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# A model for evaluating production and environmental performance of kenaf in rotation with conventional row crops

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ABSTRACT

The potential inclusion of kenaf (*Hibiscus cannabinus* L.) into the conventional corn (*Zea mays* L.) and soybean (*Glycine max* L.) rotation of the U.S. Midwest requires investigation. A new kenaf model within the Agricultural Production Systems Simulator (APSIM) was developed and subsequently used to address questions needed for decision making: 1) what is the optimum planting date of kenaf under water-nitrogen limited and non-limited conditions in central Iowa; 2) does soil nitrate accumulation vary among kenaf, corn, and soybean crops?; 3) is soil organic matter (SOC) influenced in the long term?; and 4) how do kenaf water use efficiency (WUE) and nitrogen use efficiency (NUE) compare to corn and soybean? The model indicated that simulated optimum planting date for maximizing kenaf production ranged from April 15 to June 1. Model analysis of different rotation systems showed that there was a slight tradeoff between kenaf stem biomass and soybean yield. Long term soil organic carbon simulations (30 years) indicated a slight decrease over time while inclusion of kenaf in the corn-soybean (C-S) rotation did not affect this trend. In conclusion, this study brings to the scientific literature a new kenaf model that provided information that was missing for decision support.



## 1. Introduction

Agriculture faces many environmental issues with crop production and yield effected by complex interactions with the environment. Recent studies have demonstrated that nutrient losses from cultivated soils have short- and long-term effects on soil and water profiles, and ecosystems (Joosse and Baker, 2011; Puckett et al., 2010; Sebilo et al., 2013; Turner et al., 2008). In Iowa, 80% of the landscape is dominated by corn (*Zea mays* L.) and soybean (*Glycine max* L.) fields (Newton and Kuethe, 2015). In this region, the application of N fertilizers has had negative effects on surface and groundwater quality (Burkart and James, 1999; Dinnes et al., 2002; Hatfield et al., 2009). More than 150 water resources are susceptible to contamination by $NO_3$ from corn and soybean fields in the Corn Belt (David et al., 2015). This has dramatic consequences on nitrate levels present in drinking water (Rood, 2016). Diversification of the corn-soybean system has the potential to reduce $NO_3$ leaching and improve soil quality and sustainability (Davis et al., 2012; DeHaan et al., 2016; Karlen et al., 2006).

Kenaf (*Hibiscus cannabinus* L.) is a multi-purpose, short-day, $C_3$ annual dicot that belongs to the Malvaceae family. Kenaf has shown encouraging results in terms of yield and market potential in Europe and Indonesia (Alexopoulou et al., 2004; Petrini et al., 1994; Stricker et al., 2001). Kenaf stem yields (commercial product) range from 7.4 to 24 Mg ha$^{-1}$ (Anfinrud et al., 2013; Brown and Brown, 2014; Danalatos and Archontoulis, 2010). Kenaf stems contain 60–65% inner core with short and porous fibers. Long and valuable bast fibers predominate in parenchymal areas outside the inner core, about 35–40% of total dry matter (Sellers and Reichert, 1999). Because of the quality of bast and core fibers, kenaf can be used for production of paper, textile, rope, absorbent material, films, cellulose derivatives, and bioplastics (Saba et al., 2015). Kenaf stems have potential for biofuel because of its high cellulose and total fiber concentration (Bourguignon et al., 2016a). Due to the high potential for marketability of kenaf fibers, it is a promising alternative crop to diversify the conventional corn-soybean rotation in Iowa potentially, providing positive economic and environmental benefits.

Inclusion of kenaf into existing rotation systems in Iowa requires two types of information from farmers and policy makers: a) their performance and yield potential of kenaf in this region; and b) its

*Abbreviations:* APSIM, Agricultural Production Systems Simulator; C-C, continuous corn; C-C-K, corn-corn-kenaf; C-K-S, corn-kenaf-soybean; C-S, corn-soybean; C-S-K, corn-soybean-kenaf; LAI, leaf area index; NUE, nitrogen use efficiency; SOC, soil organic carbon; WUE, water use efficiency.

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influence on productivity and the environment compared with the existing cropping system in short- and long term scenarios. This manuscript is a continuation of previously reported work on kenaf yield potential (Bourguignon et al., 2016a,b) that can be evaluated more in details to provide information to the former question. However, literature is scant for the latter, largely due to lack of long-term data.

Cropping system models such as APSIM (Holzworth et al., 2014) and DSSAT (Jones et al., 2003) which integrate various crop and soil/environmental models can be appropriate tools to explore long term crop production and potential environmental benefits. To our knowledge, there are only two crop models for kenaf. In Australia, the NTKENAF model was developed and applied to explore kenaf phenology, morphology, and production (Carberry and Muchow, 1992a,b; Carberry et al., 1993, 2001; Muchow and Carberry, 1993). In Europe, Danalatos et al. (2007), Gintsioudis et al. (2007), and Danalatos et al. (2008) developed the BIOKENAF model as part of an EU project BIOKENAF (Alexopoulou et al., 2004, 2013). However, neither of these models allow researchers to investigate kenaf in different cropping systems or compare rotation effects.

The APSIM cropping systems software platform due to its modular design (Hammer et al., 2010; Holzworth et al., 2014; Wang et al., 2002) provides an ideal environment for development of new models and connection with existing crop and soil models within the platform (e,g. biochar model; Archontoulis et al., 2016). Additionally, corn and soybean models as well as soil water, nitrogen and carbon models of APSIM have been extensively calibrated and tested to simulate production and environmental aspects of cropping systems in Iowa (Archontoulis et al., 2014a,b; Basche et al., 2016; Dietzel et al., 2016; Malone et al., 2007; Martinez-Feria et al., 2016).

