INL/EXT-08-14752
Revision 0 DRAFT

Uniform-Format Solid Feedstock Supply System:

A Commodity-Scale Design to Produce an Infrastructure-Compatible Bulk Solid from Lignocellulosic Biomass

Section 3

DRAFT

J. Richard Hess
Kevin L. Kenney
Leslie Park Ovard
Erin M. Searcy
Christopher T. Wright

April 2009

DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

INL/EXT-08-14752
Revision 0 DRAFT

Uniform-Format Solid Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Bulk Solid from Lignocellulosic Biomass

Section 3

DRAFT

J. Richard Hess
Kevin L. Kenney
Leslie Park Ovard
Erin M. Searcy
Christopher T. Wright

April 2009

Idaho National Laboratory
Bioenergy Program
Idaho Falls, Idaho 83415

Prepared for the
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

CONTRIBUTORS

Andy Aden
National Renewable Energy Laboratory

Mark E. Delwiche
Idaho National Laboratory

Duane R. Grant
Grant 4-D Farms - Idaho

Kelly N. Ibsen
National Renewable Energy Laboratory

Jacob J. Jacobson
Idaho National Laboratory

Patrick T. Laney
Idaho National Laboratory

David J. Muth
Idaho National Laboratory

Judy K. Partin
Idaho National Laboratory

Robert D. Perlack
Oak Ridge National Laboratory

Peter A. Pryfogle
Idaho National Laboratory

Corey Radtke
Shell Global Solutions (US) Inc

Allison E. Ray
Idaho National Laboratory

William A. Smith
Idaho National Laboratory

Shahab Sokhansanj
Oak Ridge National Laboratory

Anthony F. Turhollow
Oak Ridge National Laboratory

Thomas H. Ulrich
Idaho National Laboratory

Lynn M. Wendt
Idaho National Laboratory

Erin G. Wilkerson
Oak Ridge National Laboratory

INDEPENDENT REVIEWERS

Kevin Comer
Senior Project Manager
Antares Group Inc.

Bill Belden
Senior Agricultural Specialist
Antares Group Inc.

John Hickman
Biorenewable Energy and Life Sciences
Deere & Company – Moline Technology
Innovation Center

Craig Splittstoesser
Grain Operations/Project Engineering
Archer Daniels Midland Co. (ADM)

Bob Wallace
Bioenergy Bridge, Biomass Energy Center
Pennsylvania State University

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Zia Haq, John Ferrell, Sam Tagore, Alison Goss-Eng, Laura Neal, and Erin Wilkerson of the U.S. DOE Energy Efficiency and Renewable Energy (EERE) Office of Biomass Program. Idaho National Laboratory's R&D Support Team also made valuable contributions in the preparation of this report, and the authors would like to thank Kristine Burnham, David Combs, Shaun Eames, and Allen Haroldsen for their graphics support; Quinn Grover, Gordon Holt, Lisa Plaster, Heather Rohrbaugh, Penny Simon, and Jan Wright for editorial and text processing support; the INL Research Library staff for research support; and Dan Olsen for drafting support.

CONTENTS

CONTRIBUTORS iii

INDEPENDENT REVIEWERS iii

ACKNOWLEDGEMENTS iii

3. PIONEER UNIFORM-FORMAT FEEDSTOCK SUPPLY SYSTEM 3-1
- 3.1 Pioneer Uniform Harvest and Collection 3-3
  - 3.1.1 Pioneer Uniform Harvest and Collection Format Intermediates 3-3
  - 3.1.2 Pioneer Uniform Harvest and Collection Equipment 3-10
  - 3.1.3 Pioneer Uniform Harvest and Collection Cost and Sensitivity Analysis 3-20
- 3.2 Pioneer Uniform Storage 3-26
  - 3.2.1 Pioneer Uniform Storage Format Intermediates 3-28
  - 3.2.2 Pioneer Uniform Storage Equipment 3-32
  - 3.2.3 Pioneer Uniform Storage Cost and Sensitivity Analysis 3-35
- 3.3 Pioneer Uniform Preprocessing and Transportation 3-40
  - 3.3.1 Pioneer Uniform Preprocessing and Transportation Format Intermediates 3-42
  - 3.3.2 Pioneer Uniform Preprocessing and Transportation Equipment 3-48
  - 3.3.3 Pioneer Uniform Preprocessing and Transportation Cost and Sensitivity Analysis 3-53
- 3.4 Pioneer Uniform Receiving and Handling 3-63
  - 3.4.1 Pioneer Uniform Receiving Format Intermediates 3-64
  - 3.4.2 Pioneer Uniform Receiving and Handling Equipment 3-67
  - 3.4.3 Pioneer Uniform Receiving and Handling Cost and Sensitivity Analysis 3-72
- 3.5 Summary of Costs for the Pioneer Uniform Feedstock Supply System 3-77
  - 3.5.1 Selection and Definition of Input Parameters 3-77
  - 3.5.2 Monte Carlo Analysis 3-79
  - 3.5.3 Ranking of Input Parameters 3-82

FIGURES

Figure 3-1. Order of unit operations in the Pioneer Uniform feedstock supply system. Preprocessing is relocated from the biorefinery to distributed depots at or near biomass storage locations. 3-2

Figure 3-2. Pioneer Uniform harvest and collection supply logistics processes and format intermediates 3-3

Figure 3-3. Switchgrass (a) standing in the field (background, right), and after harvest and windrowed with a mower/conditioner (foreground); and (b) baled in a round format. 3-5

Figure 3-4. Single-pass grain and cob harvest: (a) harvested grain unloaded from the combine grain tank, and (b) harvested cob, plus some attached husk, unloaded from a second tank attached to or pulled behind the combine. 3-6

Figure 3-5. Harvested corn cobs being dumped into a field-side cob pile. 3-6

Figure 3-6. Biomass bales being loaded onto haul trailers: (a) large square bales can be handled two at a time, while (b) round bales can only be handled one at a time for proper orientation of the trailer. 3-7

Figure 3-7. Round Baler: (a) Vermeer 604 Super M Large Round 47×66-in. baler (b) pulled by a 115 hp mechanical front-wheel-drive tractor with a round bale that has just been discharged from the baler 3-13

Figure 3-8. Stinger Stacker 5500 loaded with round bales. 3-14

Figure 3-9. Harvesting both grain and cobs; (a) CNH combine pulling a Vermeer cob wagon in a corn field near Holloway, Minn., during the Chippewa Valley Ethanol harvesting demonstration Oct. 28, 2008 (b) John Deere combine pulling a Redekop Manufacturing cob wagon....3-15

Figure 3-10. A dual tank grain/cob cart for collecting grain from the combine and cobs from the cob wagons of single-pass harvest systems, Dethmers Manufacturing Co. (Demco) dual-cart 2-SKU Cob Cart. 3-15

Figure 3-11. With a truck positioned beside the cob wagon, the harvest operation as temporally stopped to dump the cob wagon bin. Vermeer Corp. CCX770 Cob Harvester 3-16

Figure 3-12. Pioneer Uniform harvest and collection cost distribution histogram from @Risk analysis for the round bale corn stover scenario. 3-21

Figure 3-13. Pioneer Uniform harvest and collection cost distribution histogram from @Risk analysis for the square bale corn stover scenario. 3-22

Figure 3-14. Pioneer Uniform harvest and collection cost distribution histogram from @Risk analysis for the round bale switchgrass scenario. 3-22

Figure 3-15. Pioneer Uniform harvest and collection cost distribution histogram from @Risk analysis for the square bale switchgrass scenario. 3-23

Figure 3-16. Pioneer Uniform harvest and collection cost distribution histogram from @Risk analysis for corn cobs. 3-23

Figure 3-17. Storage supply logistic processes and format intermediates. 3-26

Figure 3-18. Row of round bales wrapped with plastic with a modified baler to bind the bale rather than using twin. 3-27

Figure 3-19. On-farm corn cob storage pile located at or near field side. 3-27

Figure 3-20. Corncob water content and relative microbial activity over a range of temperatures, based upon water activity to water content data taken from Foley 1978....3-29

Figure 3-21. Division of a round bale (adapted from Rider et al. [1979]). Weather impacts were shown to affect the outer 6 in. (15 cm) of the bale in a 5-ft diameter × 4-ft thick bale. 3-31

Figure 3-22. Modeled moisture zones of cob pile stored outdoors. The thickness of the outer surface layer is independent of pile size and therefore fewer large piles would encourage dry matter preservation....3-32

Figure 3-23. Sunflower 8210 dump wagon. 3-33

Figure 3-24. 3-34

Figure 3-25. Pioneer Uniform storage cost distribution histogram from @Risk analysis for the round bale corn stover scenario. 3-37

Figure 3-26. Pioneer Uniform storage cost distribution histogram from @Risk analysis for the square bale corn stover scenario. 3-37

Figure 3-27. Pioneer Uniform storage cost distribution histogram from @Risk analysis for round bale switchgrass. 3-38

Figure 3-28. Pioneer Uniform storage cost distribution histogram from @Risk analysis for square bale switchgrass. 3-38

Figure 3-29. Pioneer Uniform storage cost distribution histogram from @Risk analysis for corn cobs. 3-39

Figure 3-30. Preprocessing and transportation supply logistic processes and format intermediates. 3-41

Figure 3-31. Relationship between truck bulk density and geometric mean particle size of corn stover, *Sorghum* stover, soybean straw, switchgrass, wheat straw, and corn cobs. 3-44

Figure 3-32. Truck configurations for a 48-ft trailer, a 53-ft trailer, and a 24-ft flatbed tractor with two 30-ft trailers carrying both square and round bales. 3-45

Figure 3-33. Truck configurations for a 48-ft and 53-ft chip van trailer carrying ground bulk feedstock. 3-46

Figure 3-34. Truck configurations for a 48-ft and 53-ft chip van trailer carrying ground bulk feedstock. The possum-belly trailer is used to transport bulk corn stover and switchgrass, while the flat-bottom trailer is used to transport corn cobs. 3-47

Figure 3-35. Bulk density changes as a function of applied pressure for corn stover and switchgrass at two different grind sizes (Pryfogle, INL test data, March 2009). 3-47

Figure 3-36. Roadrunner Hay Clamp bale handling attachment. 3-51

Figure 3-37. Telehandler loader used to load corn cobs for transport to the biomass depot. 3-51

Figure 3-38. Trinity Eagle Bridge trailer used to haul loose corn cobs from the storage site in the field to the biomass depot. 3-51

Figure 3-39. Peerless Roadrunner 53-ft chip van for transport to the biorefinery of ground, bulk material. 3-52

Figure 3-40. Pioneer Uniform handling and transportation cost distribution histogram from @Risk analysis for the round bale corn stover scenario. 3-57

Figure 3-41. Pioneer Uniform handling and transportation cost distribution histogram from @Risk analysis for the square bale corn stover scenario. 3-58

Figure 3-42. Pioneer Uniform handling and transportation cost distribution histogram from @Risk analysis for the round bale switchgrass scenario. 3-58

Figure 3-43. Pioneer Uniform handling and transportation cost distribution histogram from @Risk analysis for square bale switchgrass. 3-59

Figure 3-44. Pioneer Uniform preprocessing cost distribution histogram from @Risk analysis for the round bale corn stover scenario. 3-59

Figure 3-45. Pioneer Uniform preprocessing cost distribution histogram from @Risk analysis for the square bale corn stover scenario. 3-60

Figure 3-46. Pioneer Uniform preprocessing cost distribution histogram from @Risk analysis for the round bale switchgrass scenario. 3-60

Figure 3-47. Pioneer Uniform preprocessing cost distribution histogram from @Risk analysis for the square bale switchgrass scenario. 3-61

Figure 3-48. Pioneer Uniform preprocessing cost distribution histogram from @Risk analysis for corn cobs. 3-61

Figure 3-49. Receiving and handling supply logistic processes and biomass format intermediates. 3-64

Figure 3-50. Flowability classification ranges. Uniform-Format design target is $ff_c > 4$. 3-66

Figure 3-51. Receiving processes within the Pioneer Uniform design: Phelps drive-through truck tipper. 3-68

Figure 3-52. Need caption. 3-68

Figure 3-52. Receiving and cueing processes within the Pioneer Uniform design: bulk material being unloaded by tipper truck and being conveyed into the Eurosilo. 3-69

Figure 3-54. Pioneer Uniform receiving and handling cost distribution histogram from @Risk analysis for the round bale corn stover scenario. 3-73

Figure 3-55. Pioneer Uniform receiving and handling cost distribution histogram from @Risk analysis for square bale corn stover. 3-74

Figure 3-56. Pioneer Uniform receiving and handling cost distribution histogram from @Risk analysis for the round bale switchgrass scenario. 3-74

Figure 3-57. Pioneer Uniform receiving and handling cost distribution histogram from @Risk analysis for the square bale switchgrass scenario. 3-75

Figure 3-58. Pioneer Uniform receiving and handling cost distribution histogram from @Risk analysis for corn cobs. 3-76

Figure 59. Total Pioneer Uniform supply system design cost distribution histogram from @Risk analysis for the round bale corn stover scenario. 3-79

Figure 3-60. Total system cost summary for the Pioneer Uniform square bale corn stover scenario. 3-80

Figure 61. Total Pioneer Uniform supply system design cost distribution histogram from @Risk analysis for the round bale switchgrass scenario. 3-80

Figure 3-62. Total system cost summary for the Pioneer Uniform square bale switchgrass scenario. 3-81

Figure 3-63. Total system cost summary for the Pioneer Uniform corn cob scenario. 3-81

Figure 3-64. Percent change of variable to output. 3-82

Figure 3-65. Relative sensitivity of individual supply system parameters. 3-83

Figure 3-66. Relative cost impact of individual supply system parameters. 3-84

Figure 3-67. Tornado chart reflecting the final cost in dollars according to the distribution ranges defined. 3-85

Figure 3-68. Variable impact on supply chain processes. 3-86

TABLES

Table 3-1. Attributes of round bale collection format intermediates for corn stover (crop residue) and switchgrass (dedicated energy crop). 3-4

Table 3-2. Attributes of harvest and collection format intermediates for corn cobs (crop residue). 3-5

Table 3-3. Yield and bulk density data for round bales of various biomass feedstocks and corn cobs. 3-8

Table 3-4. Results of stover yield and moisture tests. 3-9

Table 3-5. Harvest and collection equipment specifications for corn stover (crop residue) and switchgrass (energy crop) in the Pioneer Uniform design. 3-11

Table 3-6. Harvest and collection equipment specifications for whole corn in the Pioneer Uniform design. 3-11

Table 3-7. Typical field speeds and field efficiencies for corn cob and round baler equipment. 3-17

Table 3-8. Field capacities for harvesting machines calculated using the typical field efficiencies and field speeds (ASABE, ASAE EP496.3 2006a; ASAE 497.5 – 2006b). 3-18

Table 3-9. Static model costs for major harvest and collection equipment in the Pioneer Uniform switchgrass scenario. Costs are expressed in $/DM ton unless otherwise noted. 3-20

Table 3-10. Static model costs for major harvest and collection equipment in the Pioneer Uniform corn cob scenario. Costs are expressed in $/DM ton unless otherwise noted. 3-20

Table 3-11. Harvest and collection cost summary for the Pioneer Uniform corn stover scenario. 3-24

Table 3-12. Harvest and collection cost summary for the Pioneer Uniform switchgrass scenario. 3-24

Table 3-13. Harvest and collection cost summary for the Pioneer Uniform corn cob scenario. 3-24

Table 3-14. Attributes of storage format intermediates for corn stover, a crop residue, and switchgrass, a dedicated energy crop. 3-28

Table 3-15. Storage equipment specifications for the Pioneer Uniform design. 3-33

Table 3-16. Modeled comparison of typical storage improvements and structure costs compared to dry matter loss and its impact on feedstock costs. 3-35

Table 3-17. Static model costs for major storage equipment in the Pioneer Uniform corn stover and switchgrass scenarios. Values are expressed in $/DM ton unless otherwise noted. 3-36

Table 3-18. Storage cost summary for the Pioneer Uniform corn stover and switchgrass scenarios. 3-40

Table 3-19. Attributes of preprocessing and transportation format intermediates for corn stover and corn cobs (crop residues) and switchgrass (a dedicated energy crop). 3-42

Table 3-20. Bulk density required to maximize various load capacity configurations to accommodate a range of load limits. 3-45

Table 3-21. Bulk density required to maximize various load capacity configurations to accommodate a range of load limits. 3-46

Table 3-22. Bulk density required to maximize various load capacity configurations to accommodate a range of load limits. 3-46

Table 3-23. Handling and transportation equipment specifications for the Pioneer Uniform design. 3-50

Table 3-24. Preprocessing and queuing equipment specifications for the Pioneer Uniform design. 3-52

Table 3-25. Static model costs for major handling and transportation equipment in the Pioneer Uniform corn stover and switchgrass scenarios. Costs are expressed in $/DM ton unless otherwise noted. 3-54

Table 3-26. Static model costs for major preprocessing equipment in the Pioneer Uniform corn stover and switchgrass scenarios. Costs are expressed in $/DM ton unless otherwise noted. 3-56

Table 3-27. Bale and bulk transportation cost summary for the Pioneer Uniform corn stover and switchgrass scenarios. 3-62

Table 3-28. Preprocessing cost summary for the Pioneer Uniform corn stover and switchgrass scenarios. 3-63

Table 3-29. Preprocessing cost summary for Pioneer Uniform corn cob scenario. 3-63

Table 3-30. Attributes of receiving and handling format intermediates for corn stover, switchgrass, and corn cobs. 3-64

Table 3-31. Flow function value ranges and the corresponding flowability classification....3-66

Table 3-32. Receiving equipment specifications for the Pioneer Uniform Design....3-67

Table 3-33. Advantages and disadvantage of wood fuel conveying systems (Badger, 2002). 3-70

Table 3-34. Static model costs for major receiving and handling equipment in the Pioneer Uniform corn stover, switchgrass, and corn cob scenarios....3-72

Table 3-35. Receiving and handling cost summary for the Pioneer Uniform corn stover, switchgrass, and corn cob scenarios. 3-76

Table 3-36. Input parameter distributions for sensitivity analysis. 3-77

Table 3-37. Summary of costs for the Pioneer Uniform feedstock supply systems, presented in $/DMton....3-82

3. PIONEER UNIFORM-FORMAT FEEDSTOCK SUPPLY SYSTEM

The Pioneer Uniform-Format (Pioneer Uniform) feedstock supply system design introduces forward-deployed preprocessing that occurs at distributed locations established by a group of growers, an independent business entity, or the biorefinery (Figure 3-1). These distributed preprocessing locations are referred to as depots and encompass a number of operations, including short- to medium-term storage; preprocessing activities such as size reduction, separation, and densification; biomass queuing; and loading of transportation systems. The Pioneer Uniform supply system design addresses three fundamental constraints of the Conventional Bale supply system: (1) producers limited to use of a particular biomass bale format and/or biomass resources that can be baled; (2) inefficiencies of handling and transport of biomass of multiple size, shapes, and bulk densities; and (3) multiple, capital-intensive feed systems at the front end of the biorefinery that limit the transferability of biorefinery designs from one location to another.

Similar to the discussions presented in the Conventional Bale supply system (Section 2), the following section describes the impact of feedstock format intermediates and machinery on each unit operation in the order it occurs within the Pioneer Uniform supply system (Figure 3-1). However, only the format intermediates and machinery that are different from the Conventional Bale supply system are discussed in the respective sections. For example, a discussion of the square bale harvest and collection unit operation does not include details on format intermediates or machinery already discussed in the Conventional Bale supply system (Section 2). On the other hand, a discussion of several format intermediates and machinery options associated with the preprocessing unit operation is presented because of significant changes in the preprocessing operation resulting from its forward deployment in the Pioneer Uniform supply system. In addition, individual sections focus on one unit operation, providing a full description, in terms of cost, performance, logistics, and operational assumptions for an integrated Pioneer Uniform feedstock supply system. Additional cost and performance detail for each unit operation in the Pioneer Uniform supply system is provided in Appendix A.-3.

Like the Conventional Bale system, the Pioneer Uniform feedstock supply system is also designed to supply a biorefining facility with 800,000 DM tons of biomass annually (Section 2, Table 2-1). This Pioneer Uniform supply system design would be appropriate for supplying biomass to both biochemical (Aden et al., 2002) and select thermochemical (Phillips et al., 2007) conversion facility designs that depend on a year-round biomass delivery schedule.

