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Research Application Summary

Calibration and application of DSSAT Model to estimate area yield index insurance premium for common bean at different growth stages and weather perils

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Abstract

CROPGRO-Dry bean model of Decision Support Tool for Agro technology Transfer (DSSAT) was calibrated and validated using observed yield data collected from field experiments conducted in three bean growing areas of Rwanda. These experiments were conducted to identify the most critical bean growth stage to natural bean disease pressure, drought stress and waterlogging and their impact on yield losses. The calibrated DSSAT showed good agreement with the observed bean yields with relative root mean square error (RRMSE) of around 0.5 for both drought and waterlogging and around 1.5 for no pesticide application. The findings revealed that GROPGRO-Dry bean model was an effective tool for predicting bean yield under the investigated crop growing conditions. The estimated yield losses due to investigated treatments were further used to estimate corresponding insurance premium rate of an area yield index insurance model. Drought affected most the seed filling stage with bean yield reduction rate estimated at 23% and a corresponding premium rate of 257 kg ha^{-1}. Pod setting stage was the most sensitive to natural bean disease pressure with yield reduction rate of 30% and a corresponding premium rate of 467 kg ha^{-1}. Seed filling was most sensitive to waterlogging with a yield reduction of 28% and a corresponding premium rate of 429 kg ha^{-1}. This study provides scientific knowledge and basis that can inform insurers to set up area yield index insurance sub-products targeting to cover weather related perils with specific focus on crop developmental stages.

Key words: Area yield index insurance, CROPGRO, *Phaseolus vulgaris,* premiums, Rwanda

Résumé

Le modèle CROPGRO-Dry Bean de l'Outil d'Aide à la Décision pour le Transfert de Technologie Agro (DSSAT) a été étalonné et validé à l'aide des données de rendement observées collectées à partir d'expériences sur le terrain menées dans trois zones de culture de haricots du Rwanda. Ces expériences ont été menées pour identifier le stade de croissance du haricot le plus critique face à la pression naturelle de la maladie du haricot, au stress dû à la sécheresse et à l'engorgement et leur impact sur les pertes de rendement. Le DSSAT calibré a montré une bonne concordance avec les rendements de haricots observés avec une erreur quadratique moyenne relative (RRMSE) d'environ 0,5 pour la sécheresse et l'engorgement et autour de 1,5 pour aucune application de pesticide. Les résultats ont révélé que le modèle GROPGRO-haricot sec était un outil efficace pour prédire le rendement du haricot dans les conditions de croissance des cultures étudiées. Les pertes de rendement estimées dues aux traitements étudiés ont ensuite été utilisées pour estimer le taux de prime d'assurance correspondant d'un modèle d'assurance indicielle de rendement surfacique. La sécheresse a touché le plus la phase de remplissage des semences avec un taux de réduction du rendement des haricots estimé à 23% et un taux de prime correspondant de 257 kg ha-1. Le stade de la formation des cabosses était le plus sensible à la pression naturelle de la maladie du haricot avec un taux de réduction du rendement de 30% et un taux de prime correspondant de 467 kg ha-1. Le remplissage des semences était le plus sensible à l'engorgement avec une réduction de rendement de 28% et un taux de prime correspondant de 429 kg ha-1. Cette étude fournit des connaissances et des bases scientifiques qui peuvent informer les assureurs pour mettre en place des sous-produits d'assurance indicielle de rendement surfacique visant à couvrir les risques liés aux conditions météorologiques avec un accent particulier sur les stades de développement des cultures.

Mots clés : Assurance indicielle de rendement surfacique, CROPGRO, *Phaseolus vulgaris,* primes, Rwanda

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Introduction

The unaffordable premium rates associated with too slow process of making payouts for the traditional indemnity based agricultural insurance have led to the development of index-based insurance (Daron and Stainforth, 2014). Despite its associated basis risk, where an insured may experience a loss but receive no payout or experience no loss but receive payout, index-based insurance is a promising insurance option, especially for developing economies where transactions costs tend to be high. Due to its low transaction costs, index-based insurance is considered as an attractive and alternative solution to protect farmers against adverse weather perils particularly for resource limited farmers in developing countries (Barrett *et al*., 2007). In East Africa region, area yield index insurance product is being implemented by Agriculture and Climate Risk Enterprise Ltd (ACRE-Africa).

