 1993; Boote *et al*., 2003). They summarize quantitatively how a particular genotype responds to environmental factors.

However, if the genotypes used are new local cultivars that have not been used previously with the crop simulation model, one first has to determine the cultivar coefficients and then evaluate/re–confirm them with independent data.

The cultivar coefficients are normally estimated based on sampling data from detailed field experiments conducted under optimum conditions for plant growth and development, avoiding drought, nutrient and other stresses (Hunt and Boote, 1998). Typically, data of each cultivar needs to be sampled several times throughout its life cycle on field experiments conducted over several planting dates at the same location or for the same planting date across multiple locations (Hoogenboom *et al*., 1999).

For the model, if user have the correct of input data such as crop coefficient, soil properties, weather condition and crop management practice they will get the good results. In practice, there are limitation of the input data especially weather data so for particular area the results from simulation were not accuracy. Therefore, crop model normally uses to simulates yield and yield response to environmental change in the large area for making the policy but for specific area, the method to evaluate yield need to be developed.

The goal of this research was to develop the new cultivar coefficients of sugarcane so that the CANEGRO model in the DSSAT V.4.5 and DNDC model can be used to assist with the sugarcane research especially the variability of environments and to develop the simple model for estimating sugarcane yield and evapotranspiration for specific area with limitation of meteorological data for input. The objectives were to (i) to optimized sugarcane parameters for use with the CANEGRO model and DNDC model, (ii) using the model to simulated yields and profitability of sugarcane under environmental variability to provide the best return from irrigation development, (iii) to develop the simple model for estimating sugarcane yield and (iv) to develop the simple model for estimating evapotranspiration and changes of soil moisture in sugarcane fields.

CHAPTER II

Literature Review

Sugarcane Production

Sugarcane (*Saccharum spp*.) is an important food crop, bioenergy source and significant component of the economy of many tropical and sub-tropical countries, including Thailand. In the production year 2010/2011, 2011/2012 and 2012/2013, the area for planting sugarcane were 1.34, 1.44 and 1.52 million hectares (OCSB, 2011; 2012; 2013). The area was sudden increasing from the past with the tendency to increase due to the increase of sugar mills and the policy of the Government which changing the paddy field where not suitable for rice production to sugarcane. In overall, despite the area for planting sugarcane and sugar yield are increasing but the yield per area is not increased. The average of sugarcane in 2013 was 73.7 ton per hectare. It is very low when compare with the others country such as Australia that equal to 76.9 ton per hectare (FAO, 2012). In some area can produce more than 93.7 ton per hectare of sugarcane, however there is high variability of sugarcane yield because of high environmental variability and different response of sugarcane to different environment.

Sugarcane Anatomy and Morphology

Sugarcane is the perennial crop with the harvesting age of 12-15 month. Rae *et al*., (2014) were summarized the anatomy and morphology of sugarcane as underpin the specialized ability of plant to accumulate large amounts of sucrose. As in other members of the family Poaceae, the aboveground part of the plant comprises a series of internodes with attached blade-shaped leaves, generated by an apical vegetative meristem. The internodes contain the cellular structures that are specialized for the transfer and storage of sucrose. When flowering is induced, the developmental patterning of the apical meristem alters to produce a large branched rachis carrying numerous bisexual florets. Root are produced either as seedling roots following the germination of seed or as adventitious root originating from the note of the stalk.

The sugarcane root system. The function of root system is twofold: first, it enables the intake of water and nutrients from the soil; and second, it serves to anchor the plant (Smith *et al*., 2005). Preecha *et al*., (2010) found that the both of commercial cane and hybrid sugarcane cane can penetrate to depth exceed 1.5 m and most of root were found at 20-30 cm depth from the surface. Kobkiat *et al*., (2008) reported that type of sugarcane can have divided by colour to 3 types. First, the white root is the active root, second, the brown root is non-active root and the last one, the black root is the root that going to compose. Most of root were found in the brown root (46-73%) after that black root (28.8-50%) and a little of white root around 1-7%.

The stalk: the stalk consists of segments called joints. Each joint is made up of a node and an internode. The node is where the leaf attaches to the stalk and where the buds and root primordia are found. A leaf scar can be found at the node when the leaf drops off the plant. The length and diameter of the joints vary widely with different varieties and growing conditions. In general, however, the joints at the base are short and internodal length gradually increases.

The lateral bud: A single lateral bud generally is located of each internode, arranged, like the leaves on alternating sides in successive internodes. Each bud comprises the lateral meristem covered by leaf3like bud scales that protect the meristem from desiccation, physical damage, and from pathogen attack. Under normal growth, each node can fine one of bud although the bud and leaves are alternate, they are not exactly opposite (180^{o} around the stalk from each other).

The leaf: The major sections of the mature sugarcane leaf are the blade, the sheath, and the articulated joint between them, called the collar. The mature leaf displays parallel venation in both the blade and sheath, which is the characteristic of monocots. The leaves are usually attached alternately to the nodes, thus forming two ranks on opposite sides. The mature sugarcane plant as an average total upper leaf surface of about 0.5 square meter and the number of green leaves per stalk is around ten, depending on variety and growing conditions.

The Inflorescence: When a sugarcane plant has reached a relatively mature stage of development, its growing point may, under certain photoperiod and soil moisture conditions, change from the vegetative to reproductive stage. This means the growing point ceases forming leaf primordia and starts the production of an inflorescence. The inflorescence, ortassle, of sugarcane is an open-branched panicle. Each tassle consists of several thousand tiny flowers, each capable of producing one seed. The seeds are extremely small and weigh approximately 250 per g. For commercial sugarcane production, inflorescence development is of economic importance. Generally, a day length close to 12.5 hours and night temperatures between 20 and 25 C^{o} will induce floral initiation. Temperatures that are too low and/or water stress inhibit inflorescence development.

Sugarcane growth and development.

Bonnett (2014) reviewed that there are ten stages of phenology to describe the rate of sugarcane development are primarily driven by temperature. The other factors, such as cultivar, have been shown to influence the rate of development of a process. The Biologische Bundesanstalt, Bundessortenamt and Chemical Industry (BBCH) scale is the basis of new guides for a range of plants including sugarcane. To be consistent with the BBCH scale, the stages are labelled from 0-9 following

Stage 0: germination, sprouting. The BBCH scale is sufficiently broad to accommodate the production of new shoots from different botanical origins. In sugarcane, shoots can arise from true seed (germination) or from vegetative buds (sprouting). In sugarcane production systems crops are established not from true seed but from the sprouting of vegetative bud ether from planted stalk pieces (plant crop) or from the part of the plant (stool) remaining in the ground after harvesting.

Stage 1: leaf development of the main shoot. Leaf emerging from a shoot originating from a true seed are successively longer until a relatively constant size is reached. This differs in the beginning on shoots emerging from a vegetative bud where several of the initial leafs have only a very vestigial blade or maybe even none at all. Consequently, some authors define the first emerged leaf as one with a blade over specific size, e.g. with a leaf lamina length 0f more than 0.02 m.

Stage 2: tillering and side shoots. Tillering is the process of side shoots emerging from the axillary buds of an existing stalk to form additional stalk. Tillers arise at the base of the plant from the buds on internode. Because optimal yield depends on establishing sufficient stalk density, tillering can be a major yield increasing process and differs between cultivars.

Stage 3: stem elongation. Although internode tissue is produced above each node, not all internodes have expanded tissue. Stem elongation occurs when the intercalary meristem produces cells that subsequently expand. An internode starts its expansion by the time the leaf attached at it base has fully expanded. Elongation is completed at the individual cell and internode level by the time the four next youngest leaves are fully expanded.

Stage 4: development of harvestable vegetative plant parts or vegetatively propagated organs. For sugarcane, the stalk is the harvested organ. Structural development of the stalk occurs during stem elongation. However, the accumulation of sucrose occurs coincidentally in the lower internodes while the internodes at the top of the stalk are expanding.

Stage 5: emergence of inflorescence. The external signs that flowering is about to occur are an increased length of leaf sheaths and internode lengths making the blades further apart and with a reduce size of the leaf blade. However, changes occur at the apex long before the altered morphology is visible. Several months are involved between the start of the induction process and emergence of the inflorescence.

Stage 6: flowering. The sugarcane inflorescence is a characteristic grass panicle having branches bearing paired flowers call spikelets. Individual spikelets start to flower at the distal ends of the top branches of the inflorescence and proceed basipetally in a wave down the inflorescence. Both stigma and anthers protrude from the spikelet during the night and the anthers dehisce as the humidity drops shortly after dawn. Production of fertile pollen is reduced at temperature below 21 ^{o}C, the temperature which can limit production of viable seed in many areas where sugarcane is grown.

Stage 7: development of fruit. There is no development of a fleshy fruit around sugarcane seed. The mature fuzz (seeds and adhered parts of the inflorescence) consists of the caryopsis, glumes, callus hairs, and remaining anthers and stigma.

Stage 8: ripening of seed. When the spikelets are mature, they start to dehisce from the branches of the inflorescence beginning at the tips. The spikelets have a series of hairs at the base. Seed developed most rapidly in the first 10 days after pollination. Seeds reached their maximum width and length 20 and 30 days after pollination, respectively. Ability of the seed to geminate increased from 15 to 30 days after pollination.

Stage 9: senescence and dormancy. Sugarcane is a perennial crop with no real period of whole plant dormancy. In natural settings individual stalk may senesce but removal of the whole aboveground biomass would be rare. Individual leaves senesce throughout the life of the sugarcane crop and their rate of senescence can be accelerated through moisture stress and lack of nitrogen.

Sugarcane grows comparatively slowly in dry mass during both the early and the late part of its growth period. The slow growth during the late part of the growth period is associated with a decrease in rate of stem elongation and an increase in the mass of non-structural material in the stem. Rate of respiration (total dark, and maintenance) is lower at normal temperature than other warm-climate grasses. The slow stem elongation during the late part of the growth period might be indicative of a decrease in rate of respiration, reflecting rate of metabolism, hence of synthesis of structural dry mass, to the benefit of storage of sucrose (Allison *et al*., 2007) and the growth rate was directly affected by leaf area (Inman-Bamber *et al*., (2005). However, Lingle (1997) and Allison and Pammenter (2002) found that although growth of sugarcane was slowly but don't effect to the canopy when harvesting. The study from Keating *et al*., (1999) reported that when leaf area index is more than 5 they are not effect to sugarcane growth even through there are many factors effected them. Muchow *et al*., (1994) found that the maximum biomass production was 72 t $ha^{-1}$and the maximum fresh cane yield was 201 t ha^{-1}. However, these maximum yields were attained up to 4 months before the final sampling and suggested that in the future research should examine the wider applicability of this early yield plateau, and focus on the factors responsible for the early cessation in yield accumulation. Singels *et al*., (2005) suggested that there is scope for improving yields but that the optimisation process should include all components of the sucrose production process in sugarcane, including radiation capture, net photosynthetic efficiency and stalk partitioning. Sufficient understanding of the interactions between these components is lacking. There is a need for models to distinguish between photosynthesis and respiration and the strong dependence of both on temperature should be taken into account.

For sugarcane production, they have the long period since planting to harvesting. It is more than ten months. In this period, sugarcane production is constrained by many stresses. The four abiotic stresses are water deficit or exceed, temperature variability, soil properties (mineral nutrients salinity, sodicity, compaction), and the amount of solar radiation are major. In addition to this environmental stress, there is now increasing evidence that sugarcane cultivation could be affected by global climate change (De Souza *et al*., 2008).

Response of sugarcane to water deficit

Depending on the agro-ecological, cultivation practice, and crop cycle, the annual water requirement of sugarcane varies from about 1000 to 2900 mm (Robertson and Muchow, 1997). The estimated water use efficiency (WUE) in Hawaii, Australia, and South Africa, varies between 4.8 and 27 t cane per 100 mm of irrigation. The crop canopy average vapor pressure deficit and water application appear to be a major influence on the WUE of sugarcane. For instance, irrigation for supply only 9% of the total water input made a substantially improvement in WUE through increased canopy development and increased efficiency in use of rainfall (Inman-Bamber *et al*., 2012). In addition, water stress effect to decrease stalk elongation and causes low in yield (Hsiao, 1973). Water stress also resulted in marked changes in dry matter partitioning (Inman-Bamber, 2004). On the other hand, water deficit imposed when the canopy was well-established (leaf area index >2) had more deleterious impact on final yield of total biomass, stalk biomass, and stalk sucrose. Reductions in millable stalk biomass, could be solely explained by reductions in total biomass (Robertson *et al*., 1999). While Batchelor *et al*., (1992) found that water deficit is not decreased the leaf number but more effect on leaf canopy and different response depend on cultivars (Smit and Singels, 2006). However, response of sugarcane to water deficit depend on crop age, environments, soil type, and cultivars (Wiedenfeld, 1995; Moroizumi *et al*.,2009; Muchow *et al*.,1994; Singels *et al*.,2005). The application of water for maximum growth, produces high fresh weight of cane yield, but reduce sugar content. Therefore, reducing the amount of water applied to only 85% of that required for maximum growth still give the same amount of sugar as that produced under full irrigation.

Response of sugarcane to temperature stress

Sugarcane is sensitive to chilling, i.e., low temperature that inhibit growth or inflict injury (10^{o}C-15^{o}C) but not low enough to be lethal as occurs during freezing. Generally, tropical and subtropical species when grown in warmer climate (25^{o}C-35^{o}C) are more susceptible to chilling injury than are temperate species. Both chilling and freezing affect all aspects of plant growth and development (Thomashow, 2010). Sugarcane grows optimally at 35^{o}C (Grantz *et al*., 1987). Temperature in many sugarcane growing region often fall below 20^{o}C, at which point growth is severely reduced (Ebrahim *et al*., 1998). Foliar discoloration, leisons, and vitrification are common symptoms of chilling injury. The most obvious effect of chilling in sugarcane is a transverse bar of chlorotic mesophyll on leaf blade. Chlorotic banding occurs when night air temperature falls to about 5^{o}C, which arrests chloroplast development, but daytime is warm enough for leaf expansive growth. Frost damage occurs when the ambient air temperature reaches -3.5^{o}C and the shoot apical meristem experiences about -2.0^{o}C.

Low temperature stress has been studied in relation to bud sprouting, tillering, photosynthesis, stalk growth, dry matter partitioning, and juice quality. Bud sprouting from setts and ratoon stubble is significantly delayed and reduced at lower temperatures and poor sprouting was correlated with reduced availability of sugar and lower acid invertase activity (Jain *et al*., 2007). Tiller growth and development are also sensitive to chilling and freezing (Kanwar and Kaur, 1978; Jain *et al*., 2007). Sugarcane plant grown at 15^{o}C for 10 months in the greenhouse grew very slowly, with fewer and smaller leaf and shorter internodes than those grown at 27^{o}C (Ebrahim *et al*., 1998). The minimum temperature for sugarcane growth and development or base temperature were shown on many studies. Ritchie *et al*., (1986) reported that the base temperature was 9 ^{o}C and optimum temperature was ranged from 32-45 ^{o}C. and this value used for the APSIM model. The base temperature for growth and development of sugarcane are vary by crop stage such as Inman-Bamber (1994) reported that base temperature for sugarcane is 8 ^{o}C while Robertson *et al*., (1998) reported that 15 ^{o}C.

Response of sugarcane to soil mineral nutrition stress

Mineral nutrition of sugarcane is the one factor that directly effect to growth and development. Response of sugarcane to nitrogen depend on available water in the soil and distribution of the rain fall during the crop growth period. Sugarcane was highest respond to nitrogen followed by potassium and phosphorus, respectively. So nitrogen is an essential nutrient for food and bioenergy production that can be highly pollutant to water bodies and the atmosphere if not properly used in agriculture (Liu *et al*., 2010). Sugarcane extracts 100 to 300 kg ha^{-1}N from soil to produce 100 Mg ha^{-1} of millable stalks in each cycle (Fortes *et al*., 2013). Significant yield responses to N fertilization have been reported, as well as possible residual effects of repeated N applications on subsequent sugarcane cycles (Wiedenfeld, 1998; 2000; Dourado-Neto *et al*., 2010). Mineral N can also enhance root growth within the crop residues of unburned harvested sugarcane and reduce the C:N ratio of those residues, building a nutritional N reserve on soil organic matter and in crop underground parts (Fortes *et al*., 2011).So green cane management or harvesting without burning is a current practice in producing countries worldwide used to reduce environmental impacts and to prevent respiratory illnesses related to airborne ash particles in surrounding neighbourhoods (Cançado *et al*., 2006). This cropping method preserves 5 to 20 Mg ha^{-1} of crop residues (dry leaves, tops, and previous crop ratoons) on soil surface, which comprise an important source of carbon and nutrients that can potentially increase sugarcane lifespan and yields due to the reduction of N losses throughout the soil-plant system (Hemwong *et al*., 2009). However, residues from green harvested sugarcane also decrease the rate of soil organic matter oxidation and soil acidification, enhance erosion control, and increase soil biological activity and water infiltration(Dourado-Neto *et al*., 2010).Global models suggest that recovery rates of the overall N applied in agriculture are around 55%, being 35% in harvested products and 20% in crop residues; but the latter are still underestimated in nutrient recycling in developing countries (Liu *et al*., 2010). Therefore, N fertilization management is a challenge beyond the replacement of crop requirements and must take into account the agronomic and environmental impacts of mineral fertilizers and crop residues on the agroecosystems, as well as in C, N, and other nutrient balances in soil-plant-atmosphere (Dourado-Neto *et al*., 2010; Fortes *et al*., 2011; Thorburn *et al*., 2011).

Climate change affected to agricultural system

Climate change has the potential to affect the productivity of agricultural enterprises with the ability to adapt varying among farm system (Lieffering *et al*., 2016). Development of effective strategies whereby agriculture can adapt to climate change over the coming decades requires farmers, agribusiness, crop scientist, and policy makers to understand potential climate risks posed by climate change (Howden *et al*., 2007). The increase in abnormally high or low temperature, change of precipitation and climate pattern, extreme weather event, and unsustainable irrigation in the uplands can give rise to drought and floods and affect the security of water resources, crop productivity, and crop yields (Mo *et al*., 2013; Saadi *et al*., 2015). In recent decades, climate change effects are becoming evident worldwide, for example, Valverde *et al*., (2015a) found that, in the Guadiana river basin (Portugal), the climate change effected to the rainfed crop yields will decrease in the future period 1 (2011-

2040) and higher losses in the future period 2 (2041-2070) and they also found that increasing in crop irrigation requirement on irrigated agriculture (Valverde *et al*., 2015b). Chen *et al*., (2016) found that there are nonlinear and inverted U shaped relationships between crop yields and weather variable and the global warming has caused an economic loss of about $820 million to China's corn and soybean sector. In addition, they found that corn and soybean yields are projected to decline by 3-12% and 7-19%, respectively, by 2100.In Thailand also has the effect of climate change to crop production. Studied by Boonpradab *et al*., (2009) shown that simulated cassava and maize yield in 2090-99 will be decreased by 43% and 15% respectively from 1980-89 (base year) but increased by 6% in sugarcane. However, the yields are much fluctuating in both temporal and spatial of the future climate systems by 41% and 45% on maize, 34% and 33% on cassava and 18% and 23% on sugarcane due to change in climate and soil and their interactions between climate and soil properties at the given area throughout the country.

For sugarcane production, in the Northeast of Thailand, is produced under environmental variability. Preecha *et al*., (2014) defined the land unit for sugarcane production in the Northeast of Thailand to 130 land unit composts with 36 soil types and 28 zones of weather stations. The environmental variability cause to the varies of sugarcane yield. Preecha and Krirk, (2012) have analysed the variability of sugarcane yield in Kalasin province and found that the temporal variability equal to 2.2 ton per rai and 2.1 ton per rai for spatial variability as same as Boonpradub *et al*., (2009) they found that the high varies of sugarcane yield both spatial and temporal variability. The result indicated that growth and development of sugarcane most effect from climate change. Under the climate change, sugarcane yield need to evaluate and crop simulation model is the most efficiency for use to evaluate sugarcane yield.