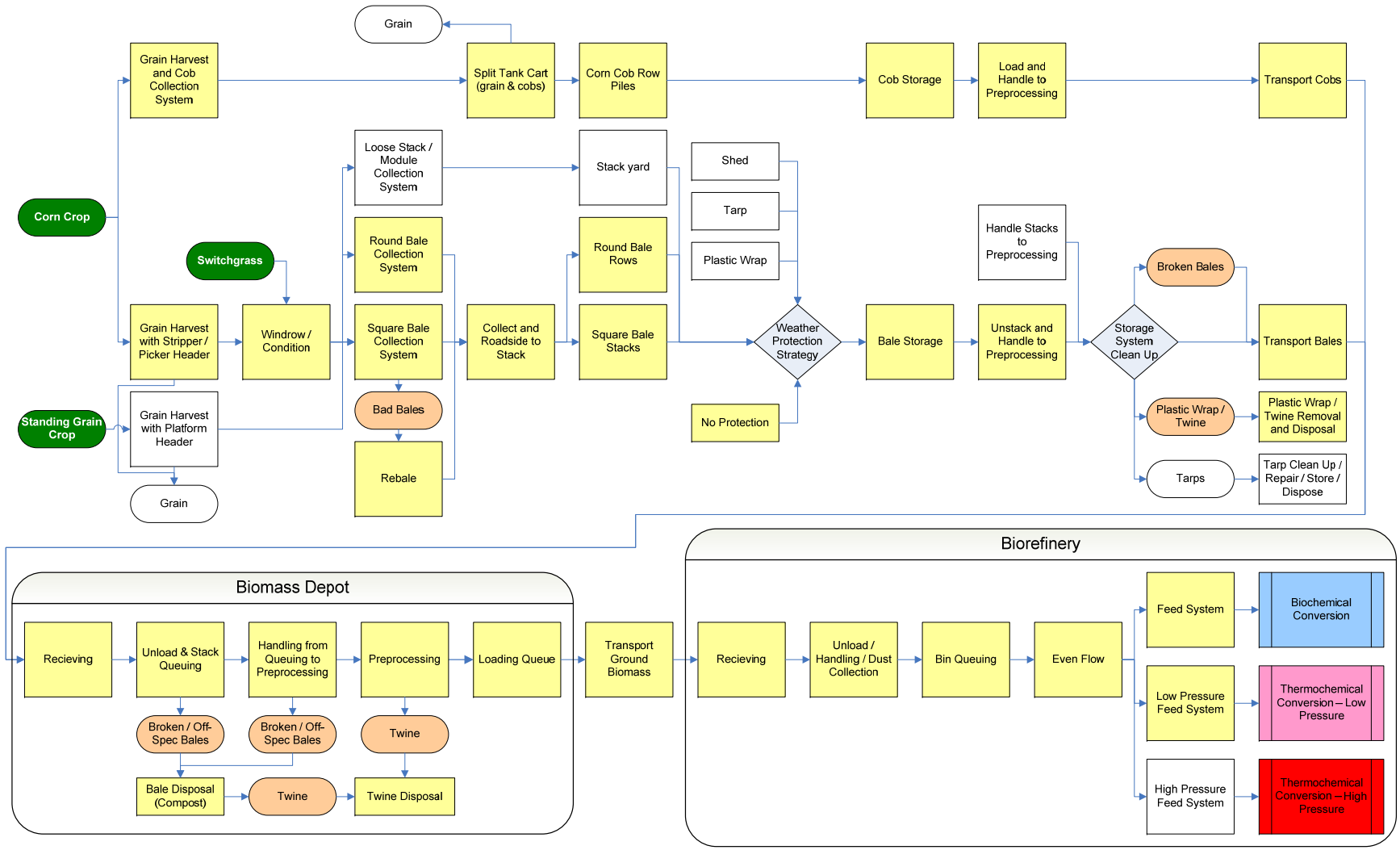

Figure 3-1. Order of unit operations in the Pioneer Uniform feedstock supply system. Preprocessing is relocated from the biorefinery to distributed depots at or near biomass storage locations.

(Note: Green ovals represent format intermediates, tan ovals represent potential waste streams, yellow rectangles represent individual modeled processes, and white rectangles represent alternate processes that were not modeled.)

3.1 Pioneer Uniform Harvest and Collection

The Pioneer Uniform design expands upon the Conventional Bale design and adds round-bale collections systems for corn stover and switchgrass (Figure 3-2). This design also introduces a single-pass corn residue harvest system that collects corn cobs along with selected fractions of the corn stalk, leaves, and husks. This corn cob harvest system represents a first implementation of a bulk harvest and collection approach for crop residues. Additionally, selective harvest of specific corn stover residue fraction(s) has potential sustainability and feedstock logistics/conversion advantages ranging from bulk density to conversion recalcitrance to soil amendment value. Finally, and possibly the most prominent feature of this design, is that the Pioneer Uniform system is tolerant of a diversity of alternate collection formats (e.g., square bale, round bale, bulk corn cob), thus giving the producer flexibility to chose harvesting and collection systems that are most economical and practical to their respective operations (Figure 3-2).

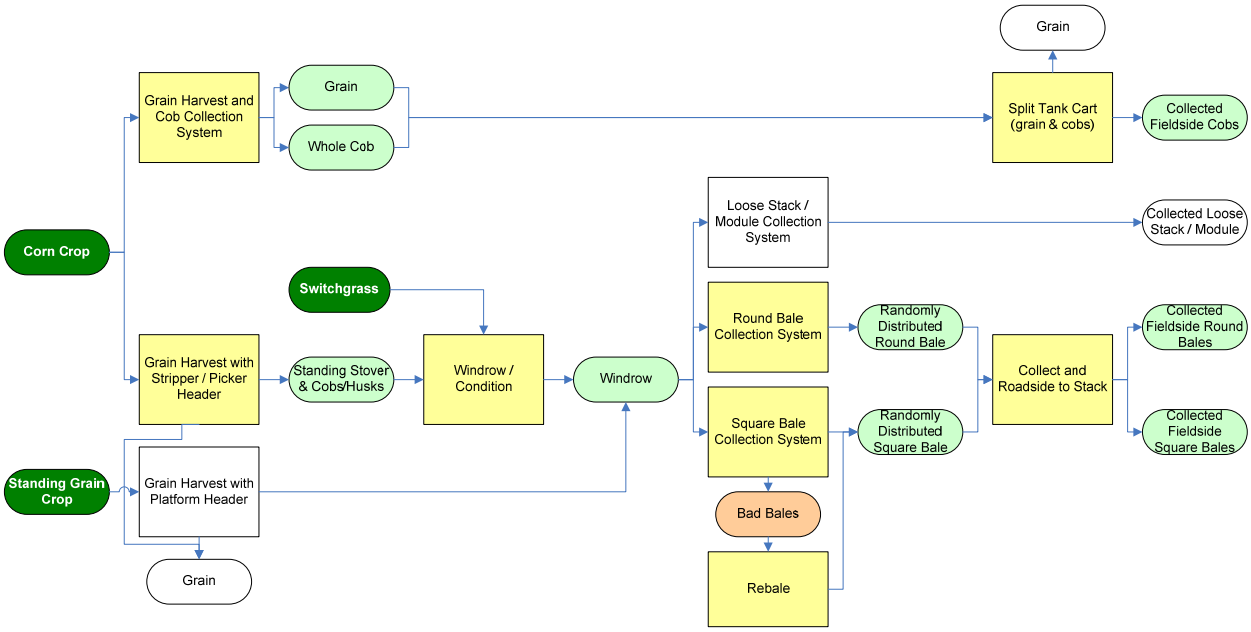

Figure 3-2. Pioneer Uniform harvest and collection supply logistics processes and format intermediates.

(Note: Green ovals represent biomass format intermediates, tan ovals represent potential waste streams, and yellow rectangles represent processes modeled in this report. White rectangles represent alternative processes not modeled.)

3.1.1 Pioneer Uniform Harvest and Collection Format Intermediates

The Pioneer Uniform harvest and collection unit operation removes corn stover and switchgrass from the field in both large square bale and round bale formats. For corn stover and switchgrass, the harvesting, windrowing/conditioning, and field drying processes are the same as those presented in the Conventional Bale design (Section 2.1.1, Tables 2-2 and 2-3), and that data is not repeated in this section of the report. The processes of baling, collecting, and roadsiding include both large square bale (Section 2.1.1, Tables 2-2 and 2-3) and round bale formats (Table 3-1). “Roadsiding” refers to the process of moving the collected biomass to a location that is generally next to a road that borders the field or is nearby.

Table 3-1. Attributes of round bale collection format intermediates for corn stover (crop residue) and switchgrass (dedicated energy crop).

	Crop Standing in the Field	Grain Harvest	Conditioned/ Windrowed Biomass	Baled Biomass	Collected/Roadsided Biomass
Corn Stover					
Biomass Anatomical Output				Stalk, cob, and husk (collectively stover)	Stalk, cob, and husk (collectively stover)
Yield (DM ton/acre)				1.63 (3.9 bale/acre)	N/A
Format Output				Randomly distributed[a]	Collected at fieldside[a]
Bulk DM Density Output				9.0 lb/ft^3 (829 DM lb/bale)[b]	9.0 lb/ft^3 (829 DM lb/bale)[b]
Output Moisture (% w.b.)				12%	12%
Switchgrass					
Biomass Output				Whole crop less stubble (switchgrass)	switchgrass
Yield (DM ton/acre)				4.1 (9.4 bale/acre)	N/A
Format Output				Randomly distributed[a]	Collected at fieldside[a]
Bulk DM Density Output				9.4 lb/ft^3 (or 865 DM lb/bale)[c]	9.4 lb/ft^3 (or 865 DM lb/bale)[c]
Output Moisture (% w.b.)				12%	12%

Data same as Table 2-2 Section 2

Data same as Table 2-2 Section 2

a. 5.5-ft diameter × 4-ft wide round bales

b. Shinners et al., 2007.

c. INL/UofIL test data, switchgrass and *Miscanthus* harvest in Illinois, January 2008.

For the round bale scenario in the Pioneer Uniform design, the corn stover and switchgrass are allowed to dry in the windrow to 12% moisture content and then are baled into 5.5-ft diameter × 4-ft wide round bales. The biomass field drying and 12% moisture input assumptions discussed in Section 2.1.1 for square baling were also applied to round baling, even though it is recognized that optimum biomass moistures for round and square bale equipment are not always the same. When the biomass moisture drops below 10 to 12%, some round baler designs will not work effectively, and baling operations may need to be suspended until evening or nighttime after the dew comes on (Grant, 2003). Conversely, round bales have a greater baling and storage tolerance than square bales for biomass moistures above 12 to 15% (ref.). Similar to square baling in the Conventional Bale design, the round baling operation in this design drops the bales in the field as they are formed (Figure 3-3). The bales are then collected and roadsided. The harvest and collection unit operation is complete once the bales are delivered to the field side and placed into a storage stack.

(a) (b)

Figure 3-3. Switchgrass (a) standing in the field (background, right), and after harvest and windrowed with a mower/conditioner (foreground); and (b) baled in a round format.

The corn cob harvesting process in the Pioneer Uniform design is a single-pass operation in which the grain and cob are collected simultaneously (Table 3-2). This process does not produce a biomass windrow behind the harvester that must be collected with a subsequent process. The two most common cob harvest systems are (1) the grain and cob mix (often referred to as "CCM" for "corn and cob mix") and (2) cob separation and collection into a second cob collection bin. The grain and cob mix harvest process collects both the grain and cob together in the harvester grain tank, and separation of the grain and cob is performed in a later process. (For an overview of the grain and mix process, see Kenney 2008 and Christiansen 2009.)

Table 3-2. Attributes of harvest and collection format intermediates for corn cobs (crop residue).

	Crop Standing in the Field	Single-Pass Grain and Cob Harvest		Cob Transferred to Roadside
Biomass Output	Whole crop (grain and cob only)	Corn grain	Whole cob	Whole cob
Yield (DM ton/acre)[a]	8.52	4.26 (180 bu/ acre corn)	0.77	N/A
Format Output	Standing whole crop	Grain	Whole cob (90%) and some attached husk	Collected in field-side piles
Bulk DM Density Output	N/A	52 lb/bu[b]	8.0 lb/ft^3[c]	8.0 lb/ft^3[c]
Output Moisture (% w.b.)	N/A	15%[d]	34%[e]	34%[e]

a. Process output yield calculations based on equipment dry matter loss (Table 3-6).

b. The standard grain bulk density is 56 lb/bu at __% moisture Grain Bulk Density.

c. Corn cob bulk density, based on a 90% whole cob purity (Foley 1978).

d. Grain moisture at harvest.

e. Cob moisture at harvest and relationship to grain harvest.

The cob collection system presented in this Pioneer Uniform design separates and maintains the grain and cob as distinct product streams from the point of harvest (Figure 3-4). Single-pass cob harvest systems provide no opportunity for field drying, so the grain and cob are both removed from the field at

the respective harvest moisture levels. The modeled harvest moisture level for grain is targeted at 20%. Based on the grain moisture, the relative cob moisture is assumed to be 40% (Table 3-2).

(a) (b)

Figure 3-4. Single-pass grain and cob harvest: (a) harvested grain unloaded from the combine grain tank, and (b) harvested cob, plus some attached husk, unloaded from a second tank attached to or pulled behind the combine.

While single-pass harvesting processes eliminate biomass field drying opportunities that may present moisture management issues for downstream storage and handling unit operations, they also provide advantages because cobs are not returned to the ground. By eliminating the windrow, single-pass harvest and collection systems have the benefits of not having to pass through the field again and of improved biomass product quality, since cobs are not left in the field to risk adverse weather exposure or contamination with soil as a result of field drying and subsequent collection operations. Once the cobs are harvested, separated, and collected, they are transferred to a field-side location and dumped into a pile (Figure 3-5).

Figure 3-5. Harvested corn cobs being dumped into a field-side cob pile.

3.1.1.1 Biomass Deconstruction, Fractionation, and Yield

The biomass deconstruction, fractionation, and yield issues for corn stover and switchgrass are the same as those described in the Conventional Bale design (Section 2.1.1.1). However, the Pioneer Uniform design includes whole cob harvesting, which presents several new plant deconstruction and separation/fractionation challenges. Separating the grain from cob is well understood and a fundamental function of modern grain combines. However, separating cob from the remainder of the corn stover residue continues to present separation challenges, particularly with regard to husk material attached at the cob base (Figure 3-4b). Cob purity is the focus of cob harvester development programs being conducted by John Deere, Vermeer, CNH, and others. Having the husk or other stover material present in the whole cob product stream is not a concern for biorefineries tooled to convert whole stover, but the husk material reduces the bulk of the cob product stream and may impact preprocessing and other material handling processes in the supply chain. Since the husk is physically connected to the cob base, the engineering challenge is the development of threshing/chopping mechanisms as part of existing combine harvester systems that can detach the husk from the cob and keep the cob whole (Birrell 2008).

The grain and cob mix harvest system is more successful at achieving higher cob purities because the cob is broken up and the husk is detached in the harvester threshing process (Kenney 2008) However, this process breaks the cob into small pieces that co-mingle with the grain and requires subsequent specialized handling and separation processes. The purpose of the whole cob harvest system is to collect a cob product stream that is not chopped up and co-mingled with the grain, thereby maintaining the integrity of the corn grain product stream and producing a durable whole cob product for subsequent feedstock logistics and biorefining operations. As such, the development of harvester threshing and separation technologies is essential for producing high-purity whole-cob product streams.

3.1.1.2 Format and Bulk Density Impact on Supply System Processes

Although the square bale format discussed in Section 2.1.1.2 does not share the same storage benefits as the round bale format (Section 3.2), square bales do have distinct handling, transportation, and storage footprint advantages. Square bales can be handled two or three at a time for 4×4×8-ft and 3×4×8-ft sizes respectively (Figure 3-6a). They also rapidly stack together on trucks and can be automatically stacked, making the handling and stacking operations rapid and efficient (Figure 2-14). Round bales must be handled one at a time, which causes handling and stacking operations to be slower and less efficient (Figure 3-6b). Loading a 53-ft semi trailer with square bales can be accomplished in less than 30 minutes (80 bales/hr, Table 2-24), whereas loading the same trailer with round bales takes nearly 1 hr (40 bales/hr, Table 3-23).

(a) (b)

Figure 3-6. Biomass bales being loaded onto haul trailers: (a) large square bales can be handled two at a time, while (b) round bales can only be handled one at a time for proper orientation of the trailer.

Similar to the square bale format, different crops baled in the round bale format result in different densities, which impacts the number of bales per acre at the respective crop yield for each design scenario. Even with round bales, cereal straw residues produce some of the lowest bale densities, resulting in relatively high bale counts per ton of biomass (Table 3-3). The cost to handle each bale is essentially the same, irrespective of bale density or size; thus, using plant material or engineering configurations that produce fewer bales per ton of biomass will improve bale collection and handling efficiencies. Regardless of the selected biomass handling format, bale density is a key factor in collection and handling efficiencies, capacity, and ultimately costs.

Table 3-3. Yield and bulk density data for round bales of various biomass feedstocks and corn cobs.

	Crop Yield (baled DM ton/acre)	Bale/Pile Wet Bulk Density (lb/ft^3)	Bale/Pile DM Bulk Density (lb/ft^3)	Round Bales/Acre
Corn Stover	1.6[a]	10.2[b]	9.0[b]	3.9
Corn Cob[c]	0.77	10.4–11.7	6.8–8.7	N/A
Cereal Straw[d]	1.1	7.3–9.4	6.6–8.5	3.3–4.2
Switchgrass[e]	4.0	10.7	9.4	9.4
Miscanthus[e]	5.1	9.4–11.4	8.5–10.3	12.6–15.3

a. INL data, modeled scenario (Table 2-2).

b. Shinners (2007).

c. Based on INL field test data, corncobs harvested in Iowa and Minnesota, November 2008.

d. INL test data, wheat straw harvest in Colorado and Idaho, July to August 2007.

e. INL test data, switchgrass and *Miscanthus* harvest in Illinois, January 2008.

Unlike stover or switchgrass, cobs in this design are handled as a bulk solid material from the point of harvest. With the whole cob harvest system modeled herein, the cob biomass is not compacted into a higher density package. The whole cob harvest and logistic system takes advantage of the inherent density of the cob. A pure cob product will have a dry matter density of 9 to 10 lb/ft^3 and an assumed moisture content of 30% at the time of harvest (Smith et al. 1983). Compared to bulk stover, which is about 1 lb/ft^3 (Table 2-2), cob is nearly 10 times more dense (Table 3-3). For this reason, any contamination of the whole cob stream with other stover materials can greatly reduce the bulk density of whole cobs. Depending on the amount of husks that remain attached to the cob, the density will be reduced to 6 to 8 lb/ft^3. Assuming 90% cob purity, the dry matter density of a whole cob product stream would be approximately 8 lb/ft^3 (Foley, 1978).

Cob purity ranges from 80 to 90% on a weight percentage basis (Stukenholtz 2008). The impurities consist primarily of husks. Many of the husks are attached to the base of the cob, and corn variety appears to influence how much husk is attached (Stukenholtz 2008). The husks usually either remain attached to the shank or to the cob when the ear is picked from the stalk during harvesting. If it remains attached to the shank, then the husk stays with the stalk and does not pass through the combine. Otherwise, the husk enters the combine with the cob. The husk may be removed from the cob during the process of shelling the corn in the combine threshing cylinder/rotor. In this case, the cleaning system of the cob wagon can effectively separate cob and husk.

A cob purity of 80% seems acceptable for subsequent cob handling and storage operations, and the main issue with cob purity is bulk density. Assuming cobs have a density of 9 lb/ft^3 and husks have a density of 0.5 lb/ft^3, a cob purity of 80% reduces bulk density to about 7 lb/ft^3, which adds more than $1 per dry ton to a 25-mile haul. The grinding behavior of husks as compared to cobs is also different, and changes in the cob/husk ratio can affect grinder performance (e.g., more husk makes it more difficult to grind).

3.1.1.3 Biomass Moisture Impact on Supply System Processes and Material Stability

The moisture content of biomass is a key consideration in the selection of field operations for harvest and collection. Like the Conventional Bale design (Section 2.1.1), the round bale Pioneer Uniform design requires wet biomass to be field-dried prior to baling. Section 2.1.1.3 discusses typical moisture levels at harvest for corn stover, cereal grains, and dedicated energy crops that are collected and stored in bales. If high-moisture biomass cannot be dried in the field, it is unsuitable to be baled and stored with this Pioneer Uniform design, which has no wet storage processing system. Without a wet storage system to stabilize the biomass in the presence of water (e.g., ensiling), or an active moisture mitigation system to remove the water at some later point in the supply system (e.g., Section 4, Advanced Uniform-Format Supply System), other alternate moisture management strategies may be employed to handle high-moisture biomass in the Pioneer Uniform design. The first, and likely simplest, strategy is to eliminate storage and go to just-in-time delivery, preprocessing, and conversion of the biomass. This would require the crops and environment that allow a year-round green harvest, much like the sugar cane feedstock supply system, and is certainly a viable option in many of the southern areas of the United States. A second option would be to selectively harvest only the plant parts that have an acceptable moisture level. The cob harvest system presented in this Pioneer Uniform design is an example of such a selective harvest system.

Selective harvest provides an effective approach for dealing with high-moisture biomass. Because a portion of crop residues may be required to be left in the field during harvest to sustain soil health, selectively removing the low-moisture portions while leaving the high-moisture portions would satisfy agronomic sustainability. This would also provide biomass that may have more desirable bulk density and moisture levels (e.g., corn cobs). Studies performed by Hoskinson et al. (2007) and Shinners et al. (2006a) provide the basis for moisture-based selective harvest. Hoskinson et al. (2007) evaluated an actual harvest scenario in Ames, Iowa, using a modified grain combine, whereas Shinners et al. (2006a) collected whole-plant samples from Arlington Agricultural Research Station (AARS), in Wisconsin, manually, with subsequent anatomical separation performed in a laboratory (Table 3-4).

Table 3-4. Results of stover yield and moisture tests.

	Hoskinson et al. 2007	Shinners et al. 2006
Bottom stalk	64%	>70%
100% of stover	34%	64–48%
Top stalk + ear	20%	48–34%
% of potential stover in material other than grain (MOG) fractions	55%	40%
Grain moisture	<12%	<30%

Both studies found that the lower portion of the corn stalk exhibited the highest moisture content (>60%) at the time of grain harvest (Table 3-4). The top stalk and ear fractions of the stover were considerably dryer than the bottom stalk. The entire composite stover moisture (including all stover fractions) ranged from 48 to 64% for the 3-year Shinners et al. (2006) study. These stover moisture levels were considerably higher than those reported by Hoskinson et al. (2007). The difference appears to be largely attributed to the timing of grain harvest. The Shinners et al. (2006) harvest occurred when the grain moisture dropped below 30%, whereas the Hoskinson et al. (2007) study delayed harvest until the grain moisture was below 12%. Another possible contributing factor in the moisture discrepancy is that Shinners et al. (2006) collected whole plants, while Hoskinson et al. (2007) cut the plants with a combine at 10 cm above the ground. Both studies reported similar bottom stock moistures, so the amount of bottom stalk in the composite stover measurement may have been greater in the Shinners et al. (2006) study than in the Hoskinson et al. (2007). Further efforts to understand this discrepancy are important, since harvest timing combined with selective removal could be a very effective moisture management strategy.

The dry stover fractions (the MOG), which include about 40% of the available stover mass, including all the cobs and husk, and 50% each of the leaf and top stalk, pass through the combine (Table 3-4). These results are of particular interest to single-pass harvester development because they suggest that as much as 40 to 55% of the available stover fractions may be harvested as a dry product (<20% w.b.), depending on a number of variables including growing conditions, harvest conditions, and timing of harvest. However, whether the crop is standing in the field or lying in a windrow, decisions to delay harvest to allow for field drying must be balanced with the risk of crop loss.