In partnerships with local insurance companies, the enterprise has shown rapid scale-up in the region, cumulatively, by the end of 2016, over 1,000,000 farmers were insured in the three countries and is projected to reach 3,000,000 farmers across ten Africa countries by 2018 (ACRE-Africa, 2017). Giertz *et al*. (2015) suggested reduction of insurance premiums as a key factor to sustain provision of both weather and area yield index insurance products in Rwanda in the region). Particularly, limited resource farmers have been hesitant to buy the full contract cover of area yield index insurance (AYII) as it is beyond their purchase power. Indeed, AYII product is presented to farmers as a full cover product whereas weather index insurance products are sold in insurance sub-products based on the plant developmental stages (World Bank, 2015). In addition, with ACRE-Africa policy, scribers to AYII require to wait for pay out claim until harvesting time so that their realized area yield can be compared to the threshold yield. This calls for diversification of AYII product into possible insurance sub-products, based on crop growth stages, to increase its uptake by limited resource farmers. This study therefore aimed at estimating actuarially premium rates for the AYII model for common bean based on the effect of drought, waterlogging and natural bean disease pressure at different crop growth stages. The study, with the aid of DSSAT, investigated to what extent, water stress and natural bean disease pressure observed at a particular plant growth stage, can be utilized to explain bean yield losses and subsequently estimate guaranteed yield and payouts for an area yield index insurance product.

Materials and methods

Experimental treatments, study site and data collection. Two field experiments (Greenhouse and on-farm experiments) were conducted to estimate bean yield losses due to water stress and natural bean disease pressure at selected plant growth and developmental stages. Under netted greenhouse, an experiment was conducted for two successive cropping seasons (September 2015-February 2016 and March-July 2016) to identify the most critical bean growth stages to water-stressed conditions and their weight in reducing grain yield. The effect of watering regime with three levels (drought stress, waterlogging and control) on yield of dry beans was investigated. These treatments (drought and waterlogging stress) were imposed at seed filling, pod setting, flowering and vegetative stages. On-farm experiment was conducted in three districts selected from the main agro-climatic zones of Rwanda: (i) Musanze for the high land region, (ii) Huye for the Eastern and central plateau, and (iii) Bugesera for the Western low land for two successive cropping seasons (March-July 2016 and September-February 2017).

This experiment aimed at quantifying the amount of yield loss due to natural bean disease pressure and investigating the relationships between disease and yield of common beans. The evaluated treatments consisted in applying or not applying pesticide (insecticide and fungicide) at the beginning of the selected growth and developmental stages i.e. seed filling, pod setting, flowering and vegetative stage. Two bean genotypes with different growth habit - bush type (RWR2245), climbing type (MAC44) - were used for the on-farm experiment.

DSSAT Model calibration and validation. The DSSAT model is composed of various crop simulation models which include CROPGRO for leguminous crops (common bean, soybean, peanut), SUBSTOR for root and tubers crops (cassava, potato), CERES for cereal crops (maize, rice, sorghum, wheat) and CROPSIM for crops such as tomatoes, , sunflower and pasture (Khan and Walker, 2015).

Data collected from two field experiments carried out during 2016-2017 cropping seasons were used to calibrate and validate CROPGRO-Dry bean model of DSSAT. Specifically, for the model calibration, genetic coefficients were adjusted by using phenological, morphological and yield data collected from the experiment conducted during 2016 B cropping season (February to July 2016). Whereas, data collected from experiment conducted during the 2017A copping season (September 2016 to January 2017) were used for the model validation.

The Relative root mean square error (RRMSE) was used as a statistical test to calculate the deviation between the predicted measured values (Singh *et al*., 2013).

$$RRMSE = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - P_i)^2}}{X_{av}}$$

Where, N is the number of observations; Xi are the measured values; Xav is the average of the measured X_i values and P_i being the simulated (predicted) values. The relative yield loss due to the effect of each treatment on yield of climbing and bush bean was estimated in percentage of yield decrease (%).

$$Y_D = 100\ x \left[\frac{Y_C\ -\ Y_T}{Y_C} \right]$$

Where: YD is the percentage of grain yield decrease; YC is the average yield obtained under fcast scaley control “C”; and YT is the average yield obtained under the treatment “T”.

