Cost and profit impacts of modifying stover harvest operations to improve feedstock quality

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Abstract:
Biomass quality attributes, and the potential tractability of those attributes, are key to a successful biomass feedstock supply chain, in addition to quantity and price. Modifying harvest operations is one potential approach to managing biomass feedstock quality for corn stover. For example, eliminating raking from stover harvest operations is proposed as an approach to reduce ash content. However, changes in the stover harvest configuration cause changes in per-acre profits, per-ton costs, and available supply at specified prices. Here we evaluate sensitivity of profit, cost, and supply to conversion from a three-pass to a two-pass stover harvesting configuration as a means to reduce ash content. For all simulated yields, per-ton harvest costs are $2-$3 per ton cheaper for three-pass vs two-pass systems wherever residue retention coefficients are less than 0.5, and per tons costs for both systems increase dramatically where residue retention coefficients are greater than 0.7. Per-acre net returns are greater under all simulated yields wherever residue sustainability retention coefficients are less than 0.6. Under these conditions, farmers lose between $13 and $49 per acre by harvesting with a two-pass rather than a three-pass system. Where competing with stover markets with less stringent quality specifications, meeting ash targets by harvesting with a two-pass system may require higher grower payments on the order of $9-$25 per ton to make up for the per-acre lost revenue. When solving for the least-cost supply, agronomic simulations suggest about 2/3 of stover is harvested with a three-pass system.

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1. Introduction:

Corn stover, the residue of stalks, leaves, cobs, and husks remaining after grain harvest, is identified as a biomass resource with great potential to contribute to a growing bioeconomy (Cantrell et al. 2014). Upwards of 100 million dry tons per year of corn stover are identified as potentially available in the USA (USDOE 2016a). This resource is available in the field even in the absence of market demand, in contrast with energy crops, which require a market to incentivize deployment. However, challenges remain to the development of a biofuels and bioproducts industry using stover, e.g. low per-acre yields, limited seasonal availability as a biproduct, and quality control, particularly of ash content due to entrained soil.

Attributes of biomass feedstock cost, quality, and quantity are factors in the successful development of any bio-based industry. Commercialization requires adequate feedstock supply, but at prices low enough to be cost effective, and with quality specifications suitable for a given conversion strategy. Feedstock quality specifications include various physical, structural, and compositional attributes. One key compositional attribute of feedstock quality is ash content (Li et al. 2016). Biomass contains both physiological ash, which is inherently present from some nutrients needed for plant growth, and exogenous ash, which is extraneous soil contamination that can vary with harvest and collection methods. Lower ash content is universally better from a conversion standpoint (USDOE 2016b). Ash content increases costs associated with equipment ware, handling, and disposal costs. Ash also reduces convertible product per unit of biomass, with some conversion processes being more sensitive to ash content than others (Thompson et al. 2017). Thermochemical processes are typically more sensitive to ash content than biochemical processes (Li et al. 2016). However, ash increases buffering capacity in biochemical processes, decreasing biofuel yield per unit of biomass. Generally, feedstock value decreases proportionally with ash content (Bonner, Smith, et al. 2014). Because of these costs, feedstock development strategies aim to reduce ash (Lacey et al. 2016).

Modifying harvest operations is one potential approach to managing ash content in stover (Bonner, Smith, et al. 2014). A two-pass corn stover harvest operation has been proposed as an approach to manage feedstock quality. Compared with the three-pass stover harvesting system, the two-pass system eliminates windrowing and cuts higher, which reduces entrained soil. However, the economic availability of corn stover, i.e., the potential supply as a function of price, may be affected by the change in harvest configuration and the associated change in harvest cost. Here we revisit stover harvest operations and harvest cost assumptions in the 2016 Billion-Ton Report (USDOE 2016a) to evaluate the sensitivity of stover supply and cost to stover harvest configuration as a means to reduce ash content and improve feedstock quality.