Cob harvest and stability is also affected by moisture content at the time of grain harvest. In a study of individual corn stover component dry down, cobs retained less moisture than whole stover at grain harvest (Pordesimo et al. 2004), within the range of 40 to 50% versus 50 to 60% for the whole stover. Additionally, cobs reached equilibrium moisture content sooner than the whole stover and suffered fewer dry matter losses after grain harvest. These trends were observed in both standing plants and on-ground residues. Selective cob harvest may provide a benefit during unusually wet harvest seasons or when grain storage space is limited. Cob moisture content was lower than that of whole stover, and whole plants could be left standing in the field until suitable conditions permitted later grain and cob harvests. Cob dry matter content was essentially constant from 128 to 213 days after planting; whole stover dry matter content decreased over this time, primarily due to the loss of leaves and husks (Pordesimo et al. 2004). In addition to its merit as a bulk-handled feedstock, selective cob harvest could be an attractive moisture management strategy during off-normal corn and stover harvest conditions.

3.1.2 Pioneer Uniform Harvest and Collection Equipment

The Pioneer Uniform design differs from the Conventional Bale design by allowing multiple harvest and collection systems to supply biomass though a common feedstock supply system. In the Conventional Bale design, only one harvest and collection system was used (Section 2.1). In this Pioneer Uniform design, harvesting machinery for corn stover and switchgrass are the same as the Conventional Bale design (Section 2.1.2). However, for these crops, the Pioneer Uniform design allows the use of multiple collection systems The collection systems modeled here are the large square bale (Table 2-7) and the round bale (Table 3-5).

Table 3-5. Harvest and collection equipment specifications for corn stover (crop residue) and switchgrass (energy crop) in the Pioneer Uniform design.

Operation	Grain Harvest Only	Condition and Windrow Stover Residue	Condition and Windrow Switchgrass	Baling	Move to Field Side (Roadsiding)
Equipment				Vermeer 604 Super M Large Round 47 × 66-in. with 105 hp mechanical front wheel drive tractor	Stinger Stacker 5500
Haul Distance				N/A	0.3 miles
Rated Capacity[a]				25.6 bales/hr	110.8 bales/hr
Field Efficiency (%)[a]				80%	100%
Dry Matter Loss (%)[b]				Stover, 46% Switchgrass, 10%	0% (assumed)
Operational Window					
hr/day				14.0	12.0
day/year				36	36

Data same as Table 2-2 Section 2

a. See machinery capacity and efficiency calculations (???).

b. Stover based on Richey et al., 1982; Switchgrass based on INL test data, switchgrass, and *Miscanthus* harvest in Illinois, January 2008. Harvest efficiency = 1-DM_Loss.

In addition to accepting biomass in various bale formats, the Pioneer Uniform design can accept biomass collected and handled with bulk harvesting systems. In this case, the modeled system is whole corn cobs harvested and collected with single-pass equipment (Table 3-6).

Table 3-6. Harvest and collection equipment specifications for whole corn in the Pioneer Uniform design.

	Single-Pass Grain and Cob Harvest		Cob Transferred to Roadside
Equipment	JD 9670 STS Combine with JD 608C 8-Row Corn Header, towing cob wagon	Vermeer Corp. CCX770 Cob Harvester	Sunflower 8210 Dump Wagon
Haul Distance	N/A	N/A	N/A
Rated Capacity[a]	2000 bu/hr	8.6 ton/hr	25.9 ton/hr
Field Efficiency (%)[a]	67%	100%	57%
Dry Matter Loss (%)[b]	18%	0%	0%
Operational Window			
hr/day	14.0	14.0	14.0
day/year	36	36	36

a. See machinery capacity and efficiency calculations (?????).

b. dry matter loss data?. Harvest efficiency = 1-DM_Loss.

3.1.2.1 Equipment Used in Pioneer Uniform Design Model

The harvesting and collection equipment for large square bales is presented in Section 2.1.2, and the description of that equipment will not be repeated in this section. Since the round bale collections system relies on the same harvest systems as square bales, only the baling and collection/roadsiding equipment that are unique to the Pioneer Uniform design will be presented here. The whole corn cob harvest and collection system, which is new to the Pioneer Uniform design, and the equipment of this system will be presented in its entirety.

Baling

The round baling equipment selected for this design is pulled behind a tractor, and the baler's mechanical systems are powered by the tractor's PTO drive. The round baler has a pickup system to lift a windrow of biomass and feed it into the baling mechanism. The baling mechanisms of the round and square balers are quite different. Biomass in square balers is stuffed and pressed into the bale (Section 2.1.1), whereas biomass in a round baler is rolled into a bale. A round baler rolls the biomass with a series of rotating belts (or in some designs a single large belt). This design uses a Vermeer 604 Super M large round baler that forms 47-in. thick by 66-in. diameter bales (Figure 3-7a). Round bale width is set by the baler model, but bale diameter can be adjusted on most models. The 66-in. diameter size maximizes the number of bales that can fit on a semi-tractor flatbed for transport to the biomass depot.

Bale compaction in a round baler is achieved with a belt tension mechanism that tightens the belts around the rolling biomass. As the bale grows in size, the belt tension mechanism adjusts to maintain an appropriate compaction pressure on the forming bale. Once the bale has reached the cut-off diameter, the tractor/baler operator is notified by an indicator light/buzzer. The operator halts the forward velocity of the tractor, which stops biomass from feeding into the baler. The bale wrapping and discharge cycle is then activated. As the bale continues rolling in the bale chamber, the baler then wraps it with twine or a net wrap material to prevent it from unrolling. Once the bale is wrapped, hydraulics open the bale chamber and discharge the bale (Figure 3-7b). The bale chamber closes, the operator is notified to proceed, and the process begins again. The round baler in this design is pulled/powered by a 115 hp Massey Ferguson tractor (Figure 3-7b), which is 160 hp smaller than that required to pull a large square baler (compare Tables 2-7 and 3-5).

(a) (b)

Figure 3-7. Round Baler: (a) Vermeer 604 Super M Large Round 47×66-in. baler (b) pulled by a 115 hp mechanical front-wheel-drive tractor with a round bale that has just been discharged from the baler

Collection and Roadsiding

Collection and roadsiding for the Pioneer Uniform design is similar to the Conventional Bale design (Section 2.1.2). Randomly distributed round bales are collected from the field and transported to the field-side storage location using a self-propelled Stinger Stacker 5500 (Figure 3-8). This is the same equipment used in the Conventional Bale design (Figure 2-9). This automated collection and stacking equipment picks up bales on-the-go, and the forward momentum of the stacker is necessary to properly orient and slide the round bale into the pickup mechanism, just like the square bale operation (Figure 2-9a). Once the Stacker is loaded with bales, it is driven to the field-side location for the bale drop. Bales are dropped by the Stinger's stacking rack gate being released while the machine is in motion, allowing the bales to simply slide off the bale deck onto the ground at the unload point. Because this modeled design uses 4-ft wide bales and a loader to organize the bales in the field-side stack, the Stinger's stacking deck can transport nine bales instead of seven (as shown in the Figure 3-8) to the unloading point during each collection cycle. Round bales are generally not stacked on end, so the Stinger Stacker self-stacking mechanism is not used with round bales.

Figure 3-8. Stinger Stacker 5500 loaded with round bales.

Cob Harvesting and Collection

There are currently four different machinery options for harvesting corn cobs. All of the systems collect the material other than grain (MOG) that passes through the combine, use an air-based cleaning system to remove the material other than cob (MOC), and transport the clean cobs to a collection tank. The differences in these systems are (1) whether it is a single-stream grain and cob mix or a two-stream harvester and (2) whether the cobs are collected in an onboard collection tank or in a separate wagon or cart that is towed behind the combine or pulled alongside the combine by a tractor. This design uses the whole cob collection system, which uses a cob wagon pulled behind a grain combine harvester (Table 3-6).

The grain harvesting operation of the whole cob system functions just like the corn stover system (Section 2.1.2). The combine header strips the ear of corn from the stalk and passes the ear through a threshing mechanism. The shelled corn is cleaned and then conveyed to an onboard grain tank (Table 3-6). A John Deere 9670 STS combine using a John Deere 608C 8-Row Header is the modeled grain harvesting equipment in this design (Figure 2-5). The cobs pass through the combine with the MOG stream, but instead of being discharged back onto the ground with the rest of the MOG, the cob and MOC are discharged into the hopper of a pull-behind cob wagon (Figure 3-9). The cob wagon has an onboard air cleaning system to separate the cobs from the MOC. The cobs are then conveyed to the wagon holding tank and the MOC is discharged back to the field.

(a)

(b)

Figure 3-9. Harvesting both grain and cobs; (a) CNH combine pulling a Vermeer cob wagon in a corn field near Holloway, Minn., during the Chippewa Valley Ethanol harvesting demonstration Oct. 28, 2008 /PHOTO: RYAN C. CHRISTIANSEN, BBI INTERNATIONAL; b) John Deere combine pulling a Redekop Manufacturing cob wagon /PHOTO: REDEKOP MANUFACTURING

Several agricultural manufacturers are currently developing a cob wagon type of system, including Vermeer, CNH and Redekop. An advantage of the cob wagon is that it is minimally intrusive to the combine design and function (Figure 3-10). This is an important consideration, since most farmers will use their combines to harvest soybeans, small grains, and sometimes other crops in addition to corn during a typical harvest season. The ability to install or uninstall the cob harvesting system with a simple hitch pin maintains the combine's rapid versatility. One drawback to that system is that towing a wagon reduces the maneuverability of the combine when backing up, when moving around obstacles in the field, or when harvesting the head rows to open up the field for harvest. The wagon may also pose problems harvesting on side hills or going up and down hills.

Ideally, the combine grain tank and the wagon cob tank are sized to relatively equal proportions. When the grain and cob tanks are full, they are unloaded into a tractor-drawn wagon that moves the harvested products to trucks waiting at a field-side location (Figure 3-11).

Figure 3-10. A dual tank grain/cob cart for collecting grain from the combine and cobs from the cob wagons of single-pass harvest systems, Dethmers Manufacturing Co. (Demco) dual-cart 2-SKU Cob Cart /PHOTO: DETHMERS MANUFACTURING CO.

Both the CNH and Redekop cob wagons have the ability to unload on-the-go, with the former using a belt conveyor and the latter using an auger to move cobs from the wagon to receiving cart or truck. In contrast, the Vermeer cob wagon, which is modeled in this design, is a high-dump wagon. This wagon is capable of unloading at a faster rate than the CNH or Redekop systems, but it requires the harvest operation to be stopped for unloading (Figure 3-11). The CNH system is powered off the combine hydraulic system, and the Vermeer system is powered off its own dedicated on-board engine.

Figure 3-11. With a truck positioned beside the cob wagon, the harvest operation as temporally stopped to dump the cob wagon bin. Vermeer Corp. CCX770 Cob Harvester /PHOTO: RYAN C. CHRISTIANSEN, BBI INTERNATIONAL

In addition to the cob wagon harvest systems, CCM grain and cob collection systems, cob collection systems that are integrated into the combine, and single-pass harvesters with rear cob separation are all being developed. Each of these systems has advantages and disadvantages over the cob wagon systems.

The CCM harvest system collects corn and cobs into the existing combine harvester grain tank as a mixture of corn grain and chopped cob. This process reduces the cleaning efficiency of a combine, so that the cobs pass through the grain cleaning system with the grain rather than being deposited on the ground behind the combine. While this can be achieved to some degree by appropriate combine adjustments, CCM kits have been developed by combine manufacturers to improve cob collection. As the cob is mixed with the grain, unloading during harvest is inherent in the process. However, CCM has lower flowability than grain, so the grain carts will likely need to be equipped with large augers to handle this material. Further, a separator is needed to separate the cob and grain after harvest.

The cob collection systems that are integrated with the combine are functionally the same as the cob wagon system, except that the cob separator and cob holding tank are installed directly onto the combine. One of these integrated cob collection systems, the Ceres Residue Recovery System, is easily differentiated from its competitors by the residue tank that sits atop the grain tank on the combine. After the MOC is removed by the Ceres cleaning system, the cobs are blown into the cob tank above the grain tank. The Ceres cob system has the advantages of an onboard collection system like CCM, the two-stream

advantages of the wagon systems, and is capable of unloading on-the-go using a drag-chain system in the cob tank. However, compared to cob wagon systems, these integrated cob collection systems require modifications and installation of additional after-market components onto the combine.

Another cob harvesting system is offered by John Deere and is based on single-pass harvester developed by Deere and Iowa State University (Birrell, 2008). This harvester has been under development for the last several years with a focus on single-pass stover harvest, but more recently the focus has included cob-only harvest. As such, this harvesting system is fundamentally a bulk residue harvester that can collect everything from whole stover to cob only. The cob harvesting settings operate similarly to the Ceres system in that the cob cleaning system and a blower are positioned at the rear of the combine to collect the MOG that passes through the combine, remove the MOC, and blow the clean cobs into a collection tank. What differentiates this harvester from a regular grain combine is the chopper, blower, and separator at the rear of the combine.

One of the primary criteria in evaluating these systems is the impact the added cob systems have on grain harvest, with the basic rule that anything that reduces the efficiency and rate of grain harvest is unfavorable. Thus some of the features that must be evaluated include the ability to unload the cobs from the combine without stopping the combine, logistical issues such as the amount of addition time, labor and equipment needed to collect cobs, installation and combine modifications required of the cob harvesting system, and cob purity. Both CCM and two-stream cob harvesting systems will likely play a role in the cob harvesting market. Smaller farmers that may not be able to afford the capital investment of the more efficient systems and that do not have the acreage and thus the time-constraint of harvesting large acreage in a limited harvest window may be able and willing to accept delays in grain harvest associated with the CCM approach. Large farms, on the other hand, that are able to afford the higher capital investment of a two-stream harvester may adopt this method because of the improved logistics.

3.1.2.2 Equipment Capacity and Operational Efficiency (field efficiency)

Machine field capacity, field efficiency, yield, and field speed are the same for the Pioneer Uniform and Conventional Bale designs for combining, shredding, windrowing, and raking, and are described in Section 2.1.2.2 and in Tables 2-8 and 2-9. Table 3-7 shows the range and typical values of field speed and field efficiency for round baler equipment (ASABE D497.5, 2006b) and cob harvesting equipment. These values were used in the modeling of the design scenarios, with the exception of the field speeds noted in the "Model" column of Table 3-7.

Table 3-7. Typical field speeds and field efficiencies for corn cob and round baler equipment.

Machine/Equipment	Field Speed (mph)			Field Efficiency (%)	
	Range	Typical	Model[a]	Range	Typical
Corn Combine towing Cob Wagon[b]	2.0–5.0	3.0	3.8	65–80	67
Cob Wagon[b]	N/A	N/A	10	N/A	57[b]
Round Baler[c]	3.0 – 8.0	5.0	3.6	55–75	65%

a. Adjustment based on INL 2007 harvest field data.
b. Model assumes that cob wagon services three cob harvesters.
c. ASABE D497.5, 2006b

Field capacities of cob and round baler equipment used in the Pioneer Uniform harvest and collection operation of crop residues and herbaceous energy crops are shown in Table 3-8. The grain combine is the same machine as that use in the Conventional Bale design, and as such has the same rated capacity (Tables 2-9 and 3-8). However, the same combine towing a cob wagon only has a field capacity of 8.6 tons of cob per hr (1,425 ft^3 per hour) because of the reduced maneuverability due to towing the cob wagon and the additional logistics of managing the second cob product stream (Table 3-8). Factors such as needing to unload two product tanks (i.e., grain and cob) that may have mismatched or variable fill

rates, or needing to stop harvesting to unload one or both tanks, result in reduced stand-alone combine field efficiency from 70% (Table 2-8) to 67% when pulling a cob wagon (Table 3-7).

Table 3-8. Field capacities for harvesting machines calculated using the typical field efficiencies and field speeds (ASABE, ASAE EP496.3 2006a; ASAE 497.5 – 2006b).

Machine/Equipment	Yield		Capacity		
	Value	Units per acre	Rated[a]	Field[b]	Units per hour
Corn Combine towing cob wagon[c]	180	bushels	2,000	1,340	bushels
Cob Wagon[d]	0.77	DM tons	8.6	5.7	tons
Corn Stover Round Baler[e]	1.6[f]	Baled DM ton/acre	25.6	20.5	bales

a. Rated capacities are calculated using the field speed shown in Table 2-8.
b. Field capacities are calculated by de-rating the rated capacity by the "typical" field efficiencies shown in Table 2-8.
c. Corn combine: Class 6 combine with 8-row, 30-in. spacing (24-ft overall with) corn header.
d. Vermeer Corp. CCX770 Cob harvester
e. Baler: round baler, 4-ft wide × 5.5-ft diameter, 8.5 lb/ft^3.
f. Baler yield is based on 3.0 DM ton/acre in the windrow with 71% harvest efficiency.

A key factor for improving the capacity and field efficiency of a given machine is reducing unproductive operational time. In the grain harvest industry, combine field capacity has been greatly improved by using grain carts that virtually eliminate downtime for crop unloading. Dealing with present day cob wagons and any other cob harvesting add-ons increase unproductive operational time. Solutions to improved field capacities and efficiencies while harvesting a second product stream (i.e., cobs) will come as a combination of new technologies, additional pieces of equipment, and management.

The smaller size and horsepower requirements of round balers make round bale equipment less expensive to purchase and operate than square bale equipment, but the capacity of square balers is greater than round balers (compare Tables 2-9 to 3-8). This document does not attempt to determine which system is better, but it does identify different advantages and disadvantages of each. When considering the overall supply system costs per ton, the larger capacity square bale system will report the lower costs per ton (compare Tables 2-12, 2-13, 3-11, and 3-12). However, feedstock supply systems are collections of many producer enterprises that supply many markets. As such, the optimization drivers for these independent enterprises might be different than the overall biomass supply system for biorefining. As an example, smaller, diversified producers who may not benefit from the increased capacity of large square bale systems, and may not need the handling advantage of square bales, may opt for the lower cost round bale systems for their respective enterprises.

This is a key feature of the Uniform-Format supply system design. This design allows for a high-volume "standardized" biomass supply system to couple to a diversity of independently optimized production enterprises without imposing suboptimal requirements on either system. For example, the Pioneer Uniform supply system does not have to handle round bales into the biorefinery, nor do producers have to have the more expensive square bale harvest and collection equipment of the Conventional Bale design. In fact, the Uniform-Format design allows each enterprise to choose what is best to optimize the capacity and efficiency for their respective operations.

3.1.2.3 Operational Dry Matter Losses (complement of loss = harvest efficiency)

Dry matter loss in harvesting and collection systems (the complement of harvest loss [1-DM_harvest loss] is referred to as harvest efficiency) can be one of the biggest cost factors in both the Conventional Bale and Pioneer Uniform supply system designs (Tables 2-12, 2-13, 3-11, 3-12, and 3-13). For harvesting and windrowing operations with corn stover and switchgrass, the factors affecting losses in the

Pioneer Uniform design are as described for the Conventional Bale design in Section 2.1.2.3. In baling systems, harvest efficiency is a combination of many factors, including but not limited to biomass material size and physical properties, moisture content, and baler design. While it is not possible here to discuss every material-loss-inducing combination, a short discussion of some of the more frequently encountered effects will be presented.

Baler design presents the greatest near-term opportunity for improving total harvest efficiency, but it is the interactions between baler design and the biomass material being baled that dictates the effectiveness of a design to control losses. For example, round bale harvest and collection systems have a harvest efficiency of 38% (71% harvesting, 54% baling) in corn stover and 81% (90% harvesting, 90% baling) in switchgrass (Tables 2-7 and 3-5). Square bale systems have a harvest efficiency of 38% (71% harvesting, 54% baling) in corn stover and 81% (90% harvesting and 90% baling) in switchgrass (Table 2-7).

These differential losses are the result of how biomass materials can perform differently in the various baler designs. Corn stover that has been in part passed through a combine and a shredding operation has been chopped and conditioned to the point that much of the anatomical structure of the plant has been broken up, resulting in many friable and detached small plant pieces. These smaller, more friable tissues do not readily mat onto the surface of the forming bale, and the rolling action of the round baler further disintegrates and separates these materials from the forming bale. These fine materials that don't mat to the bale surface create a pile of material inside the bale chamber that sifts through the baling belt gaps and is lost back to the field. The harvesting process for switchgrass crushes the grass stems to accelerated drying, but does not severely destroy the plant structure. The more intact condition of the switchgrass (i.e., friable tissues are still connected to long stems), mats all of the material to the forming bale surface thereby greatly reducing losses. The moisture content of the corn stover and switchgrass at the time of baling can also greatly affect losses. In the arid western states, baling is often suspended in the heat of the day when the biomass is at its lowest moisture levels to reduce baling losses (Grant, 2003).

Conversely, large square bale systems have very little, if any, losses once the biomass material is in the baling chamber regardless of the material (i.e., corn stover or switchgrass) being baled. In a square baler, the biomass is stuffed into the baling chamber, and a 4×4-ft plunger compresses the material into a large "flake" to form a bale. This process doesn't rely on a matting process, and the square baler design provides no opportunity for material loss once the biomass is inside the baler.

The single-pass corn cob harvest system does not return the cob to the ground after grain harvest like is done in the Conventional Bale and Pioneer Uniform corn stover harvest systems. This single-pass system eliminates opportunity for field losses resulting from multiple harvest and collection processes. As such, cob losses are the result of threshing and separation processes within the single-pass harvesting system. Corn cob losses are generally the results of a trade off between whole cob purity and cob yield. Producing a higher purity cob stream will have the tendency to break up the cobs. Broken cob is not a problem in the CCM system, since those systems by design chop the cob. However, for the whole cob system modeled here, broken cob pieces can be lost in the cob separation system and returned to the field along with the MOC.