Therefore, the first objective of this work was to develop, parameterize, and validate a kenaf model within the APSIM simulation platform. The second objective was to use the new model to explore the following four questions that can assist decision making: 1) what is the optimum planting date of kenaf under water-nitrogen limited and non-limited conditions in central Iowa; 2) how does soil nitrogen accumulation (and thus potential leaching) compare between kenaf, corn, and soybean crops, 3) is long-term soil organic carbon influenced by the inclusion of kenaf into the conventional corn-soybean system, and 4) how do kenaf performance indices such as water use efficiency (WUE) and nitrogen use efficiency (NUE) compare to corn and soybean?

## 2. Material and methods

### 2.1. Description of available datasets

Three different sets of data were used for model calibration and one independent set of data was tested on the model during the validation step. The in-season dataset was from a 2014 and 2015 experiment (Table 1; Supplementary data 1; dataset 1), conducted and replicated at the Iowa State University Agronomy and Agricultural Engineering Research Farm, in Boone, Iowa (42°01′N, 93°46′W) and the University of Kentucky Spindletop Research Farm, in Lexington, Kentucky (38°10′N, 84°49′W). The experiment evaluated kenaf phenology, crop productivity, and morphology of Tainung 2, grown at 18.5 and 37.1 seed $m^{-2}$ in 2014 and 2015. Each treatment (year × location × seeding rate; n = 8) was replicated 3 times. Destructive harvests were performed seven times during the growing season at each location. Additional details of the experiment design and the measurements were described in Bourguignon et al. (2016b). Daily minimum and maximum temperature, solar radiation, and precipitation were collected at a weather station located approximately 3 km and 18 km from the Iowa and Kentucky research sites, respectively, and data were accessed from Iowa Environmental Mesonet (2016) and Kentucky Mesonet (2016).

Another experiment, conducted in Boone County, IA, also was used for calibrating the kenaf model in APSIM (Table 1; Supplementary data 1; dataset 2). Tainung 2 was planted at 24.7 and 37.1 seed $m^{-2}$, in 38.1- and 76.2-cm rows, and fertilized with 0, 56, 112, 168, and 224 kg $ha^{-1}$ N in 2014 and 2015. The experimental design was a split-plot, where N rate was the whole plot and the randomized combination of seeding rate and row spacing represented the sub-plot. Each treatment (year × seeding rate × row spacing × N rate; n = 40) was replicated 4 times. Stem height was measured biweekly from planting to harvesting, non-destructive leaf area index (LAI) was measured monthly in the summer, and stem dry yield, bast:core ratio (which led to dry bast and dry core weight), and N concentration in stem were collected at the end of season. Measurements were performed similarly to those from Bourguignon et al. (2016b).

A third experiment was conducted in the same locations in Iowa and Kentucky that investigated the aboveground and belowground weight of kenaf. The focus was on root weight at six different depths and at three different distances from the row (Table 1; Supplementary data 1; dataset 3). Each root collection was performed four times during the growing season and replicated twice. A 1.2 m-depth soil core was taken and separated into six segments of equal volume. Samples were washed and sieved, and roots present in each sample were dried, and weighed.

To test the calibrated model, an independent dataset was used that was from an experiment conducted in Boone County, IA (Table 1; Supplementary data 1; dataset 4) in 2004 and 2005 (n = 36). The fourth dataset included end-of-season stem dry yield of kenaf planted at three different planting dates with seeding rates of 19, 28, and 37 seed $m^{-2}$ and fertilized with 0 and 168 kg $ha^{-1}$ N. Each treatment was replicated 4 times. The 36 cases are described in Supplementary Table 1.

### 2.2. Model parameterization

As a starting point for building the kenaf model within APSIM (version 7.7), we used an existing crop model in APSIM [pigeonpea, *Cajanus cajan* (L.) Millsp.] that shares many similarities in growth, development, and biomass partitioning with kenaf (Peter Carberry, personal communication). The pigeonpea crop model consists of two sets of parameters, as for all APSIM crop models: the crop and the cultivar (Wang et al., 2002). During the parameterization of the kenaf model, we checked and updated crop and cultivar parameters using published literature and then during calibration, we used experimental data to further improve kenaf modeling.

The following updates were made to the crop parameters of the pigeonpea model during model parameterization: 1) N-fixation routine deactivated from the crop model; 2) Radiation use efficiency parameter updated from 0.90 to 1.50 g $MJ^{-1}$ (Muchow, 1990); 3) Cardinal temperatures updated to 10 (base), 31 (optimum), and 43 (ceiling) °C (Carberry and Abrecht, 1990); 4) Activated function to drop senesced leaves during the growing season to reflect better kenaf concurrent leaf production and drop to the soil surface over time and allow decomposition of these materials before crop harvest. In the cultivar parameters, the following modifications were added: 1) Photoperiod updated to 12.9 h (Carberry et al., 1992); 2) Rate of harvest index and maximum harvest index potential changed to 0.00075 $d^{-1}$ and to 0.35, respectively (Angelini et al., 1998); 3) Cumulative vernalization days deactivated; 4) updated thermal requirements of different crop stages (from emergence to grain filling; Carberry et al., 1992). The detailed list of changes made are presented in Supplementary Table 2.