2. Background:

With appropriate management, some stover supplies can be harvested sustainably (Karlen et al. 2011), although excessive rates of stover removal can exacerbate soil erosion (Cruse and Herndl 2009). Results from the first four years of an industrial stover-to-ethanol operation suggest that stover removal has a minimal effect on corn grain yield or soil attributes (Birrell et al. 2014). Sustainable stover supply in the USA is estimated to be over 150 million metric tons per year even after constraining to avoid soil erosion and loss of soil organic carbon (Muth et al. 2013). Operationally, subfield stover removal decisions, combined with cover crops and vegetative barriers, can increase stover availability while improving soil conservation over corn grain removal alone (Bonner, Muth, et al. 2014).

The 2016 Billion-ton Report (BT16) indicates that sustainable and operationally available stover supplies in the USA will range from about 85 million Mg in 2018 to 140 million Mg in 2040, under a base-case scenario of $66 per dry ton (USDOE 2016a). These estimates are based on agronomic modeling of the agricultural sector, with embedded assumptions including sustainability constraints, harvest efficiency, operational costs, and harvesting operations (USDOE 2016a, appendix C). The two-pass and three-pass harvesting operations are shown in Figure 1. The harvest operation assumed in the BT16 is a three-pass operation, where the residue from the grain harvest is shredded and windrowed then baled. The three-pass system was assumed because it is widely available, harvests more stover than other harvesting configurations, and, in turn, minimizes harvest cost per ton. A two-pass harvesting system, which picks up less ash by skipping a raking operation, allows for cleaner biomass, although at a lower harvestable fraction due to the higher cutting height. Advantages of ash content reduction are made evident by the use of the EZ Bale™ process used by Poet-DSM to supply their Project LIBERTY facility in Emmetsburg, Iowa. Currently, Project LIBERTY is the only DOE-funded pioneer-scale biorefinery utilizing agricultural residue that is still in operation. The ash content of harvested stover is particularly susceptible to contact with the soil as attributable to harvest operations (Bonner, Smith, et al. 2014). The ash content of corn stover is estimated to be 4%, 6%, or 10 % from single-pass, two-pass, and multipass harvest operations, respectively (Shinners et al. 2012). Changing assumptions of the stover harvest configuration as a means to reduce ash content also changes the supply, cost, and ash content of the harvested stover. Here we evaluate changes in profits, costs, and supply that can be expected with changes in stover harvest configuration as a means to reduce ash content.