3.1.2.4 Operational Window

The operational window for harvesting and collection is the same for the Conventional Bale and Pioneer Uniform designs. See Section 2.1.2.4, which includes information on the harvest window and daily hours of operation.

3.1.3 Pioneer Uniform Harvest and Collection Cost and Sensitivity Analysis

3.1.3.1 Static Model Cost Summary

A breakdown of the costs associated with each piece of equipment used in the harvest and collection unit operation identifies significant cost components that are valuable for making individual comparisons and recognizing areas of research potential (Tables 3-9 and 3-10). These costs are reported in terms of DM tons entering each process respectively.

Table 3-9. Static model costs for major harvest and collection equipment in the Pioneer Uniform switchgrass scenario. Costs are expressed in $/DM ton unless otherwise noted.

	Condition and Windrow Switchgrass	Baling	Move to Field side (Roadsiding)
Equipment	Agco 8365 Windrower with 9180 disc header	Vermeer 604 Super M Large Round 47×66-in.	Stinger 5500
Installed Equipment Quantities	49	208	45
Installed Capital[a]	6.41	8.71	7.43
Ownership Costs[b]	1.10	2.23	1.09
Operating Costs[c]	1.71	10.53	0.99
Labor	0.32	1.49	0.28
Non-Labor	1.40	9.04	0.71
Dry Matter Loss Costs	N/A	0.59	N/A
Energy Use (Mbtu/DM ton)	30.6	31.0	20.1

a. Installed capital costs are $ per annual DM ton capacity.

b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-2, Table A-7).

c. Operating costs include repairs, maintenance, fuel, lubrication, labor, and consumable materials (Appendix A-2, Table A-7).

d. Energy use of tractor included in the baler value.

Table 3-10. Static model costs for major harvest and collection equipment in the Pioneer Uniform corn cob scenario. Costs are expressed in $/DM ton unless otherwise noted.

	Single-Pass Grain and Cob Harvest		Cob Transferred to Roadside
Equipment	JD 9670 STS Combine with JD 608C 8-Row Corn Header, towing cob wagon	Vermeer Corp. CCX770 Cob Harvester	Case IH Puma 180 hp MFD with Sunflower 8210 Dump Wagon
Installed Equipment Quantities	365	365	122
Installed Capital[a]	129.34	31.76	14.66
Ownership Costs[b]	3.23	4.74	2.19
Operating Costs[c]	3.09	6.88	4.59
Labor	0.35	N/A	0.77

Non-Labor	2.73	6.88	3.82
Dry Matter Loss Costs	N/A	N/A	N/A
Energy Use (Mbtu/DM ton)	364.1	59.7	84.5

a. Installed capital costs are $ per annual DM ton capacity.

b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-2, Table A-7).

c. Operating costs include repairs, maintenance, fuel, lubrication, labor, and consumable materials (Appendix A-2, Table A-7).

d. Energy use of tractor included in the baler value.

3.1.3.2 Cost Sensitivity Analysis

A histogram of the harvest and collection cost (Figure 3-12) for the round bale corn stover scenario shows that with 90% confidence the cost of the unit operation ranges between $20.29 and $30.67 per DM ton. Further, the mean and standard deviation of this range is $25.12 ± 3.16 per DM ton. The mode value of the harvest and collection cost is $25.00 per DM ton. This value closely represents the result of the static model, which is $23.31 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

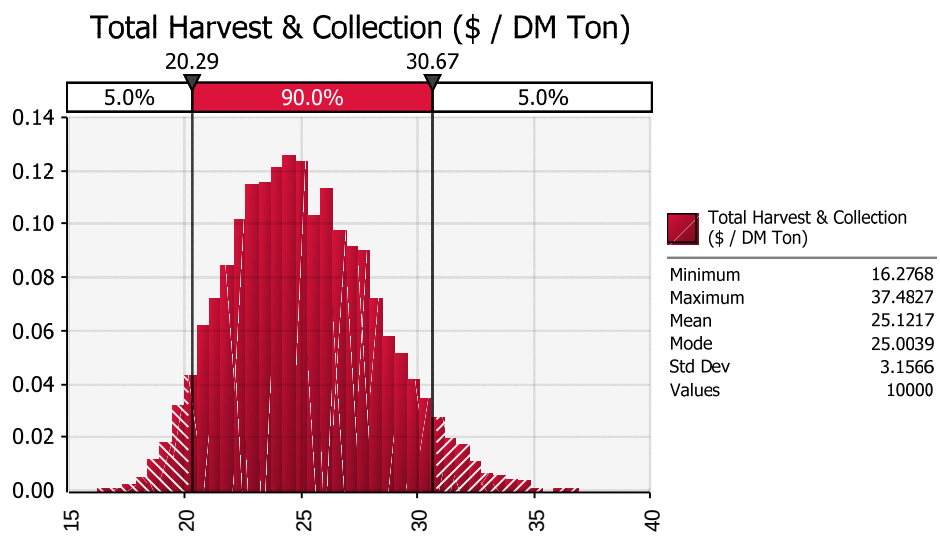

Figure 3-12. Pioneer Uniform harvest and collection cost distribution histogram from @Risk analysis for the round bale corn stover scenario.

A histogram of the harvest and collection cost (Figure 3-13) for square bale corn stover shows that with 90% confidence the cost of the unit operation ranges between $17.36 and $23.52 per DM ton, with a mean and standard deviation of $20.21 ± 1.90 per DM ton. The mode value of the harvest and collection cost is $19.82 per DM ton. This value closely represents the result of the static model, which is $20.12 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

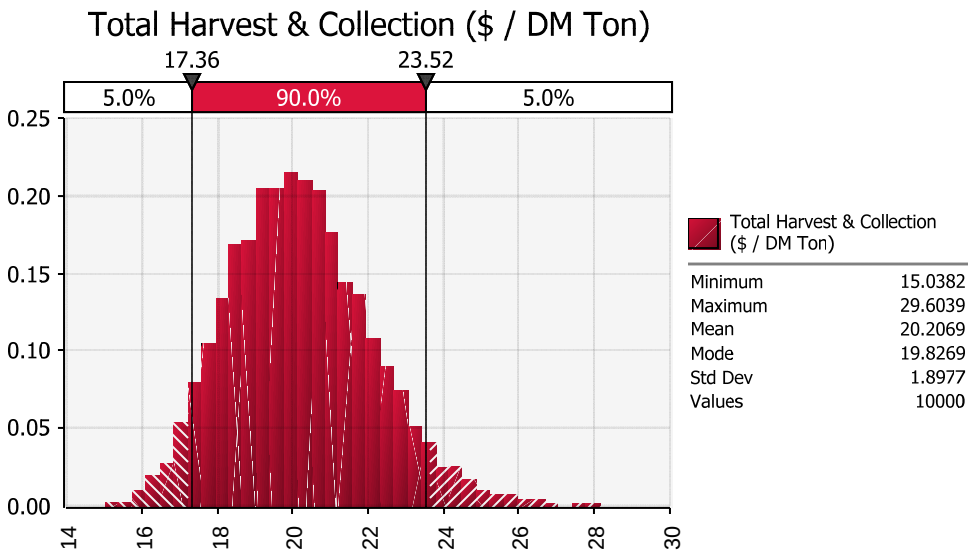

Figure 3-13. Pioneer Uniform harvest and collection cost distribution histogram from @Risk analysis for the square bale corn stover scenario.

Similarly, a histogram of the harvest and collection cost (Figure 3-14) for round bale switchgrass shows that with 90% confidence the cost of the unit operation ranges between $18.05 and $27.45 per DM ton, with the mean and standard deviation of this range being $22.45 ± 2.86 per DM ton. The mode value of this cost range is $20.55 per DM ton, which closely represents the result of the static model of $21.59 per DM ton.

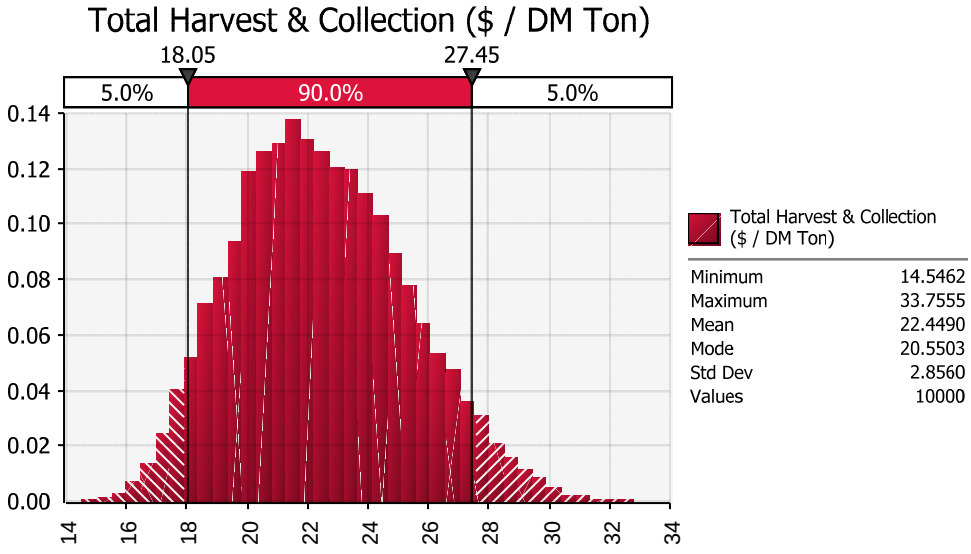

Figure 3-14. Pioneer Uniform harvest and collection cost distribution histogram from @Risk analysis for the round bale switchgrass scenario.

A histogram of the harvest and collection cost (Figure 3-15) for the square bale switchgrass case shows that with 90% confidence the cost of the unit operation ranges between $12.72 and $17.11 per DM ton, with the mean and standard deviation of this range being $14.80 ± 1.34 per DM ton. The mode value

of this cost range is $14.98 per DM ton, which closely represents the result of the static model of $14.99 per DM ton.

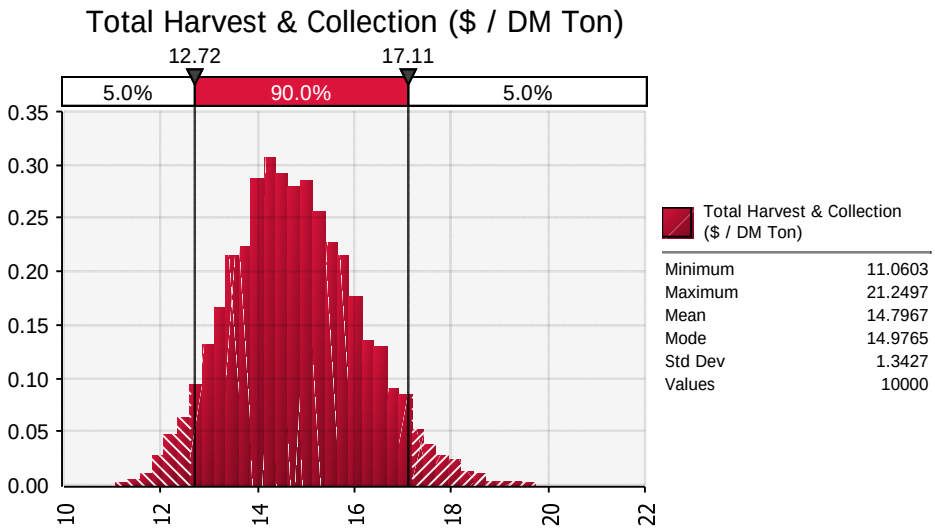

Figure 3-15. Pioneer Uniform harvest and collection cost distribution histogram from @Risk analysis for the square bale switchgrass scenario.

Finally, a histogram of the harvest and collection cost (Figure 3-16) for corn cobs shows that with 90% confidence the cost of the unit operation ranges between $23.17 and $26.48 per DM ton, with the mean and standard deviation of this range being $24.68 ± 1.01 per DM ton. The mode value of this cost range is $23.99 per DM ton, which closely represents the result of the static model of $24.71 per DM ton.

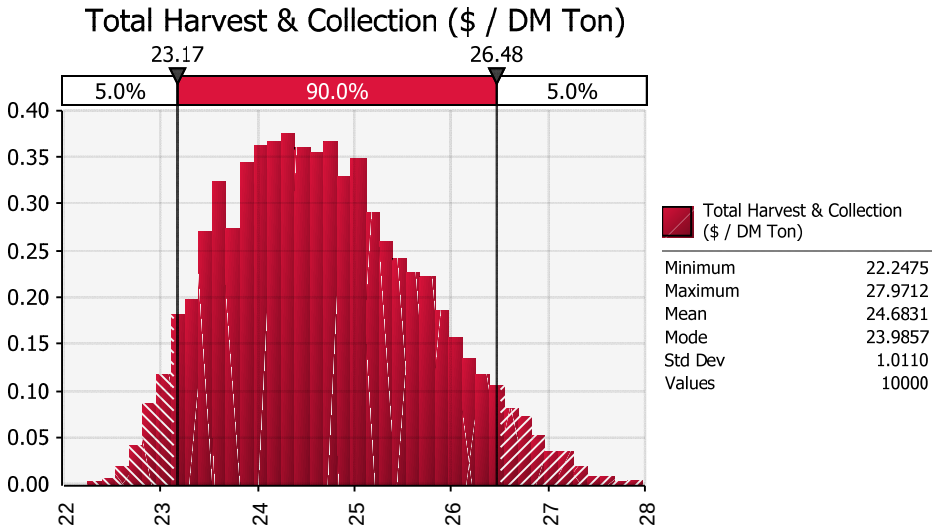

Figure 3-16. Pioneer Uniform harvest and collection cost distribution histogram from @Risk analysis for corn cobs.

The overall costs associated with the Pioneer Uniform harvest and collection unit operation for corn stover, switchgrass, and corn cobs are provided in Tables 3-11, 3-12, and 3-13, respectively, on a per-

DM-ton, per-bale, and per-acre basis. These costs, reported as a mean and standard deviation, come as a result of 10,000 model iterations of the simulated Pioneer Uniform feedstock supply system.

Table 3-11. Harvest and collection cost summary for the Pioneer Uniform corn stover scenario.

	Grain Harvest Only[a]	Condition/ Windrow Stover Residue	Baling	Move to Field side (Roadsiding)	Dry Matter Loss	Total Harvest and Collection Round Bale	Total Harvest and Collection Square Bale
Equipment	JD 9670 STS combine with JD 608C 8-row corn header	Balzer 15-ft Flail Shredder with windrowing pulled by Case IH Puma 180 tractor	Vermeer 604 Super M Large Round 47×66-in.	Stinger 5500			
Modeled Cost Totals[b]	No Cost	3.90 ± 0.61 $/DMton	14.17 ± 2.72 $/DM ton	2.57 ± 0.33 $/DM ton	3.65 ± 1.07 $/DM ton	25.12 ± 3.16 $/DM ton	20.21 ± 1.90 $/DM ton
	No Cost		5.96 ±1.08 $/bale	1.08 ± 0.12 $/bale		7.39 ± 1.08 $/bale	7.40 ± 0.51 $/bale
	No Cost	11.49 ± 1.43$/acre	22.07 ± 5.38 $/acre	3.99 ± 0.78 $/acre	5.48 ± 0.97 $/acre	43.03 ± 5.90 $/acre	36.67 ± 3.66 $/acre

a. Harvest costs associated with grain are not included in the cost of the feedstock since they are born by the grain industry.
b. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

Table 3-12. Harvest and collection cost summary for the Pioneer Uniform switchgrass scenario.

	Condition/Windrow Switchgrass	Baling	Move to Field Side (Roadsiding)	Dry Matter Loss	Total Harvest and Collection-Round Bale	Total Harvest and Collection-Square Bale
Equipment	Agco 8365 Windrower with 9180 disc header	Vermeer 604 Super M Large Round 47×66-in.	Stinger 5500			
Modeled Cost Totals[a]	5.71 ± 1.20 $/DM ton	12.77 ± 2.42 $/DM ton	2.31 ± 0.29 $/DM ton	0.90 ± 0.29 $/DM ton	22.45 ± 2.86 $/DM ton	14.80 ± 1.34 $/DM ton
		5.96 ± 1.08 $/bale	1.08 ± 0.12 $/bale		7.39 ± 1.08 $/bale	7.40 ± 0.51 $/bale
	22.48 ± 1.99 $/acre	45.00 ± 12.09 $/acre	8.15 ± 1.84 $/acre	3.03 ± 0.69 $/acre	78.67 ± 13.46 $/acre	53.26 ± 8.57 $/acre

a. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

Table 3-13. Harvest and collection cost summary for the Pioneer Uniform corn cob scenario.

	Single-Pass Grain and Cob Harvest	Single-Pass Grain and Cob Harvest	Cob Transferred to Roadside	Dry Matter Loss	Total Harvest and Collection
Equipment	JD 9670 STS Combine with JD 608C 8-Row Corn Header, towing cob wagon	Vermeer Corp. CCX770 Cob Harvester	Case IH Puma 180 hp MFD with Sunflower 8210 Dump Wagon		

Modeled Cost Totals[a]	6.16 ± $/DM ton	11.58 ± 0.62 $/DM ton	5.40 ± 0.29 $/DM ton	N/A	24.68 ± 1.01 $/DM ton
	0.02 ± 0.00$/unit	0.05 ± 0.00 $/ton	0.02 ± 0.00$/ton	N/A	0.09 ± 0.01 $/unit
	4.68 ± 0.21$/acre		4.10 ± 0.13$/acre	N/A	17.54 ± 0.29 $/acre

a. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

3.2 Pioneer Uniform Storage

Storage encompasses all processes associated with stacking, protecting the biomass from weather or other environmental conditions, and storing the biomass in a stable condition until called for by the biorefinery (Figure 3-17). Just as in the Conventional Bale design, the Pioneer Uniform storage design does not include biomass material stabilization (i.e., drying or ensiling) for corn stover or switchgrass, because stabilization of the biomass material occurs with the field drying process in the harvest and collection unit operation.

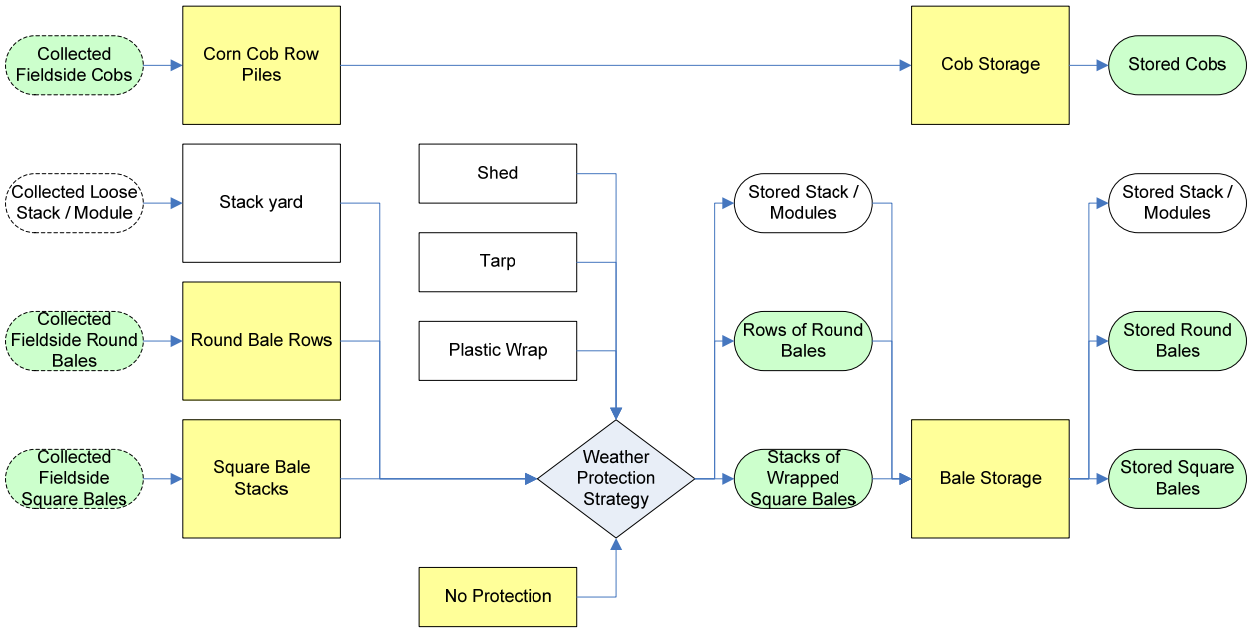

Figure 3-17. Storage supply logistic processes and format intermediates.

(Note: Green ovals represent format intermediates, yellow rectangles represent processes modeled in this report, white rectangles represent processes not modeled in this report, and grey diamonds represent multiple process options).

The storage configuration for the Pioneer Uniform design is field-side plastic-wrapped one-bale-wide by two-bale-high stacks for square bales (Section 2.2.1) and net wrapped round bales set field side in rows one-bale high (Figure 3-18). A major advantage of round bales over square bales is that they do not require a shelter for storage, as the shape allows water to shed (Cundiff and Marsh, 1995). The selection of the best storage protection strategy depends on local conditions, including the option of stacks with no protection, which is a common strategy selected in arid regions of the Western United States (Figure 3-17).

Figure 3-18. Row of round bales wrapped with plastic with a modified baler to bind the bale rather than using twin.

Storage requirements for the Pioneer Uniform square bales are identical to the Conventional Bale system (Section 2.2). For this reason, Section 2.2 in the Conventional Bale supply system applies to the Pioneer Uniform system as well. Additional storage requirements are necessary for the round bales, corn cobs and to interface with preprocessing equipment.

For corn cobs, field-side or near field-side piles are used for storage in this design (Figure 3-19). These are not massive 100-ft, 10,000-ton cob piles that are occasionally built by large-scale cob-product manufacturers, but rather they are small windrow-type piles, about 14-ft tall × 200-ft long, and 300 tons total (depending on the amount of husks mixed in with the cobs), formed by dumping the cobs directly from the cob cart along the edge of the field. The design does not use a loader to make the piles taller than the cart dump height. The size of each pile is equivalent to the yield of cob from a harvest area of about 350 acres, assuming a cob dry matter yield of 0.77 ton/acre (for 180 bu/acre grain). Unlike the stover and switchgrass designs, the single-pass harvest operation for cobs does not allow for field drying, so some change in cob moisture content will occur in storage.

