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Research Paper

Modelling the influence of crop density and weather conditions on field drying characteristics of switchgrass and maize stover using random forest

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Field drying trials were conducted using both field baskets as well as grab sampling techniques to study drying behaviour of switchgrass and maize (corn) stover (CS). Environmental conditions such as hourly solar radiation, vapour pressure deficit (VPD), average wind speed, rainfall amount, harvesting method, and field operations such as swath density were used as variables for model development. A powerful classification-based algorithm, which uses a collection of decision trees called random forest (RF) was utilised to predict moisture content (MC) of switchgrass and CS on wet basis. RF predicted the MC of switchgrass and CS with a coefficient of determination of 0.77 and 0.79, respectively. Rainfall, hours after harvest, average change in solar radiation in past 12 h, average solar radiation in past 12 h, and swath density were found to be the important variables affecting the MC of CS. Drying CS in low density (LD) and medium density (MD) swaths facilitated quick drying even in moderate drying conditions. Rainfall events ranging from 1.5 to 7.5 mm were experienced during the switchgrass drying period which delayed crop drying by one day to several days depending on the weather conditions after rainfall. Several rewetting events were also observed due to dew at night which increased the MC in LD switchgrass and CS by 5–15%. The models developed in the current study will help in decision-making of switchgrass and CS collection after harvest, based on forecast weather conditions in lower Midwestern states.

1. Introduction

The potential of biofuels to reduce pollution, benefit the economy, and provide energy security is well documented (Acheampong, Ertem, Kappler, & Neubauer, 2017; Carneiro et al., 2017; Chen & Smith, 2017). The updated billion ton study estimates an availability of 370 Mt of dry biomass from forest resources and 1 Gt from croplands under high yield and large scale planting scenarios (Perlack & Stokes, 2011).

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Switchgrass (*Panicum virgatum* L.) has a potential to be a leading bioenergy crop for bioethanol production. Crop residues such as maize (corn) stover (CS) have also been recognised as a major contributor to bioenergy and bio-based applications (Yu, Igathinathane, Hendrickson, & Sanderson, 2014). Maize stover consists of the stalk, leaf, cob, and husk portion of the plant and has a potential annual yield of 130 Mt and can produce 38.4 GL of bioethanol (Kim & Dale, 2004). As of May 2017, ten biorefineries have been funded by the bioenergy technologies at pilot, demonstration, and pioneer scales to produce biofuels from agricultural residues and energy crops in the US (USDOE, 2017). Overall, twenty-six biorefineries have been funded at different scales to produce biofuels from all renewable resources such as algae, woody biomass, municipal solid waste, vegetable and yard waste, agricultural residues and energy crops in the US (USDOE, 2017).

Moisture content (MC) of biomass is an important factor that influences the downstream handling operations for biofuel production. Depending on the plant maturity stage at harvest, the moisture in the plant might be high to avoid microbial spoilage during storage and transportation. In order to avoid microbial spoilage, a MC of less than 20% is desirable (Shinners, Binversie, Muck, & Weimer, 2007). At early maturity stages, a MC of 65–70% in switchgrass (Khanchi et al., 2013) and 34–52% in CS (Shinners et al., 2007; Womac, Igathinathane, Sokhansanj, & Pordesimo, 2005) has been reported at harvest. During harvest, several field and mechanical operations are applied for quick drying of crops. Windrows of varying densities can be obtained by controlling the windrow-forming shield at the back of the harvester. Dedicated machines such as tedders are also used to spread the crop evenly on the field which helps to capture maximum solar radiation for rapid drying. However, spreading the crop also exposes it to unfavourable events such as rainfall, which can prolong the field drying period and reduce dry matter and quality of the crop (Khanchi & Birrell, 2017b).