Crop Simulation Models

A computer model is a mathematical representation of a real–world system. However, in reality, it is impossible to include all the interactions between the environment and the modelled system in a computer model. Therefore, in most cases, a computer model is a simplification of a real–world system. A model might include many assumptions, especially when information that describes the interactions of the system is inadequate or does not exist. Depending on the scientific discipline, there are different types of models, ranging from very simple models that are based on one equation to extremely advanced models that include thousands of equations. For instance, in the aerospace industry, computer models are used to design the entire structure of an airplane and simulate its operation prior to even being built. As airplanes and their interactions with the areal environment mainly deal with the laws of physics, engineering principles can be applied. However, agriculture involves biological factors for which, in many cases, the interactions with the environment are unknown. The science of plants and crops represents an integration of the disciplines of biology, physics and chemistry. Plant and crop simulation models are a mathematical representation of this system (Hoogenboom, 2000).

Physiologically–based crop simulation models are computer software that provides the dynamic simulation of crop growth by numerical integration of constituent processes with the aid of computer (Sinclair and Seligman, 1996). Crop models have become increasingly important in recent years and have been used widely to describe systems and processes at the level of the genotype, the crop, the farming system, the region and the global environment (Matthew *et al*., 2002). The advantages of integrating simulation model approaches into a research program include (1) identification of gaps in our knowledge, (2) generation and testing of hypotheses and an aid to the design of experiments, (3) determination of the most influential parameters of a system (sensitivity analysis), (4) provision of a medium for better communication between researchers in different disciplines and (5) bringing together researchers, experimenters and producers to solve common problems (Seligman, 1990). Boote *et al*. (1996) viewed models as providing a structure to research program which is particularly valuable for synthesizing research understanding and for scaling up from a reductionist research process. He pointed out that if the efficiency of research is to be increased the modelling process must become a truly integrated part of the research activities. Sinclair and Seligman (1996) considered models as a way of structuring knowledge in an organized, logical and dynamic framework, thereby allowing the identification of faulty assumptions and providing new insights.

Several crop models have been developed, evaluated and applied towards strategic, tactical management decision making as well as yield forecasting. These include estimating the impact of climate change on agricultural production and food security (William *et al*., 1988; Boote *et al*., 1997; Alexandrov and Hoogenboom, 2000; Mall *et al*., 2004), evaluating cultivar performances (Palanisamy *et al*., 1993, 1995; Piper *et al*., 1998; Boote *et al*., 2003; Banterng *et al*., 2006; Suriharn *et al*., 2008), assessing the adaptation of a new cultivar to a region (Muchow *et al*., 1991; Shorter *et al*., 1991; Hunt, 1993; Hammer *et al*., 1996; White, 1998; Chapman *et al*., 2002), studying the nature of genotype x environment interactions (Aggarwal *et al*., 1997; White, 1998; Piper *et al*., 1998; Chapman, *et al*., 2002; Phakamas *et al*., 2008; Putto *et al*., 2008), forecasting crop yield before harvest (Duchon, 1986; Bannayan *et al*., 2003; Yun, 2003; Nain *et al*., 2004; Mercau *et al*., 2007; Soler *et al*., 2007) and evaluating improved management options (Jame and Cutforth, 1996; Ruiz-Nogueira *et al*., 2001; Nijbroek *et al*., 2003; Paz *et al*., 2007; Bhatia *et al*., 2008; Timsina *et al*., 2008).

Using of the crop model is the one method to evaluate the effect of climate change on crop production with the high efficiency (Jones *et al*., 2003). Because of the crop model can simulate yield in many environments so this method can save the budged and labor for the experiment. In addition, crop model also evaluates the effect of water deficit (Gussman *et al*., 2007) and effect of nitrogen limitation (Zhang *et al*., 2002). There are worldwide using crop model. If they have the correct data for input to the model the also gave the good results. It requires at least 2 groups of data input. One group is considered conservative, in that the parameters should remain basically constant under different growing conditions and water regimes. The other group encompasses parameters that are dependent on location, crop cultivar, and management practices, and must be specified by the user. So the model needs local calibration and validation before being applied.

For sugarcane, CANEGRO model, Singels *et al*., (2008) reported that the CANEGRO sugarcane model (Inman-Bamber, 1991, Singels and Bezuidenhout, 2002) simulates sugarcane crop growth and development from daily weather data, cultivar and soil properties, and management input data. It simulates: (1) canopy development at the tiller and leaf level, (2) radiation capture from leaf area index, (3) the water balance using soil-plant-atmosphere continuum principles, (4) biomass accumulation following a radiation use efficiency/ respiration approach, and (5) biomass partitioning to different plant components, including stalk sucrose, using a source sink approach and affected by physiological age, temperature and water stress. The CANEGRO model can be regarded as one of the leading sugarcane crop growth models that has been used extensively in research and management.

An early CANEGRO version (Inman-Bamber and Kiker, 1997) was included in version 3.5 (Tsuji *et al*., 1994) of the Decision Support System for Agrotechnology Transfer (DSSAT), Since then, amendments by different research groups resulted indifferent CANEGRO versions that were never integrated, nor incorporated into DSSAT. Simultaneously, DSSAT (version 4.0) adopted a modular structure (Jones *et al*., 2002), and many utilities were added. An up-to-date version of CANEGRO with enhanced capabilities (temperature-dependent photosynthesis and radiation, source-sink approach to biomass partitioning, lodging and an option for thermal time driven canopy development) was incorporated successfully into DSSAT v4.5. A number of species, ecotype and cultivar parameters were defined and the latter are accessible to users for calibration of new genotypes. The CANEGRO model has been using by some researchers. For example, Marin *et al*., (2011) was parameterized and its predictions evaluated using data from five sugarcane experiments conducted in Southern Brazil by the CANEGRO model. The results showed that the DSSAT/CANEGRO model simulated the sugarcane crop in Southern Brazil well, using the parameterization with they reported. Jones *et al*., (2014) had evaluated the DSSAT-CANEGRO model for simulating the climate change impacts at sites in seven countries. They found that the model performance in predicting stalk dry mass was not as good as quoted in previous studies. Using leaf and tiller phenology data for model calibration did not improve model performance, highlighting the need for using leaf area index and biomass data for meaningful calibration. The study also highlighted the need for global model testing in diverse environments and production scenarios, rather than local testing, which may lead to model-fitting by unwarranted parameter adjustments. Jones *et al*., (2015) also simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa and concluded that shortcomings of the DSSAT-CANEGRO model include the simulated responses of phenological development, photosynthesis and respiration processes to high temperatures, and the disconnect between simulated biomass accumulation and expansive growth. Proposed methodology refinements should improve the reliability of predicted climate change impacts on sugarcane yield.

The other one is the DNDC model (Li *et al*., 1992). The Denitrification-Decomposition (DNDC) model is a process-oriented computer simulation model of carbon and nitrogen biogeochemistry in agroecosystems. The model consists of two components. The first component, consisting of the soil climate, crop growth and decomposition sub-models, predicts soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles driven by ecological drivers (e.g., climate, soil, vegetation and anthropogenic activity). The second component, consisting of the nitrification, denitrification and fermentation sub-models, predicts emissions of carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), nitric oxide (NO), nitrous oxide (N_2O) and dinitrogen (N_2) from the plant-soil systems. Classical laws of physics, chemistry and biology, as well as empirical equations generated from laboratory studies, have been incorporated in the model to parameterize each specific geochemical or biochemical reaction. There are many researchers used the DNDC model as a tool for research. For example, Li *et al*., (2014) had calibration the DNDC model for studying nitrate leaching in the Northern China. The modelled results showed clear spatial patterns of nitrate leaching rates across the region due to the spatially differentiated fertilizer application rates as well as the soil water regimes. Alternative water management practices were suggested to effectively reduce nitrate leaching losses from the agricultural region in northern China. Han *et al*., (2014) used the DNDC to assist the evaluation on the film mulching application, one of the widely tested alternative farming management practices in China. They found that the results demonstrated the strength as well as weakness of the model. For example, the model appeared unsophisticated in capturing the detailed phenology, especially for the early stage of the crop growth. Further improvements are apparently required in future studies. And Zhang *et al*., (2016) used the DNDC model to estimate N_2O emissions under the different type of irrigation in China. They concluded that the DNDC model which proved to be a powerful tool for addressing the efficacy of alternative management practices, revealed that N_2O emissions can be reduced by adopting drip irrigation systems rather than traditional furrow irrigation systems.

Uncertainty for Crop Growth Model Prediction

However, deterministic crop growth models require several inputs relating to crop/variety, soil physical properties, weather and crop management. The input values used could be significantly uncertain due to random and systematic measurement errors and spatial and temporal variation observed in many of these inputs. Often soil and weather data are approximated using GIS and/or weather generators. Aggarwal (1995) concluded that outputs of crop growth models may be uncertain depending upon the range of variation/uncertainty in crop, soil and weather input parameters and production environment. However, crop models will still remain important in applications related to estimation of production potentials, strategic and tactical decisions and agro-technology transfer, since these are efficient, quantitative tools for the integration of complex, dynamic interactions of crops/genotype with climatic, edaphic and agronomic environments. The conclusions derived from conventional field experiments as well have uncertainty in view of the spatial variability and other random and systematic errors considered in this study. In addition, it may be extremely difficult to design and conduct field experiments to simultaneously investigate the effect of variations in crop, soil and weather factors. Gijsman *et al*., (2002) also have modified the DSSAT crop models for low input. They used the SOM-residue module from the CENTURY model incorporating in the DSSAT crop simulation model and found that by incorporating the CENTURY SOM-residue module, DSSAT crop simulation models have become more suitable for simulating low-input systems and conducting long-term sustainability analyses. For the regional scale, the results from Angulo *et al*., (2013) showed that yield simulations improve if growth parameters are considered in the calibration for individual regions. The calibration did not only affect the model simulations under reference climate but also the extent of the simulated climate change impacts. They recommend that future work should focus on obtaining more comprehensive, high quality data with a finer resolution allowing application of improved strategies for model calibration that better account for spatial differences and changes over time in the growth and development parameters used in crop models. Watson and Challinor, (2013) was projected future crop production of the regional scale (>100 km resolution) and found that the error in rainfall data have the most significant impact on model skill overall. Moreover, the errors in inter-annual variability of seasonal temperature and precipitation cause the greatest crop model error. To improve the ability to assess future crop productivity at the regional scale they suggested that: (i) increasingly accurate representation of inter-annual climate variability in climate models; (ii) similar studies with other crop models to identify their relative strengths in dealing with different types of climate model error; and (iii) the development of techniques to assess potential and actual yields, with associated confidence ranges, at the regional scale.

Estimation of Evapotranspiration

Estimation of evapotranspiration (ET) is an important part of agricultural water management in local and regional water balance studies. At the field scale, ET is important in irrigation planning and scheduling and is an integral part of field management decision support tools. Reference evapotranspiration estimates based on Penman-Monteith approaches are considered to be more physically realistic, but require more diverse input data. It is important to simplify the method of estimating evapotranspiration by reducing the number of variable parameters. Therefore, several methods were developed for example, the equation based on temperature such as Thornthwaite (1948), Linacre (1977), Blaney and Criddle (1950), Hargreaves and Samani (1985), and Hamon (1961) methods. From Jensen *et.al*., (1990) and Xu and Singh (2001), they concluded that The Blaney-Criddle and Hargreaves method gave the better results than others. The radiation based equation such as Turc (1961), Makkink (1957), Jensen and Haise (1963), Hargreaves (1975), Doorenbos and Pruitt (1977), Abtew (1996), and Priestley and Taylor (1972). Xu and Singh (2001) also found that the Makkink (1957) and Priestley and Taylor (1972) equations provided better results in the study region.

In addition, new method for estimating evapotranspiration, for example, Salama *et al*., (2015) was estimated actual evapotranspiration using Growing Degree Days (GDD) and found that the equation is easy to use and applied in arid climate. In addition, estimates yield, water use efficiency, irrigation water use efficiency, and heat use efficiency for wheat crop. Wang *et al*., (2007) estimated global and regional evapotranspiration using the input data, e.g., surface net radiation, temperature and vegetation indices, obtained from satellite measurements. They found that the method can be reasonable predicted evapotranspiration under a wide range of soil moisture contents and land cover types. Wang et al., (2016) also using satellite data “thermal infrared remote sensing + three-temperature model” for estimating evapotranspiration The proposed methodology is concluded to be a feasible method for estimating ET under multi-scale conditions over heterogeneous landscapes.

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CHAPTER III

Calibration and Validation of Two Crop Models for Estimating Sugarcane Yield in Northeast Thailand

Abstract

Crop models allow the assessment of management strategies under climate change. We calibrated and validated two crop models for estimating sugarcane yields in North-eastern Thailand. We used data collected in 2011–12 in the absence of water stress to calibrate DSSAT-CANEGRO and DNDC95, and validated them using data collected in 2010–11 and 2011–12 under rainfed conditions. In the calibration, we optimized parameters of both models and got realistic predictions. In the validation, optimizing water demand in DNDC95 gave good results, but DSSAT-CANEGRO overestimated yields. When we optimized water balance specific to sugarcane, DSSAT-CANEGRO also simulated yields well.

Key words: DNDC, DSSAT-CANEGRO, Sugarcane, Thailand

Introduction

Sugarcane is an important crop in Thailand. Besides sugar, it is also used for ethanol production. Thailand typically grows 1.0-1.2 million ha of sugarcane, and produces 50–70 million t per year (OCSB, 2011). In 2010-11, production reached 95.3 million t, equivalent to 9.5 million t of sugar. The main area of sugarcane production is Northeast Thailand, in both upland and lowland areas. Predicting the influence of climate change on sugarcane production is important for the sustainable development of agriculture in Northeast Thailand. Model simulations are useful for this. Boonpradub *et al*., (2009) investigated the impact of climate change on sugarcane production in Thailand using the DSSAT crop model (Hoogenboom *et al*., 2011) and weather data from 2000 to 2100 predicted by the ECHAM4-PRECIS climate model. Climate change had the most notable impact on temporal and spatial variability of yield, notably in the northeast, although the long-term average yield was not substantially changed. Appropriate management strategies must be identified to reduce this variability, for which a model that is adapted to the regional characteristics of Northeast Thailand is needed.

Many crop models are available to simulate yields. We used DSSAT-CANEGRO and DNDC models for the simulation of sugarcane yield, because these models were widely popular for the simulation of sugarcane yield and free. The CANEGRO model has been developed continually since the 1970s (O'Leary, 2000) and has been used to analyse sugarcane production (Jintrawet *et al*., 1997; Singels and Bezuidenhout, 2002; Inman-Bamber *et al*., 2002; Singels *et al*., 2005). Although Jintrawet *et al*., (1997) studied the sugarcane in Thailand, they simulated an old cultivar which was popular in that time. However, new cultivars have been developed, and they have not been simulated yet. CANEGRO has been combined with the DSSAT v. 4.5 model (Singels *et al*., 2002) to simulate the effect of water stress. DNDC (Li *et al*., 1992) is a process-based model of carbon and nitrogen biogeochemistry in agricultural ecosystems. It consists of soil, climate, crop growth, nitrification, denitrification, and fermentation submodules. The Crop-DNDC model, which is the basis for DNDC v. 9.5 (DNDC95), simulates crop growth by tracking crop physiological processes and calculating water and nitrogen stress (Zhang *et al*., 2002). Both DNDC95 and DSSAT-CANEGRO require input parameters that depend on location, cultivar, and management practices and that must be specified by the user. So the models need local calibration and validation before use. The objective of this study was to apply DSSAT-CANEGRO and DNDC95 to data recorded in Northeast Thailand and to examine their applicability for estimating sugarcane production there.

Materials and Methods

Cultivation experiments

We conducted two experiments (Table 1) at the Khon Kaen Field Crops Research Center, Northeast Thailand (16.48^o N, 102.82^o E, 181 m elevation). Experiment A (Exp. A) was conducted during 2010-11 under rainfed conditions, and Experiment B during 2011-12 under irrigated (Exp. B1) and rainfed conditions (Exp. B2). In all experiments, 24 mm of water per week was supplied by drip irrigation until 45 days after planting (DAP) to establish good shoot growth. In Exp. B1, the irrigation was continued until harvest to prevent drought. We grew most popular sugarcane cultivars in Northeast Thailand: KK3, LK92-11, and 02-2-058. They are cultivars of high yield. KK3 is planted all over Khon Kaen province. LK92-11 is suitable for the lowland, and 02-2-058 is recommend in the irrigation area. Each subplot had 9 rows 10 m long, 1.3 m apart. Fertilizer (46.75 -20.40-38.81 kg of N-P-K/ha) was applied at planting and again at 100 DAP. In both experiments, soil properties were analysed before planting (Table 2). Daily weather data were collected by a weather data logger (Fig. 1). We recorded aboveground total dry weight (TDW) and stalk dry weight (SDW) every 30 days from 90 DAP until harvest (about 390 DAP). All plant materials were removed from four 1.65-m2 areas per subplot, divided into organs, oven-dried at 80^{o}C for 24 h, and weighed.

Table 1 Summary of experimental conditions

	Experiment A	Experiment B
Planting date	1 December 2010	28 November 2011
Harvesting date	20 December 2011	22 December 2012
Experiment design	Randomized complete block 3 cultivars, 4 replicates	Split plot design, Main plot, 2 methods of water application Subplot, 3 cultivars, 4 replicates
Plot size; row spacing	99 m^2; 1.1 m × 0.5 m	
Cultivars	KK3, LK92-11, 02-2-058	
Water supply	Rainfed	Irrigated (B1) and rainfed (B2)
Rainfed	24 mm/week to 45 days after planting	
Irrigation	24 mm/week to harvest (B1)	
Fertilizer	93.5-40.8-77.6 kg of N-P-K/ha	
Sampling plot size	1.1 x 1.5 m, 4 replicates	
No. of dry matter samples	7	9

Table 2 Soil properties used as inputs for crop models

Soil depth (cm)	Texture class	BD (g/cm^3)	K-Sat (cm/h)	Water retention (% vol.)		
				MWH	FC	WP
0–20	Loamy sand	1.52	13.9	35.7	20.6	7.5
20–50	Sandy loam	1.61	9.3	39.5	23.6	11.6
50–100	Sandy clay loam	1.57	9.3	41.0	23.8	12.4

BD = bulk density, K-Sat = saturated soil hydraulic conductivity, MWH = maximum water holding capacity, FC = field capacity, WP = wilting point.

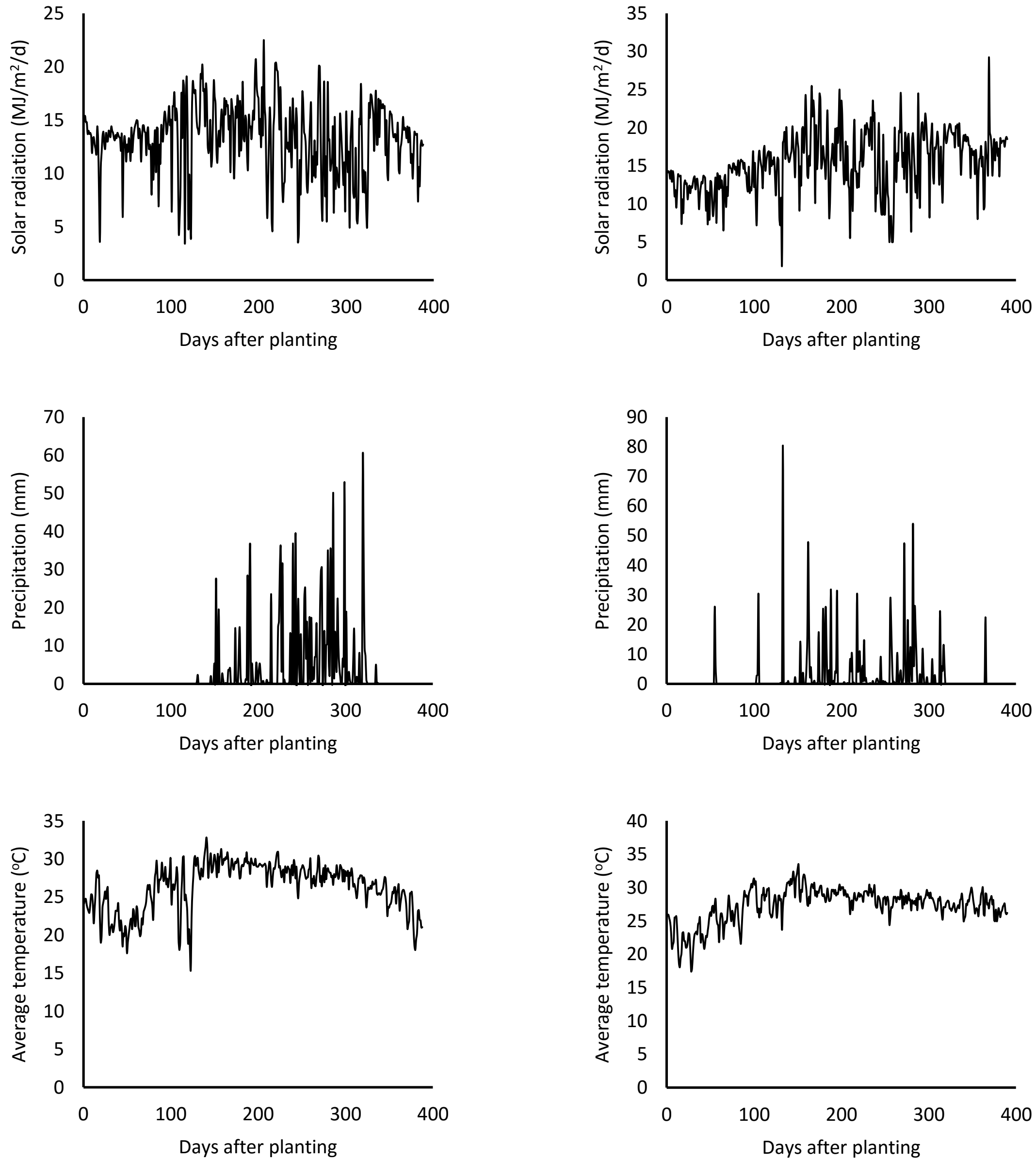

Fig. 1 Solar radiation, precipitation, and average temperature at Khon Kaen Field Crops Research Center in Experiments A (Left) and B (Right).

