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Abstract. *In order to meet the U. S. government's goal of supplementing the energy available from petroleum by increasing the production of energy from renewable resources, increased production of bioenergy has become one of the new goals of the United States government and our society. U.S. Executive Orders and new Federal Legislation have mandated changes in government procedures and caused reorganizations within the government to support these goals. The Biomass Research and Development Initiative is a multi-agency effort to coordinate and accelerate all U.S. Federal biobased products and bioenergy research and development. The Initiative is managed by the National Biomass Coordination Office, which is staffed by both the DOE and the USDA.*

One of the most readily available sources of biomass from which to produce bioenergy is an agricultural crop residue, of which straw from small grains is the most feasible residue with which to start. For the straw residue to be used its collection must be energy efficient and its removal must not impact the sustainability of the growing environment. In addition, its collection must be economically advantageous to the producer. To do all that, a single pass multi-component harvester system is most desirable.

Results from our first prototype suggest that current combines probably do adequate threshing and that a separate chassis can be developed that does additional separation and that is economically feasible.

Keywords. Single pass, multi-component, harvester, grain combine, bioenergy

Introduction

A single pass multi-component harvester is a crop harvesting system that simultaneously collects more than one component of the plant being harvested into separate containers in a single pass across the field, such as collecting the grain into the grain tank and the plant stem material into a separate container. The plant material is the *biomass*, the *biofeedstock* to be used by a *biorefinery*. "A biorefinery processes biomass into value added product streams. These can range from biomaterials to fuels such as ethanol and fuel gases, or key intermediates for the production of chemicals and other materials. Biorefineries are based on a number of processing platforms using mechanical, thermal, chemical, and biochemical processes" (DOE Roadmap, 2003).

Over the past few years, the U.S. government has made several commitments to the establishment of a biorefinery industry.

On August 12, 1999 U.S. President Bill Clinton signed Executive Order 13134, Developing and Promoting Biobased Products and Bioenergy, which was an order "to stimulate the creation and early adoption of technologies needed to make biobased products and bioenergy cost-competitive in large national and international markets."

The Biomass Research and Development Act of 2000, June 2000 (Title III of the Agricultural Risk Protection Act of 2000) created a research initiative focused on producing fuels, power, chemicals, and materials from a wide variety of biomass. Section 304 of the Act mandated cooperation and coordination in biomass research and development between the Secretary of Agriculture and the Secretary of Energy, requiring that they "shall cooperate with respect to, and coordinate, policies and procedures that promote research and development leading to the production of Biobased industrial products." Section 306 established the Biomass Research and Development Technical Advisory Committee, which superseded the advisory committee on biobased products and bioenergy established by Executive Order 13134.

The Report of the National Energy Policy Development Group, (May 2001), stated to President George W. Bush that "through improved technology, we can ensure that America will lead the world in the development of clean, natural, renewable and alternative energy supplies."

The Biomass Research and Development Technical Advisory Committee, in their Vision for Bioenergy & Biobased Products in the United States (October 2002) predicted that "By 2030, a well-established, economically viable, bioenergy and bio-based products industry will create new economic opportunities for rural America, protect and enhance our environment, strengthen U.S. energy independence, provide economic security, and deliver improved products to consumers."

The same committee, in their Roadmap for Biomass Technologies in the United States (December 2002) felt that "Achieving Vision goals will require a change in the entire biomass production system, including new and better methods for crop growth and management, harvesting, densification, transportation, storage, and pre-processing."

Most recently the U.S. DOE has published the Roadmap for Agricultural Biomass Feedstock Supply in the United States (November 2003). The roadmap lays out the research and development priorities for production, harvesting and collection, storage, preprocessing and system integration of agricultural crop residues as a biomass feedstock. The roadmap identifies crop residue biomass as an attractive starting feedstock in the near-term because, as a byproduct of grain production, it is currently abundant, underutilized, and low cost. Since corn stover and straw are the two most abundant crop residue biomass sources in the U.S., the roadmap focuses primarily on the research and technology development towards using these biomass sources as biofeedstocks.