Figure 3-19. On-farm corn cob storage pile located at or near field side.

3.2.1 Pioneer Uniform Storage Format Intermediates

As with the Conventional Bale design storage system, the objective of the Pioneer Uniform storage system is to maintain the original biomass properties throughout the duration of storage. However in practice there will always be some change resulting in biomass loss during storage, often referred to as shrinkage. The mechanism of biological impacts and moisture content increases would be similar for round and square bales (Section 2.2.1), although different in magnitude. Unlike square bales, round bales are formed such that moisture does not penetrate to the center of the bale and the round bales are therefore not plastic wrapped. Figure 2-15 illustrates the expected range of round bale shrinkage for different storage configurations in wet climates. Pioneer Uniform storage attributes for the round bale scenario are influenced by the fact that the round bales are net wrapped for long-term storage, rather than plastic wrapped. Table 3-6 outlines the attributes of round bales and cob piles during storage.

Table 3-14. Attributes of storage format intermediates for corn stover, a crop residue, and switchgrass, a dedicated energy crop.

	Stacked Bales	Stored Bales		Stored Cobs	Stacked Bales	Stored Bales
Biomass Output	Stover	Stover		Cobs	Switchgrass	Switchgrass
Yield[a] (DM tons/stack)	200 ton/stack	190 ton/stack		277 ton/pile	200 ton/stack	190 ton/stack
Format Output	Rows of round bales, stacked 1 bale wide and 1 bale high at field side	Rows of round bales, stacked 1 bale wide and 1 bale high at field side		Loose cobs, piled 14-ft high at field side	Rows of stacked round bales at field side, 1 bale wide × 1 bale high	Rows of stacked round bales at field side, 1 bale wide × 1 bale high
Bulk DM Density Output	[b]9.0 lb/ft^3 stack (0.13 acres/stack)	[b]9.0 lb/ft^3 stack (0.13 acres/stack)		8.0 lb/ft^3	[b]9.4 lb/ft^3 stack (0.11 acres/stack)	[b]9.4 lb/ft^3 stack (0.11 acres/stack)
Output Moisture (% w.b.)	12%	12%		34%	12%	12%

a. Model assumes 5% shrinkage of yielding DM tons during storage for stored bales (i.e., loss of original biomass DM), actual wet tons may be equal to or greater than starting tonnage (Table 2-7). Model assumes 16% shrinkage of yielding DM tons during storage for stored cobs.

b. Bale bulk densities as described in Section 2.1 Harvesting and Collection; model assumes wrapping results in tight stack with the same bulk density as the bales.

Feedstock Variety

Feedstock type in bulk dry storage shares many commonalities to the bale storage mentioned in the Conventional Bale design (see Section 2.2).

The composition of feedstock types in bulk dry storage will depend greatly on geographical location, as the crops that are available in a given area will determine what will be stored. This will create a wide range of macronutrient and soluble sugar levels in bulk storage structures across the country.

Geographical location will also determine how often a storage structure is used, depending on whether a location employs a single harvest or multiple harvests throughout the year. The capital investment cost of storage structures are typically amortized over 20 years, and the cost per ton is based on the number of times that a structure can be used through the year. Therefore, a structure used only once a year will be twice as expensive (on a per ton basis) as a structure used twice a year.

Environmental and Human Health

Bulk storage of dry cellulosic materials such as cobs poses a fire hazard, which is a low-probability but high-cost risk. Fire results in feedstock loss, is an immediate threat to nearby workers and community members, and is responsible for regional air quality degradation. Sources of ignition include, but are not limited to, equipment failures resulting in sparks, sparks or embers from nearby controlled burns (weeds or other refuse), lightning strikes, malicious acts such as arson, and spontaneous ignition (similar to bale and silo fires). The latter is the most complicated and least understood risk (Buggeln and Rynk 2002) and is therefore difficult to quantify.

Spontaneous heating and (rarely) subsequent combustion are generally associated with the storage of densely packed natural materials in the range of 30 to 80% water content (Buggeln and Rynk 2002, Nelson et al. 2007, Li et al. 2006, Festenstein 1971, and OMAFRA 1993). Stover moisture content at the time of grain harvest is typically 40 to 60% (w.b.) and cobs are reported to be approximately 10% less (Pordesimo et al., 2004). Spontaneous heating in biomass occurs as a result of cellular respiration by either the freshly harvested plant matter or the bacteria and fungi associated with it, and occurs in the range of 30 to 80° C (80 to 180° F), sometimes referred to as biological self heating. Biological self heating is self-limiting, as most enzymatic reactions responsible for biological activity stop before temperatures reach 80° C, and increased evaporation rates have greatly reduced the water necessary for biological activity. Figure 3-20 demonstrates the effect of microbial activity—the primary cause of dry matter and structural sugar loss in storage—with increasing water content in cobs.

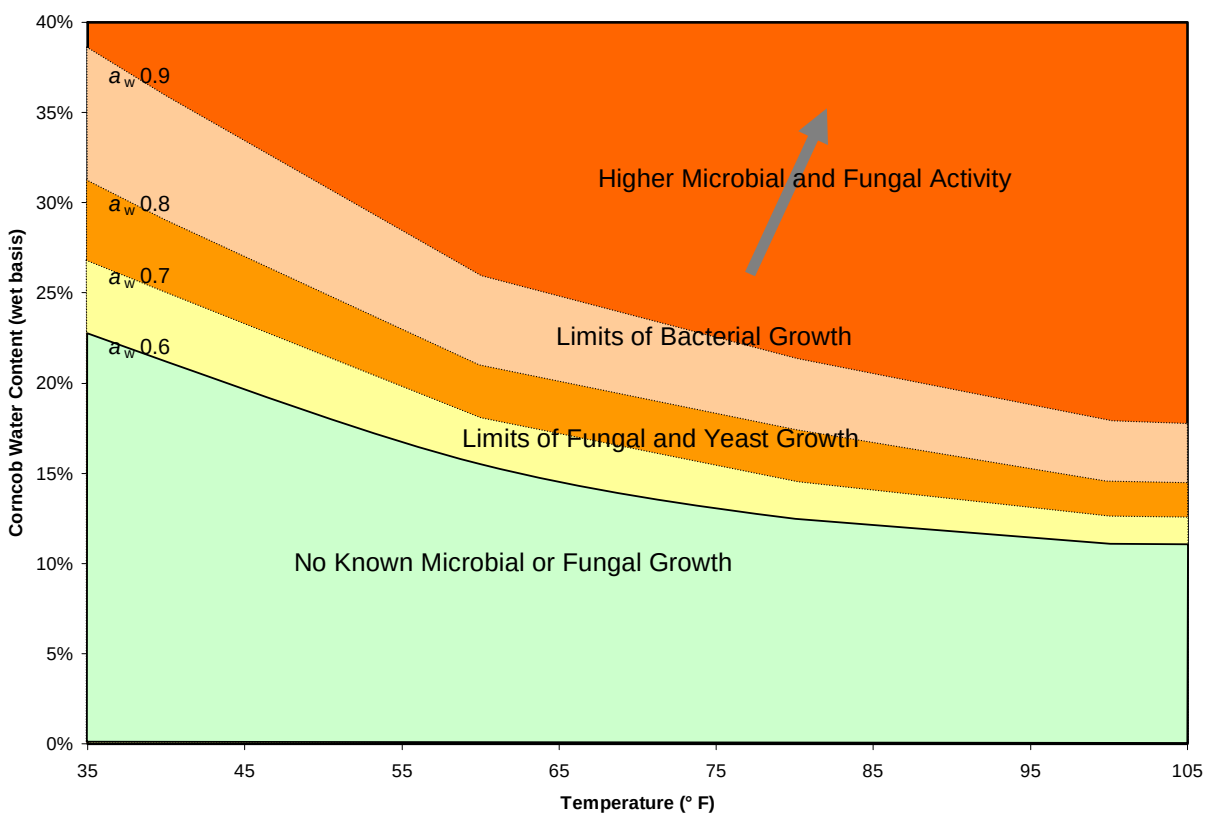

Figure 3-20. Corncob water content and relative microbial activity over a range of temperatures, based upon water activity to water content data taken from Foley 1978.

Spontaneous combustion requires: (1) an initial heat source (often provided by biological self heating), (2) insulation to trap heat and permit temperatures to rise to the point of ignition, and (3) the

proper mix of reactive materials to support combustion (Buggeln and Rynk 2002). Factors implicated in spontaneous combustion include moisture content, packing density, heat loss, air circulation in pile, pile size and time in storage (Buggeln and Runk 2002). However, there is no simple relationship among these factors that allows the construction of a general model for predicting spontaneous combustion risks (Li et al. 2006).

Reports suggest that cob pile size is an important factor that affects heat loss and air circulation; additionally, large piles are often stored for longer periods of time (Buggeln and Rynk 2002). For example, a fire in a 17,000-ton pile at the Andersons, Delphi, Indiana, which started on December, 27, 2009, was reported as "under control" as of January 7th (Massie, 2008). An earlier fire at the same plant in December 1989 burned within a 35,000-ton pile for 9 days before being extinguished. No cause for either fire has been reported to date. As a result of the uncertainties surrounding spontaneous combustion in stored cobs and the association of fires with large pile size, pile dimensions were kept small to allow for heat dissipation and reduce the risk of catastrophic feedstock loss, injury to workers, and to the surrounding community.

Mold spores are another major human health concern, and biomass that has more than the moisture threshold for dry storage could be at high risk of mold growth. Mold would be a factor in bulk storage as the high amount of surface area would increase human exposure concerns. Most exposure from the mold spores would occur during the movement of biomass from storage to transportation. Dust is also an issue in the handling of bulk stored biomass, and mitigation techniques for mold and dust handling would need to be in place.

See Section 2.2.1 for further discussion of the environmental and human health considerations when storing large amounts of biomass.

3.2.1.1 Biomass Deconstruction, Fractionation, and Yield Losses

Deconstruction, fractionation, and yield losses relating to round bales are similar to that of square bales discussed in the Conventional Bale design (Section 2.2.1.1).

3.2.1.2 Format and Bulk Density Impact on Supply System Processes

Round bales can be difficult to store because they do not stack well. It is recommended to store round bales in a shed to keep them as dry as possible. If this is not possible, the bales must be stored on a well-drained surface (preferably on crushed rocks) with space between the bales to allow for the free shedding of rainwater. Rider et al. (1979) classified different portions of a round bale according to susceptibility of each portion to deterioration (Figure 3-21). As a round bale settles, approximately 33% of its circumference surface contacts the ground. A substantial amount of moisture can be absorbed through this contact area, resulting in spoilage as far as 12 in. (30 cm) into the bale. If the weather affects the outer 6 in. (15 cm) of the round bale that is not in contact with the ground, plus an additional 6 in. at the bottom, as much as 42% of the total bale volume can be affected. Assuming a uniform bale density, the outer 6 in. of a round bale account for more than 20% of the total mass of the bale for a 5.5-ft diameter × 4-ft long bale.

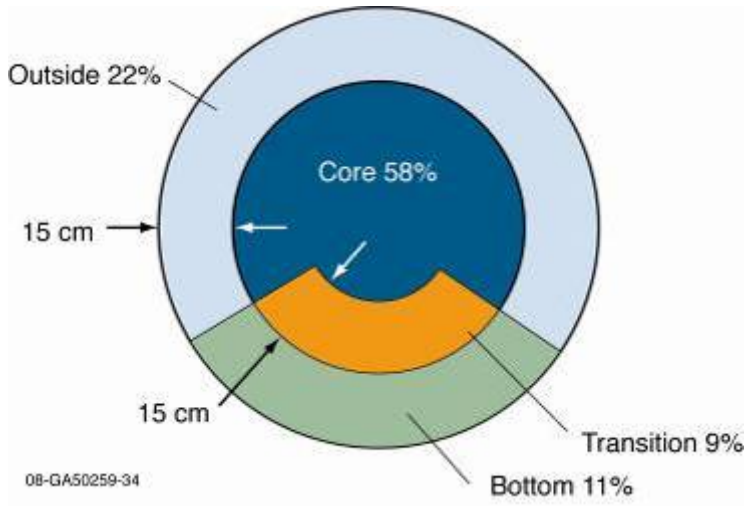

Figure 3-21. Division of a round bale (adapted from Rider et al. [1979]). Weather impacts were shown to affect the outer 6 in. (15 cm) of the bale in a 5-ft diameter × 4-ft thick bale.

The Pioneer Uniform system incorporates square bales (Section 2), 5.5-ft diameter × 4-ft long round bales, and cobs. As mentioned in Section 2.2.1.2, various factors can influence the negative impacts of storage systems including bale or pile size, stack configuration, bulk density, moisture content, and whether storage is on a well-draining surface.

The round bale design lays net-wrapped round bales horizontally, end-to-end in a row. This configuration does not minimize the stack footprint, however reflects common practice for optimizing their water shedding ability. If land use is inexpensive and available, as this design assumes, this configuration is a cost-effective storage solution.

The large round bales are transported to the field side and generally placed in a well-drained environment. The bales are placed back-to-back in long cylindrical rows to minimize the trapping or channeling of moisture between bales and separate rows of bales. Round bales are less prone to water penetration than are square bales, and net wrapping helps round bales shed water. The specific impacts of moisture on storage stability for round bales in comparison to square bales are discussed in Section 2.2.1.3.

3.2.1.3 Biomass Moisture Impact on Supply System Process and Material Stability

Cobs are stored directly on the ground in unventilated field-side piles. Moisture contents within the outdoor-stored cob piles have been found to increase in annual storage (Dunning et al. 1948, Smith et al. 1985), primarily in the outer 1 to 3 ft, resulting in a subsequent loss in dry matter and structural sugars over time (Smith et al. 1985). Ventilating the piles reduced dry matter losses from about 33% to about 20%. Changes have been seen in farm-scale piles such as employed in this design and in industrial-scale piles of greater than 1,000 ton (Smith et al. 1985). Regardless of scale, the inner-most region of the cob piles exhibits less change relative to the starting materials. However, due to the dramatic increase in moisture content in the outer-most regions, the bulk moisture content of the cob pile tends to increase. The depth of the outer wetted layer is independent of pile size, and as a result the larger surface area to volume ratio is key contributor to moisture and composition changes in storage. Thus, bulk moisture content of larger piles is expected to be lower than that of smaller piles stored under identical conditions. Additionally, increased dry matter loss and degradation of the structural sugars was associated with the wet regions (Smith et al. 1985). Despite this result, distributed storage of smaller piles and windrows

onsite was selected for the Pioneer Uniform design for logistic (transportation by cob cart to the local pile) and safety (fire risk) reasons.

The results from Smith et al. (1985) were used to construct a geometric model to predict final bulk moisture contents and dry matter loss in outdoor cob piles (Figure 3-22). Using this model small piles and windrows up to 300 ft are estimated to be within the range of 40 to 45% moisture content when storing cobs with 34% moisture content for one year. Bulk moisture contents are predicted to be only 29% in 100-ft piles. Increasing pile size to 100 ft results in predicted dry matter loss of only 12% compared to the 18 to 21% predicted in the smaller piles and windrows, but increases the material handling and transportation costs by placing a large receiving facility between the field and the biorefinery. Additionally, uncertainties surrounding self heating and spontaneous combustion drive use of smaller distributed piles at this time.

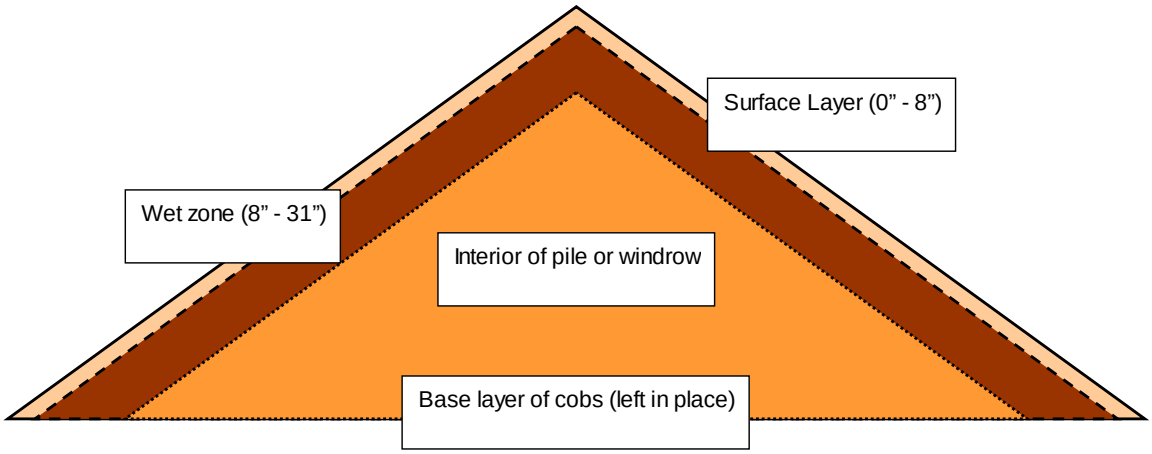

Figure 3-22. Modeled moisture zones of cob pile stored outdoors. The thickness of the outer surface layer is independent of pile size and therefore fewer large piles would encourage dry matter preservation.

Cundiff and Marsh (1995) studied the impact of dry matter loss from round bales of switchgrass stored outdoors. In general, higher initial moisture content and longer storage times caused increased dry matter loss. Also, ground storage on a well-draining surface reduces dry matter losses. Johnson et al. (1991) found that storing bales on rock decreased dry matter loss. Heslop and Bilanski (1986) reported that in Western Canada the loss of dry matter in round bales, as a result of outdoor storage, was 4 to 8%. Wrapping bales is a commonly used method of reducing moisture infiltration, and therefore reducing dry matter loss.

Wilcke et al. (1999) found that, despite the tendency for uncovered square bales to absorb moisture, there was no significant difference in average dry matter loss for round and square bales over an 8-month period.

3.2.2 Pioneer Uniform Storage Equipment

Storage equipment in the Pioneer Uniform design is the same for both corn stover and switchgrass scenarios (Table 3-15). The stacking is operationally coupled to the roadsiding process in harvest and collection. The bale collection equipment brings the biomass to the field-side storage site and simply drops the bales on the ground. Table 3-15 shows the storage equipment specifications for the Pioneer Uniform design.

Table 3-15. Storage equipment specifications for the Pioneer Uniform design.

	Square Bale Stack	Square Bale Plastic Wrapper	Round Bale Stack	Storage
Equipment	Caterpillar TH220B Telehandler	Stinger Cube-Line Wrapper	Tractor loader JD 6115D, 115 hp (95PTO) 2WD with Spear Loader	None
Rated Capacity (ton/acre)	80 bales/hr	80 bales/hr	110.8 bales/hr	200 ton/site
Operational Efficiency (%)[a]	80%	67	100%	N/A
Dry Matter Loss (%)	0%	5[c]	5%	7%
Operational Window				
hr/day	12	12	12	24
day/year	36	36	36	365

a. Estimate of the space utilization efficiency relative to corn grain.

b. Loss without protection in a semi-arid environment

c. Loss with the identified protection in a moderate environment

The Stinger Stacker 5500 is used for square bale handling in this design scenario, and is described in Section 2.2.2 (Figure 2-21). Round bales are handled using a Stinger 5500 (without the stacker). Cobs are placed in a roadside pile directly from the Sunflower 8210 Dump Wagon (Figure 3-23).

Figure 3-23. Sunflower 8210 dump wagon.

3.2.2.1 Equipment Capacity and Operational Efficiency

Cobs are placed in a roadside pile directly from the Sunflower 8210 Dump Wagon onto the ground (Figure 3-23). After being moved to the field side, a two-wheel-drive John Deere tractor loader JD 6115D, 115 hp (95PTO) with spear loader is used to arrange the round bales in a row. The bales were net wrapped during harvest and collection to reduce dry matter losses. The stack capacity is limited by international fire code which requires no more than 100 ton/stack with a minimum of 10 ft between adjacent stacks. The field stack costs are an aggregate of land rent, insurance, and land preparation costs. Land preparation costs are modeled at \$0.69/ft^2 and depreciated over 20 years with a repair and maintenance factor of 2% of initial costs annually.

Figure 3-24. (http://www.phelpsindustries.com/gallery_cornhopper.html)

3.2.2.2 Operational Losses

Placing bales on an improved surface that facilitates drainage away from the bales (for example, gravel) helps reduce losses. However, as discussed in Section 2.2.2.2, the losses would have to be in excess of 16% to cover the cost of the improved site, and construction of the surface is likely not practical.

Table 3-16 shows a comparison of dry matter losses in various scenarios and the estimated ownership costs of improvements and dry matter loss.

Table 3-16. Modeled comparison of typical storage improvements and structure costs compared to dry matter loss and its impact on feedstock costs.

	% Dry Matter		Ownership Cost of Structure or Improvements ($/DM ton)[c]	Cost of Dry Matter Loss ($/DM ton), at Feedstock Cost of $22.19/DM ton [d]	
	Dry Climate Loss, Range	Wet Climate Loss, Range[b]		Dry Climate	Wet Climate
Stack on ground	1–9	7–39	0.07 (taxes)	1.20	4.30
Stack on improved ground surface	4–18 [a]	7–36	0.40–1.60 [e]	1.50	3.30
Covered stack on ground	3–13 [a]	6–25	1.50	1.50	3.30
Covered stack on improved surface	1–5 [a]	2–10	1.80–3.02	0.50	1.10
Bale wrap on ground	1–4 [a]	1–8	6.20	0.60	1.20
Pole barn	1–4 [a]	2–7	12.30	0.50	1.00
Totally enclosed shed/building	1–4 [a]	2–8	14.10	0.40	0.90

a. Due to the lack of data on dry matter loss in dry climates, dry matter loss values in dry climates are calculated based on a relationship illustrative by Holmes, (2004) as 0.5 × wet climate values (Appendix A-2).

b. Multiple data sources; Appendix A-2.

c. Ownership costs are based on a structure to accommodate 100 DM tons, property tax of $300/acre (Bruynis and Hudson, 1998) (Edwards and Hofstrand, 2005), improvement tax rate of 2%, maintenance cost of 2% per year. Details of construction costs are available in the works cited.

d. Cost of dry matter loss in the delivery chain from harvest up to the point of discharge from storage is: (delivered cost) ÷ (1-$dry matter loss) – (delivered cost), where "delivered cost" is the cost of feedstock delivered to storage.

e. Range of site preparations is between grading with packed gravel at $0.60/ft^2 and concrete hardstand at $3.00/ft^2. (Low and high values from a telephone survey of eight paving contractors in five midwestern states). Only gravel improvement is used in this comparison (Cromwell, 2002. Dhuyvetter et al., 2005. Groover, 2003. Shinners et al., 2007.).