Model application

Parameters in DSSAT-CANEGRO

DSSAT-CANEGRO used three parameter sets: a species set, an ecotype set, and a cultivar set. The species set has common parameters for sugarcane. The ecotype set has common parameters for the group of sugarcane cultivars grown. The cultivar set has parameters for each cultivar. In the calibration of DSSAT-CANEGRO, users are recommended only to change values of the cultivar set because parameters in the species and ecotype sets affect all calculations. However, we optimized some parameters in species set which are related to water demand.

Parameters in DNDC95

The Denitrification-Decomposition (DNDC) model is a process-oriented computer simulation model of carbon and nitrogen biogeochemistry in agroecosystems. The entire model is driven by four primary ecological drivers. These are climate, soil, vegetation, and management practices. Therefore, users must prepare input parameters for application of the model, which are related to soil, weather, crop, and management. The parameters optimized in this study are crop parameters.

Two step model calibration

Both models used inputs of crop parameters, soil data, weather data, and field management data. Both used the same soil and weather data (Table 2 and Fig. 1) but different crop parameters. Therefore, we tried to optimize 20 parameters of the cultivar set in the calibration of DSSAT-CANEGRO (Table 3). In the calibration of DNDC95, we optimized 15 parameters for each cultivar (Table 3). We did model calibration in two steps. In the first step, we applied models to the result of Exp. B1. Because irrigation was done and there was no water stress in Exp. B1, we tried to calibrate parameters except for them related to water demand. Then, in the second step, we applied two models to the result of Exp. B2. In this calibration, we only optimized parameters related to water demand. In the second calculation of DSSAT-CANEGRO, we optimized two parameters of water balance in the species set. To optimize the parameters, we used values of TDW and SDW collected every 30 days. We varied parameter values by trial and error to minimize the error estimated by the coefficient of determination (*R*2), the Root Mean Square Error (RMSE), and the Agreement Index (AI). RMSE and AI were calculated as:

$$RMSE = \sqrt{\frac{\sum (S_i - O_i)^2}{N}}$$

$$AI = 1 - \frac{\sum (S_i - O_i)^2}{\sum (|S_i - \bar{O}| + |O_i - \bar{O}|)^2}$$

where *Si* is simulated value, *Oi* is observed value at time or place *i*, *N* is number of samples, and $\bar{O}$ is mean observed value.

AI gives a value between 0 and 1. A value close to 1 indicates high model efficiency.

Model validation

We validated both models against the results of Exp. A using parameters optimized in the two step calibration.

Table 3 Crop parameters needed for CANEGRO and DNDC95 models.

Model	Crop parameters
CANEGRO	(1) PARCEmax, (2) APFMX, (3) STKPFMAX, (4) SUCA, (5) TBFT, (6) Tthalfo, (7) Tbase, (8) LFMAX, (9) MXLFAREA, (10) MXLFARNO, (11) PI1, (12) PI2, (13) PSWITCH, (14) TTPLNTEM, (15) TTRATNEM, (16) CHUPIBASE, (17) TTPOPGROWTH, (18) MAX_POP, (19) POPTT16 and (20) LG_AMBASE
DNDC95	(1) Maximum biomass production kg C/ha/y, (2) Grain fraction, (3) Leaf fraction, (4) Stem fraction, (5) Root fraction, (6) Grain CN, (7) Leaf CN, (8) Stem CN, (9) Root CN, (10) Water demand, (11) Optimum temperature, (12) Thermal degree day for maturity, (13) Nitrogen fixation, (14) Vascularity and (15) Perennial Crop

Results and Discussion

Cultivation experiments

The average of maximum, minimum temperature solar radiation and total rainfall in crop season for the Exp. 1 were 32.7^{o}C, 21.9^{o}C, 15.3 MJm-1d-1 and 972 mm. and 31.7^{o}C, 21.0^{o}C, 13.2 MJm-1d-1 and 1,261 mm for Exp. A. The weather condition for the Exp. B1 and B2 look like better than Exp. A although rainfall was lower but distribution is better. Comparison of the results of each cultivar between Exp. B1 and Exp. B2 on the same sampling date by Tukey's test confirmed that the mean dry matter yields in Exp. B2 were, on the whole, smaller than those in Exp. B1 in all cultivars (Table 4). This result indicates water stress in the rainfed condition in Exp. B2. Moreover, the yields in Exp. A tended to be smaller than those in Exp. B2 because less rain fell in the early period in Exp. A than in Exp. B (Fig. 1). Observed parameters of three cultivars of sugarcane at harvesting date of Exp. B1 are shown in Table 5.

Model calibration

In the first calibration, we optimized the crop parameters except for them related to water demand of both models by using the results of Exp. B1 (Tables 6 and 7). Comparison between the observed and simulated values confirmed that both models gave acceptable estimates of TDW and SDW (Fig. 2). In the second calibration of DNDC95, we optimized the water demand in the simulation of Exp. B2. The value was 200 g water/g DM for all three cultivars. Comparison between the observed and simulated values showed that DNDC95 could simulate both TDW and SDW well in the presence of water stress (Fig. 3). In the simulation of Exp. B2 using DSSAT- CANEGRO with optimized parameters in the first step, the yields of all cultivars were overestimated. We thought that evaluation of water stress was smaller than the actual situation because parameters about water requirement were small. Following optimization of the parameters of water balance in the species set (Table 8), DSSAT-CANEGRO could simulate both TDW and SDW well in the presence of water stress (Fig. 4).

Table 4 Growth of three cultivars of sugarcane.

Days after planting	Aboveground dry matter (TDW) (g m^{-1})			Stalk dry matter (SDW) (g m^{-1})		
	KK3	LK92-11	02-2-058	KK3	LK92-11	02-2-058
Exp. B1						
99	1000 a	160 b	540 a	260 a	83 a	90 a
128	1370 a	1846 a	1140 a	529 a	573 a	480 a
185	3820 a	2700 a	3210 a	2222 a	1300 a	1720 a
238	4420 a	3890 a	3890 a	3030 a	2404 a	2460 a
267	5120 a	4280 a	5180 a	3470 a	2730 a	3430 a
299	5650 a	4510 a	4700 a	4545 a	3150 a	3500 a
329	5390 a	4890 a	5550 a	4200 a	3920 a	4060 a
360	6220 a	5070 a	6000 a	5010 a	3890 a	4400 a
390	5850 a	4870 a	6470 a	4760 a	3610 a	4390 a
Exp. B2						
99	170 b	220 a	220 b	30 b	30 b	40 b
128	740 b	650 b	490 b	130 b	100 b	80 b
185	1260 b	1130 a	1470 b	420 b	430 a	570 b
238	2490 a	2780 b	2620 a	1550 a	1630 b	1440 a
267	2810 a	2560 a	2700 b	1690 a	1540 a	1580 b
299	3640 b	3410 a	3510 a	2460 b	2100 a	2380 a
329	3860 a	3560 a	4790 a	2830 a	2380 b	3270 a
360	4050 b	3790 a	4090 b	3110 b	2540 a	2890 b
390	4830 a	3950 a	4180 b	3730 a	2760 b	2990 b
Exp. A						
96	34	37	38	22	23	26
117	49	74	51	39	56	39
147	255	372	271	188	251	195
173	700	960	824	451	601	568
244	2362	2580	1978	1676	1904	1340
293	2902	2802	2228	2386	2410	1844
388	3425	4705	3359	2623	4029	2527

In the comparison of the results of each cultivar between Exp. B1 and Exp. B2, averages on the same sampling date followed by the same letter are not significantly different at P = 0.05 by Tukey's test.

Table 5 Observed parameters of three cultivars of sugarcane at harvesting date of Exp. B1.

Cultivar	SMFMH	SUCH	STKH	LAIH	L#SM	S#AH	CHTA	HIAM
KK3	65.4	6.69	48.8	6.06	3.7	6.8	3.74	0.121
LK92-11	50.7	4.86	34.2	6.60	3.3	6.8	3.35	0.124
02-2-058	64.7	6.11	43.9	9.85	3.5	6.8	3.42	0.122

Parameters name	Description
SMFMH	Millable cane fresh weight at harvest (t ha^{-1})
SUCH	Sucrose dry mass at harvest (t ha^{-1})
STKH	Stalk dry mass at harvest (t ha^{-1})
LAIH	Leaf area index, at harvest
L#SM	Green leaf number at harvest
S#AH	Stalk population at harvest (stalks m^{-2})
CHTA	Canopy height at harvest (m)
HIAM	Harvest index [sucrose / (stalk dm + sucrose)]

Model validation

Comparison between the observed values of Exp. A and the simulated values showed that both models gave good results for cultivars KK3 and 02-2-058, but underestimated the growth of LK92-11 (Fig. 5). This result suggests that LK92-11 is drought resistant. Similarly, Peerasak (2013) showed that LK92-11 was less sensitive to water shortage than KK3. Moreover, Cha-um *et al*. (2012) also reported that LK92-11 had tolerance to water deficit. We think that the growth of LK92-11 was greater than that of the other cultivars because it experienced less drought damage in the early period in Exp. A, when less rain fell than in Exp. B (Fig. 1). Although the model developer does not recommend modifying parameters which are common to sugarcane, we confirmed that there were some cases that it was better to optimize common parameters to improve the precision of the simulation.

Conclusion

In the absence of water stress, DSSAT-CANEGRO and DNDC95 could simulate the TDW and SDW of three cultivars of sugarcane. Under water stress, DNDC95 could simulate TDW and SDW when water demand was optimized. On the other hand, DSSAT-CANEGRO overestimated them in the simulation using parameters optimized under the irrigated condition. When parameters of water balance were optimized in the species set, DSSAT-CANEGRO could simulate TDW and SDW well. Although the model developer does not recommend modifying parameters which are common to sugarcane, we confirmed that there were some cases that it was better to optimize common parameters to improve the precision of the simulation.

Table 6 Crop parameters of the three cultivars of sugarcane used in the CANEGRO model.

Parameter name	Cultivar			
	Initial	KK3	LK92-11	02-2-058
PARCEmax	**9.46**	**10.54**	**9.58**	**10.90**
APFMX	**0.910**	**0.907**	**0.902**	**0.900**
STKPFMAX	**0.780**	**0.843**	**0.671**	**0.770**
SUCA	**0.579**	**0.626**	**0.589**	**0.580**
TBFT	25	25	25	25
Tthalfo	250	250	250	250
Tbase	16	16	16	16
LFMAX	13	13	13	13
MXLFAREA	**579**	**602.7**	**512.0**	**560.0**
MXLFARNO	**17**	**17**	**16**	**16**
PI1	**71.06**	**101.1**	**103.6**	**110.5**
PI2	**215.4**	**199.0**	**190.5**	**194.1**
PSWITCH	**17.7**	**13.35**	**15.25**	**16.52**
TTPLNTEM	428	428	428	428
TTRATNEM	203	203	203	203
CHUPIBASE	1050	1050	1050	1050
TT_POPGROWTH	**418.4**	**460.8**	**424.2**	**411.2**
MAX_POP	**35.3**	**30.11**	**35.01**	**41.80**
POPTT16	**9.09**	**13.17**	**12.95**	**11.61**
LG_AMBASE	220	220	220	220

The main parameters adjusted are shown in bold. The parameters are defined in Appendix A.

Table 7 Crop parameters of the three cultivars of sugarcane used in the DNDC95 model.

Parameter name	Cultivar			
	Initial	KK3	LK92-11	02-2-058
Maximum biomass production (grain) (kg C/ha/y)	**267**	**284.0**	**264.8**	**265.6**
Grain fraction	0.01	0.01	0.01	0.01
Leaf fraction	**0.19**	**0.25**	**0.27**	**0.30**
Biomass fraction in stalk	**0.70**	**0.70**	**0.61**	**0.63**
Root fraction	0.10	0.04	0.11	0.09
Grain CN	150	150	150	150
Leaf CN	100	130	130	130
Stem CN	100	130	130	130
Root CN	150	150	150	150
Water Demand *	**500**	**200**	**200**	**200**
Optimum temperature (°C)	**32**	**32**	**32**	**32**
Thermal °C·d for maturity	**11000**	**10500**	**12000**	**11000**
N-fixation	1	1	1	1
Vascularity	0	0	0	0
Perennial	0	0	0	0

The main parameters adjusted are shown in bold.

* The value of Grain fraction has to be more than zero. Therefore, it was fixed to 0.01.

** Only water demand was optimized in the second calibration using Exp. B2.

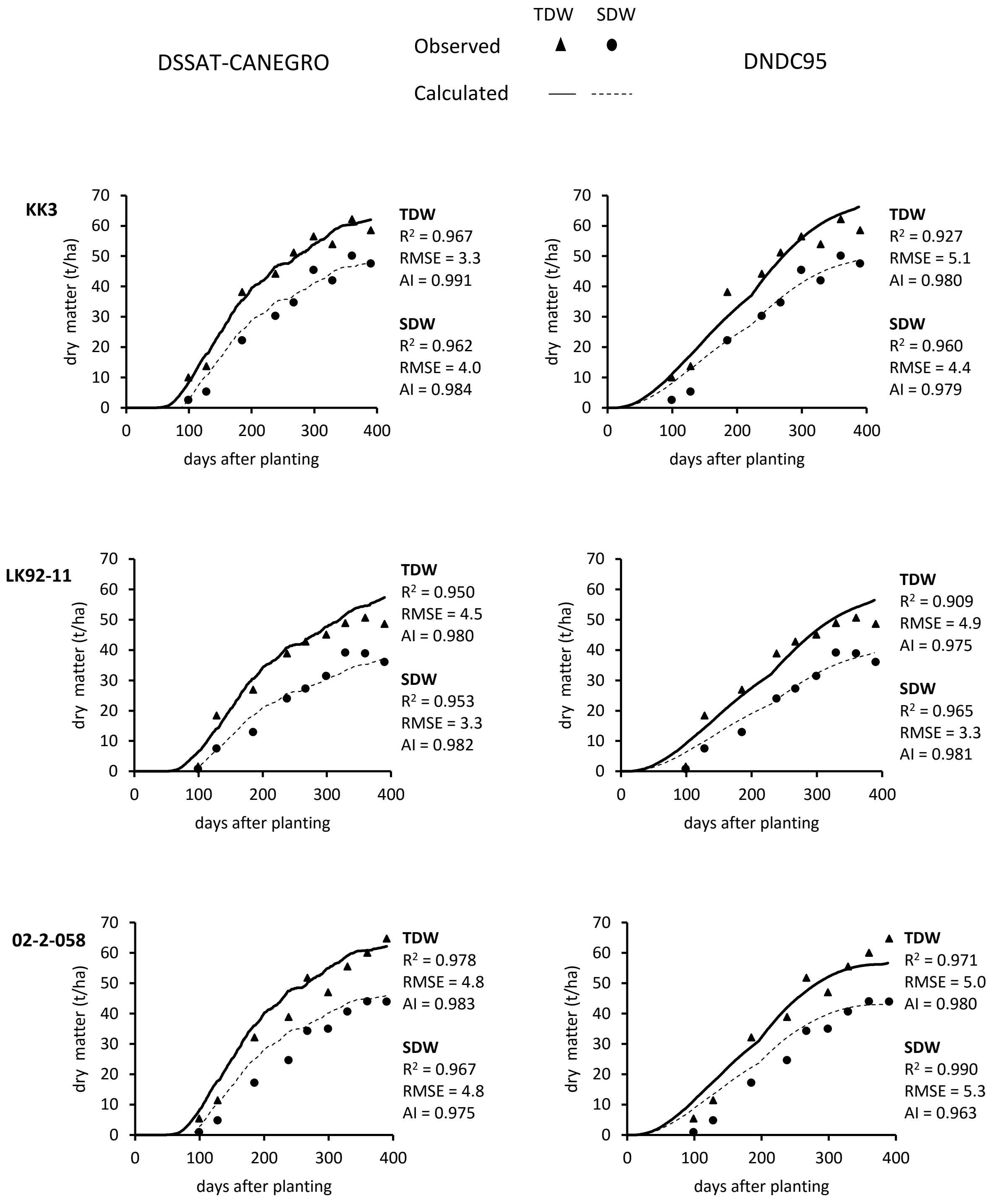

Fig. 2 Comparison between observed values of Exp. B1 and simulated values.

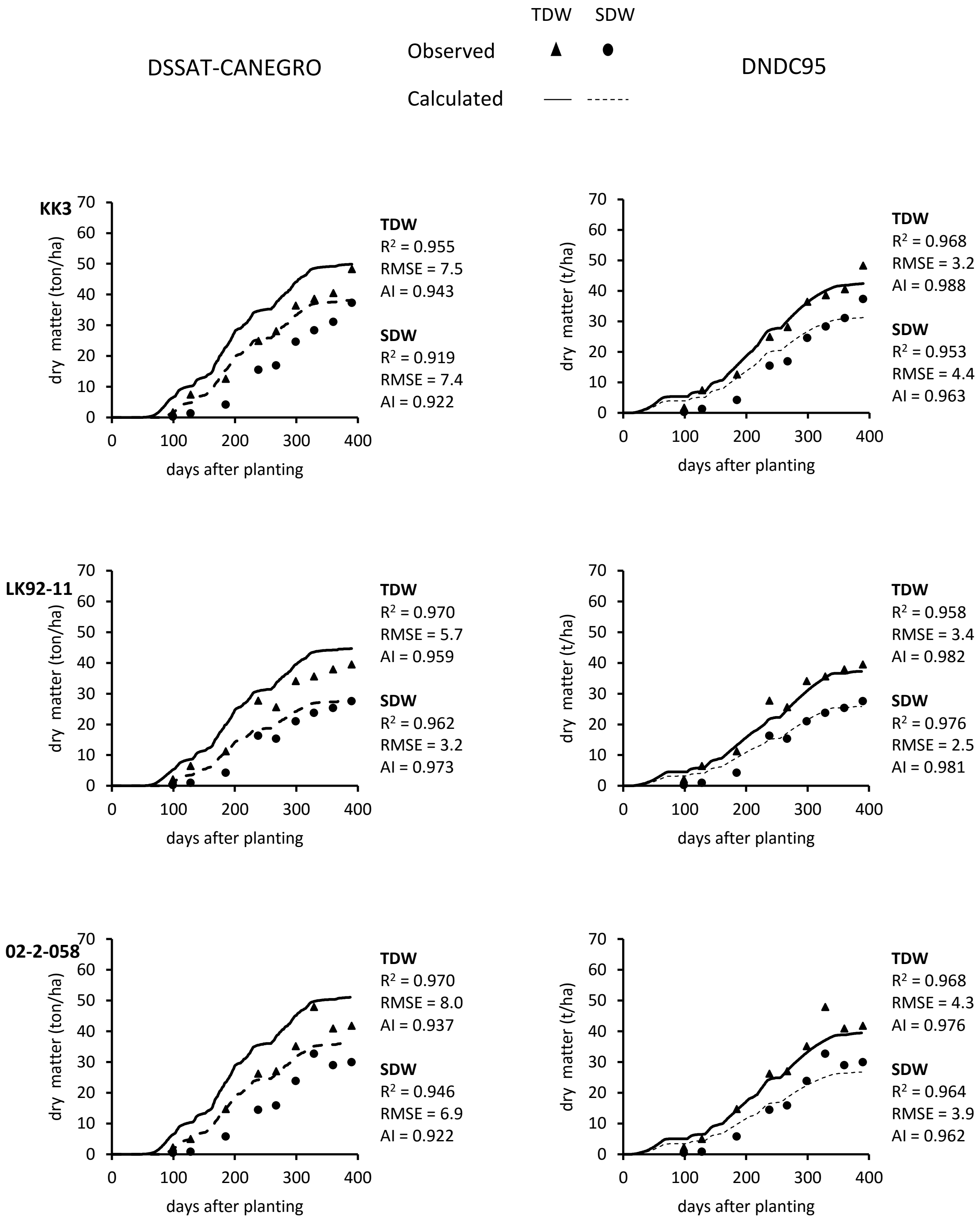

Fig. 3 Comparison between observed values of Exp. B2 and simulated values.