For harvesting and collection, the roadmap identifies sustainable biomass harvest, single pass harvest, and bulk harvesting and collection systems as the areas of needed research and development.

To address these needs, the INEEL Bioenergy Initiative is conducting field research to develop a single pass multi-component harvester that would selectively and separately collect both the grain and desirable sub-components of the plant biomass, while discharging the remaining plant biomass back onto the soil in a single pass across the field. The collected sub-components of plant biomass are those desirable as the biofeedstock, while the plant components not collected would be returned to the field in support of soil's sustainability.

Combine threshing and separation

This desired separation might be different for different crops and for different growing environments. For corn, the ears and leaves are stripped off the stalk and passed into the combine. Most of the stalk, which did not pass through the combine, and the leaf and cob material that passed through the combine, are left in the field after harvest. For corn at harvest time the plant components vary widely in moisture. Also, many corn growers are very protective of leaving the stalks in the field as erosion control. Many of these details for corn have been reported by Montross et al. (2004).

For small grains, much of the plant material is cut off above the ground and fed into the combine. Only some stubble is left standing in the field. The straw is spread back onto the field after passing through the combine. Typically, at harvest, all the plant components are dry at about 10-14% moisture. In many high production grain-growing areas the grower desires the removal of much of the straw, because it does not decompose quickly and because it clogs the next year's disking operation. To eliminate the straw the grower often burns the field, causing ever-growing concern from local city-folk.

While the grain plant is still standing in the field prior to harvest, the straw chaff fraction makes up the majority of the straw (Figure 1). The grain fraction will comprise about 61% of the harvestable straw (Patterson et al., 1995). The chaff fraction is comprised of the non-stem tissues of leaves, sheaths, and awns. When harvested, it is primarily this chaff material that passes through the combine concaves, dropping onto the separation shoe with the grain, and once on the separation shoe is referred to as MOG (Material Other than Grain). The separated grain goes to the combine grain tank, and the MOG discharges off the back of the cleaning shoe. The straw stems do not drop onto the combine cleaning shoe but exit the combine threshing system through another route. This effectively creates three separate biomass streams in the combine that can be managed for selective harvest of multiple crop components.

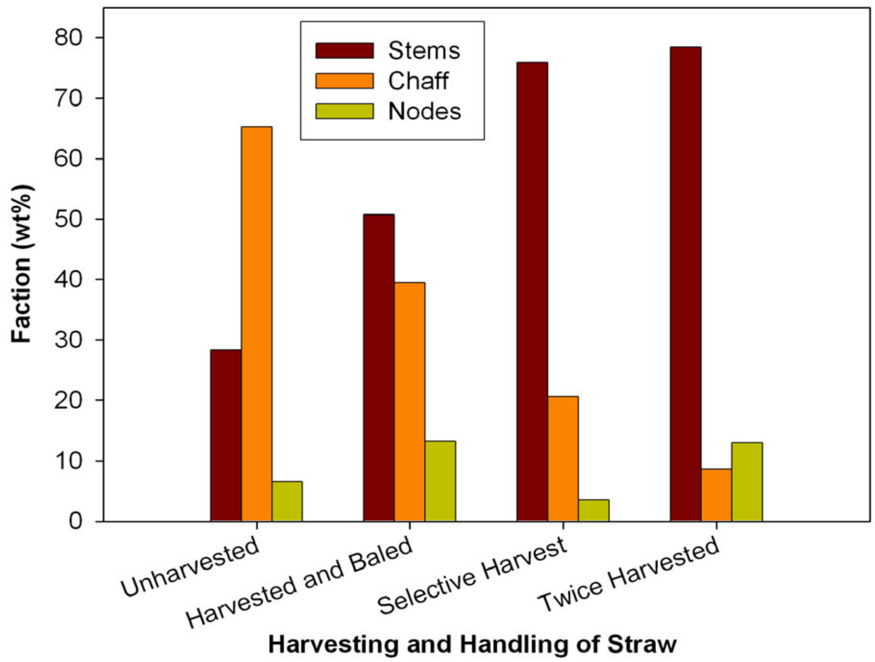


Figure 1. The effect of different harvesting methods on straw composition.