From Table 3-16, dry matter losses were estimated to range between $0.4 and $4.30/DM ton, and were higher in wet climates than in dry climates. In many cases, the cost of improving the site to reduce dry matter losses was found to be higher than the cost of the dry matter loss. For dry climates, the ownership costs were lower than the dry matter loss for stacking on the ground with and without an improved surface. When considering a wet climate, it was also more economic to cover the stack on the ground than to accept the material loss.

3.2.2.3 Operational Window

The storage operation begins at the point of roadsiding and there is no interface between operations.

3.2.3 Pioneer Uniform Storage Cost and Sensitivity Analysis

3.2.3.1 Static Model Cost Summary

A breakdown of the costs associated with each piece of equipment used in the storage unit operation identifies significant cost components that are valuable for making individual comparisons and recognizing areas of research potential (Table 3-17). These costs are reported in terms of DM tons entering the storage process.

Table 3-17. Static model costs for major storage equipment in the Pioneer Uniform corn stover and switchgrass scenarios. Values are expressed in $/DM ton unless otherwise noted.

	Equipment	Square Bale Stack	Square Bale Plastic Wrapper	Round Bale Stack	Storage
		Caterpillar TH220B Telehandler	Stinger Wrapper	Tractor loader JD 6115D, 115 hp (95PTO) 2WD with Spear Loader	Insurance, Land Rent, Stack Maintenance
Corn Stover	Installed Equipment Quantity	43	43	47	N/A
	Installed Capital[a]	3.55	2.04	12.83	N/A
	Ownership Costs[b]	0.47	0.30	0.25	0.28
	Operating Costs[c]	0.42	5.41	0.62	N/A
	Labor	0.29	0.29	0.29	N/A
	Non-Labor	0.14	5.12	0.33	N/A
	Dry Matter Loss Costs	N/A	N/A	N/A	1.24
	Energy Use (Mbtu/DM ton)	4.5	3.0	6.0	N/A
Switchgrass	Installed Equipment Quantity	39	39	45	N/A
	Installed Capital[a]	3.22	1.85	11.86	N/A
	Ownership Costs[b]	0.42	0.27	0.24	0.27
	Operating Costs[c]	0.38	4.87	0.59	N/A
	Labor	0.26	0.26	0.28	N/A
	Non-Labor	0.12	4.61	0.32	N/A
	Dry Matter Loss Costs	N/A	N/A	N/A	1.15
	Energy Use (Mbtu/DM ton)	4.0	2.7	5.7	N/A

a. Installed capital costs are $ per annual DM ton capacity.

b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-2, Table A-7).

c. Operating costs include repairs, maintenance, fuel, lubrication labor, and consumable materials (Appendix A-2, Table A-7).

3.2.3.2 Cost Sensitivity Analysis

A histogram of the storage cost for the round bale corn stover case (Figure 3-25) shows that with 90% confidence the cost of the unit operation ranges between $0.93 and $2.26 per DM ton, with a mean and standard deviation of $1.57 ± 0.41 per DM ton. The mode value of the storage cost is $1.62 per DM ton. This value closely represents the result of the static model, which is $1.52 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

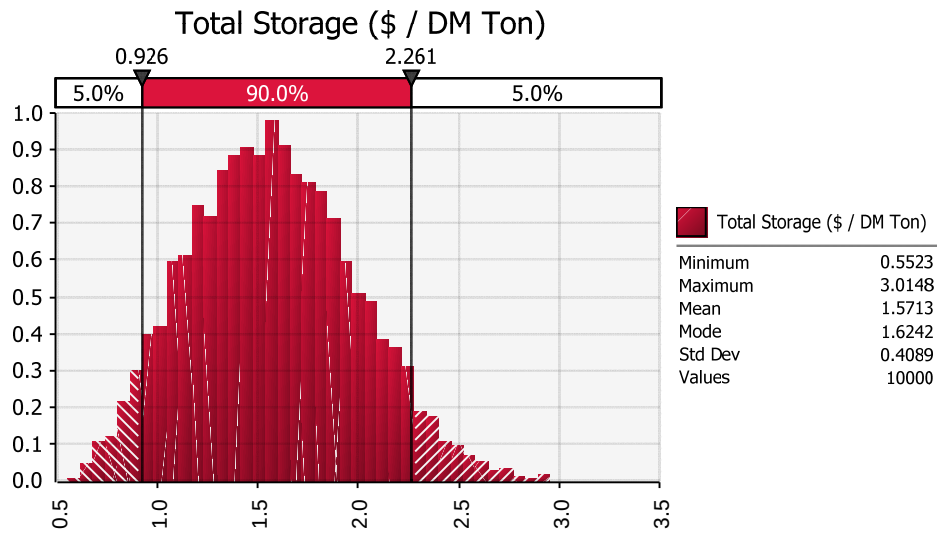

Figure 3-25. Pioneer Uniform storage cost distribution histogram from @Risk analysis for the round bale corn stover scenario.

A histogram of the storage cost for the square bale corn stover scenario (Figure 3-26) shows that with 90% confidence the cost of the unit operation ranges between $7.03 and $9.06 per DM ton. Further, the mean and standard deviation of this range is $8.03 ± 0.61 per DM ton. The mode value of the storage cost is $7.97 per DM ton, which is similar to the result of the static model of $8.12 per DM ton. This is as expected since the defined value of the parameter distributions was set equal to the static value in the model.

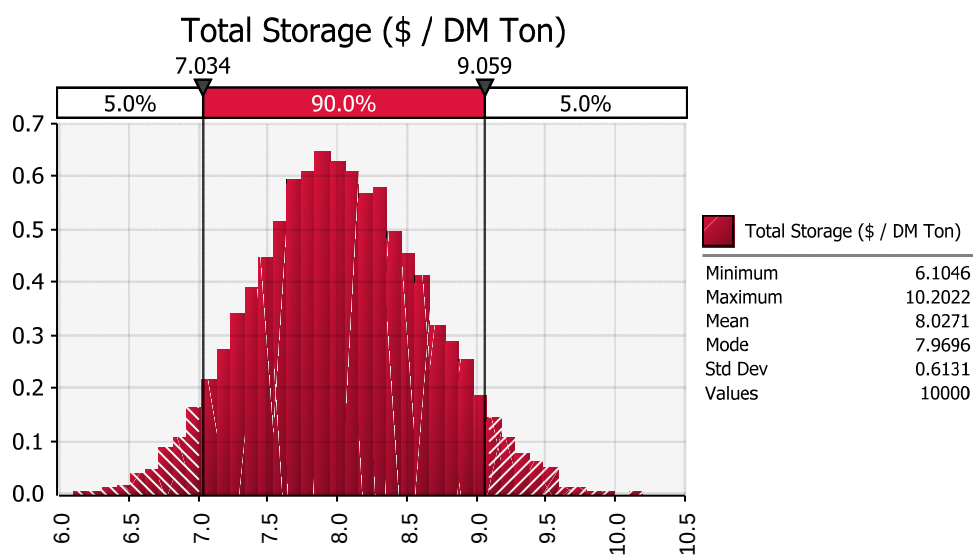

Figure 3-26. Pioneer Uniform storage cost distribution histogram from @Risk analysis for the square bale corn stover scenario.

Similarly, a histogram of the storage cost for the round bale switchgrass case (Figure 3-27) shows that with 90% confidence the cost of the unit operation ranges between $0.84 and $2.03 per DM ton with the mean and standard deviation of this range being $1.41 ± 0.36 per DM ton. The mode value of this cost range is $1.31 per DM ton, which closely represents the result of the static model of $1.42 per DM ton.

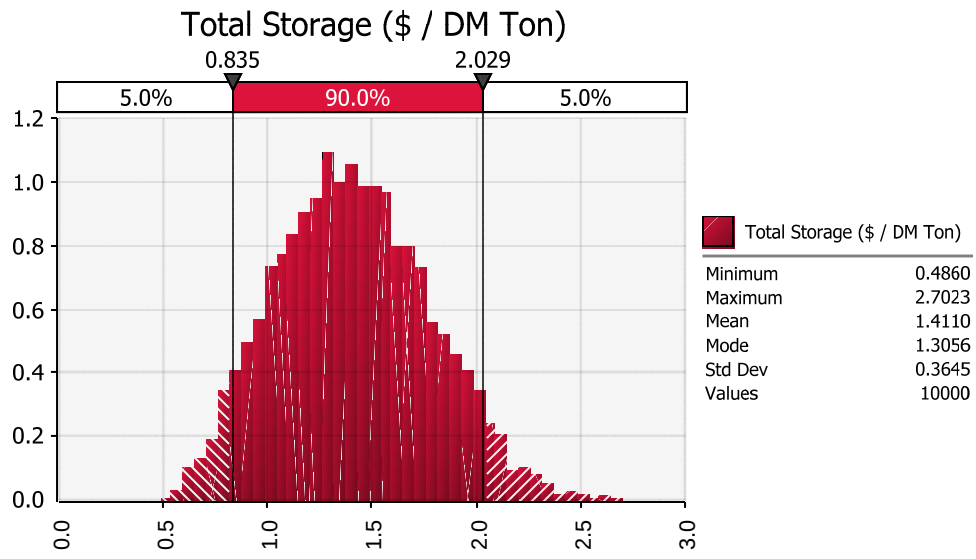

Figure 3-27. Pioneer Uniform storage cost distribution histogram from @Risk analysis for round bale switchgrass.

Similarly, a histogram of the storage cost for the square bale switchgrass case (Figure 3-28) shows that with 90% confidence the cost of the unit operation ranges between $6.27 and $7.89 per DM ton with the mean and standard deviation of this range being $7.06 ± 0.49 per DM ton. The mode value of this cost range is $7.00 per DM ton, which is close to the static model result of $7.16 per DM ton.

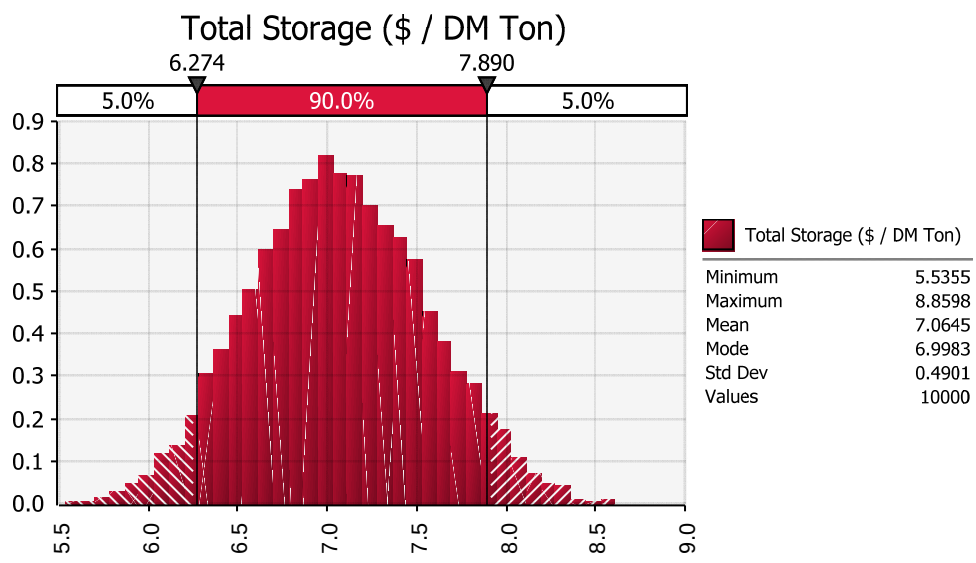

Figure 3-28. Pioneer Uniform storage cost distribution histogram from @Risk analysis for square bale switchgrass.

Finally, a histogram of the storage cost for corn cobs (Figure 3-29) shows that with 90% confidence the cost of the unit operation ranges between $3.72 and $5.08 per DM ton with the mean and standard deviation of this range being $4.38 ±0.41 per DM ton. The mode value of this cost range is $4.30 per DM ton, which closely represents the result of the static model of $4.58 per DM ton.

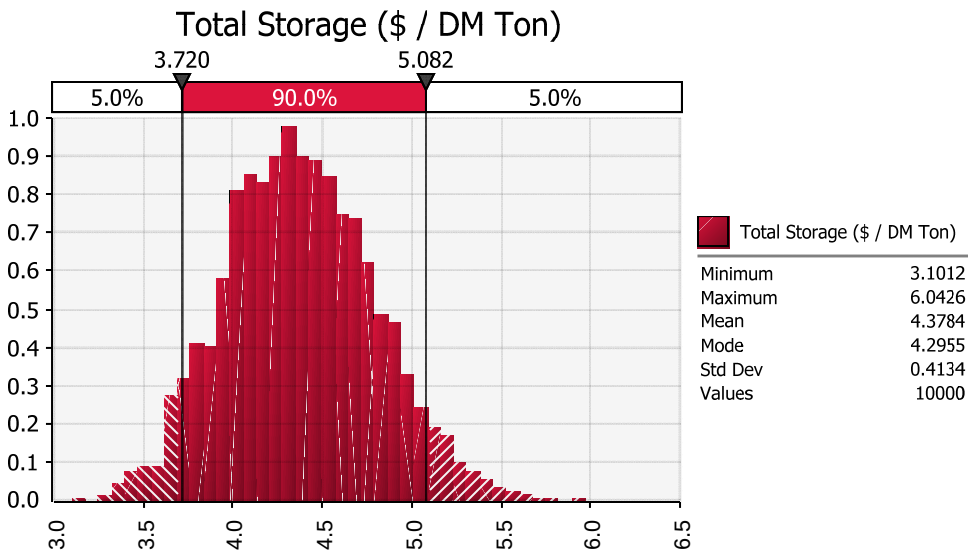

Figure 3-29. Pioneer Uniform storage cost distribution histogram from @Risk analysis for corn cobs.

The overall costs associated with the Pioneer Uniform storage unit operation for corn stover, switchgrass, and corn cobs are provided in Table 3-18 on a per-DM ton and per-bale basis. These costs, reported as a mean and standard deviation, come as a result of 10,000 model iterations of the simulated Conventional Bale feedstock supply system.

Table 3-18. Storage cost summary for the Pioneer Uniform corn stover and switchgrass scenarios.

		Square Bale Stack	Square Bale Plastic Wrapper	Dry Matter Loss (Square Bale)	Round Bale Stack	Storage (Round Bale and Cob Pile)	Dry Matter Loss (Round Bale or Cob Pile)	Total Round Bale or Cob Pile Storage	Total Square Bale Storage
Equipment		Caterpillar TH220B Telehandler	Stinger Wrapper		Tractor loader JD 6115D, 115 HP (95PTO) 2WD with Spear Loader	Insurance, Land Rent, Stack Maintenance			
Corn Stover	Modeled Cost Totals[a]	0.90 ± 0.08 $/DM ton	5.65 ± 0.34$/DM ton	1.37 ± 0.41 $/DM ton	0.83 ± 0.05 $/DM ton	1.57± 0.41 $/DM ton	1.30 ± 0.41$/DM ton	1.57 ± 0.41 $/DM ton	8.03 ± 0.61$/DM ton
		0.52 ± 0.03$/bale	3.30 ± 0.03 $/bale	0.80 ± 0.24 $/bale	0.35 ±0.002 $/bale		0.55 ± 0.17 $/bale	0.66 ± 0.17$/bale	4.69± 0.24 $/bale
Switchgrass	Modeled Cost Totals[a]	0.81 ± 0.07 $/DM ton	5.09 ± 0.28 $/DM ton	1.06 ± 0.31 $/DM ton	0.75 ± 0.04 $/DM ton	1.41 ± 0.36 $/DM ton	1.16 ± 0.36 $/DM ton	1.41 ± 0.36 $/DM ton	7.06 ± 0.49 $/DM ton
		0.53 ± 0.03 $/bale	3.30 ± 0.03 $/bale	0.69 ± 0.20$/bale	0.35 ± 0.002 $/bale		0.54 ± 0.17 $/bale	0.66 ± 0.17 $/bale	4.58 ± 0.21 $/bale
Corn Cobs	Modeled Cost Totals[a]	N/A	N/A	N/A	± $/DM ton	4.38 ± 0.41$/DM ton	4.29 ± 0.41 $/DM ton	4.38 ± 0.41 $/DM ton	
						525.11 ± 275.28 $/unit		525.11 ± 275.28 $/unit	

a. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

3.3 Pioneer Uniform Preprocessing and Transportation

Distributed preprocessing (grinding) is established as part of the Pioneer Uniform design to manage feedstock diversity upstream of the biorefinery and allow receiving and handling systems at the biorefinery to be reduced to a specific uniform feedstock format. This design minimizes capital costs at a biorefinery by eliminating the need for multiple receiving lines necessary to accept various feedstock formats such as square bales, round bales, loose bulk material, etc. Thus, the preprocessing operation is moved forward in the supply system from a location just before the conversion process to a location just after field-side storage (Figure 3-30). In general, the forward-deployed preprocessing unit will match the preprocessing operation modeled in the Conventional Bale design in terms of equipment, operating parameters, and operating time. The primary advantage of a forward-deployed preprocessing unit

(referred to in this report as a Biomass Depot) is its ability to accept and process any feedstock format including square or round bales, broken bales, loose material, and unprocessed bulk material (i.e., corn cobs) and deliver a uniform-format feedstock to the biorefinery.

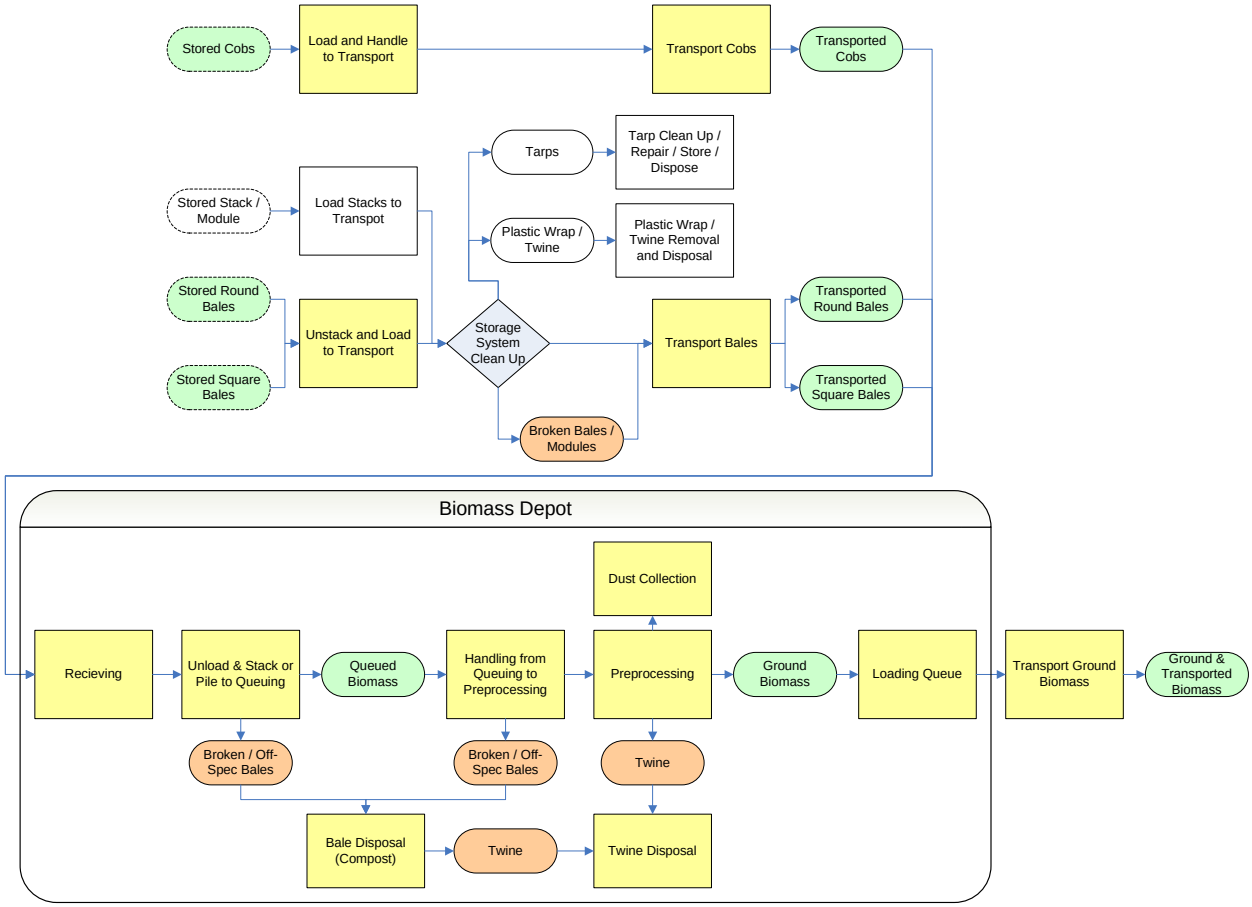

Figure 3-30. Preprocessing and transportation supply logistic processes and format intermediates.

(Note: Green ovals represent format intermediates, tan ovals represent potential waste streams, yellow rectangles represent processes modeled in this report, white rectangles represent processes not modeled in this report, and grey diamonds represent decision points).