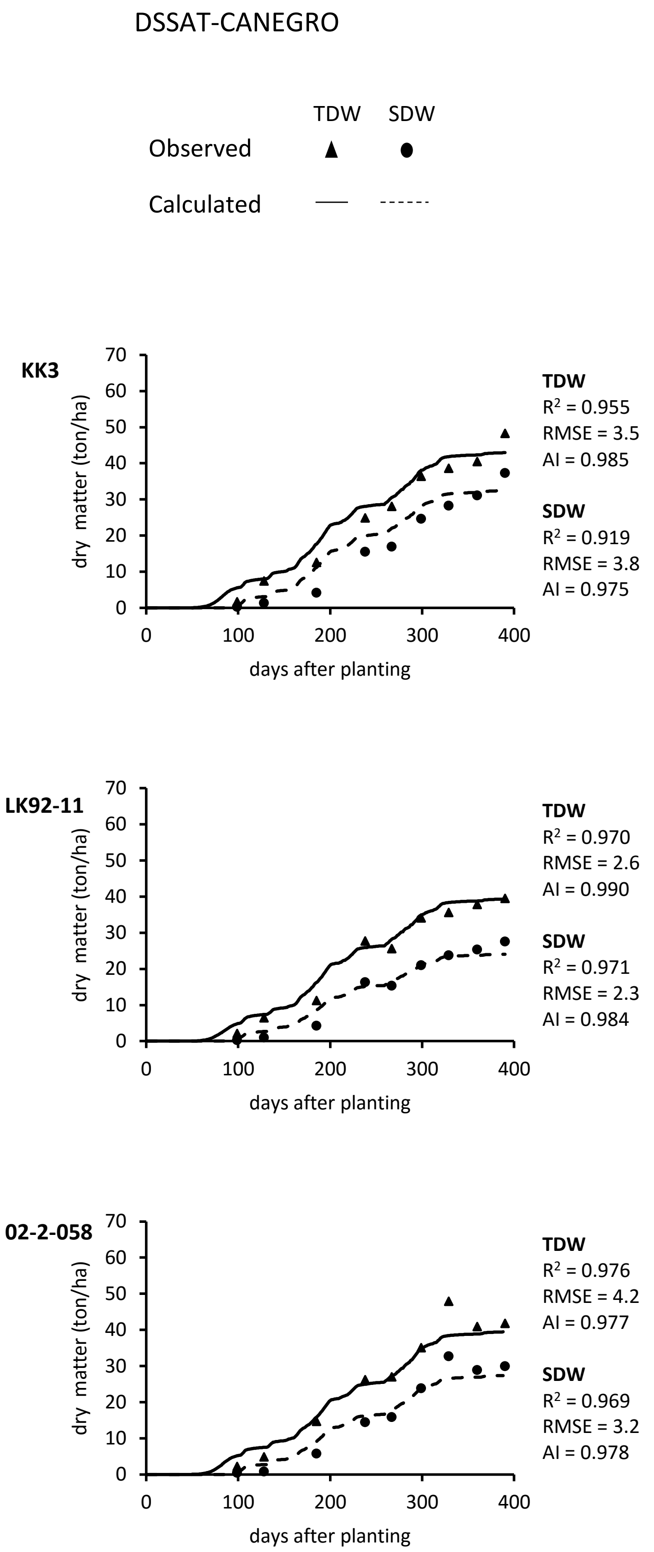

Fig. 4 Comparison between observed values of Exp. B2 and simulated values using modified parameters.

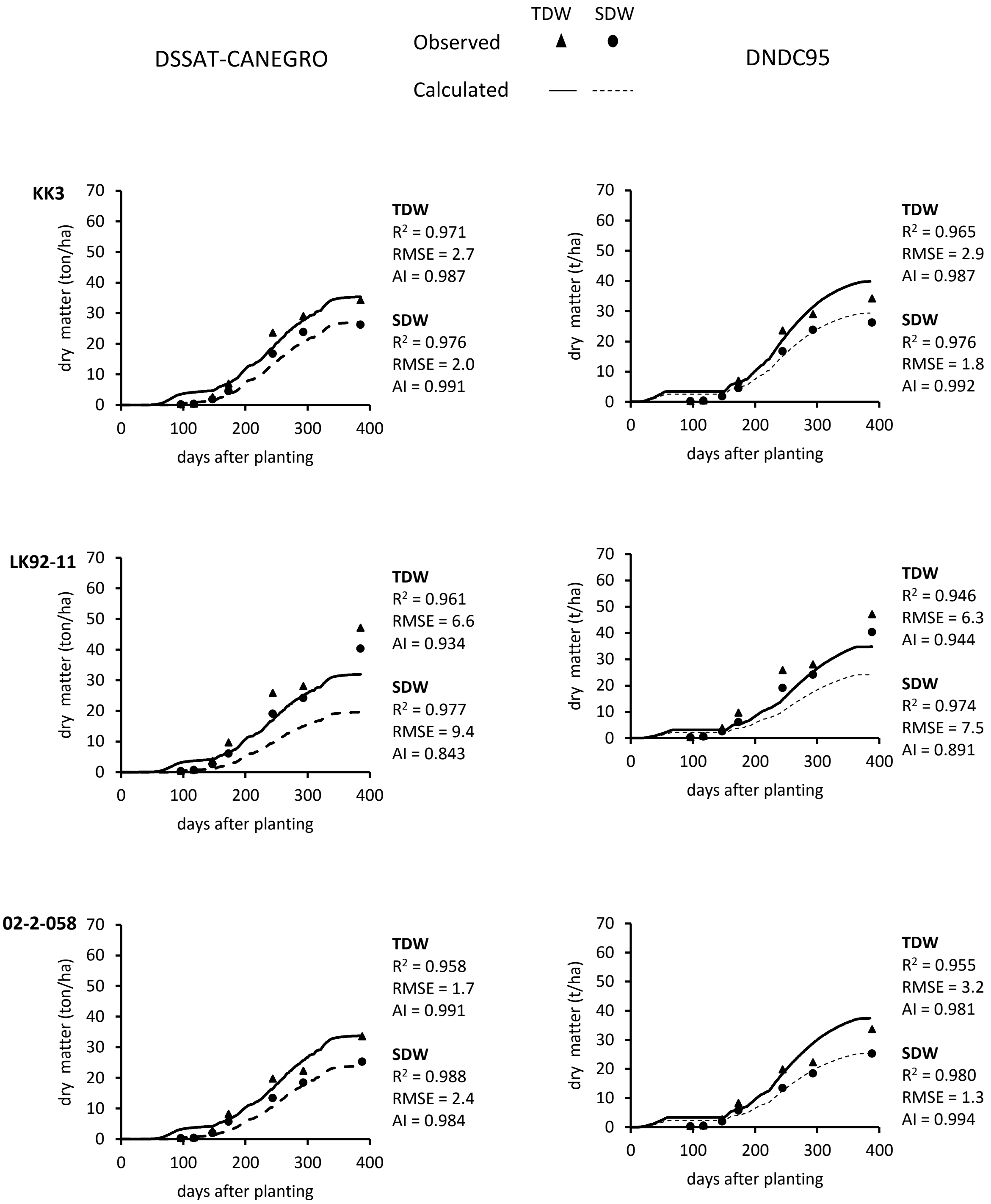

Fig. 5 Comparison between observed values of Exp. A and simulated values.

Table 8. Parameters of water balance used in the CANEGRO model.

Parameter name	Cultivar			
	Initial	KK3	LK92-11	02-2-058
Water balance				
EORATIO	1.15	1.15	1.15	1.15
RWUEP1	**1**	**1.75**	**1.75**	**2.15**
RWUEP2	**2**	**1.70**	**1.50**	**1.50**
RWUMX	0.07	0.07	0.07	0.07

The main parameters adjusted are shown in bold.

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Appendix A Description of crop parameters in Table 2

Parameter name	Description
PARCEmax	Maximum (no stress) radiation conversion efficiency expressed as assimilate produced before respiration, per unit PAR (g/MJ)
APFMX	Maximum fraction of dry mass increments that can be allocated to aerial dry mass (t/t)
STKPFMAX	Fraction of daily aerial dry mass increments partitioned to stalk at high temperatures in a mature crop (t/t on a dry mass basis)
SUCA	Sucrose partitioning parameter: maximum sucrose content in stalk base (t/t)
TBFT	Sucrose partitioning: temperature at which partitioning of unstressed stalk mass increments to sucrose is 50% of the maximum value
Tthalfo	Thermal time to half canopy (°C·d)
TBase	Base temperature for canopy development (°C·d)
LFMAX	Maximum number of green leaves a healthy, adequately watered plant will have after it is old enough to lose some leaves
MXLFAREA	Maximum leaf area assigned to all leaves above leaf number MXLFARNO (cm^2)
MXLFARNO	Leaf number above which leaf area is limited to MXLFAREA
PI1	Phyllochron interval 1 (for leaf numbers below PSWITCH) °C·d
PI2	Phyllochron interval 2 (for leaf numbers above PSWITCH) °C·d
PSWITCH	Leaf number at which the phyllochron changes
TTPLNTEM	Thermal time to emergence for a plant crop (°C·d, base TTBASEEM)
TTRATNEM	Thermal time to emergence for a ratoon crop (°C·d, base TTBASEEM)
CHUPIBASE	Thermal time (base TTBASEEM) from emergence to start of stalk growth
TTPOPGROWTH	Thermal time to peak tiller population (°C·d, TTBASEPOP)
MAX_POP	Maximum tiller population (stalks/m^2)
POPTT16	Stalk population at/after 1600 °C·d (/m^2)
LG_AMBASE	Aerial mass (fresh mass of stalk, leaf, and water attached to them) at which lodging starts (t/ha)
Eoratio	Ratio of potential ET from fully canopied unstressed sugarcane canopy to grass reference ET
RWUEP1	Soil water supply/potential evaporation ratio threshold below which evaporation and photosynthesis
RWUEP2	Soil water supply/potential evaporation ratio threshold below which expansive growth is limited
RWUMX	Maximum root water uptake per unit length of root (cm^3 water/cm RLV)

CHAPTER IV

Analysis of Land Characteristics for Efficient Irrigation Development of Sugarcane Growing Areas in Khon Kaen Province, Thailand

Abstract

North-eastern Thailand has little rainfall and requires efficient irrigation development to enhance stable sugarcane production. However, identifying the highest priority areas for irrigation development is complex because the benefit derived from irrigation development depends on rainfall, available irrigation water, and soil characteristics. We used the CANEGRO model to simulate the sugarcane yield of existing cultivation areas under rainfed and irrigated conditions, taking into account actual weather and soil type. We then calculated the benefit of the irrigation development using the simulation results and actual data for groundwater well capacities, sugarcane prices, and irrigation development and running costs. We then analysed the results of the benefit calculation by ABC analysis and the decision tree method. The decision tree analysis confirmed that well capacity most influenced benefit. Areas with higher rainfall had high yields under rainfed condition, so the benefit from irrigation was small (or even negative as the cost of irrigation exceeded the increased income). A notable finding was that low soil available water content resulted in low yields in both rainfed and irrigated conditions, and high available water content resulted in high yields under rainfed conditions; Therefore, both low and high available water content resulted in low benefit from irrigation development.

Keywords: CANEGRO, Sugarcane, ABC analysis, Decision tree, Irrigation development

Introduction

Thailand is the fourth ranked sugarcane producer and the second ranked sugar exporter in the world. The sugarcane growing area in Thailand is 1.7 million ha, and 117 million t of sugarcane is produced per year (OCSB, 2015). Production is also steadily increasing because of the increasing area under sugarcane cultivation. However, the productivity of land under cultivation is not improving. Because 80% of sugarcane fields are rainfed, some areas face drought stress. Moreover, the sugarcane yield is unstable because of rainfall variability. Irrigation development is therefore an important objective to improve sugarcane production level and stability. However, irrigation development requires public investment, which demands efficient use of the funds. It is therefore important to prioritize areas for development by taking into account variations in climate and soil. Crop models are a powerful tool that could be employed to address this issue of spatial prioritization for investment. The CANEGRO model is widely used to simulate sugarcane production and has been continually improved since the 1970s (Inman-Bamber *et al*., 2002; Jintrawet *et al*., 1997; O'Leary, 2000; Singels and Bezuidenhout, 2002; Singels, *et al*. 2005). CANEGRO has been combined with DSSAT ver. 4.5 (Singels and Bezuidenhout, 2002) to simulate the effect of water stress, but not nitrogen stress. Preecha *et al*., (2015) calibrated CANEGRO for sugarcane production in north-eastern Thailand and found that it could validly simulate the aboveground dry matter and stalk dry matter of three cultivars of sugarcane under irrigated and rainfed conditions. In this study, we used CANEGRO to simulate sugarcane yield in current sugarcane production areas, first under rainfed conditions and then assuming automated irrigation. We then calculated the benefit that would be obtained from irrigation development using the results of the simulation and well capacity data (irrigation water availability). We sorted the results by the benefit per area and calculated the total benefit. We then used ABC analysis of the total benefit to highlight the priority areas. Finally, we conducted decision tree analysis to more clearly characterize the conditions that provide the best return from irrigation development.

Materials and Methods

1. Spatial Data and Land Units for Simulating Sugarcane Production

The study employed spatially distributed digital data of current sugarcane growing areas, soil groups, weather stations, and well capacities in Khon Kaen province. The data were collated and manipulated in the ArcView 3.2a (Esri, Redlands, CA, USA) geographic information system (GIS) software. The digital map (polygons) of sugarcane growing area (Fig. 1) was obtained from the Office of the Cane and Sugar Board (OCSB, 2013; 2015). The data were collected in the year 2012/13. Soil data were obtained from the Land Development Department, Ministry of Agriculture and Cooperatives (LDD, 2000). The attributes of the soil data were soil group and land type arranged in polygons. The sugarcane growing area included 28 soil groups (Fig. 2). The majority of the soils in the sugarcane growing area were sandy loam. The soil data were used as input data to the CANEGRO model. The available water content, saturated hydraulic conductivity, and bulk density of each soil group are shown in Table 1. The weather station data were obtained from the Department of Meteorology (TMD, 2010). There are seven weather stations in Khon Kaen province (WS-1 to WS-7; Fig. 3). The delineation of areas allocated to each station was determined by the Thiessen method. The 30-year-average annual rainfall of each weather station is shown in Table 2.

We defined the land units of the sugarcane growing area according to the soil group and weather station. Overlaying the soil map of Fig. 2 on the weather station map of Fig. 3 produced 82 simulation conditions. Each land condition was considered discrete for sugarcane production because of its unique combination of soil group and weather conditions. We simulated the sugarcane production for each of these 82 simulation conditions.

The groundwater map for well capacity was obtained from the Department of Groundwater Resources (DGR, 2014), and groundwater yield (m^3hr^{-1}) in the sugarcane growing area is shown in Fig. 4. The groundwater yield was used to define four categories of well capacity. WC-1, -6, -15, -25 represent well capacity of 1, 6, 15, and 25 m^{-3} hr^{-1}. Overlaying the groundwater yield map of Fig. 4 on simulation conditions produced 179 land units.

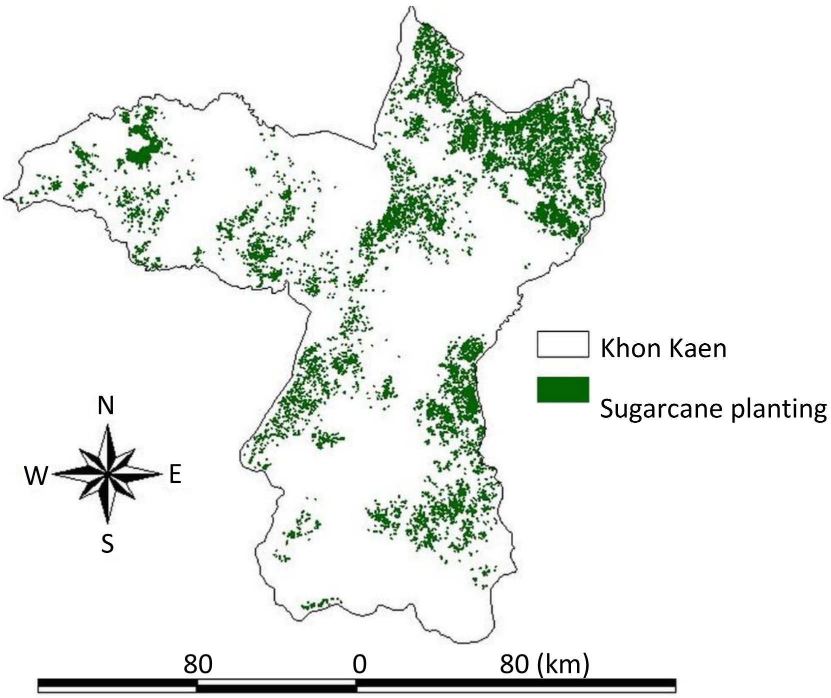


Figure 1 Area of sugarcane growing in Khon Kaen province, Thailand, 2012/13

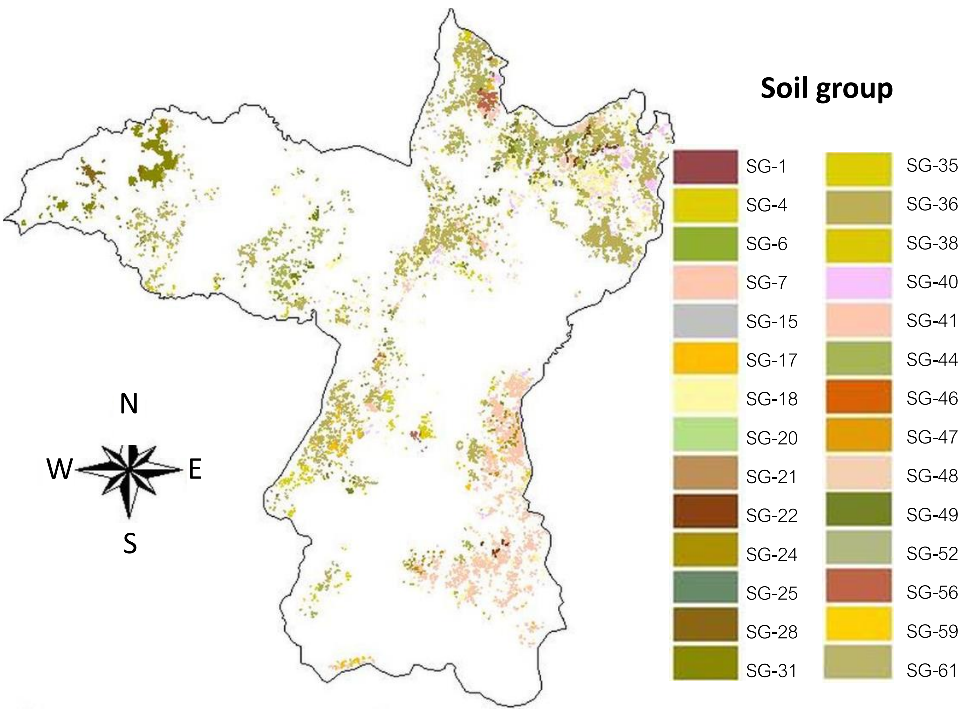


Figure 2 Distribution in area of sugarcane growing in Khon Kaen province, Thailand, of soil groups belonging to the Soil Database System of the Land Development Department, Ministry of Agriculture and Cooperatives, Bangkok, Thailand. The numbers correspond to groups in the classification of LDD, (2000).