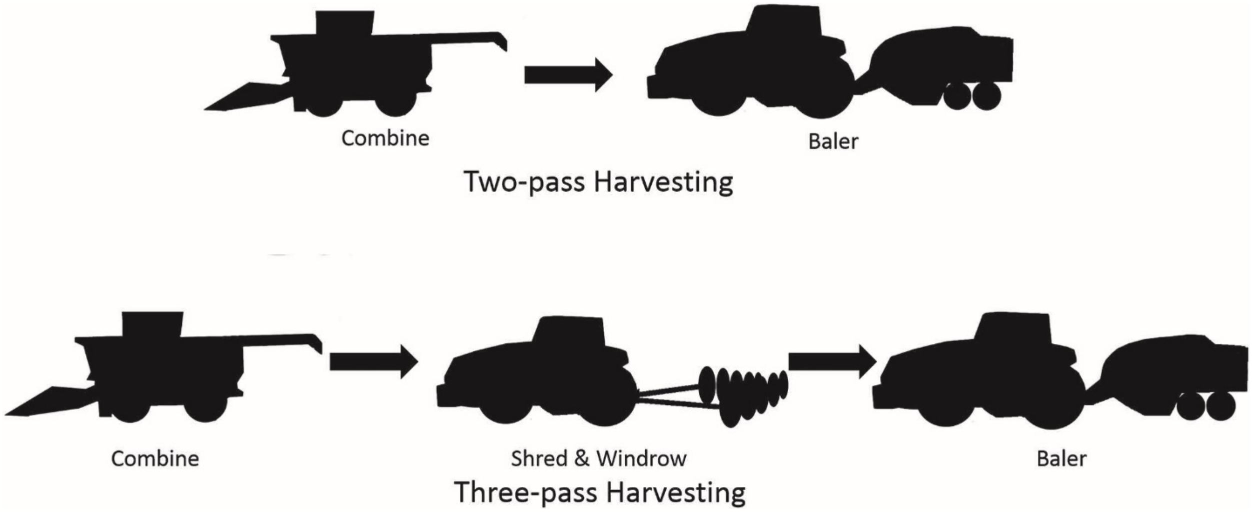

Figure 1. Illustration of two-pass and three-pass harvesting systems.

3. Methods and assumptions:

The corn stover supplies at specified prices in the BT16 are impacted by 1) harvest cost as a function of yield (tons per acre), and 2) sustainability retention coefficient as determined by modeling site-specific residue retention requirements needed to maintain soil organic carbon (USDOE 2016a appendix C; Muth and Bryden 2012). Stover harvest cost components include shredding, baling, and stacking. In the three-pass system assumed in the BT16, pass one is a grain harvester with a spreader, pass two is windrowing with a flail shredder, and the pass three is the bailer. In the two-pass system, the header is raised with the flail shredder turned off, and the windrowing step is eliminated. Harvest cost components in two-pass and three-pass systems are shown in Figure . Overall, the two-pass system has lower costs on a per-ton basis. This analysis applies a two-step approach. First, costs on a per-acre and per-ton basis are characterized as a function of per-acre yields and sustainability constraints. Second, potential stover supplies at specified prices are reported as a function of changing harvest configuration.

1.1. Two-pass and three-pass cost and landowner profit characterization

Three-pass stover collection operations assumed in the BT16 (USDOE 2016a, Appendix C) include 1) turn off spreader behind combine, 2) shred, 3) bale with large rectangular baler, and 4) move bales to roadside with automated bale wagon. Two-pass stover collection operations are the same as for three-pass, with the shredder turned off, eliminating the need for wind rowing. Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL) harvest cost components, for two-pass and three-pass operations under yields ranging from 0.5-4.5 dry tons per acre are shown in Figure . Both INL and ORNL use American Society of Agricultural and Biological Engineers (ASABE 2006) cost calculation methods. Differences in results are attributable to different assumptions in operating hours per year, acres harvested per hour, and fuel consumption. The results from INL are based on assumptions reflecting custom harvest operations with some improved efficiencies, and the ORNL assumptions are based on farmer-owned operations. This analysis uses the more conservative ORNL harvest cost assumptions shown in Figure 2. Although harvest costs on a per-ton basis are cheaper for the two-pass system, the three-pass stover harvesting system is assumed to collect more stover per acre (60%), and thus can potentially provide more profit to the landowner (all else being equal). These costs are used to compare the per-acre returns and the per-ton harvest costs of the two systems.