The location within the assembly system of the biomass depot provides an opportunity to add value to the biomass and other unit operations to improve the overall efficiency and capacity of the system. This is done by putting the biomass into a bulk-flowable format early in the supply system, such that handling and transportation logistics and costs are significantly reduced. In addition, the biomass depot provides a distributed queuing system that reduces the quantity of feedstock and the associated capital to queue at the biorefinery. Thus, the biomass depot is a key component in the Pioneer Uniform design in that it provides flexibility in feedstock format, improves the efficiency and capacity of downstream operations, and reduces capital investment at the biorefinery.

Since transportation distance is still a key factor in the cost of moving feedstocks from the field to the biorefinery, the location of the biomass depot is such that it minimizes the overall handling and transportation cost primarily as a function of feedstock bulk density. Thus, the biomass depot is located closer to the production site than the biorefinery since the bulk density of baled or loose bulk feedstocks leaving the fields is less than the preprocessed feedstocks leaving the biomass depot. The shorter distance

between the biomass depot and the production site allows lower density feedstocks to be cost competitive with higher density feedstocks in this design. As a result, the biomass depot is particularly advantageous for accepting round bales that, due to higher transportation costs, may be cost prohibitive in a centralized (at the biorefinery) grinding design such as the Conventional Bale design. The specific logistics and cost components of handling and transporting baled feedstocks is the same as discussed in Section 2.3 of the Conventional Bale design. Additional information on handling, transporting, and preprocessing bulk material (i.e., corn cobs) is presented in the following sections.

3.3.1 Pioneer Uniform Preprocessing and Transportation Format Intermediates

The same feedstock attributes that affected preprocessing in the Conventional Bale design affect preprocessing in the Pioneer Uniform design. Some minor changes are discussed that account for improvements in the material format to help optimize adjacent unit operations (Table 3-19). Of primary consideration are the handling and transportation processes, which occur directly after preprocessing. Unlike at the biorefinery, preprocessing now must, at the very least, achieve bulk densities comparable to baled material, but ideally be much higher to allow for optimization of the handling and transportation system. Thus, the new bulk density requirement for preprocessing is the bulk density required to put the maximum amount of weight on a tractor-trailer unit within the given state road limits (Section 2.2.2.2, Table 2-11). Preprocessing must also adhere to more stringent bulk-flowability requirements since the material must be handled within the transportation, receiving, and biorefinery queuing systems and not just evenflow bins before the conversion process as discussed in the Conventional Bale design. A discussion of bulk density attributes will be presented in this section of the report, while a discussion of flowability attributes will be presented in Section 3.4.1.2, Receiving and Handling.

Table 3-19. Attributes of preprocessing and transportation format intermediates for corn stover and corn cobs (crop residues) and switchgrass (a dedicated energy crop).

Operation	Load/Unload Bale Transport	Transport to Depot	Bale/Bulk Queue for Preprocessing	Bulk Queue for Transport	Transport to Biorefinery
Corn Stover					
Yield (DM tons/day)	2,600 (34 bales/truck)	2,600 (34 bales/truck)	2,600		2,600
Format Output	Unwrapped round bales loaded on flatbed trailer	Round bales on bale conveyor	Bulk (1 – ½-in. minus)	Bulk (1 – ½-in. minus)	Bulk (1 – ½-in. minus)
Bulk DM Density Output	9.0 lb/ft^3	9.0 lb/ft^3	7.4 lb/ft^3	7.4 lb/ft^3	7.4 lb/ft^3
Output Moisture (% w.b.)	12	12	12	12	12
Switchgrass					
Yield (DM tons/day)	2,600 (34 bales/truck)	2,600 (34 bales/truck)	2,600		2,600
Format Output	Unwrapped round bales loaded on flatbed trailer	Round bales on bale conveyor	Bulk (1 – ½-in. minus)	Bulk (1 – ½-in. minus)	Bulk (1 – ½-in. minus)
Bulk DM Density Output	9.4 lb/ft^3	9.4 lb/ft^3	10.3 lb/ft^3	10.3 lb/ft^3	10.3 lb/ft^3
Output Moisture (% w.b.)	12	12	12	12	12
Corn Cobs					
Yield (DM tons/day)	–	2,600	2,600		2,600
Format Output	–	Cobs with	Bulk (1 – ½-	Bulk (1 – ½-	Bulk (1 – ½-

		some husks	in. minus)	in. minus)	in. minus)
Bulk DM Density Output	–	8 lb/ft^3	14 lb/ft^3	14 lb/ft^3	14 lb/ft^3
Output Moisture (% w.b.)	–	34	12	12	12

Based on the two baled feedstock formats modeled in the Pioneer Uniform design (square and round), trucks arrive at the biomass depot where they are weighed and unloaded into either a very short-term queuing yard (~200 tons) or directly into the preprocessing system. Since the grinding units used in this design are the same as those used in the Conventional Bale design, the feedstock characteristics discussed in Section 2.4.1 still apply. The ground feedstock coming out of the preprocessing system is queued in evenflow bins that feed the bulk transport system. The short-term queuing yard and queuing bins at the biomass depots provide the biorefinery a distributed queuing system (~2300 tons or one day supply) that minimizes some risk due to weather delays, field conditions, or other feedstock security issues. The bale and bulk queuing systems are still subject to fire code constraints as discussed in Section 2.4.1.

The corn cob feedstock arrives in enclosed trailers from field-side storage locations at the production sites. Similar to the baled feedstock, the corn cobs are weighed and unloaded into either a very short-term queuing yard (~200 tons) or directly into the preprocessing system. The cobs are then preprocessed into a smaller size and queued in evenflow bins for the bulk transport system.

3.3.1.1 Biomass Deconstruction, Fractionation and Physical Property Changes

Many feedstock physical property specifications will remain the same as those required in the Conventional Bale design because they will largely be imposed by the biorefinery. However, additional requirements will be imposed by the handling and transportation operation, which will not only include previously discussed size reduction but will also include more stringent bulk density and flowablity requirements. These requirements will directly impact the capacity and efficiency of the handling and transportation system and will be the source of savings that will justify moving preprocessing from the biorefinery to the biomass depot. Specific considerations for particle size and distribution, beyond those needed to maintain pretreatment and conversion efficiencies, is the effect these parameters have on bulk density. Figure 3-31 shows a graph relating bulk density to geometric mean particle size of corn stover, *Sorghum* stover, soybean straw, switchgrass, and wheat straw. The data shows distinct differences between feedstock varieties, regardless of moisture content, indicating a need to fully understand the variety of feedstock being considered in the supply system. Certainly, further investigations into grinding parameters, such as fractionation mechanism, screen shape, and screen thickness, will be needed to determine more precise relationship between mean particle size, bulk density, and the influence of moisture for specific feedstock varieties, including corn cobs.

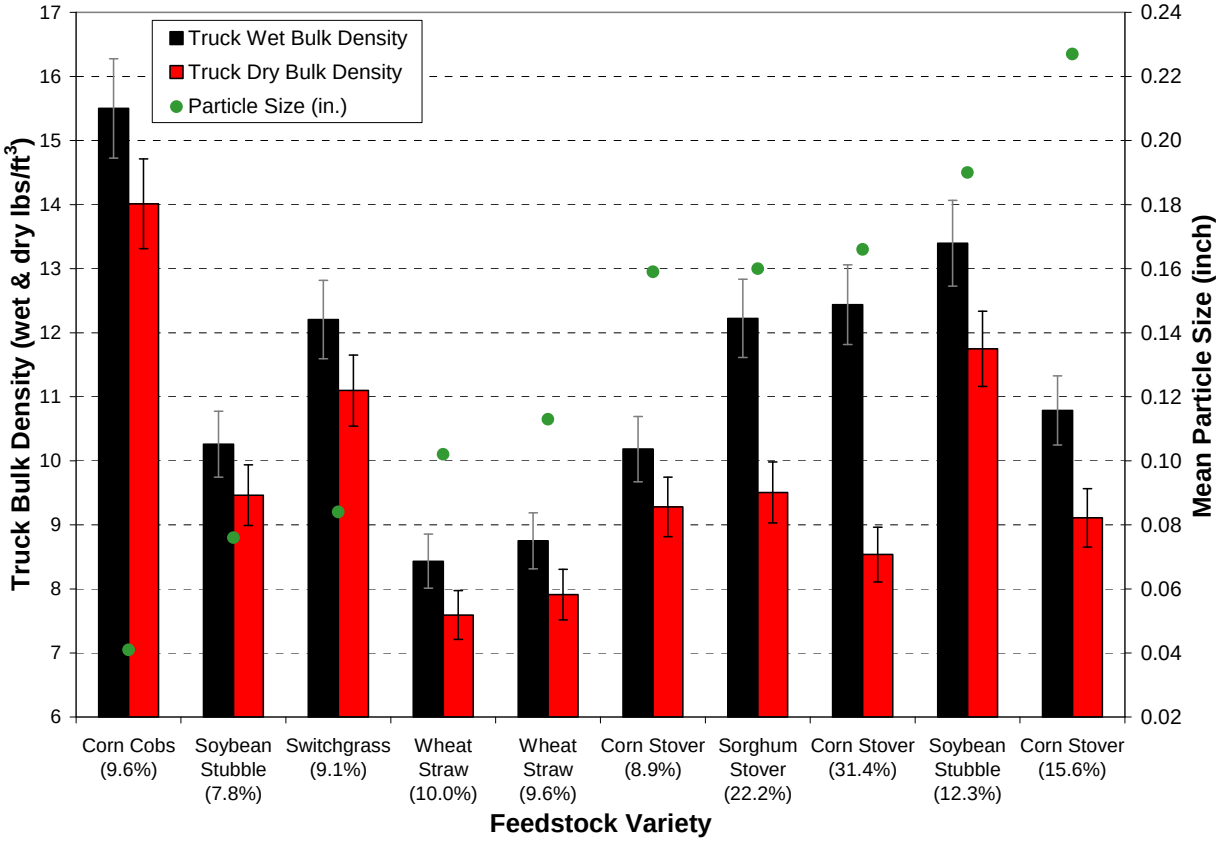

Figure 3-31. Relationship between truck bulk density and geometric mean particle size of corn stover, *Sorghum* stover, soybean straw, switchgrass, wheat straw, and corn cobs.

(Corn cob data from Foley 1978. Remaining data from INL grinder field tests in Kansas, November 2007, and Iowa, July 2008.)

Particle size and size distribution have an influence on almost all bulk handling properties. These parameters, however, encompass a large range of shape factors such as aspect ratio, volume, and roughness, whose interactive influence on bulk density and flowability are not completely understood. Nevertheless, it is generally true that larger particles with more uniform shapes and sizes would be more desirable than smaller particles with varying shapes and sizes in that particle uniformity provides advantages in predicting feedstock behavior and optimizing processes dependant on flowability parameters or size-based reactions. However, controlling the size distribution of feedstock materials can be more difficult that improving grinding efficiency or capacity.

3.3.1.2 Format and Bulk Density Impact on Supply System Processes

The impact baled feedstock format has on transportation and handling from the field to the biomass depot and on distributed preprocessing systems is generally the same as those discussed in Sections 2.3.1.2 and 2.4.1.2, because the equipment used in these processes are the same as those assembled in the Conventional Bale design. However, the Pioneer Uniform design, with its forward-deployed preprocessing, will have to handle, transport, and preprocess large round bales and loose materials (i.e., corn cobs) in addition to large square bales as discussed in Sections 2.3 and 2.4. In terms of the baled formats, the reduced scale of the biomass depot operations, compared to centralized biorefinery operations, will limit options to use larger and more complex automated bale unloading and queuing

systems (i.e., rail mounted cranes). Therefore, bale handling out of the fields and at the biomass depot will be done with self-propelled loaders and flatbed trailers, or in the case of corn cobs, with self-propelled loaders and enclosed trailers.

Even though handling and transportation costs for baled feedstocks are directly impacted by the relatively low bulk density of the baled feedstock (Table 2-5 and 3-3), the shorter transportation distance modeled in the Pioneer Uniform design helps to minimize this cost impact. In order to maximize the handling and transport of baled feedstock, the bale bulk density would have to be high enough to allow a truck to reach its maximum gross vehicle weight (GVW) limit. To achieve this on National Network highways, square and round bale bulk densities would have to reach approximately 15 to 18 DM lb/ft^3 (Table 3-20 and Figure 3-32). Many states allow a 53-ft semi trailer on National Network roads, which leads to a target bulk density of 16 DM lb/ft^3 for both large square and round bales.

Table 3-20. Bulk density required to maximize various load capacity configurations to accommodate a range of load limits.

Truck Configurations	Load Limits		Payload			Maximum Load Bulk Density (DM lb/ft^3)
	Length (ft)	GVW (lb)	Max (lb)	Square Bale Count	Round Bale Count	
48-ft Flatbed Trailer	48[a]	80,000[a]	51,100	24 – 4×4×8-ft 36 – 3×4×8-ft	30 – 4×5.5-ft	16.6 – 4×4×8-ft 14.8 – 3×4×8-ft 18.3 – 4×5.5-ft
53-ft Flatbed Trailer	53[b]	80,000[a]	50,800	26 – 4×4×8-ft 39 – 3×4×8-ft	34 – 4×5.5-ft	15.3 – 4×4×8-ft 13.6 – 3×4×8-ft 16.1 – 4×5.5-ft
24-ft Flatbed Tractor with two 30-ft Flatbed Trailers	95[c]	105,500[d]	59,500	44 – 4×4×8-ft 66 – 3×4×8-ft	50 – 4×5.5-ft	10.6 – 4×4×8-ft 9.4 – 3×4×8-ft 12.8 – 4×5.5-ft

a. Federal minimum trailer length or gross vehicle weight (GVW) that states must allow on National Network (NN) highways.

b. Common state maximum trailer length allowable on National Network (NN) highways.

c. Common allowable trailer length in AK, AZ, CO, FL, ID, IN, IA, KS, MA, MO, MT (93-ft), NE, NV, NY, ND, OH, OK, SD, and UT for two trailing units on non-NN highways.

d. Common allowable GVW limit in AZ, CO, ID, IN, IA, KS, MA, MI, MO, NE, NV, NY, ND, OH, OR, SD, UT, WA, and WY for two trailing units on non-NN highways.

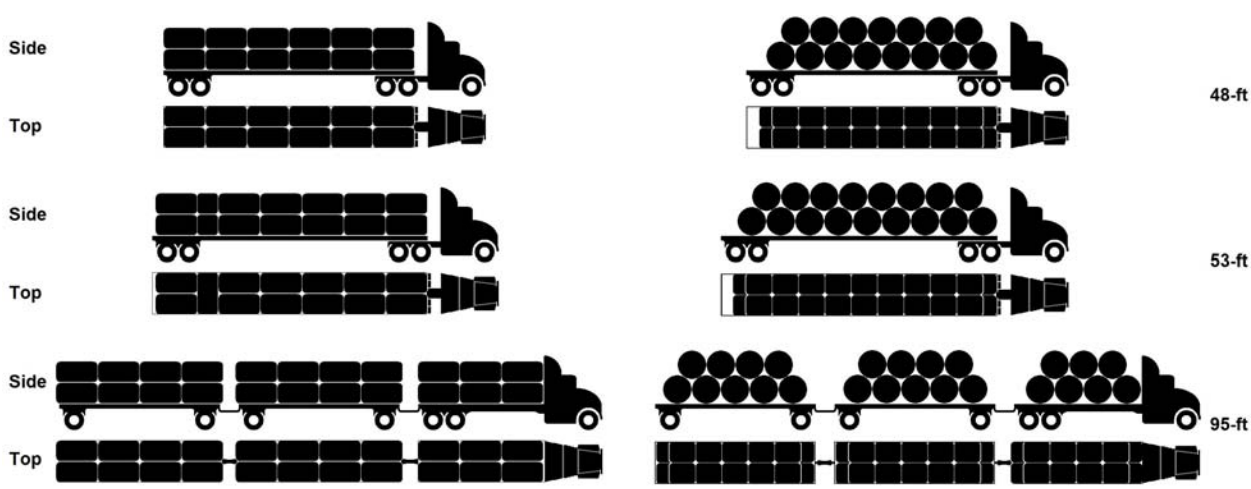

Figure 3-32. Truck configurations for a 48-ft trailer, a 53-ft trailer, and a 24-ft flatbed tractor with two 30-ft trailers carrying both square and round bales.

Transportation of corn cobs from the field to the biomass depot will also be most efficient when cob bulk density is high enough to maximize the GVW of the enclosed tractor-trailer unit. For this to occur, cob bulk density would need to be approximately 14 DM lb/ft^3. The National Network compliant truck configuration and an allowable non National Network configuration with corresponding maximum truck load bulk density is shown in Table 3-21 and Figure 3-33.

Table 3-21. Bulk density required to maximize various load capacity configurations to accommodate a range of load limits.

Truck Configurations	Load Limits		Payload		Maximum Load Bulk Density (DM lb/ft^3)
	Length (ft)	GVW (lb)	Max Weight (lb)	Trailer Volume (ft^3)	
48-ft Live-bottom Trailer	48[a]	80,000[a]	48,110	3,940	10.7
53-ft Live-bottom Trailer	53[b]	80,000[a]	46,880	4,371	9.5

a. Federal minimum trailer length or gross vehicle weight (GVW) that states must allow on National Network (NN) highways.
b. Common state maximum trailer length allowable on National Network (NN) highways.

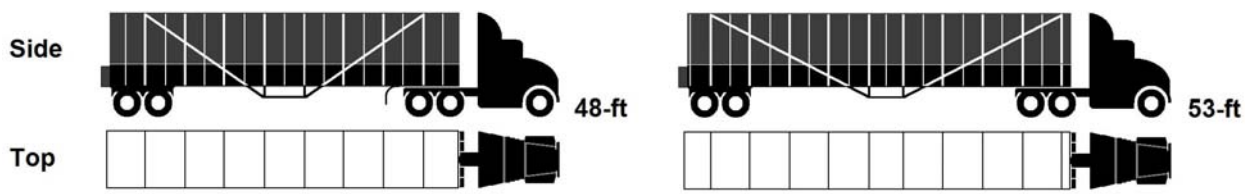

Figure 3-33. Truck configurations for a 48-ft and 53-ft chip van trailer carrying ground bulk feedstock.

The preprocessing of round baled feedstocks will require slight changes to the square bale system described in Section 2.4. These changes will account for the larger round bale cross section (approximately 4×6-ft) that will have to fit into the infeed mechanism of the preprocessing system. By removing the bale wrap or twine and implementing an aggressive infeed roller on the grinding system, the same grinder as discussed in Section 2.4 will be used in the model of the Pioneer Uniform preprocessing system.

Once the baled material is preprocessed in the biomass depot, the ground feedstock is queued for transport to the biorefinery. At this stage of the process, bulk density becomes a critical parameter directly impacting the capacity and efficiency of the transportation system. Similar to the bale transport system, the most efficient bulk transport from the biomass depot to the biorefinery will be a system that reaches the GVW limit. Using truck configurations that are legal on National Network roads, the bulk density of the ground feedstock would have to reach approximately 9.5 to 10.7 DM lb/ft^3 (Table 3-22 and Figure 3-34). Many states allow a 53-ft semi trailer on National Network roads, which leads to a target bulk density of 9.5 DM lb/ft^3.

Table 3-22. Bulk density required to maximize various load capacity configurations to accommodate a range of load limits.

Truck Configurations	Load Limits		Payload		Maximum Load Bulk Density (DM lb/ft^3)
	Length (ft)	GVW (lb)	Max Weight (lb)	Trailer Volume (ft^3)	
48-ft Possum-belly Chip Trailer	48[a]	80,000[a]	48,110	3,940	10.7
53-ft Possum-belly Chip Trailer	53[b]	80,000[a]	46,880	4,371	9.5

48-ft Flat-bottom Chip Trailer	48[a]	80,000[a]	48,110	3,940	10.7
53-ft Flat-bottom Chip Trailer	53[b]	80,000[a]	46,880	4,371	9.5
a. Federal minimum trailer length or gross vehicle weight (GVW) that states must allow on National Network (NN) highways. b. Common state maximum trailer length allowable on National Network (NN) highways.					

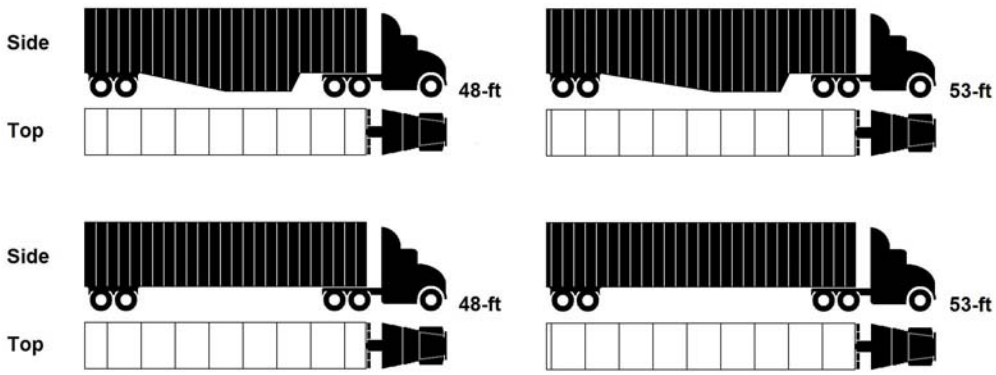

Figure 3-34. Truck configurations for a 48-ft and 53-ft chip van trailer carrying ground bulk feedstock. The possum-belly trailer is used to transport bulk corn stover and switchgrass, while the flat-bottom trailer is used to transport corn cobs.

Smaller, more uniform bulk materials tend to be more dense and compressible compared to less uniform materials. As a result, the bulk density becomes a function of applied pressure as well as particle size. Figure 3-35 presents the change in bulk density as a function of applied pressure and moisture for a standard 1/4-in.-minus grind and a smaller 1/12-in.-minus grind fraction of corn stover, switchgrass, and wheat straw. In reviewing the data, it is noted that the smaller particle grind exhibits larger densities at lower compaction pressures. Applied pressures in the range of 2,000 to 3,500 lb/ft^2 are required to produce feedstock densities needed to fully load a semi-trailer with dry (<15% moisture) bulk materials.