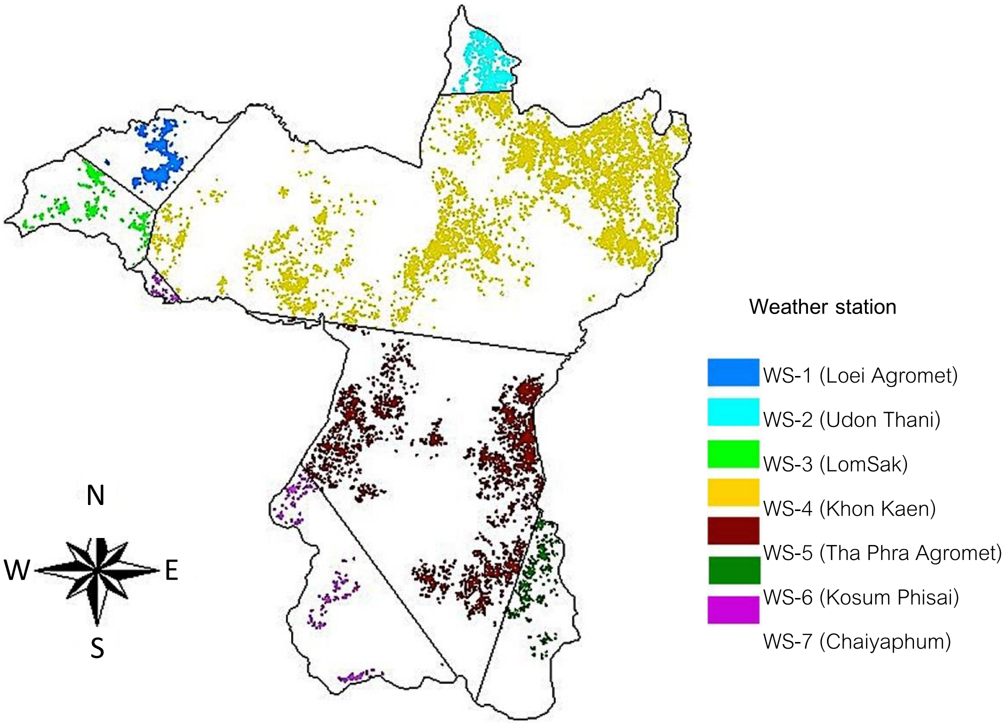


Figure 3 Division of Khon Kaen province, Thailand, into areas represented by weather stations of the Department of Meteorology, Thailand. The areas were defined by the Thiessen method. Areas of sugarcane growing are shown in different colours corresponding to the respective weather stations.

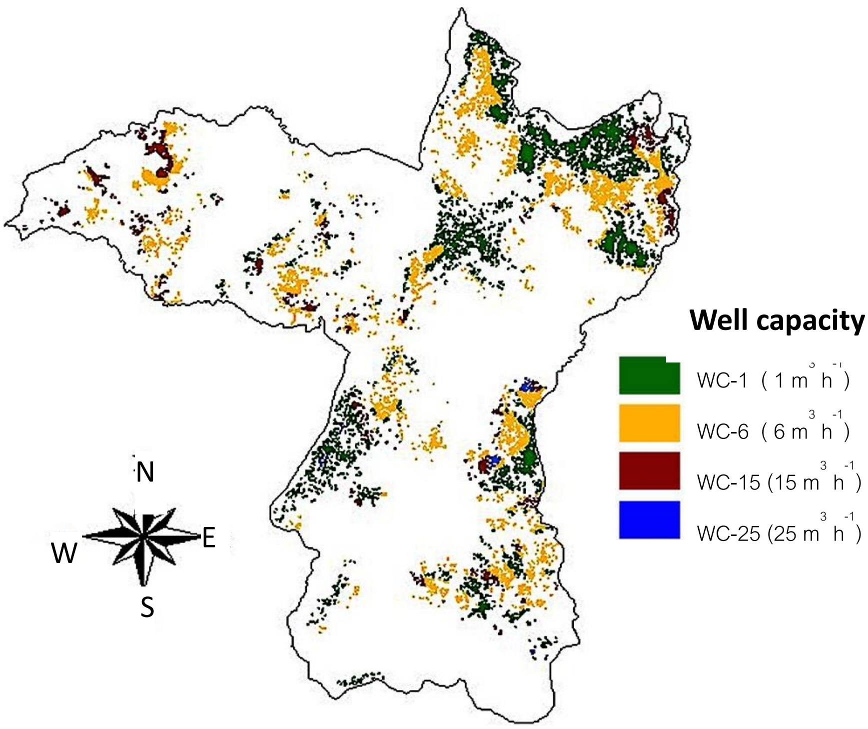


Figure 4 Classification of sugarcane fields in Khon Kaen province, Thailand, by groundwater well capacity

Table 1 Representative values of available water content (AWC), saturated hydraulic conductivity (Ks), and bulk density (BD) of the 28 soil groups that occur in sugarcane farmlands in Khon Kaen, Thailand.

SG	1	4	6	7	15	17	18	20	21	22	24	25	28	31
AWC (mm mm^{-1})	0.13	0.13	0.14	0.13	0.14	0.11	0.13	0.12	0.19	0.22	0.07	0.13	0.23	0.13
Ks (cm hr^{-1})	0.06	0.34	0.15	3.01	0.15	0.61	0.40	1.54	0.40	0.87	6.10	1.32	0.28	1.23
BD (g cm^{-3})	1.44	1.44	1.43	1.49	1.45	1.61	1.41	1.58	1.40	1.55	1.40	1.49	1.43	1.41
SG	35	36	38	40	41	44	46	47	48	49	52	56	59	61
AWC (mm mm^{-1})	0.12	0.13	0.25	0.12	0.10	0.08	0.10	0.12	0.13	0.13	0.13	0.13	0.13	0.12
Ks (cm hr^{-1})	2.59	1.70	2.31	6.84	10.06	13.34	0.36	0.06	1.31	2.59	0.15	0.69	0.09	0.06
BD (g cm^{-3})	1.57	1.48	1.60	1.71	1.68	1.70	1.52	1.37	1.51	1.56	1.38	1.51	1.44	1.37

Table 2 Average annual rainfall of the seven weather stations of Khon Kaen province, Thailand. SD is the standard deviation.

Station name		Average rainfall (mm y^{-1})	SD
Loei Agromet	WS-1	1311.3	177
Udon Thani	WS-2	1458.8	268
Lom Sak	WS-3	1080.7	209
Khon Kaen	WS-4	1306.6	234
Tha Phra Agromet	WS-5	1247.2	204
Kosum Phisai	WS-6	1309.5	178
Chaiyaphum	WS-7	1201.5	264

2. Model Simulations

We applied the CANEGRO model bundled with DSSAT ver. 4.5 (Hoogenboom *et al*. 2011) to simulate sugarcane yields for 30 years from 1980 to 2009. The input data consisted of crop management factors, crop genetic coefficients, daily weather data (rainfall, maximum and minimum temperature, and solar radiation), and physical and chemical properties of the soils. We used the input data for crop management recommended by the Department of Agriculture. The planting density was 5 plants m^{-2}. Sugarcane was planted on 15 October and harvested on 15 December of the next year. The genetic coefficients of the sugarcane variety KK3 were used, because this is a popular variety in Khon Kaen.

The conditions used for the simulations were the rainfed condition (RFC) and the automatic irrigation condition (AUIC) set in DSSAT. In the AUIC, irrigation water was supplied to 100% of the available water when the water content decreased to 50% of the available water. Adequate nitrogen fertilizer was provided in both conditions to remove soil fertility as a variable.

We simulated the sugarcane production of the 82 simulation conditions under the two conditions for the period 1980 to 2009. The output data extracted for the subsequent analyses were the sugarcane yield and the amount of irrigation water consumed.

3. Benefits Calculation

We calculated the yield gap, the yield under AUIC minus that under RFC, for each simulation condition and overlaid it with the underground water capacity. For each discrete area, the benefit values were calculated from

$$BF = IC - CS \tag{1}$$

$$IC = GP \times A \times Ps \tag{2}$$

$$CS = FC + VC \tag{3}$$

$$FC = K_{FC} \times A \tag{4}$$

$$VC = K_{VC} \times T_I \tag{5}$$

$$T_I = \frac{10 \times IR \times A}{WC \times n} \tag{6}$$

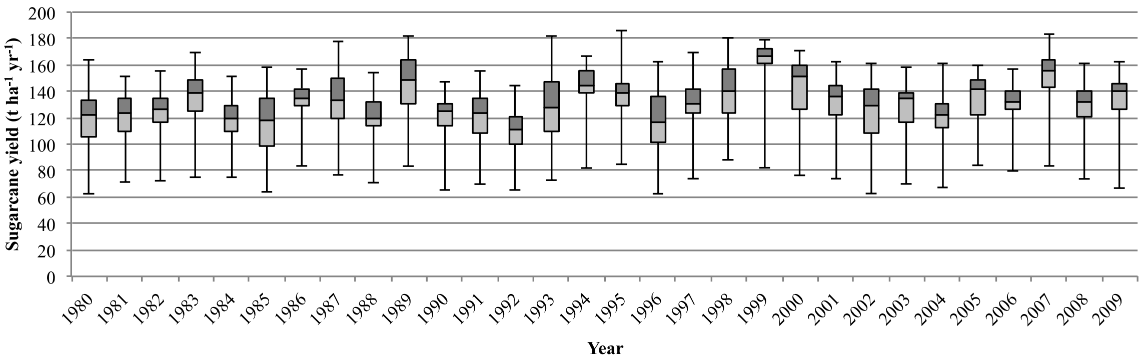
$$n = \frac{10{,}000 \times A}{32{,}000} \tag{7}$$

where *BF* is the benefit in Thai baht (THB), *IC* is the income (THB), *CS* is the cost (THB), *GP* is the yield gap (kg ha^{-1}), *A* is the area (ha), *Ps* is the price (THB kg^{-1}), *FC* is the fixed cost (THB ha^{-1}), *VC* is the variable cost (THB hr^{-1}), K_{FC} (THB ha^{-1}) and K_{VC} (THB hr^{-1}) are coefficient, and T_I is the hours of pump operation. n is a number of pump installed in the one polygon, *IR* is the simulated irrigation water (mm), and *WC* is the well capacity (m^3 hr^{-1}). The fixed cost is the initial investment cost of developing the irrigation scheme.

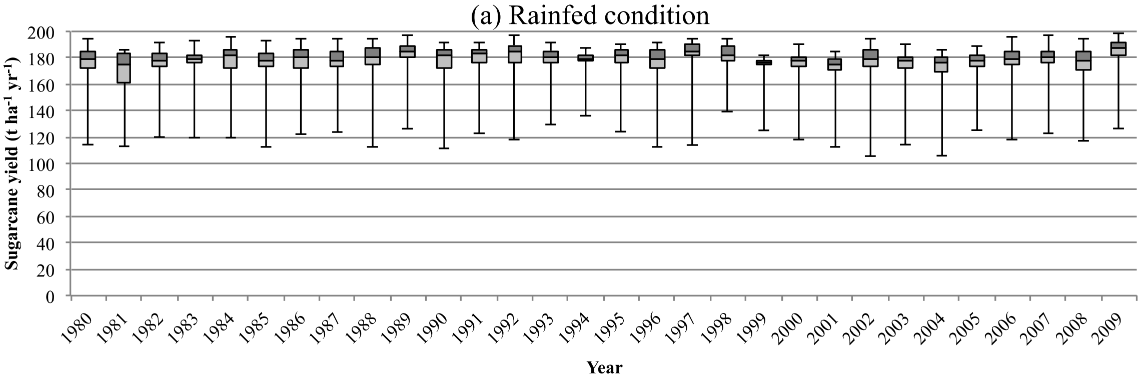
The variable cost is the running cost of providing irrigation water. In this study we used 0.7603 THB ha^{-1} for K_{FC} and 5 THB hr^{-1} for K_{VC} (OCSB and KKU, 2015). We calculated the hours of pump operation from the amount of irrigated water divided by the underground water capacity.

4. ABC Analysis

ABC analysis is often used in inventory control to classify items of inventory into a three-level ranking of importance to decide the level of control and record-keeping to which they should be subjected (Dhoka and Choudary, 2013). We used it here to classify the 179 land units into a three-tier system of benefit from providing irrigation. We sorted the results of the benefit calculation by the benefit per unit area (THB ha^{-1}) and accumulated benefit (THB). Then divided the areas into A, B, and C categories as follows: A, 0.0-69.8%; B, 69.8-89.9%, and C, >89.9%.



(a) Rainfed condition



(b) Automatic irrigation condition

Figure 5 Simulated sugarcane yield of 82 defined simulation conditions every year from 1980 to 2009 under rainfed (a) and automatic irrigation (b) growing condition in Khon Kaen province, Thailand.

5. Decision Tree

For irrigation to be developed efficiently, priority areas for irrigation development should be determined explicitly and objectively. Areas categorized as A rank in the ABC analysis can be regarded as more efficient for irrigation development than areas ranked B and C. Therefore, we tried to analyse the attributes that distinguished areas in Rank A from those in Rank B or C using the decision tree method.

We applied the C4.5 algorithms (Wei Dai and Wei Ji 2014) to construct the decision tree. In the C4.5 algorithms, the amount of entropy is calculated from,

$$E(S) = -\sum_{i=1}^{n} P_i \log_2 P_i \tag{8}$$

where *E*(*S*) is the entropy of the data set *S*, *n* is the number of classes, and *pi* is the proportion of the *i*th class in *S*. Then the weighted average entropy *E*(*A,S*) is calculated by

$$E(A,S) = -\sum_{i=1}^{m} \frac{|S_j|}{|S|} E(S_j) \tag{9}$$

where *Sj* is the subset *j*, and *m* is the number of subsets. The gain *Gain*(*A,S*) is calculated from

$$Gain(A,S) = E(S) - E(A,S) \tag{10}$$

The intrinsic information of the split *IntI*(*A,S*) is calculated as follows:

$$IntI(A,S) = -\sum_{i=1}^{m} \frac{|S_j|}{|S|} \log_2 \frac{|S_j|}{|S|} \quad (11)$$

The gain ratio *GR*(*A,S*) is calculated as follows:

$$GR(A,S) = \frac{Gain(A,S)}{IntI(A,S)} \quad (12)$$

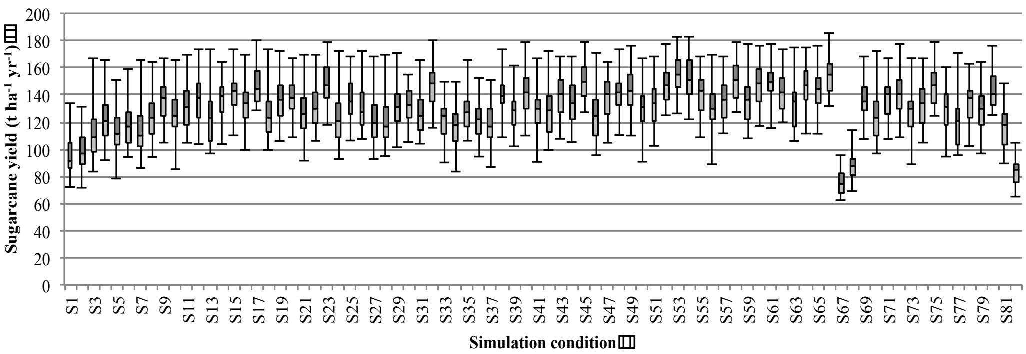
We defined areas ranked A as Class 1 (C-1), efficient for irrigation development, and those ranked B or C as Class 2 (C-2), inefficient for irrigation development. We used three attributes as explanatory variables: the weather station, the soil group, and the well capacity. We calculated the *GR* of each attribute and selected the internal nodes attribute with the largest *GR*. We stopped splitting when all data in a subset belonged to the same benefit class. In this study, we did not use the number of land units but the area of land units to calculate the entropy and the intrinsic information, because the area of each land unit was widely different.

Results and discussion

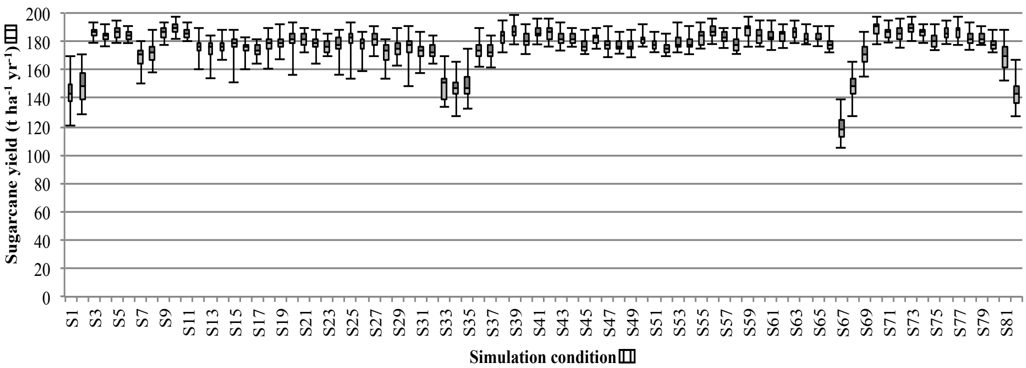
1. Simulation of the Sugarcane Yield

The calculated sugarcane yields of the RFC ranged from 92to 194 t ha^{-1} yr^{-1}, and the average was 153 t ha^{-1} yr^{-1}. That of the AUIC ranged from 105 to 199 t ha^{-1} yr^{-1}, and the average was 177 t ha^{-1} yr^{-1}. The average calculated sugarcane yield of the 82 simulation conditions under each condition in each year of the simulation is shown in Fig. 5, and that over the 30 years for each simulation condition is shown in Fig. 6. The average standard deviation of the calculated annual sugarcane yield over the 30 years was 15.2 t ha^{-1} for RFC and 12.4 t ha^{-1} for AUIC (Fig. 5). For all simulation conditions, the average standard deviation of the annual yield over the 30-year period was 11.0 t ha^{-1} for RFC and 3.0 t ha^{-1} for AUIC (Fig. 6). The difference in standard deviation between RFC and AUIC was larger for calculated yield averaged across simulation conditions (Fig. 6) than across years (Fig. 5). This suggests that irrigation reduced the variation in calculated sugarcane yield caused by differences in rainfall from year to year. Conversely, irrigation was less effective at reducing differences in yield caused by soil type.

The average irrigation water used across the 82 simulation conditions in each year is shown in Fig. 7 and that for the 30 years in each land unit is shown in Fig. 8. The average standard deviation in Fig. 7 was 63 mm yr^{-1} and that in Fig. 8 was 142 mm yr^{-1}. Thus, the temporal variability was considerably larger than the spatial variability.



(a) Rainfed condition



(b) Automatic irrigation condition

Figure 6: Sugarcane yield over 30 years of simulation for each of 82 defined simulation conditions under rainfed (a) and automatic irrigation (b) in Khon Kaen province, Thailand. Vertical bars are standard deviation.