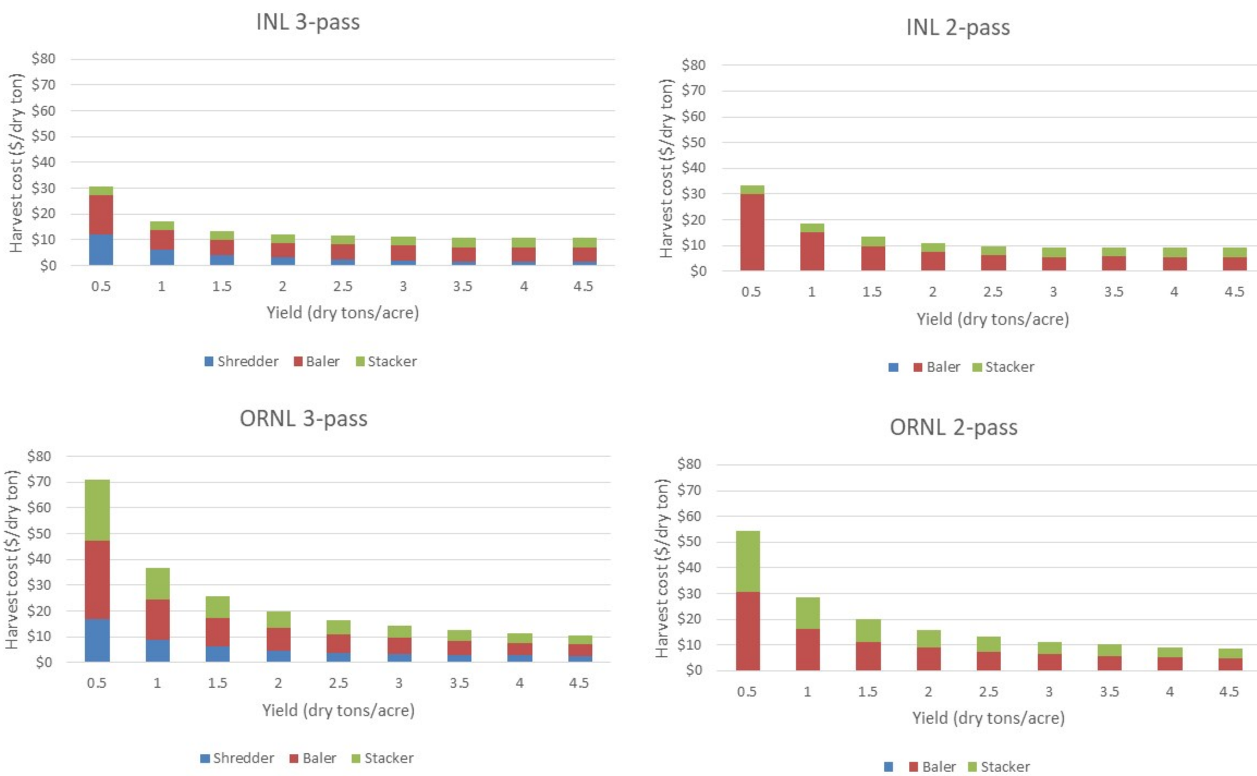

Figure 2. Two-pass and three-pass stover harvesting operations and cost components, by yield scenario.

1.2. Total supplies

POLYSYS is a partial equilibrium model of the US Agricultural sector, which solves the most profitable land-use allocation from the landowners' perspective. In the BT16, the three-pass harvest system was assumed, because 1) quality characteristics like ash content were not included in the economic modeling, and 2) the three-pass system can harvest more stover on a per-acre basis than the two-pass system, thus increasing per-acre profits. In this analysis, a module was added to solve endogenously between a two-pass and a three-pass system. The revised logic assumes stover producers are rational decisionmakers and choose harvest technology for fields given tillage, yield, and sustainable retention to supply stover in order to maximize profit at given price according to following logic:

- The harvested yield of the three-pass system is calculated as standing yield minus the residue retention coefficient or harvest losses of the three-pass system, whichever is greater.
- The harvested yield of the two-pass system is calculated as standing yield minus the residue retention coefficient or harvest losses of the two-pass system, whichever is greater.
- If the harvested yield of both the two-pass and three-pass systems are greater than zero, harvest costs of the two-pass and three-pass systems are looked up as a function of per-acre yield and the harvest system with the lowest per-ton harvest cost is chosen.

This logic is based on cost minimization. Future work could expand on this to solve for profit maximization.