In order to better measure and understand the effects of the threshing and separation systems in the combine, and their impact on the composition of the straw fractions discharged we conducted several field tests of different processing scenarios.

Straw that has been windrowed behind the combine and then baled demonstrates a significant loss of chaff material relative to the initial plant composition (Figure 1). This is because, while the windrowing process typically recombines the chaff and stem streams as they discharge from the combine, the process of baling the straw normally results in loss of much of the chaff material. To completely recover straw chaff, special chaff recovery equipment and systems may be required (Redekop, 2004). Our combine set up to selectively harvest the straw stem biomass stream yielded a straw that was between 70 and 80% straw stems. The 20% chaff component was primarily the result of needing to improve the stem and chaff separation process. Passing harvested straw through the combine a second time and selectively capturing the straw stem fraction further reduced chaff levels (Twice Harvested, Figure 1). However, this reprocessing of straw was never able to increase the stem fraction much greater than 80% or decrease the chaff fraction much below 10%, but it would increase the node fraction. Additionally, each time the straw is reprocessed through the combine, more and more of the stem material breaks down and becomes part of the chaff stream. Thus the rethreshing of straw would break up the straw stems to shorter stem segments around each node, resulting in a general loss of stem material to the chaff stream and an increasing percentage of nodes in the stem stream. While threshing the stems into shorter segments improved separation, stem losses as high as 30-50% are not acceptable. Our results suggest that the threshing process must be carefully controlled, so as not to destroy the stem structure, which results in losses of stem material to the chaff stream.

To use less aggressive threshing systems for preventing stem yield losses and still achieve high purity stem and chaff fractions, INEEL is studying the fluidized bed separation process to effect development of separation systems capable of stem-chaff separations for straw and other biomass sources (Hess et al., 2003). This is necessary for efficient separation of structurally intact stem biomass, as it is more difficult to separate fine chaff material from longer stems. We expect this is due to matting of the stem stream, which traps chaff material. Development of better and more robust biomass separation systems is necessary to ensure that the threshing system can be operated within parameters that do not degrade any of the potentially valuable crop components (i.e., grain, stems or chaff).

The INEEL single pass multi-component harvesters

The INEEL "commercial-concept" single pass multi-component harvester

The INEEL has designed a single pass multi-component harvester system that might represent the characteristics most desirable in a system, which includes a separate chassis that could be manufactured by a small equipment manufacturer and marketed when the biorefinery infrastructure is in place. The system (Figure 2) includes a standard grain combine, a standard baler, and a "commercial-concept" separate chassis that would be the new piece of equipment.

The design factors considered for this system were that the system

- Must maintain the sustainability of the growing environment
- Must not interfere with normal harvest to an unacceptable degree
- Must be economically feasible.

To maintain the sustainability of the growing environment, the system must selectively harvest the biomass material "good" as a feedstock and leave the material "good" for the soil. Therefore, the system should receive the discharge from the combine, or a subset of the discharge, and be able to do additional separation of the material. And it must be able to accommodate the differences between corn harvest and small grain harvest.

Figure 2. The INEEL "commercial-concept" single pass multi-component harvester.

In order to not interfere with normal harvest to an unacceptable degree, the system had to be a separate chassis or separate attachment that could be quickly removed from the combine if it failed, in order to allow normal grain harvest to continue.

This separate chassis or separate attachment also contributed to making the system economically feasible. The agricultural equipment manufacturers could not be expected to design and produce a new and unique harvesting system for an emerging market. And the grower could not be expected to invest a significant amount of capital into new equipment for the same emerging market.

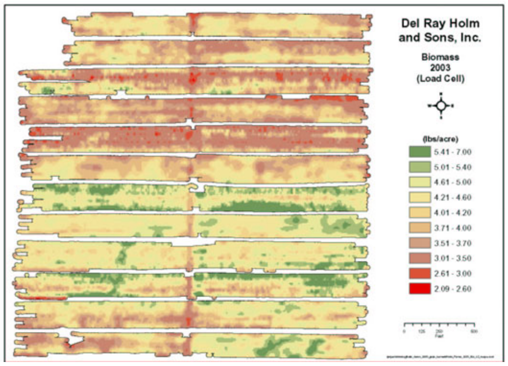
Figure 3. The separate chassis of the single pass multi-component harvester system, attached to a baler.