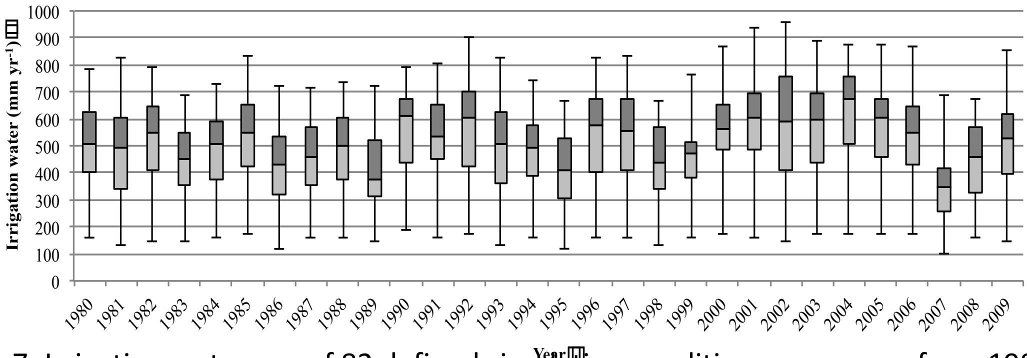


Figure 7: Irrigation water use of 82 defined simulation conditions every year from 1980 to 2009 in Khon Kaen province, Thailand.

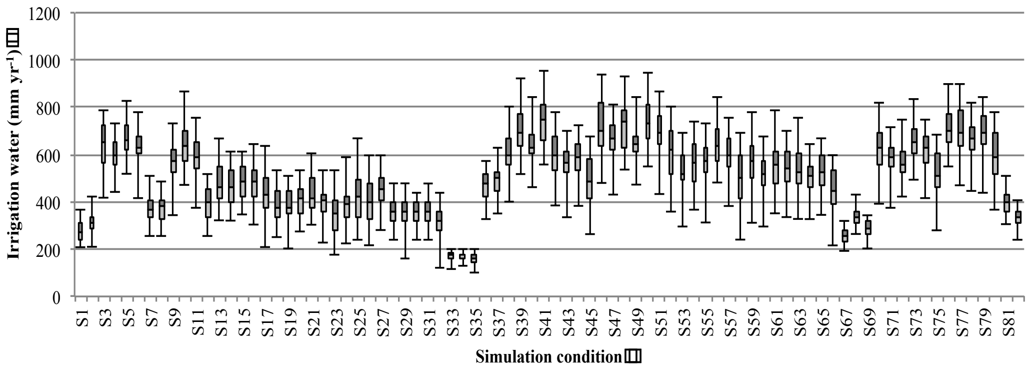


Figure 8: Irrigation water use over 30 years of simulation for each of 82 defined simulation conditions from 1980 to 2009 in Khon Kaen province, Thailand.

2. ABC Analysis

Figure 9 shows the spatial distribution of land units by ABC ranking as well as the land units with negative benefit. All land units with a negative benefit were in the area of well capacity WC-1. Moreover, many of these areas belonged to weather stations WS-2 and WS-4. For these weather stations, the calculated sugarcane yield was large for RFC, so there was little difference between the yields for RFC and AUIC, and the benefit was less than the cost of irrigation.

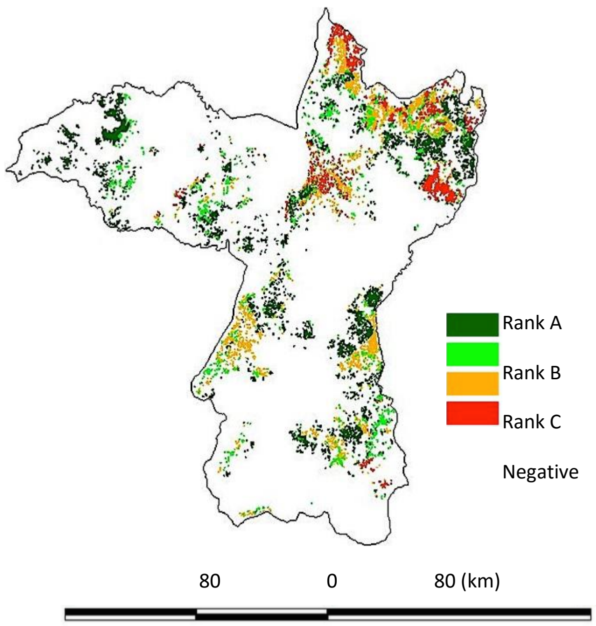


Figure 9 Classification of the sugarcane growing fields in Khon Kaen province, Thailand, into ranks by ABC analysis of the estimated benefit of irrigation development. Benefit was estimated from yield modelling, sugarcane prices, and irrigation costs.

Figure 10 shows the accumulated benefit of land units plotted against their accumulated percentage of the total area, with land units sorted in order of largest to smallest benefit par area (THB ha^{-1}). The plot is divided to show the contributions of the A, B, and C benefit ranks. We found that 69.8% of the total benefit (rank A land units) is achieved by irrigation development of just 46.7% of the area. The next 20.1% of benefit requires 22.6% of the area, and the final 10.1% of benefit requires 30.7% of the area. The efficiency of irrigation development, calculated by the proportion of the benefit divided by the proportion of the area, was 1.49 in the rank A land units, 0.89 in the rank B land units, and 0.33 in the rank C land units.

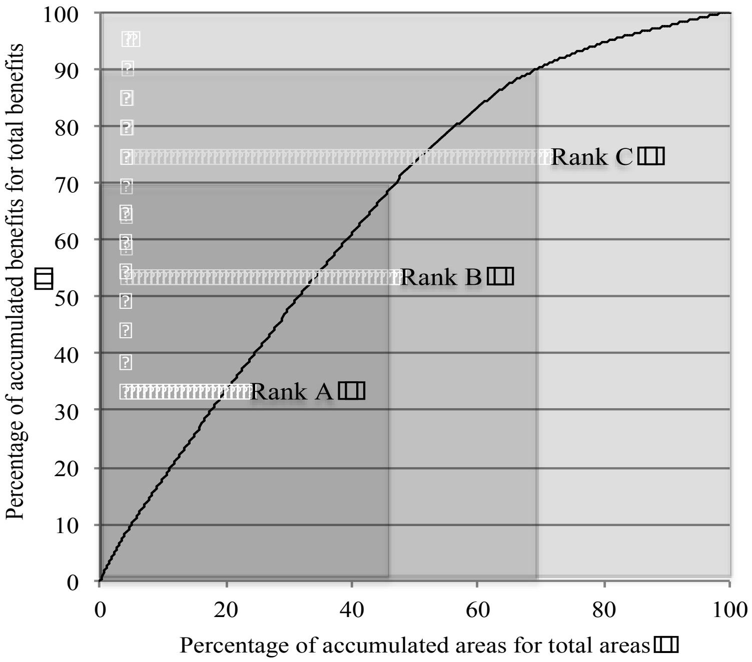


Figure 10: Accumulated area–benefit curve from the estimated benefit derived from irrigation development of sugarcane fields in Khon Kaen province, Thailand.

3. Decision Tree

Recall that from the ABC analysis, we classified rank A land units as class C-1 (efficient for irrigation development) and rank B and C land units as class C-2 (inefficient for irrigation development). The complete classification tree is shown in Figure 11.

For the first internal nodes attribute after the root, well capacity (WC) gave the lowest entropy and had the largest gain and gain ratio (Table 3). Therefore, we chose well capacity (WC) as the first internal nodes attribute. All land units in WC-25 belonged to C-1. From this result, we confirmed that the variable cost in of irrigation (Eq. 5) strongly influenced the benefit.

Table 3 Results of a decision tree analysis of estimated irrigation benefit for 179 defined land units in Khon Kaen, Thailand. Classification variables are weather station (WS), soil group (SG), and well capacity (WC).

	Entropy	Gain	IntI	Gain Ratio
WS	0.886	0.110	1.811	0.061
SG	0.835	0.161	2.955	0.055
WC	0.301	0.696	1.477	0.471

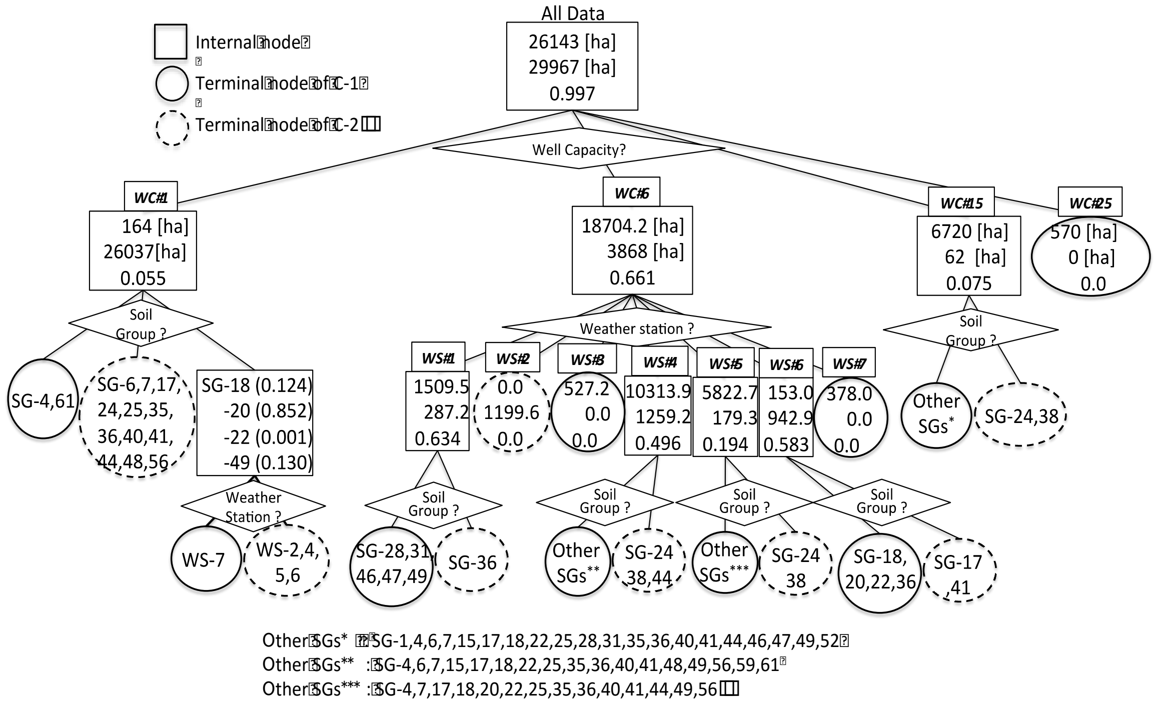


Figure 11: Decision tree of irrigation development simulation data to place the benefit of irrigation development into C-1 (efficient) or C-2 (inefficient) categories based on land attributes of well capacity, weather station, and soil group. WC-1, -6, -15, -25 = well capacity of 1, 6, 15, and 25 m^3 hr^{-1}; WS-1 to -7 = weather stations 1 to 7; SG-1 to -61 = soil groups (see Fig. 2 for list of soil

To identify the next internal nodes attribute, we calculated the entropy, gain, and gain ratio for all land units in WC-1, -6, and -15 by soil group and weather station (Table 4). In WC-1 and WC-15, the soil group had the largest gain ratio so was chosen as the second internal nodes attribute. In WC-6, the weather station had the largest gain ratio so was chosen as the second internal nodes attribute. In WC-1 and WC-6, there were terminal nodes of C-1 and C-2, and the internal node. In WC-15, all land units were in terminal nodes. Then, we tried to classify land units in internal nodes by weather station in WC-1 and by soil group in WC-6. As the result, all land units were in terminal nodes.

Table 4 Results of a decision tree analysis of estimated irrigation benefit for land units in each well capacity class (WC) (see Table 4 for further information).

		Entropy	Gain	Intl	Gain Ratio
WC-1	WS	0.042	0.013	1.351	0.009
	SG	0.025	0.030	2.505	0.012
WC-6	WS	0.385	0.276	1.538	0.180
	SG	0.397	0.264	2.984	0.088
WC-15	WS	0.060	0.015	1.232	0.012
	SG	0.000	0.075	2.750	0.027

We examined characteristics of classification by examining some terminal nodes (Figure 11). Examining the distribution of land units in C-1 and C-2 in WC-6 by weather station, all land units in WS-3 and WS-7 were in C-1, and all those in WS-2 were in C-2, so these formed the next terminal nodes. Weather stations WS-3 and WS-7 had low and WS-2 high average rainfall (Table 2). Thus, the benefit from irrigation development was large in areas with low rainfall and small in areas with high rainfall. Examining terminal nodes in the branch of well capacity WC-6, most soil groups were in C-1. The soil groups in C-2 were SG-17, -24, -36, -38, -41, and -44, but of these soil groups, SG-17, -36, and -41 were also in C-1 in some weather station areas (see "Other SGs" in Figure 11). So SG-24, -38, and -44 formed a C-2 terminal node, SG-17, -36, and -41 needed further analysis, and all other soil groups formed a C-1 terminal node.

For the remaining three soil groups, SG-17, -36, and -41, the C-1 and C-2 terminal nodes were defined by weather station, with WS-1 and WS-6 forming the C-2 terminal node and WS-4 and WS-5 forming the C-1 terminal node.

We examined the yield, rainfall, irrigation, and benefit data for these three soil groups (Table 5). Among these data, we see that the yields under irrigated condition are almost the same within the same soil group. However, under rainfed condition, yields were more varied within soil group, and the land units with larger rainfed yields had smaller yield gaps and lower benefit, and weretherefore classified as C-2. The land units with lower rainfed

Table 5 Results of simulation of sugarcane yield for soil groups (SG) 36, 17, and 41 grouped by benefit class and weather station for land units in well capacity class WC-6 and weather stations WS-1, WS-4, WS-5, or WS-6. Data are simulated yields under irrigated (Y_I) or rainfed (Y_R) condition, the Gap between Y_I and Y_R (calculated as $Y_I - Y_R$), the irrigation water applied (Ir), rainfall received (P) and benefit of irrigation development (Benefit). The number in parenthesis following the soil group number is the available water content (AWC).

SG	Class	WS	Y_I (t ha^{-1})	Y_R (t ha^{-1})	Gap (t ha^{-1})	Ir (mm yr^{-1})	P (mm/yr)	Benefit (THB/ha)
36 (0.130)	1	WS-4	178.0	137.6	40.4	670.4	1306.6	34842.6
		WS-5	178.0	134.4	43.6	694.4	1247.2	37772.6
	2	WS-1	177.4	143.3	34.1	647.2	1311.3	28705.9
17 (0.117)	1	WS-5	175.4	133.7	41.7	480.1	1247.2	37718.4
	2	WS-6	177.8	143.0	34.8	482.5	1309.5	30738.4
41 (0.098)	1	WS-4	183.6	147.1	36.5	517.3	1306.6	32218.4
		WS-5	184.1	143.4	40.7	545.3	1247.2	36135.1
	2	WS-6	184.1	150.8	33.3	548.4	1309.5	28729.2

yields showed a greater yield gap and larger benefit and were therefore classified in C-1.

At the lowest level of the classification, the classification as C-1 or C-2 appeared to depend on the rainfall of each weather station. However, even though the average rainfall of WS-1, -4, and -6 were almost the same, WS-1 and WS-6 were classified as C-2 and WS-4 was classified as C-1. The standard deviations of annual rainfall at WS-1, -4, and -6 were 177, 234, and 177, respectively (Table 2). The annual rainfall, and therefore yield under rainfed condition, varied widely for WS-4 resulting in the average yield being less than those of the other two weather stations.

Then, we extracted the results of the simulation for the C-2 soil groups (SG-24, -38, -44) occurring in the areas of WS-4 and WS-5 (Table 6). The available water content of SG-24 and SG-44 was low, whereas that of SG-38 was large. When the available water content was low, the yield gap was small because the irrigated yield was low. On the other hand, when the available water content was large, the gap was small because the rainfed yield was large. From these data we conclude that the effect of irrigation development is low when water holding capacity is either low or high.

Table 6 Results of simulation of sugarcane yield for soil groups (SG) 36, 17, and 41 grouped by benefit class and weather station for land units in well capacity class WC-6 and weather stations WS-1, WS-4, WS-5, or WS-6. Data are simulated yields under irrigated (Y_I) or rainfed (Y_R) condition, the Gap between Y_I and Y_R (calculated as $Y_I - Y_R$), the irrigation water applied (Ir), rainfall received (P) and benefit of irrigation development (Benefit). The number in parenthesis following the soil group number is the available water content (AWC).

WS	SG		Y_I (t ha^{-1})	Y_R (t ha^{-1})	Gap (t ha^{-1})	Ir (mm yr^{-1})	P (mm/yr)	Benefit (THB/ha)
WS-4	44	(0.082)	182.4	147.1	35.4	507.1	1306.6	31123.4
	24	(0.067)	148.6	121.2	27.4	166.8	1306.6	26039.2
	38	(0.253)	179.4	155.7	23.7	532.1	1306.6	19285.1
WS-5	24	(0.067)	146.1	117.6	28.5	168.3	1247.2	27136.7
	38	(0.253)	179.3	152.8	26.5	562.0	1247.2	21795.9

Examining the distribution by area of C-1 and C-2 between the four well capacities in Figure 11, most of the area in WC-15 and WC-25 belonged to C-1, and most of the area in WC-1 belonged to C-2. From this result, we concluded that irrigation development could be conducted in areas of WC-15 and WC-25, but not in areas of WC-1.

Conclusion

From this study, we conclude the following

From the ABC analysis, 70% of the potential benefit could be carried out by the irrigation development of 47% of the cultivation area.

In the decision tree analysis, we confirmed that well capacity was the attribute that most influenced the efficiency of irrigation development. Irrigation development was efficient in the areas with high well capacity (>15 m^{-3} hr^{-1}), but was clearly inefficient where well capacity was low (1 m^{-3} hr^{-1}). At intermediate well capacity, irrigation development was efficient in the majority of the area (18,704 ha efficient versus and 3868 ha inefficient). In areas with higher rainfall, the yield under rainfed conditions was large so the benefit of irrigation development tended to be low. Moreover, soil groups with either low or high available water content resulted in low efficiency of irrigation development.

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CHAPTER IV

Simple Equation for Estimating Sugarcane Yield

Abstract

Estimation on sugarcane yield before harvesting is required by sugar mills and farmers. Normally, they estimate yield by sight which was low accuracy. To have more accuracy yield estimation, sample sugarcane needed to be cut for weighting. However, It is difficult to do and cause yield lose. The objective of this study was to develop the equation for estimating sugarcane yield which was easy to use and high accuracy. Two hundred stalk samples of each Khon Kaen3 and LK92-11 cultivar were taken to measure and then calculate the correlation between stalk height, stalk circumferences, and stalk weight. The results showed that there was high correlation between stalk height and stalk weight in both cultivars, R^2 =0.976 and 0.955 for Khon Kaen3 and LK93-11 respectively. A simple equation was developed based on stalk weight, and stalk number per area. Then it was validated and found good estimation for both cultivars. R^2, RMSE and nRMSE were 0.842, 4.2 t/rai and 19 % in Khon Kaen3 while there were 0.884, 2.2 t/rai and 12.9% in LK92-11. Finally, these equations had developed to the application namely *Cal Cane* that available for downloading on the Google play store. This can be either used on smart phone with the android operation system.

Introduction

Sugarcane production and sugar industry is the major economic in Thailand. Each year, there are 1.5-1.7 million hectares of planting area, and produce 95-100 million tons of sugarcane (OCSB, 2015). Although, Thailand is the fourth biggest sugarcane producing country and the second biggest sugar exporter in the world, the area of plantation is varying between the year. Production was fluctuated due to drought as well as the epidemic of disease and insects, especially sugarcane borer and the area of plantation is rebound back due to an incentive from higher price. The increased planting area of sugarcane are cassava area where it has aphid problems and upper paddy area where rice cannot grow well because of drought. The most popular sugarcane cultivars are cultivar Khon Kaen 3 (KK3) and LK92-11 cover more than 85% of total planting (OCSB & KKU, 2015). Sugarcane production is controlled by the act. Farmers who want to plant sugarcane and sell for sugar mill must register as the farmer for sugarcane production. In 2015, the act said only farmers who has the land for growing sugarcane more than 16 hectares with can sell the sugarcane to sugar mill. Therefore, not all farmers can sell the products directly to sugar mill. Small-farm farmers who have the land less than 50 rai, usually sell their production to the big farmers (registered farmers) who have been already registered. In sugarcane production, there is high yield variability. Some year the sugarcane production affected by extremely drought stress and it caused very low yield. Every year big farmers must have amount of cane to meet the quotas which they promise to the sugar mill. So that the cash trading systems for sugarcane production, between big farmers and small farmers are occurs. This deals conduct around two or three months, before harvesting season. In generally, sugarcane yield will be visual estimated on the field by both buyer and seller. After that the big farmers normally pay to the small farmers to guarantee the products in the harvesting season. The estimation of sugarcane yield by sight is low accuracy and high risk, depend on their experience. Because sugarcane yield varies to stalk weight, if they need more accuracy, cutting sugarcane needed to take sample for weighting. It is difficult to do and cause yield loss. Therefore, the methodology for estimating sugarcane yield with the high accuracy and easy to use, **i**s needed to be developed. The objective of this study is to develop the methodology for estimation of sugarcane yield of sugarcane cultivar Khon Kaen 3 and LK92-11.