2. Results and Discussion

2.1. Two-pass and three-pass harvest costs

Per-ton harvest costs for two-pass and three-pass systems as a function of corn yields and residue retention coefficients are shown in Figure 2 and Figure 3, respectively (150, 175, and 200 bushels per acre correspond to 3.7, 4.3, and 5.0 dry tons of stover per acre, respectively). Generally, three-pass harvest systems are about \$2-\$3 per ton less expensive than two-pass harvest systems where residue retention coefficients are less than 0.5. Harvest costs from two pass-systems are shown to be about \$4-\$7 cheaper on a per-ton basis than three-pass systems where residue retention coefficients range from 0.5-0.7.

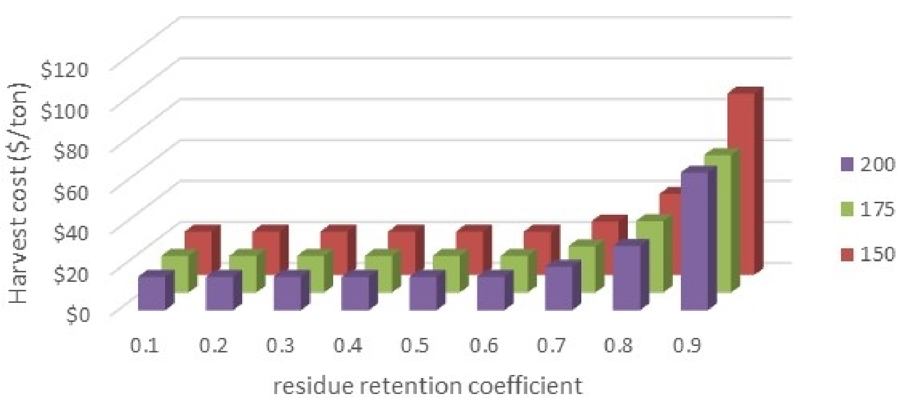

Figure 2. Two-pass harvest costs as a function of yield (bushels per acre) and residue retention coefficient (ORNL).

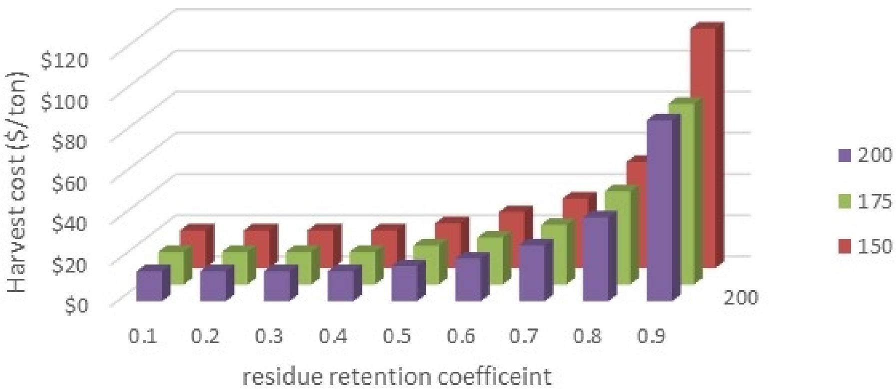

Figure 3. Three-pass harvest costs as a function of yield (bushels per acre) and residue retention coefficient (ORNL).

2.2. Two-pass and three-pass landowner profit characterization

The per-ton harvest costs described above are relevant from a cost-minimization perspective. However, three-pass harvest systems, which have higher removal rates in terms of tons per acre, can have competitive advantages with regards to per-acre incomes. At sustainability retention coefficients less than 0.6, net returns range from $58-$86 per acre from two pass systems (Figure), but range from $71-$135 per acre from three-pass systems (Figure) due to higher collection rates associated with the three-pass system. Per-acre net returns across yield scenarios are higher from the three-pass system where residue retention coefficients are less than 0.6, and higher from two-pass systems where residue retention coefficients are greater than 0.5.