The separate chassis prototype, attached to a baler, is shown in more detail in Figure 3. The chassis is hitched to the rear of the combine, and the combine discharge enters the front of the chassis. As the material passes through the chassis, additional separation of some of the fine material is accomplished as the material passes over the feed chains. The chassis discharge is picked up by a baler for containment.

In its present configuration, as a proof-of-concept, the INEEL single pass multi-component harvester captures the discharge from the straw chopper at the rear of the combine, and collects the biofeedstock in a round baler.

In a true production environment, the chassis might be expected to have adjustments to allow selecting different combine discharge streams, might be designed to do more or less separation using additional separation technologies such as a fan or a straw walker, and the round baler might be replaced with another type of baler, a baler accumulator, a chopper, or a stacker loafing system.

In support of the field-testing in small grains in Idaho, we are also conducting field tests to measure the variability of the crop production based on varying soil fertility. Using another of INEEL's grain combines, equipped with standard GPS and grain yield monitor as well as a prototype biomass sensor system that measures total biomass input to the combine, we have measured the variability in both biomass and grain yield across a 154 acre field of both grain and biomass (Figure 4).



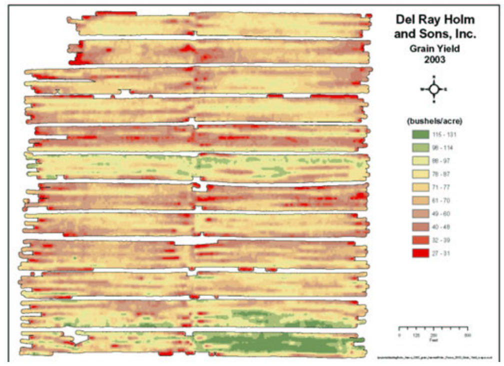


Figure 4. Spatially variable biomass and grain yield.

Using artificial intelligence and data mining methods we will begin to analyze these production data in light of additional data describing the spatially variable soil fertility of the field in which this 2003 crop grew. These analyses will begin to help us understand the spatial relationships between growing conditions and production of the grain and biomass. Understanding those relationships will allow the single pass multi-component harvester to do variable rate harvesting (VRH). The ability to do VRH will be a valuable tool in the management of the growing environment to assure its sustainability.

The INEEL research system single pass multi-component harvester

The INEEL is also developing a single pass multi-component system to be used as a tool to support our Bioenergy Initiative. This system consists of a grain combine, equipped with a Redekop™ Model 925 chaff blower and tube kit, and a flume and tube to convey the output from the straw chopper. The combine tows two Redekop™ chaff wagons side-by-side. One wagon receives the chaff discharge and the other the straw discharge. Both wagons are equipped with load cells so that the wagonloads can be weighed and their weights logged in the combine's on-board data acquisition system. The combine, as discussed earlier, is equipped with a biomass sensor on the feeder chain that measures total biomass into the combine, a grain yield monitor, and a GPS.

Using this system, we can measure the total biomass produced across an area, and break down the production into its components, capture samples of the components for post-harvest analyses, and compare these data to the spatially varying characteristics of the growing environment such as soil fertility. All these data will help develop our ability to do VRH.

This system will be field-tested during the 2004 grain harvest in Idaho.

Conclusion

The INEEL "commercial-concept" single pass multi-component harvester system has demonstrated that a separate chassis system can be developed that will meet the goals of maintaining soil sustainability while not interfering too much with regular harvest, and be economically feasible. Our preliminary data suggest that the threshing capability of current grain combines is adequate but that additional separation can reduce the chaff stream. Having a separate chassis with additional separation capability in order to reduce the chaff in the selectively harvested biomass stream will solve the need for more separation. A better understanding of the relationships between the growing environment and the plant production will help develop the ability to do VRH.

Acknowledgements

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