Materials and methods

Methodology to calculate sugarcane yield

Yield of sugarcane per rai (1600 m^2) can calculate by the yield components such as number of stalk per rai and each stalk weight and can write to the equation below:

$$Y = S_{no}W \tag{1}$$

Where *Y* is Yield (t/rai), S_{no} is stalk number per rai, and *W* is stalk weight (kg), and stalk number per rai calculate by the equation

$$S_{no} = 16\frac{S_{10}}{L_{ro}} \tag{2}$$

When $S_{10}$is number of stalk in the row with 10 m long, L_{ro} is row spacing (cm), and 16 is the constant value for transfer the unit to t/rai

Methodology to calculate stalk weight

Methodology for calculation each stalk weight is calculated by the correlation between stalk height and stalk circumference. For this study, each sugarcane cultivar KK3 and LK92-11, 200 stalks were sampling from different field condition and size. After that, each stalk was measured stalk weight and stalk circumference at the middle of stalk. Finally, correlation between stalk weight and stalk circumference was done by the six regression models as below:

$$W = bH + c \tag{3}$$

$$W = bD + c \tag{4}$$

$$W = bH^2 + c \tag{5}$$

$$W = bD^2 + c \quad (6)$$

$$W = bHD + c \quad (7)$$

$$W = bH + aD + c \quad (8)$$

Where *W* is stalk weight (kg), *H* is stalk high (cm), and *D* is stalk circumference (cm)

The best regression model with the highest correlation evaluated by the coefficient of determination (R^2) will select to calculate sugarcane yield.

Validation of the equation

After select the equation for calculation of the sugarcane yield, validation of the equation was validated with sugarcane yields that harvested in the field experiment by Peerasak (2014) for 39 samplings. The three statistically, the Coefficient of Determination (R^2), Root Mean Square Error (RMSE) and normalize Root Mean Square Error (nRMSE) were used to evaluate the efficiency of the equation. The RMSE and nRMSE can calculate by

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(S_i - O_i)^2}{N}} \quad (9)$$

$$nRMSE = \frac{RMSE \times 100}{\bar{O}} \quad (10)$$

When *S* is sugarcane yield that calculated by the equation, *O* is sugarcane yield from the observed, *N* is number of sampling, and $\bar{O}$ is the mean of sugarcane yield from the observed.

The accuracy of the equation for calculation of sugarcane yield was considered of the RMSE. The RMSE close to 0 is shown the high accuracy but if the RMSE close to infinity (∞) it mean the equation cannot use for calculating sugarcane yield because of not accuracy. For then RMSE, used for estimation of the efficiency of the equation. The equation is considered excellent with a nRMSE of less than 10%, good if the nRMSE is greater than 10 and less than 20%, fair if the nRMSE is greater than 20% and less than 30%, and poor if the nRMSE is greater than30% (Jamieson *et al*., 1991).

Development of the equation to the application

After validation of the equation, the equation was developed to the application. This application designed for the smart phone with android operation system. The application must easy to use with the 4 input data such as the average of stalk high from 10 stalks, the average of stalk circumference from 10 stalks, stalk number in the row with 10 m long, and row spacing. After input data the application can calculate the sugarcane yield.

Results

Equation for the calculation of sugarcane yield

The six regression models (Eq. 3-8) showed high correlation between stalk height and stalk circumference. Their R^2 ranged from 0.902-0.976 and 0.805-0.955 for sugarcane cultivar KK3 and LK92-11, respectively (Table 1).

Table 1 Six regression models and their statistically regression coefficients (R^2) of sugarcane cultivar KK3 and LK92-11.

Cultivar	Regression models	R^2
KK3	Eq. No. (3) W = 0.015H - 1.354	0.926
	(4) W = 0.406D - 2.450	0.906
	(5) W = 0.00004H^2 + 0.188	0.925
	(6) W = 0.0194D^2 – 0.356	0.902
	(7) W = 0.0009HD – 0.134	0.967
	(8) W = 0.0088H + 0.1987D – 2.0861	0.976
LK92-11	Eq. No. (3) W = 0.012H – 0.846	0.887
	(4) W = 0.406D - 2.450	0.805
	(5) W = 0.00004H^2 + 0.188	0.885
	(6) W = 0.0194D^2 – 0.356	0.840
	(7) W = 0.0009HD – 0.134	0.945
	(8) W = 0.0080H + 0.1968D – 2.0521	0.955

The highest R^2 was shown by the equation number 8 for both cultivars so the equations were used to calculate their stalk weight and can rewrite into equation 9 for cultivar KK3 and equation 10 for LK92-11.

$$W_{kk} = 0.00882H + 0.19871D - 2.0861 \qquad (9)$$

$$W_{lk} = 0.00797H + 0.19681D - 2.0504 \quad (10)$$

When W_{kk} is the stalk weight of sugarcane cultivar KK3, W_{lk} is the stalk weight of sugarcane cultivar LK92-11, H is stalk height, and D is stalk circumference. Equation (9) was integrated with equation (1) and rewrite to equation (11) while equation (10) was integrated with equation (2) and rewrite to equation (12) as below.

$$Y_{kk} = (0.14112H + 3.1792D - 33.3776)\frac{S_{10}}{L_{ro}} \quad (11)$$

$$Y_{lk} = (0.12750H + 3.1490D - 32.8333)\frac{S_{10}}{L_{ro}} \quad (12)$$

When Y_{kk} is estimated sugarcane yield for cultivar KK3 (t/rai), Y_{lk} is estimated sugarcane yield for cultivar LK92-11 (t/rai), H is stalk height (cm), D is stalk circumference (cm), S_{10} is stalk number counting from the row of 10 m long, and L_{ro} is row spacing (cm)

Validation the equation

The results from validation found that both equation (11) and (12), gave the good efficiency for calculation of the sugarcane yield. R^2, RMSE, and nRMSE were 0.847, 4.2 t/rai, 19.5%, and 0.884 for sugarcane cultivar KK3 and were 2.2 t/rai, and 12.9% for cultivar LK92-11 (Fig. 1).

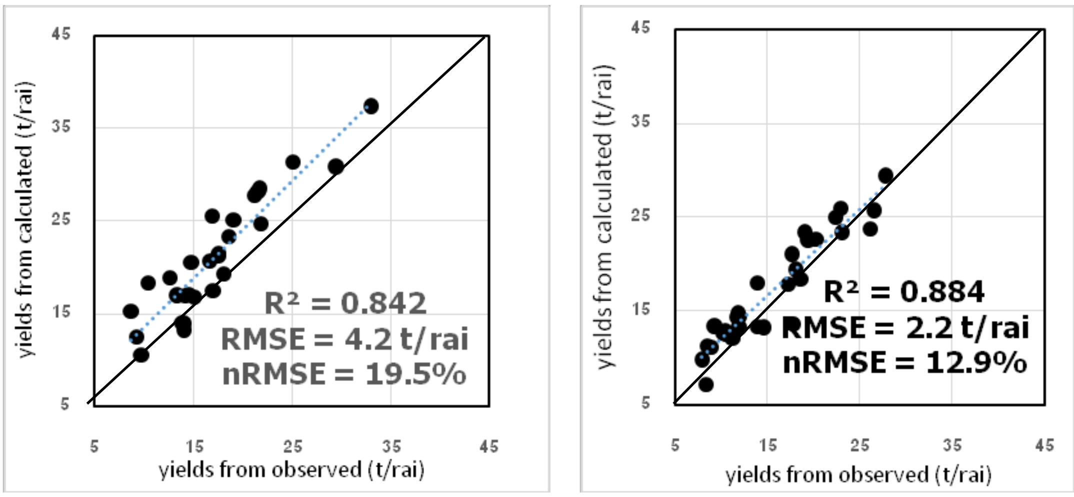

Figure 1 Correlation coefficient (R^2), Root Mean Square Error (RMSE), and normalize Root Mean Square Error (nRMSE) between estimated and observed sugarcane yields of sugarcane cultivar KK3 (left) and LK92-11 (right)

Development of the equation to the application

The application on simple equation to estimate yield of sugarcane cultivar KK3 and LK92-11 was developed named as *Cal Cane* that. It can be used by the smartphone with the android operation system. User can download from the google play store. More over users can download this application directly by link http://play.google.com/store/apps/details?id=calsugarcane. There are three steps for the application use. First step, users need to measure stalk height and stalk circumference in the field and count stalk number in the row with 10 m long and measure the row spacing. Step two, input the four values on the application form and step three, select the cultivar to calculate the sugarcane yield. Finally, the result of the sugarcane yield with the unit t/rai will show on screen. The example for using the application showed in the Figure 2

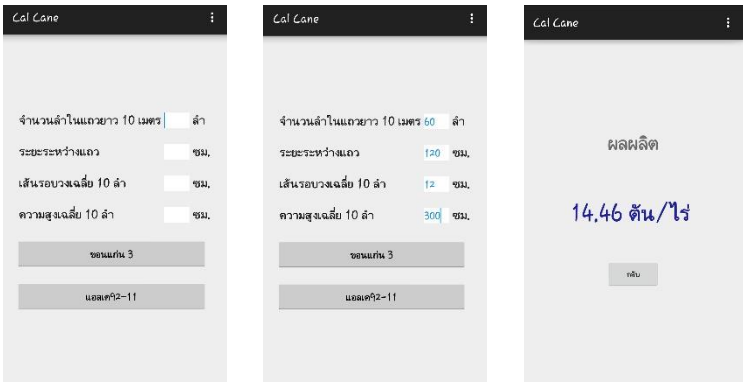

Figure 2 The exampled use of the application Cal Cane for on sugarcane yield estimation.

Discussion and conclusion

The simple equations

All six regression models are the simple equations and easy to calculate sugarcane yield. There is high correlation between stalk height, stalk circumference and stalk weight. Using only stalk height or stalk circumference gave the lower R^2 than used both stalk height and circumference. The simple equation was developed from the 200 samplings of sugarcane stalks under the variability of environments. So this equation can be used to calculate sugarcane yield for all sugarcane fields.

Validation of the simple equation

The results from validation showed the nRMSE ranged from 10 % to 20% indicated that the simple equation has a good performance to calculate sugarcane yield. Although the R^2 for the developed the equation for the sugarcane cultivar KK3 was better than LK92-11 but when validated with the field the equation for calculate sugarcane yield for cultivar LK92-11 was better and both gave the over estimation. Because the sampling in the field was measured stalk length after the harvesting which normally shorter than stalk height around 5-10 cm, so they gave over estimating. In general, farmers harvested by cutting and also cut the top of the stalk with closely near to stalk height therefore when used the equation for calculate sugarcane in the fields gave better results than validation.

Development of the application

The *Cal Cane* application was developed for only smartphone with android operation system. For the other operation system will be developed. However, users can use this equation for calculation of sugarcane yield by both manual and computer. Because of the application was install in smartphone with already install the Global Positioning System (GPS), so users will know the coordination. If they know the information of soil type and weather zone by overlaid the map into the smartphone and also have the information for field managements, the application will be high efficiency and can develop to the decision support system for sugarcane production.

Suggestion

The application *Cal Cane* will be high accuracy if users have a good sampling in the field. If the sugarcanes in the field are not uniform, users should take sampling more than 10 samples. This application can give high accuracy for calculation of sugarcane yield only both cultivars. KK3 and LK92-11. It can be use for other cultivars but may be lower accuracy. Linked this application with soil map and weather map can be more useful. The application will be developed in next step.

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CHAPTER VI

Evaluation of the Efficiency of Simple Equation for Estimating Evapotranspiration and Changes of Soil Moisture in Sugarcane Field

Abstract

Improvement of sugarcane yield has considered to be in parallel with that of water use efficiency. Analysis to find options for better yield and water use efficiency need to be estimated of evapotranspiration of which the Penman-Monteith FAO-56 (PM-56) has been widely used. However, the unavailability of complete local weather data has largely restricted its application. This study has evaluated the simple equation and linked to water balance model for estimating soil moisture in the sugarcane field. Soil Moisture was measured by TDR soil moisture sensor and automatic recorded by data logger in the experimental field. The experiment was conducted in Khon Kaen Field Crops Research Center during March to September, 2014. Sugarcane cultivar KK3 was planted in plot size of 36x40 m with spacing of 1.20x0.50 m. After that simple equations were developed for estimating evapotranspiration and changes of soil moisture in sugarcane field. Comparison the simple equation with Penman-Montieth FAO-56 (PM-56) and Priestley-Taylor (PT) for evapotranspiration and compared with experiment and CANEGRO model for soil moisture. Simple equation performance was evaluated using the statistical parameters such as correlation coefficient (R^2) and normalized root mean square error (NRMSE). The result showed that the simple equation was excellence for estimating evapotranspiration when compared with PT. The total evapotranspiration was closed to PT equation with the difference of 2.2% lower than PM-56 equation which of 19.1%. The simple equation also gave the good estimation of soil moisture with the NRMSE of 10.2%. The results indicated that the evapotranspiration and soil moisture in sugarcane field can be estimated by the simple equation.

Keywords: Sugarcane, Simple equation, Evapotranspiration, Soil moisture

Introduction

Thailand is an agricultural country. The economics of the country as a whole depends on crop production. Sugarcane is important economic crop of Thailand. Besides using as raw material for sugarcane and sugar industries, it plays an important role as raw materials for producing ethanol. In production year 2014/2015, there are 1.7 million hectares for planting sugarcane, and produce 106 million tons of sugarcane. (OCSB, 2015). Presently, there are 51 sugar mills with total capacity of producing sugar more than 100 million tons per year. In addition, sugar industry provided jobs for more than 60,000 people, and the export worth of more than 88,000 million baht.

Although, Thailand is the fourth biggest sugarcane producing country and the second biggest sugar exporter in the world, however the area of plantation is varying between the year. Some year was decreased due to drought as well as the epidemic disease and insects in some areas, especially sugarcane borer and the area of plantation is rebound back due to in incentive from higher price. The increases of planting areas expand to cover cassava planting area where is having problems with aphids, and upper paddy areas where rice grown not well because of drought. Therefore, these environmental indicated that production of sugarcane in the Northeast of Thailand would be most affected by drought stress with the main cause for getting the average lower yield than the others.

Water management is important to sugarcane production. To know the efficiency to water management needs to evaluate soil moisture. Because there are many soil type and variation of rainfall soil moisture must be evaluated by the model. Recently, many crop models can evaluate soil moisture such as the Decision Support System for Agro Technology Transfer program (DSSAT) (Hoogenboom et. al.,2015), including many crop models and the AquaCrop model (Steduto et. al., 2012). Most of crop models have the water balance module. The equation for calculate the reference evapotranspiration that world wild using is the Penman-MonteithFAO-56 (PM-56) (Allen etal., 1998), showed in equation (1)

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

Where:

ET_o = reference evapotranspiration (mm d^{-1}), Δ = slope of saturation vapor pressure curve at air temperature T [kPa °C^{-1}], R_n = is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G = soil heat flux [MJ m^{-2} day^{-1}], γ = psychrometric constant [kPa °C^{-1}], T = the air temperature, u_2 = wind speed at 2 m above ground surface [m s^{-1}], e_s = the vapor pressure of the air at saturation (kPa), e_a = actual vapor pressure [kPa]

This equation needs four meteorological parameters: air temperature, net radiation, wind speed, and relative humidity, however some location not all parameters are available. So the equation with low meteorological data can be used such as Priesley-Taylor (PT) (Priestley and Taylor, 1972), shows in the equation (2)

$$ET_o = \frac{1}{\lambda} \propto \frac{\Delta}{\Delta+\gamma} R_n \quad (2)$$

When using the value of $\propto$ = 1.25 (Monteith and Unsworth, 2008), R_n = 0.62S (Yoshida, 1981), and $\frac{\Delta}{\Delta+\gamma}$ = 0.78 (Krirk, 2009), the results found that the reference evapotranspiration estimating by PT gave the lower output than PM-56. In addition, Krirk (2009) had been applying the PM-56 to the simple equation with the assume that if temperature, relative humidity, and wind speed is not substantially changed then the reference evapotranspiration is only depending on the solar radiation and can calculate by linier equation as the equation (3)

$$ET_o = (bR_n + a)/\lambda \quad (3)$$

when

$$R_n = (1 - albedo)S + ln \quad (4)$$

b and a is the constant value for the equation, λ =latent heat of vaporization, R_n is net solar radiation (MJ $m^{-2}d^{-1}$), S is solar radiation (MJ $m^{-2}d^{-1}$), and *ln* is the long wave. The results showed that the linier equation gave the good estimation of reference evapotranspiration in the rainfed paddy field. The objective of this study is to apply the simple equation for estimating the reference evapotranspiration and changes of soil moisture in the sugarcane field.

Material and methods

Field experiment

Sugarcane cultivar Khon Kaen 3 (KK3), planting all over Khon Kaen province, were planted at Khon Kaen Field Crops Research Center (KKFCRC) during March 2014-September 2014. KKFCRC is located at 16.48N, 102.82E, 181 m elevation, in the Northeast of Thailand. Soil properties such as water holding capacity at field capacity and permanent wilting point, bulk density, soil texture, and soil hydraulic conductivity were sampling before planting. Sugarcane were planted on big plot size (36x40 m) with 30 rows of 40 m long, 1.2 m apart. Fertilizer of 46.75N -20.40P_2O_5-38.81K_2O kg /ha were applied at planting followed with 100 kg/ha of DAP. For irrigation, 24 mm of water per week was supplied by drip irrigation until harvest to prevent drought. The other managements such as weeds and diseases control were manual. In the experiment, soil moisture sensors (EC5) were installed for four points at 15 cm depth and automatic recorded by the data logger (EM50) since planting to harvesting.

Applied of simple equation for estimating the reference evapotranspiration

From equation (3) and (4), replacing with 0.25 for albedo in sugarcane field (Pereira *et al*., 2013), 2.45 for latent heat of vaporization, and -1 for long wave, can rewrite to the new equation as below

$$ET_o = 0.24S + 0.49 \tag{5}$$

Using equation (5) estimated the reference evapotranspiration (ET_o). The meteorological data from 1 January 2014 to 30 September 2014 were used for input to this equation. Compared the results with the outputs from the PM-56 and the PT equation.

Applying the simple equation for estimating changes of soil moisture in the sugarcane field

The simple equation for estimating changes of soil moisture is shown as the equation (6)

$$ET = ET_o \times Ks \times Kc \tag{6}$$

When ET = Crop evapotranspiration, ET_o = reference evapotranspiration, Kc = crop coefficient of sugarcane =0.39-2.25 depend on crop stage (Kobkiat *et al*., 2013), and Ks is the allowing of soil for evaporation. The Ks can be calculated using the following equation:

$$Ks = \frac{(\theta - \theta_{wp})}{(\theta_{fc} - \theta_{wp})} \tag{7}$$

When ϑ= soil moisture (mm/mm), ϑ_{wp} = soil moisture at the permanent wilting point (mm/mm), and ϑ_{fc}= soil moisture at the field capacity (mm/mm).