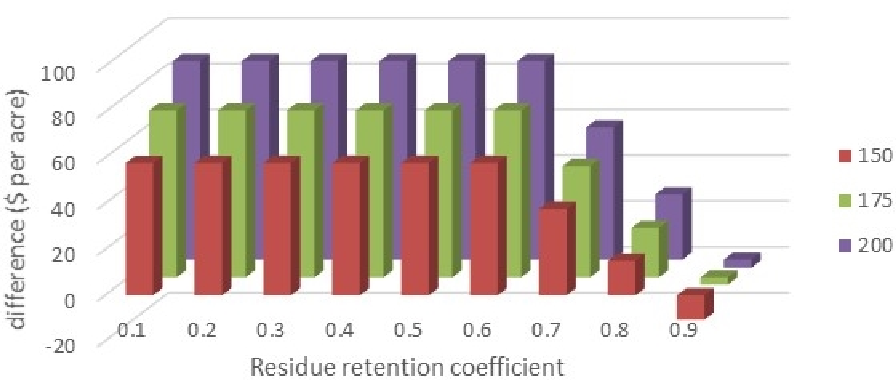

Figure 5. Two-pass net returns ($ per acre) as a function of yield (bushels per acre) and residue retention coefficient (ORNL).

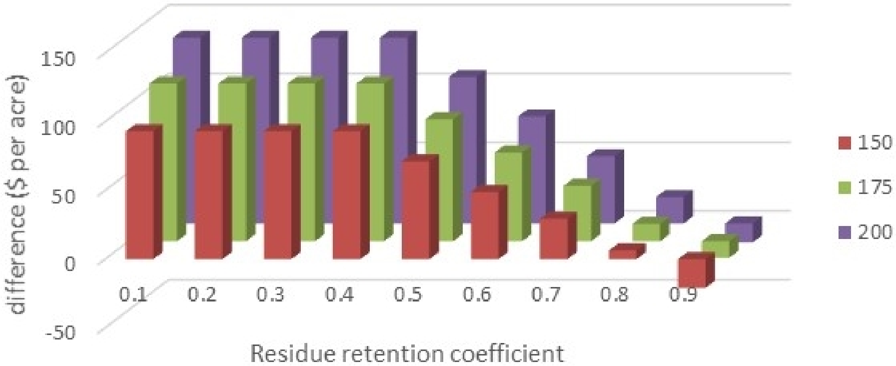

Figure 6. Three-pass net returns ($ per acre) as a function of yield (bushels per acre) and residue retention coefficient (ORNL).

In the BT16, as with this analysis, it is assumed that farmers seek profit maximization on a per-acre basis. It is also assumed that costs associated with stover production up to the farmgate, including harvesting, are incurred by farmers. Notably, per-acre profit maximization from the farmers' perspective differs from per-ton cost and quality preferences from the biorefinery perspective. From the biorefinery perspective, increased ash content of the feedstock decreases the content of fermentable material leading to reduced yield of fuel per ton of biomass, while increasing the disposal cost for the unfermentable fraction. The increased ash content also provides buffering capacity for the material resulting in a further decrease in biofuel yield. Ultimately the value of the feedstock is decreased proportionally to the amount of ash contamination contained within (Bonner, Smith et al. 2014). Within this context, deviating from the harvest configuration that is most profitable to the farmer requires either contracting only for a specified operation, or incentivizing less profitable but more desirable harvest configurations. Here we quantify the change in supply and cost associated with modifying the stover harvest configuration and the associated changes in per-acre profits, per-ton costs, and potential quantities available at specified prices.

2.3. Total supplies

The logic described above was applied in POLYSYS to assess the proportion of stover potentially available from the two-pass vs the three-pass harvest system based on cost minimization. At $40 per dry ton, approximately 15 million and 50 million dry tons of stover are available from two-pass and three-pass systems, respectively (Figure). Under a range of prices, approximately two-thirds of total supply is available from three-pass harvesting systems.