Calculation of area yield index insurance premium rate. The following area yield index insurance model described in Skees *et al*. (1997) was used in this paper to estimate area premium rates. For any selected crop, the area yield, y , is a random variable. The insurer’s forecast of the area yield is calculated by the critical or guaranteed yield estimated as:
yc = yfcast x cov. 1

The policy holder selects a yield coverage level (cov) of between 70 and 95%. Binici & Zulauf (2006) denoted the yield coverage level as a smoothing constant (á) that lies between 0 and 1. The insured also selects an indemnity of between 90 and 150%. The indemnity scale level is selected based on the area yield variability. According to Skees *et al*. (1997), a farmer should be authorized to “over insure” the crop if the yield variability is higher for the farm than for the selected area. In our study, coverage levels were set at 80%, 90%, 100% and 110%. The policy holder receives a compensation “indemnity”, indem , whenever y < . The compensation is computed as:

$$Indem\ =\ \max \left[\left(\frac{y_c - y_i}{y_c} \right) (yfcast)\ (scale),\ 0 \right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 2$$

Where: yfcast is the forecast area yield (i.e. grain yield for the control treatment), yc is the guaranteed or critical area yield [= *cov.] with cov. = 85%. is the actual area yield [=* âi], with âi the yield decrease rate (%) due to the different weather stresses at seed filling, pod setting, flowering and vegetative stages, and representing the indemnity scale levels (80%, 90%, 100% and 110%).

Results and discussion

Both simulated grain yield and yield reduction rate for each treatment were fitted in the equation (2) to estimate the expected premium rate for each treatment (Table 1). For ease of presentation, expected premium rates are estimated in kg ha^{-1} (1 ha = 2.47 acre). To illustrate the interpretation of the calculated premium rates, a bean farmer would pay 231 or 282 kg ha^{-1} to obtain coverage of 80% of any shortfall of area bean yield due to drought stress at seed filling stage for bush and climbing bean, respectively. The expected premium rate (EPR) varies substantially among the treatments for a selected coverage level. At 80% coverage level, the expected premium rates range from range from 0 kg ha^{-1} (DS-V) to 411 kg ha^{-1} (NP-P) for RW2245, and from 0 kg ha^{-1} (DS-V, DS-F) to 604 kg ha^{-1} for MAC44. The zero premium rates indicate that the yield shortfall did not exceed 20% of the expected bean yield for the temporal drought stress at the specified crop growth stage. EPR increases with the coverage level for a selected treatment with a positive correlation of premiums at various coverage levels. Consequently, a treatment with a high compensation at the 80% coverage level has also a high compensation rate at 90%, 100% and 110% coverage levels. For the drought stress treatment, the highest expected premium rate was observed at seed filling stage and estimated at 231 kg ha^{-1} for

RWR2245 and at 282 kg ha^{-1} for MAC44.

Seed filling stages was the most sensitive to waterlogging with an expected premium rate of 334 kg ha^{-1} for RWR2245 and 523 kg ha^{-1} for MAC44. Pod setting stage was the most sensitive to natural bean disease pressure with expected premium rate of 411 kg ha^{-1} for RWR2245 and 523 kg ha^{-1} for MAC44. With the yield reduction rates, expected premium rates for investigated treatments, at any defined yield coverage level, can be generated for any forecasted area yield. Higher expected premium rates were observed for drought, waterlogging and natural bean disease pressure at pod developmental stages.

The high sensitivity of pod developmental stages to these weather related perils is attributed to the disturbance of the physiological functioning of plants during these plant growth stages. Darkwa *et al*. (2016) reported the decrease in photosynthate assimilation and poor carbohydrate partitioning to the developing grain as the reason of grain yield reduction due to water stress of dry beans at reproductive stage.