So the rate of soil moisture changes (d_ϑ) (mm/d) can be calculated by the equation (8)

$$d_\theta = Rf - ET - Ro - Dp \tag{8}$$

When

$$Rf = 0.3Ro$$

$$Inf = Rf - Ro$$

$$as = (\theta_{fc} - \theta)z$$

For this equation, if the value of *Inf* equal to or less than *as,* then D_p= 0 but if the value of *Inf* more than *as,* then the value of D_p can be calculated by the equation (9)

$$Dp = Inf - as \tag{9}$$

When *Rf* is the daily precipitation (mm), *Ro* is run off from the soil (mm), *inf* is the infiltration rate in to the soil (mm/d), *as* is available water capacity (mm), *z* is soil depth (mm), and D_p is deep percolation to lower layer (mm/d)

Finally, changes of soil moisture can be calculated by equation (10)

$$\theta = \theta + d_\theta \tag{10}$$

Evaluation the efficiency of the simple equation

Comparison the soil moisture that calculated by the simple equation with the soil moisture that observed from the experiment field and from the CANEGRO model. The three statistically, the coefficient of determination (R^2), the root mean square error (RMSE), and normalized RMSE (NRMSE) were used to evaluate the efficiency of the simple equation. The RMSE and NRMSE can be calculated by the equation below:

$$RMSE = \sqrt{\frac{\sum(S_i - O_i)^2}{N}}$$

$$NRMSE = \frac{RMSE}{\bar{O}} 100$$

When S_i is the calculated value, O_i is the observed value, *N* is number of sampling and $\bar{O}$ is mean of the value from observation.

The simulation is considered as excellent when a normalized RMSE of less than 10%, good if the normalized RMSE is in a range of 10% - 20%, fair if the normalized RMSE is 20% - 30%, and poor if the normalized RMSE is greater than 30% (Jamieson *et al*., 1991).

Results and discussion

Soil properties

Soil at the top profile (0-30 cm) is the sandy loam with bulk density of 1.63 g cm^{-3} and the hydraulic conductivity is 4.48 cm hr^{-1}. For the water holding capacity, soil moisture at field capacity is 0.243 mm/mm and at the permanent wilting point is 0.121 mm/mm. This soil is upland soil and defines as the soil group 35. Because soil is the sandy loam with low available water capacity and high rate of water percolation, this field will have the high risk to water deficit.

Reference evapotranspiration

The reference evapotranspiration ranged from 1.7 to 8.5 mm d^{-1} totally 1,858 mm in this year. The result from simple equation is as same as from the PT equation (1,899 mm). While the result from the PM-56 equation showed higher than the previous two equations. The reference evapotranspiration from PM-56 equation was 2,296 mm higher than PT equation 17.3% and simple equation 19.1% (Fig.1). However, reference evapotranspiration from three equations showed high correlation. There is high correlation between the reference evapotranspiration that calculated by the simple equation and PM-56 equation with the R^2 = 0.959. When compared the results from the simple equation with PT equation, the high correlation was showed with the R^2 = 0.974. The highest correlation showed the R^2 = 0.985 resulted from PM-56 equation and PT equation (Fig. 2a, 2b, 2c). Reviewed by Widmoser (2009) found that many studies were shown the reference evapotranspiration from PM-56 equation normally higher than the observed.

The study by Osorio *et al*., (2014) confirmed that the reference evapotranspiration in sugarcane field calculated by PM-56 equation was higher than PT equation around 30% because the wind speed was the most influential climatic parameter over the reference evapotranspiration. However, Sentelhas *et al*., (2010) found that the PT equation was also a good option for estimating ETo when wind speed and vapor pressure deficit data were missing, mainly when calibrated locally. For this study, the result showed good estimating reference evapotranspiration when compared with PT equation with RMSE equal to 0.3 mm and NRMSE value was shown 5.9%. Therefore, the simple equation (Eq.5) can be used for estimating the reference evapotranspiration.

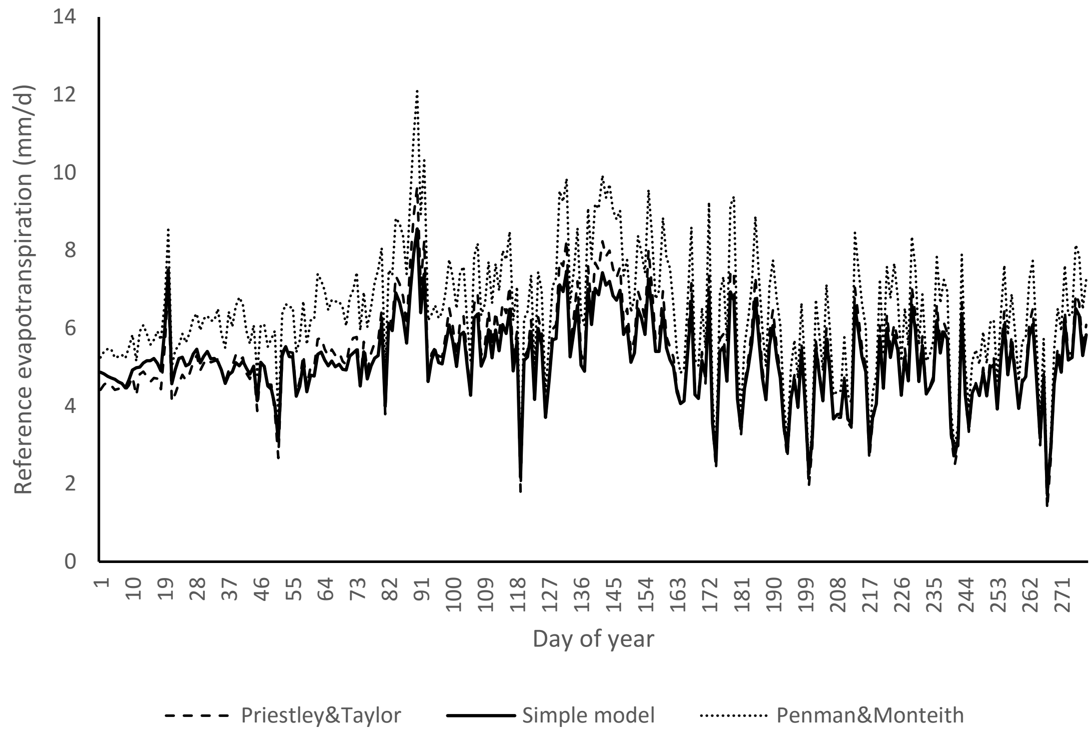
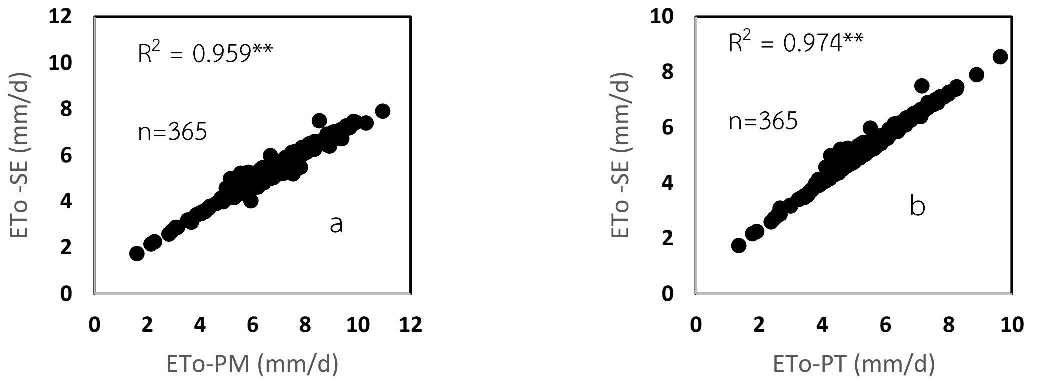


Figure 1 The reference evapotranspiration that calculated by three equations.

Changes of soil moisture

Comparison the soil moisture values estimated by the simple equation and observed found that the simple equation showed good efficiency with the R^2, RMSE, and NRMSE equal to 0.632, 0.018 mm/mm and 10.2%, respectively (Fig.3a). While the result from the CANEGRO model showed higher efficiency than the simple equation, the R^2, RMSE, and NRMSE equal to 0.711, 0.015 mm/mm and 8.68%, respectively (Fig.3b). The CANEGRO model has the complete module of water balance including input data with more parameters than the simple equation so they can give the good results. However, both CANEGRO model and simple equation gave the same results (Fig. 4). In the case of high precipitation, because the simple equation and CANEGRO model were limited the highest soil moisture with the field capacity value of soil parameter, the soil moisture from the observed showed higher than simulated. In the simple equation used, the constant value a and b from Krirk (2009) with study in the paddy field. The period of paddy field studying was shorter than the study in sugarcane field. The constant values from the long period with the different season may be different. The study for address the constant value (a and b) will be understanding of the correct value and can make the simple equation to estimating the accuracy of soil moisture change.



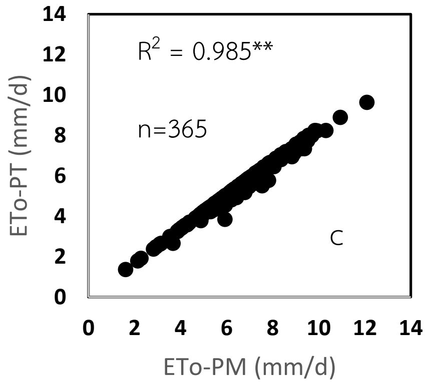


Figure 2 The correlation between simple equation (SE) and Penman-Monteith (PM) (a), simple equation (SE) and Priestley&Taylor (PT) (b) and Priestley&Taylor (PT) and Penman-Monteith (PM) (c) for calculate reference evapotranspiration.

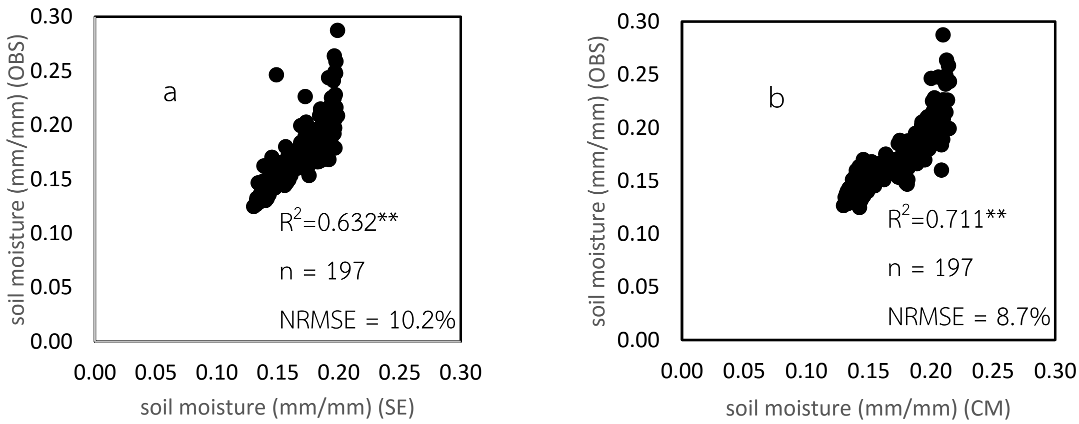


Figure 3 Correlation of soil moisture between simulated from simple equation (SE) and observed data (OBS) (a) and CANEGRO model (CM) and observed data (OBS) (b)

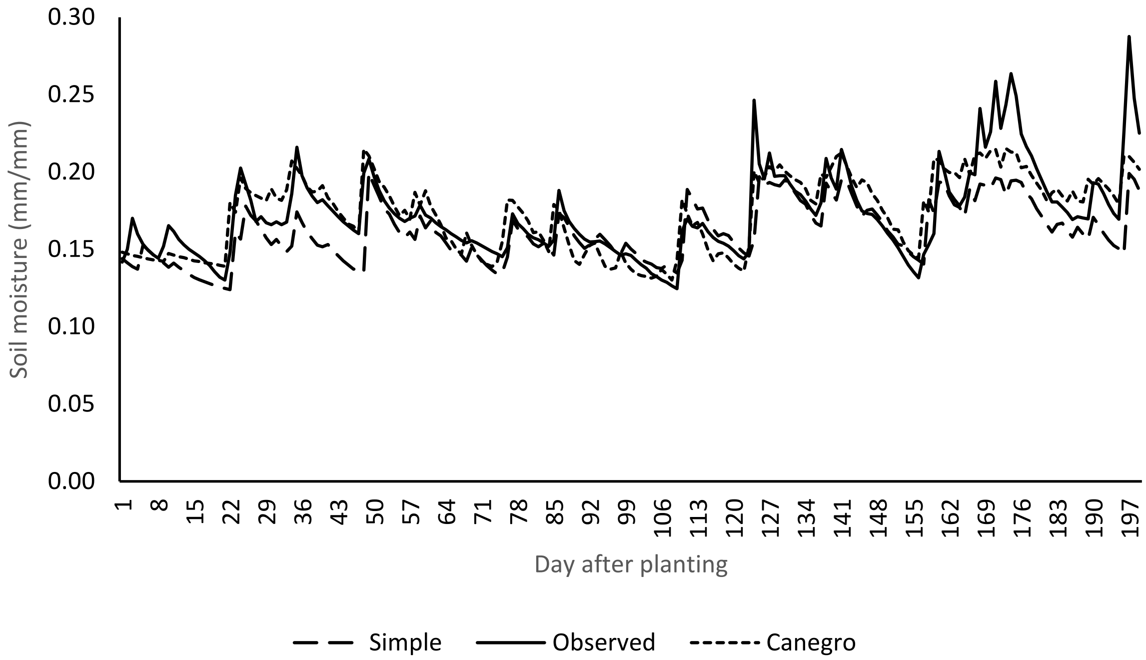


Figure 4 comparison of two models and observed data for changes of soil moisture in sugarcane field.

Conclusion

Our study was focused on the limiting of meteorological data for calculated the reference evapotranspiration. In this case, only solar radiation can be used to estimate reference evapotranspiration and gets high efficiency. However, both simple equation and PT equation showed lower than PM-56 equation, 19.1% and 17.3%, respectively. In addition, linked the simple equation for estimation reference evapotranspiration with simple equation for estimating soil moisture gave the good efficiency for estimating changes of soil moisture in sugarcane field when compared with the observed. However, the simple equation still using the constant value (a and b) from previous study with paddy field. The different weather between season may be effect to these constant value. The study to understanding these constant value can make the accuracy for the simple equation.

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CHAPTER VII

General Discussion and Conclusion

Although crop model has been developing more than 40 years, at present, new versions of the crop models with more efficiency have been continuing released for users. The parameters for input to crop model also have changed. For example, an early CANEGRO version (Inman-Bamber and Kiker, 1997) was included in version 3.5 (Tsuji *et al*., 1994) of the Decision Support System for Agrotechnology Transfer (DSSAT v.3.5), Since then, amendments by different research groups resulted in different CANEGRO versions that were never integrated, nor incorporated into DSSAT. Simultaneously, DSSAT v.4.0 adopted a modular structure (Jones *et al*., 2003), and many utilities were added. In effect, the DSSAT v.4.5 version of CANEGRO differs from the DSSAT v3.5 version, primarily regards to the calculation of biomass accumulation and partitioning. Not only the calculation was changed but also the crop parameters. The crop parameter for DSSAT-CANEGRO v3.5 needed only 7 values while in v4.5 needed 20. Therefore, study of the crop coefficient for the up to date model is still needed. Moreover, in plan t breeding program, they have to release a new cultivar with better than the older. A new one must have new characteristics that adapt to the changes of the environment. Study of the crop coefficient for a new cultivar also needed. In addition, the data observed from the experiment showed the different response between cultivars when planting under rainfed condition. The results indicate that in the crop parameters for the DSSAT-CANEGRO model need to optimize the water balance in the cultivar file with now available optimize only in the species file that cannot showed the effect of water stress between cultivars. In contrast, the DNDC model has the water balance for each cultivar so it is easy to use for the estimation of sugarcane yield from different cultivar under rainfed condition when compare with DSSAT-CANRGRO model. In overall, DSSAT-CANEGRO model and DNDC model can estimated sugarcane yield under full irrigation condition and gave the good result. In the rainfed condition, DSSAT-CANEGRO model need to optimize water balance in the species file with not recommend by model developers but it available for DNDC model. However, after adjusted the water balance for each cultivar for DSSAT-CANEGRO model, both model gave the good estimation of sugarcane yield under rainfed condition and the output of water balance simulation from DSSAT-CANEGRO are useful than DNDC model. For this study, we consider in only water limiting. In the future, if ones want to study with nitrogen limitation. The DSSAT-CANEGRO model in the DSSAT v4.5 is not available for simulated nitrogen limited, so DNDC may be useful.

In chapter V, the study used the DSSAT-CANEGRO model which have been calibrated and validated before to simulate sugarcane yield in the sugarcane planting area in Khon Kaen province, Northeast of Thailand. Simulation was done under two condition, rainfed and full irrigated, to find the yield gap and after that analysed the benefit to define the area that priority to develop wells for irrigation. From the results, there are three points must consider. First is the rainfall, in the area that have enough rainfall for sugarcane production resulted to not different between rainfed and irrigated. Second is the underground water most effect to the benefit. Finally, the available water content in the soil, Soil type that have much water holding cause to higher yield in both rainfed and irrigated conditions. In this case, results from da silva *et al*., (2013) showed that ET and WUE are strongly influenced by soil water availability, confirmed that the ability of soil type to holding water for sugarcane is very important.

From the second study, indicated that data input to the model is a key for having the accuracy result. For the large scale, using GIS map for input to the model is possibility to make the policy but in practically, limitation of input data is more consider especially the weather data and soil type. Therefore, the area with nearby the weather station must be more accurate those far from the station. So in these areas the method for estimating both sugarcane yield and evapotranspiration need to be developed and have been conducted in the third and fourth study.

The third study was done to solve the accuracy for estimating sugarcane yield in the field experiment or the specific area. With finally we get the application that can estimate sugarcane yield. The advantage of this application is easy to use, sugarcane need not to cut for sampling. It gives high accuracy when users get the input data as a representative of the field. The minimum data for input to this model are the stalk number in the row with 10 m long, stalk high, stalk circumference, and row spacing. The technique for getting the data for the all data is the uniform of the sugarcane growth in the field with first evaluated by sight. If the sugarcane growth is uniform, only one replication is enough for getting the accuracy but if the sugarcane growth with ununiformed, more replication need to take the sampling. The number of replication depend on the uniformity of crops. Although the sugarcane growth is uniformed, more replication can make the model has more accuracy for estimating sugarcane yield. However, the application can use for only sugarcane cultivar Khon Kaen 3 and LK92-11, for the others cultivars, this application can use to estimate sugarcane yield but the accuracy may be lower than both cultivars. In addition, this application, can use for the smartphone that has the android system for operation. The others such as iOS or windows phone cannot use it. Therefore, this application need to be developed in the future.

For the fourth study, the simple model for estimating evapotranspiration and the changes of soil moisture in sugarcane field, was explored to solve the limiting data, especially meteorological data, for input to the model. The estimation of evapotranspiration, finally, we used only the solar radiation and found that the model gave the good estimated evapotranspiration when compare with the Preitley-Taylor equation, but underestimated when compare with the Penman-Montieth equation. Indicated that if the area was limited the meteorological data, only solar radiation that can calculate by the position on the earth, Coordinator Cane be used for estimating evapotranspiration. The equation which used in the model was calculated from solar radiation and the constant value, a and b, resulted from the studied in paddy field. Rice production cycle is shorter than sugarcane's by only three months. The constant values are from the assumption that, if the wind speed, temperature and relative humidity are not substantially change, the evapotranspiration depend on only solar radiation. So in the paddy field, the equation can give the good estimating evapotranspiration but not in sugarcane fields, where sugarcane production period is long, at least 12 months.

There are three seasons including winter, rainy, and summer, so between the season the wind speed, temperature, and humidity may be different, the constant values may be different too. The others value such as, Kc, ro, dp, as, and inf were from the previous study. However, these values were not substantially changed. For this study, it gave the good results. So it can be use if the study doesn't consider to the accuracy of the soil moisture. In contrast, if the study is focusing on the accuracy of soil moisture, these values need to be studied. This study focus on the limiting data for the model inputs. When the data input is limited the simple model can be use but when the full data available, the Penman-Monteith equation and available crop models will be better used.

In conclusion, we are successful to optimize crop parameters for three cultivars of sugarcane, Khon Kaen 3, LK92-11, and 02-2-058, for the use of DSSAT-CANEGRO model v4.5 and DNDC model. The model has used to simulated sugarcane yield under rainfed and irrigated condition. However, for the specific area, the correct data for the model input were limited. We are also success in develop the simple model for estimating sugarcane yield and evapotranspiration and changes of soil moisture in the sugarcane field.

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