Temperature, relative humidity, solar radiation, wind, soil moisture, and rainfall are the major environmental factors that affect the drying of crops in the field. The drying process is driven by differences between the vapour pressure of biomass material and that of surrounding air. The solar radiation supplies most of the energy for evaporation of water (Atzema, 1992). The radiation is able to penetrate up to 5 cm into the swath, after which the heating effect is reduced and the crop dries slowly (Atzema, 1992) in the bottom layers. Therefore, drying in a low-density swath or tedding is recommended to promote more even and quick drying. Previous studies on drying of grass have concluded that, of all of the weather parameters studied, solar radiation is a more important factor than vapour pressure deficit or wind speed in determining the drying rates (McGechan & Cooper, 1995; Wright, Frost, Patterson, & Kilpatrick, 2001). However, at night, vapour pressure deficit (VPD) is the most important factor in determining the drying rates of crops (Khanchi & Birrell, 2017a). When the crop is moistened by rainfall or dew, most of the water is adsorbed on the surface and is called free water (Atzema, 1992). The moisture gain by rain or dew is also influenced by the conditioning of the crop material. During conditioning, the crop passes through conditioning rolls which break open the stems, resulting in faster drying of crops. Highly conditioned biomass loses and gains moisture more easily than unconditioned biomass. All of these factors should be considered while implementing any field operation for biomass drying.

Models predicting the drying behaviour of CS and switchgrass are limited in the literature. Models have been previously developed for other crops such as alfalfa (*Medicago sativa* L.) (Dyer & Brown, 1977; Hayhoe & Jackson, 1974; Kemp, Misener, & Roach, 1972) and ryegrass (*Lolium perenne*) (Wright et al., 2001) which utilise environmental variables and pan evaporation to predict the drying of crops. In the case of CS, models were developed by Womac et al. (2005) and Manstretta and Rossi (2015). Womac et al. (2005) developed models for the southeast U.S. and found that moisture measured in the morning was significantly greater than moisture in the afternoon. They also concluded that conditioning resulted in a 10% higher moisture reduction than unconditioned stover. However, conditioned stalk also gained greater moisture after rainfall. Manstretta and Rossi (2015) developed models to study the effect of weather on moisture fluctuations in maize stalk residues as an important inoculum source for plant disease in Italy. In the absence of rainfall, they also found a diurnal pattern with decreasing MC during the day and increasing moisture at night. Shinners et al. (2007) compared wet and dry maize stover harvest but no models were developed during the study. They observed that out of four trials, only in one trial did the stover reach a safe storage moisture level (20%) in four days after grain harvest. In the other trials, the ambient temperature was low and there were frequent rainfall events which kept the stover at a higher MC during the 10 day drying period. All these studies show the significance of environmental conditions on final MC of CS. In the case of switchgrass, field drying studies are even more limited. Shinners, Boettcher, Muck, Weimer, and Casler (2010) studied the effect of three swath densities and two conditioning treatments. They found that switchgrass dried more quickly when it was placed in a wide swath. However, there was no significant difference observed between the roller and impeller conditioning treatments. Popp et al. (2015) studied the influence of weather on the predicted moisture content of field-chopped energy sorghum and switchgrass. They concluded that the weather, and specifically rainfall, impacts harvesting cost by affecting the seasonal production capacity. Additionally, they found that temperature impacted the rate of drying and suggested artificial drying instead of longer field drying periods when the drying conditions are not favourable.

The models developed to predict the MC in crops, using environmental factors and field operations, use multiple linear regression (MLR) as a common prediction technique. MLR is popular due to simplicity in application, computational efficiency, and ease of interpretation (Zhang et al., 2017). MLR can detect a linear relationship between the response variable and the environmental variables used for moisture prediction. However, MLR models can result in errors when the relationships are inter-correlated, complex and nonlinear (Zhang et al., 2017). In past studies (Khanchi & Birrell, 2017a; Khanchi et al., 2013; Wright, Frost, & Kilpatrick, 2000) an interaction between solar radiation and wind speed was observed while predicting the drying rate of switchgrass and other crops. Prediction techniques such as classification and