Furthermore, Ahmed *et al*. (2013) indicated that the greater sensitivity to water-stressed conditions at reproductive stage would be associated to plant hormones that are responsible of altering pod formation in addition to increased dropping of flowers. Singh *et al*. (2013) also reported that this yield reduction is attributed to a decline in leaf conductance and C assimilation following waterlogging stress in *Phaseolus vulgaris*. Larger yield reductions when flooding is imposed at reproductive rather than vegetative growth stages have been reported for grain legume crops such as soybeans and mungbean (Rezene *et al*., 2011). According to Buruchara *et al*. (2010), bean disease affecting leaves and pods are generally prominent during the late flowering and early pod formation stages (Buruchara *et al*., 2010). The least sensitivity of weather related stress at vegetative stage may be explained or attributed to a possible low transpiration rate and recovery of plant growth and physiological processes which may have led to the slight grain yield reduction and a small corresponding EPR. These findings imply a possible ability of common bean to recover from the water stressed conditions at pre-flowering stages. Mukeshimana *et al*. (2014) and Ahmed *et al*. (2013) also highlighted that bean genotypes that wilted slowly were able to conserve water in leaves and stem tissues, survive the dry period, resume growth, and reproduce. Similarly, Barrett *et al*. (2007) and Rezene *et al*. (2011) found that genotypes with slow wilting trait may have ability of regulating their transpiration rates and then maintain their soil moisture reserves.

Conclusion

The effect of water stressed conditions and natural bean disease pressure on bean yield was associated with plant developmental stage at which the stress occurred. The pod developmental stage was the most sensitive to investigated weather related stresses. Drought and waterlogging stresses highly affected seed filling stage, whereas pod setting was highly affected by the natural bean disease pressure. Based on the estimated yield reduction losses, expected compensation rates for AYII product were estimated for the investigated weather perils at selected growth stages of common bean.

As for the yield reduction rates, the expected premium rates were also higher for the weather related perils at pod developmental stage and estimated at 257 kg ha^{-1} for drought, 429 kg ha^{-1} for waterlogging and 467 kg ha^{-1} for natural bean disease pressure. This study, with the aid of the DSSAT model, suggested an anticipated claim formula that can be used to estimate expected compensation rates for AYII product for any forecasted area yield for drought, waterlogging and natural bean disease pressure at different plant growth stages. In addition, this research provided useful information on the plant developmental stages to focus most with an estimated associated premium rates based on the selected weather related perils.

Table 1. Estimated premium rates per hectare for area yield index insurance product

Bean type	Forecast area yield "yfcast"	Critical area yield (yc) at α = 85%	TTT	Yield decrease rate in % (â)	Actual area mean yield "y"	Indem = max $\left[\frac{Y_C - Y_T}{Y_C}\right]$ (yfcast (scale), 0]			
						80%	90%	100%	110%
RWR2245	2,729	2,320	DS-V	11	2,424	0	0	0	0
	2,729	2,320	DS-F	19	2,207	103	116	128	141
	2,729	2,320	DS-P	16	2,294	26	29	32	35
	2,729	2,320	DS-S	24	2,073	231	260	289	318
	2,729	2,320	WL-V	20	2,192	128	144	161	177
	2,729	2,320	WL-F	20	2,179	128	144	161	177
	2,729	2,320	WL-P	21	2,167	154	173	193	212
	2,729	2,320	WL-S	28	1,973	334	376	417	459
	2,729	2,320	NP-V	19	2,218	103	116	128	141
	2,729	2,320	NP-F	22	2,141	180	202	225	247
	2,729	2,320	NP-P	31	1,893	411	462	514	565
	2,729	2,320	NP-S	19	2,213	103	116	128	141
MAC44	4,278	3,636	DS-V	9	3,874	0	0	0	0
	4,278	3,636	DS-F	12	3,748	0	0	0	0
	4,278	3,636	DS-P	15	3,619	1	1	1	1
	4,278	3,636	DS-S	22	3,329	282	317	352	388
	4,278	3,636	WL-V	30	3,014	604	679	755	830
	4,278	3,636	WL-F	27	3,133	483	544	604	664
	4,278	3,636	WL-P	26	3,186	443	498	554	609
	4,278	3,636	WL-S	28	3,088	523	589	654	720
	4,278	3,636	NP-V	21	3,393	242	272	302	332
	4,278	3,636	NP-F	22	3,327	282	317	352	388
	4,278	3,636	NP-P	28	3,072	523	589	654	720
	4,278	3,636	NP-S	20	3,434	201	226	252	277

TTT = Treatment, DS = Drought stress, WL = Waterlogging, NP = No disease control measure, V = Vegetative, F = Flowering, P = Pod setting, S = Seed filling, Indem = Indemnity

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