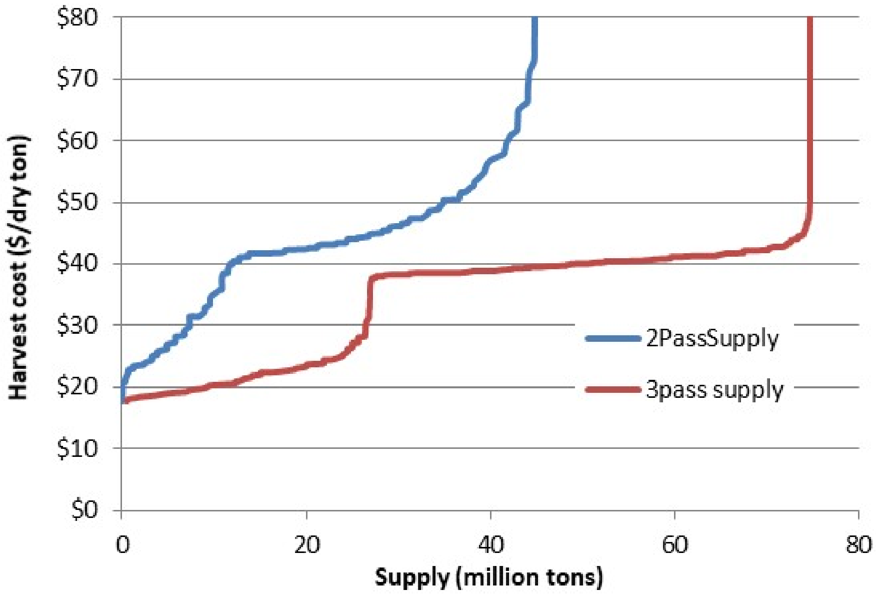

Figure 7. Three-pass and two-pass national potential stover supplies as a function of harvest cost, base case scenario, 2040.

3. Summary

Quality characteristics can be impacted by harvesting operations, and ash content can be reduced by harvesting from a two-pass rather than a three-pass harvesting system. For example, the annual INL State-of-technology (SOT) reports support technical progress to meet delivered feedstock cost for conversion pathways in the Bioenergy Technology Office (BETO) portfolio. The 2017 Herbaceous SOT (Roni et al, 2017), presents a blend of herbaceous feedstocks to minimize cost while meeting quality specifications. Biomass resources considered in the 2017 Herbaceous SOT include corn stover harvested by a mix of three-pass and two-pass harvesting systems, in addition to other feedstocks. This blend includes 12.15% three-pass corn stover, 75.72% two-pass stover, 8.23% switchgrass, and 3.91% grass clippings.

In the absence of vertical integration, stover from two-pass harvesting operations is expected to be more expensive than stover from three-pass harvesting operations where residue retention coefficients are less than 0.6. In these areas under three-pass vs two-pass systems, harvests costs are $2-$3 cheaper per ton, and returns to the landowner are $13-$49 per acre greater. If the harvest decision solves to minimize costs to the landowner, approximately 2/3 of the stover supply is derived from three-pass harvesting. The additional cost of meeting spec with two-pass stover is between $3-6/dry ton. Alternative approaches (e.g. washing) that may compete with this cost should be considered.

As described above, this analysis assumes that production costs, including harvest costs, are incurred by farmers. In a vertically integrated business model, harvest costs may instead be incurred by the biomass buyer rather than the biomass producer. In this scenario, higher harvest costs may not drive the harvest decision but still would influence the potential quantity available and associated price.

In areas with abundant stover supplies and low competition for those supplies, two-pass systems may be a cost-competitive approach to reducing ash content. However, if alternative markets with a higher tolerance for ash content are present (e.g. animal bedding) farmers may prefer the higher per-acre returns achievable with three-pass harvesting systems, and a premium on the order of $20-$50 per acre may be needed to incentivize harvesting with a two-pass system.

In areas with residue retention coefficients greater than 0.5, the two-pass harvesting system is advantageous both in terms of per-ton costs and per-acre returns. However, these lands may not offer the greatest supply or ideal biomass sourcing locations.

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