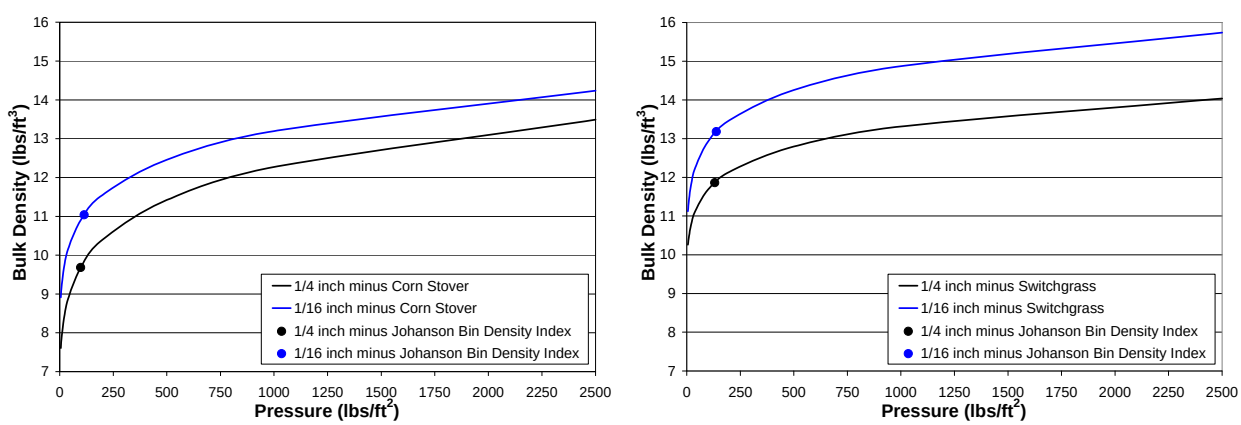

Figure 3-35. Bulk density changes as a function of applied pressure for corn stover and switchgrass at two different grind sizes (Pryfogle, INL test data, March 2009).

The bulk density of the feedstock loaded into a 10-ft deep semi-trailer, or similar transportation container, can be estimated by testing the same material shown in Figure 3-31 in a Johansen bin density index measurement instrument. The bin density measurement accounts for the hydrostatic pressure applied to the bulk feedstock from its own weight. Comparing bin density values with the applied force data shown in Figure 3-35, the hydrostatic pressure is approximately equivalent to 1,000 lb/ft^2 of

mechanically applied force. Therefore, the particle size and distribution and the hydrostatic force from the weight of the feedstock can either reduce or eliminate all together the required mechanical force needed to fully load a semi-trailer.

If mechanical compacting is required, there are several tools for compressing feedstock materials as they are loaded into trucks from the grinding operation. For example, hydraulically operated tamper platens used in cotton module builders operate at pressures in the range of 2,100 to 2,880 lb/ft^2 with a typical tamping cycle of 5 to 10 seconds for a 1 to 2-ft stroke. This speed could allow the material compaction to occur at processing rates that are competitive with truck loading rates from grinding operations. Compacting auger systems could also be used as feeders to densify bulk materials prior to loading onto conveying systems. These systems can also be designed for high throughput capacities.

While grinding to smaller particle sizes and applying large compression forces can aid with increasing the bulk density of the feedstock, there are other handling complications that may result from these actions. Smaller particles tend to be more frictional and, consequently, may generate more flow problems than coarser materials. The permeability also decreases with decreasing particle size, limiting fluidization and flow of materials through hoppers and storage silos. Because the cohesive strength of materials is dependent upon the applied pressure, the compacted materials may have a higher probability of arching or rat-holing within transfer equipment and storage facilities.

In summary, the handling and conveying of loose, bulk feedstock materials is clearly dependent upon the particle size and size distribution of the material. The small size spread in these materials seen in the 1/12 and 1/4 in. minus grinds results in significant changes in the bulk density and flowability properties of the materials. Materials as large as 1/4 in. can be compressed to target limits and handled within the feedstock assembly operation; however, specialized tools and equipment will be required. The trade-off between grinding to smaller particle sizes, mechanically compacting the feedstock, and meeting biorefinery specifications for conversion while incorporating new technologies is the path toward an Advanced Uniform supply system.

3.3.1.3 Biomass Moisture Impact on Supply System Processes and Material Stability

Since the bale receiving, handling, and preprocessing systems used in the biomass depots are the same as those used at the biorefinery in the Conventional Bale design, the impact of feedstock moisture content on these systems is essentially the same as those discussed in Section 2.4.1.3. Corn cobs, on the other hand, will be handled, transported, and ground at a moisture content of approximately 40%. The transportation bulk density requirements discussed above already take this moisture content into account. Likewise, the grinding capacity, which can be significantly impacted by feedstock moisture content, is assumed to be the same for corn cobs as it is for corn stover and switchgrass, at 12% moisture. This assumption is conservatively based on the experience of a preprocessing equipment manufacturer (Kenney 2008).

However, once the feedstock is ground and loaded into the bulk transport system, moisture absorbed from the environment or weather events can influence a number of other properties, such as the tendency of the material to agglomerate and swell, possibly reducing bulk density. Moisture may also impact flow properties, including the compressibility, cohesiveness, and frictional characteristics that affect the flow of material from hoppers and storage facilities. The intent of the biomass depot is to minimize these variables through engineering control of the bulk feed and queuing systems.

3.3.2 Pioneer Uniform Preprocessing and Transportation Equipment

The Pioneer Uniform design uses the same set of bale handling, transportation, and preprocessing equipment for all processes from the field to the biomass depot as was used in the Conventional Bale

design (Sections 2.3.2 and 2.4.2), thus equipment describing the square bale system will not be described in this section. A different set of handling and transportation equipment for corn cobs from the field to the biomass depot is used due to its bulk format. Equipment used for round baled material and corn cobs, as well as bulk material resulting from the preprocessing operation at the biomass depot, will be discussed in the following section.

Handling and Transportation

The handling and transportation processes in the Pioneer Uniform design include the movement of baled material and corn cobs from the field to the biomass depot and the movement of bulk material from the biomass depot to the biorefinery. In addition to the square bale format, both a round bale and loose bulk (corn cob) formats are modeled in the Pioneer Uniform design. Handling and transportation equipment specifications used in the model are shown in Table 3-23.

Table 3-23. Handling and transportation equipment specifications for the Pioneer Uniform design.

	Bale Transport			Bulk Cob Transport		Bulk Biomass Transport			
	Load/ Unload Bale Transport	Transport to Depot	Bale Receiving and Queue for Preprocessing	Load Bulk Transport	Transport to Depot	Bulk Receiving and Queue for Preprocessing	Bulk Queue for Transport	Bulk Cob Transport to Biorefinery	Bulk Stover/ Switchgrass Transport to Biorefinery
Equipment	TH220B Telehandler	Kenworth T800 3-axle Day Cab with Fontaine Phantom 53-ft Flatbed Trailer	Scales Unlimited, Inc. Model AGETS-1171 1-NTEP Semi-truck Scale and Asphalt Pad	TH220B Telehandler	Kenworth T800 3-axle Day Cab with Trinity Eagle Bridge Trailer	Scales Unlimited, Inc. Model AGETS-1171 1-NTEP Semi-truck Scale and Unloading pit	Surge Bin, Foreign Material Eliminators and other Conveying Equipment	Kenworth T800 3-axle Day Cab with Western Trailer Flat-bottom Trailer	Kenworth T800 3-axle Day Cab with Western Trailer Possum-bottom Trailer
Rated Capacity	47 ton/hr	N/A	100 ton	24.9 ton/hr	2,511 ft^3	100 tons	N/A	3,456 ft^3	4,371 ft^3
Field Capacity [a]	40 bales/hr	34 bales/truck	100 ton	24.9 ton/hr	2,511 ft3	100 tons	14.0 tons/hr	3,456 ft^3	4,371 ft^3
Operational Efficiency (%) [b]	40	100% [c]	N/A	100%	100% [c]	N/A	46% [c]	100% [c]	100% [c]
Dry Matter Loss (%)	0	0	0	0	0	0	0	0	0
Operational Window									
hr/day	14	14	14	14	14	14	24	24	24
day/yr	300	300	300	300	300	300	300	300	300

a. Estimate of the operating time that is actually spent working and the amount of capacity used.

b. Ratio of field capacity to rated capacity.

c. Calculated efficiency from the analysis model based on the operating time that is actually spent hauling and the amount of capacity used.

The loading, transport, and unloading of the round baled material is accomplished with a Roadrunner hay clamp attachment on a telehandler loader and a Kenworth T800 semi-tractor with a Fontaine Phantom 53-ft flatbed trailer. This same loader and flatbed semi tractor-trailer was described in Sections 2.2.2 and 2.3.2 and shown in Figures 2-21 and 2-29, respectively. The Roadrunner attachment for round bales is shown below in Figure 3-36.

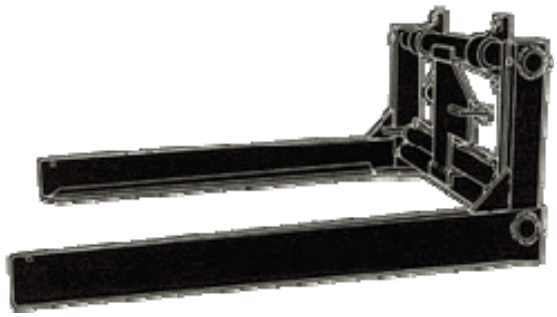

Figure 3-36. Roadrunner Hay Clamp bale handling attachment.

(Photograph from Roadrunner Manufacturing Co., Inc. website < www.roadrunnermfg.com> Permission for use is being requested.)

The corn cobs are loaded in the field with a telehandler into a Trinity Eagle Bridge Live-bottom trailer pulled by a Kenworth T800 semi-tractor. The cob loader is a Caterpillar TH220B telehandler with 100 gross hp and a bucket capacity of 14.7 DM ton/hr (Figure 3-37). The loader and semi tractor-trailer work in tandem to minimize loading time.

(Photo to be inserted)

Figure 3-37. Telehandler loader used to load corn cobs for transport to the biomass depot.

The Kenworth T800 semi-tractor was described in Section 2.3.2 and shown in Figure 2-29. The accompanying Trinity Eagle Bridge Live-bottom trailer is a longitudinally oriented V-bottom trailer capable of discharging bulk material through a hydraulically driven back gate with a 48-in. conveyer belt (Figure 3-38). This type of trailer is ideal for loose bulk material that needs an active flow system to assist in the discharge process, such as corn cobs.

(Photo to be inserted)

Figure 3-38. Trinity Eagle Bridge trailer used to haul loose corn cobs from the storage site in the field to the biomass depot.

The truck scale implemented in this design is the same one used in the Conventional Bale design (Section 2.4.2, Figure 2-40). The asphalt pad at the biomass depot, though similar to the one used in the Pioneer Uniform design, is only used to queue baled material prior to insertion into the grinder. The timing of the unloading process and the loading of the grinder requires that the asphalt pad be much smaller (only 500 ft^2) than the one modeled at the biorefinery in the Conventional Bale design. The queued bales are loaded this asphalt pad onto the bale-merging conveyor and into the grinding process.

Once the feedstock is preprocessed, the ground material is queued in a serge bin system where it is metered into the bulk transport system. The serge bin system is described in Section 2.4.2 and shown in Figure 2-45.

A Kenworth T800 semi-tractor and a Peerless Roadrunner 53-ft chip van are used to transport the bulk material to the biorefinery. The Kenworth T800 is described in Section 2.3.2 and shown in Figure 2-29, and the Roadrunner chip van is shown below in Figure 3-39.

(Photo to be inserted)

Figure 3-39. Peerless Roadrunner 53-ft chip van for transport to the biorefinery of ground, bulk material.

Preprocessing

Preprocessing at the biorefinery as modeled in the Conventional Bale design (Section 2.4) uses a total of nine grinding systems to handle the necessary capacity. Within the Pioneer Uniform design, these nine complete grinding systems are divided among the nine biomass depots. Thus, all preprocessing equipment located at each biomass depot is the same as the preprocessing equipment used in the Conventional Bale design. This system in its entirety is described in Section 2.4.2 and shown in Figures 2-42, 2-43, and 2-44. The equipment specifications for the preprocessing system used in the Pioneer Uniform model are shown in Table 3-24.

Table 3-24. Preprocessing and queuing equipment specifications for the Pioneer Uniform design.

	Preprocessing					
	Grinder Loader from Bale Queue	Grinder Infeed System	Grinder	Dust Collection	Surge Metering Bin	Bale and Twine Disposal
Equipment	Caterpillar TH220B Telehandler	Schuon conveyor	Vermeer HG6000 Horizontal Grinder	Cyclone, Baghouse, Conveying Equipment	Sukup hopper bottom surge bin	Dump Truck
Rated Capacity	14.0 ton/hr	14.0 ton/hr	17.1 ton/hr	14.0 ton/hr	100 ton/hr	14.0 ton/hr
Field Capacity	14.0 ton/hr	14.0 ton/hr	14.0 ton/hr	14.0 ton/hr	14.0 ton/hr	14.0 ton/hr
Operational Efficiency (%)[a]	100%	100%	82%	100%	14%	100%
Dry Matter Loss (%)	0	0	0	0	0	0
Operational Window						
hrs/day	24.0	24.0	24.0	24.0	24.0	24.0
days/year	300	300	300	300	300	300

a. Grinder field capacity is conservatively assumed to be the same for corn cobs as it is for corn stover and switchgrass as per personal correspondence with Scott Rempe at Vermeer Manufacturing.

b. Estimated efficiency based on the actual operating time and the amount of capacity used.

c. Published efficiency input into the analysis model (Appendix B-2).

3.3.2.1 Equipment Capacity and Operational Efficiency

Table 2-34 shows that the grinder capacity and power requirement will vary for different types of feedstock materials. The capacity value reported in Table 2-34 is provided for both dry ton/hour, a metric widely used in the grinding industry, and dry ton/kilowatt hour, a metric used to capture the power required to produce a given dry tons per hour value. Because of the variance in grinding capacity and efficiency as a function of feedstock variety, the selection of specific grinding configurations or conditions will be important to consider in the preprocessing operation. However, feedstock moisture is still the most influential parameter on grinding capacity and efficiency (Figure 2-39).

The tightly coupled relationship between bulk density and transportation makes truck configurations and road limits critically important in the overall supply system. The location of the biomass depot and the bulk density required to maximize truck capacity is directly dependant on local road laws. For the purpose of identifying a broadly applicable supply system, U.S. National Network truck road limits are used in the Pioneer Uniform design (Tables 3-20 to 3-22, Figures 3-32 to 3-34). These limits specify the truck volume, based on trailer configuration, resulting in a bulk density target to maximize the GVW.

3.3.2.2 Dry Matter Losses

Even though dry matter losses at the biomass depot cost less than the same losses experienced at the biorefinery, because the feedstock has a lower value earlier in the supply chain, losses still constitute too high of an economic and regulatory risk not to be mitigated. Therefore, a cyclone separator and baghouse dust collection system (Figure 2-44) is implemented within each preprocessing system at the biomass depots. This system collects nearly all dust and other small particulates emitted by the grinding and handling processes and provides a way to reintroduce the collected material back into the feed system, thereby minimizing net material losses and their associated costs. The Pioneer Uniform model uses this dust collection system and does not factor operational dry matter losses into the analysis.

3.3.2.3 Operational Window

The bale receiving processes at the biomass depot operate 14 hours per day, six days per week, for 50 weeks a year. This schedule is based on anticipated constraints imposed by typical field operations and field conditions. On the other hand, all preprocessing and bulk transport processes operate 24 hours a day, seven days a week for 350 days a year. The conflicting schedules, along with the lower equipment capacity of bale transport units, decreases the distance between feedstock production sites and a biomass depot and increase the distance between the biomass depot and the biorefinery. The mismatch in schedules will also necessitate a small bale queuing yard at the biomass depot to feed the preprocessing system during times when bale receiving is not operating. Optimizing the distance between individual depots and the production sites will help maximize both bale and bulk transport efficiencies and optimize the size of the bale queuing yard.

3.3.3 Pioneer Uniform Preprocessing and Transportation Cost and Sensitivity Analysis

3.3.3.1 Static Model Cost Summary

A breakdown of the costs associated with each piece of equipment used in the Preprocessing and Transportation unit operation identifies significant cost components that are valuable for making individual comparisons and identifying areas of research potential (Tables 3-25 and 3-26). These costs are reported in terms of DM tons entering each process.

Table 3-25. Static model costs for major handling and transportation equipment in the Pioneer Uniform corn stover and switchgrass scenarios. Costs are expressed in $/DM ton unless otherwise noted.

		Bale Transport			Bulk Transport	
		Load and Unload	Transport to Depot	Receiving and Queue for Preprocessing	Queue for Transport	Transport to Biorefinery
	Equipment	Telehandlers	Kenworth T800 3-axle Day Cab with Fontaine Phantom 53-ft Flatbed Trailer	Scales Unlimited, Inc. Model AGETS-11711-NTEP Semi-truck Scale and Asphalt Pad	Surge Bin, Foreign Material Eliminators and other Conveying Equipment	Peerless Roadrunner 53-ft Chip Transport and Kenworth T800 3-axle day cab
Corn Stover	Installed Equipment Quantity	12 × 2 =24	35	9	9	8
	Installed Capital[a]	1.98	6.19	0.07	9.61	1.44
	Ownership Costs[b]	0.79	1.18	0.01	1.16	0.39
	Operating Costs[c]	3.67	6.95	0.19	2.28	3.22
	Labor	2.92	5.47	0.19	0.00	1.25
	Non-Labor	0.75	1.48	0.00	2.28	1.97
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	23.6	40.8	N/A	85.7	54.4
Switchgrass	Installed Equipment Quantity	24	34	1	9	8
	Installed Capital[a]	1.98	6.01	0.07	9.61	1.44
	Ownership Costs[b]	0.73	1.14	0.01	1.16	0.39
	Operating Costs[c]	3.51	6.66	0.19	2.28	3.24
	Labor	2.79	5.24	0.19	0.00	1.25
	Non-Labor	0.72	1.41	0.00	2.28	1.98
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	22.6	39.0	N/A	85.7	54.7

a. Installed capital costs are $ per annual DM ton capacity.

b. Ownership costs include depreciation, interest, taxes, insurance, and housing (Appendix A-2, Table A-7).

c. Operating costs include repairs, maintenance, fuel, lubrication labor, and consumable materials (Appendix A-2, Table A-7).

		Cob Transport			Bulk Transport	
		Load and Unload	Transport to Depot	Receiving and Queue for Preprocessing	Queue for Transport	Transport to Biorefinery
Equipment		TH220 B Telehandler (1)	Kenworth T800 3-axle Day Cab with Trinity Trailer Eagle Bridge 42-ft, 29”/4’ side	Scales Unlimited, Inc. Model AGETS-11711 -NTEP Semi-truck Scale	Corn Hopper, Foreign Material Eliminators and other Conveying Equipment	Kenworth T800 3-axle day cab with Western Trailer 48-ft Flat Floor Chip Trailer
Cobs	Installed Equipment Quantity	13	26	12	12	13
	Installed Capital[a]	1.07	2.34	0.07	7.45	2.34
	Ownership Costs[b]	0.43	0.69	0.01	2.28	0.69
	Operating Costs[c]	2.07	5.75	0.19	6.76	5.75
	Labor	1.65	1.99	0.19	4.46	1.99
	Non-Labor	0.42	3.76	0.00	2.30	3.76
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	13.3	103.8	N/A	117.1	103.8

Table 3-26. Static model costs for major preprocessing equipment in the Pioneer Uniform corn stover and switchgrass scenarios. Costs are expressed in $/DM ton unless otherwise noted.

		Grinder Loader from Bale Queue	Grinder Infeed System	Grinder		Dust Collection	Bale and Twine Disposal
		Caterpillar TH220B Telehandler	Schuon Conveyor	Vermeer HG6000 Horizontal Grinder	Surge Metering Bin	Cyclone, Baghouse, and Other Conveying Equipment	Twine Remover, Moisture Meter, etc
Corn Stover	Installed Equipment Quantity	9	9	9	9	9	9
	Installed Capital[a]	0.74	4.84	4.66	0.14	3.15	1.47
	Ownership Costs[b]	0.47	0.53	1.87	0.02	0.45	0.17
	Operating Costs[c]	1.65	0.85	5.54	0.02	1.29	0.11
	Labor	1.14	N/A	1.45	N/A	0	0
	Non-Labor	0.51	0.85	4.10	0.02	1.29	0.11
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	15.9	4.1	129.8	N/A	79.6	2.0
Switchgrass	Installed Equipment Quantity	9	9	9	9	9	1
	Installed Capital[a]	0.74	4.84	4.66	0.14	3.15	1.47
	Ownership Costs[b]	0.47	0.53	1.87	0.02	0.45	0.17
	Operating Costs[c]	1.65	0.85	5.54	0.02	1.29	0.11
	Labor	1.14	N/A	1.45	N/A	0	0
	Non-Labor	0.51	0.85	4.10	0.02	1.29	0.11
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	15.9	4.1	129.8	N/A	79.6	2.0

		Grinder Loader from Queue	Grinder Infeed System	Grinder	Dust Collection	Surge Bin	Waste Disposal
		Phelps 40-ft Corn Hopper	12,000 BPH, 180-ft En Masse conveyor	Vermeer HG6000 Horizontal Grinder	Cyclone, Baghouse, and other Conveying Equipment	Sukup, hopper bottom surge bin	Truck Scale, moisture meter, electro magnet
Cobs	Installed Equipment Quantity	12	12	12	12	12	1
	Installed Capital[a]	1.09	0.33	6.21	4.50	0.12	1.41
	Ownership Costs[b]	1.43	0.04	2.49	0.64	0.01	0.16
	Operating Costs[c]	2.79	0.23	7.39	1.72	0.02	2.00
	Labor	2.53	0.00	1.93	0.00	0.00	1.93
	Non-Labor	0.26	0.23	5.46	1.72	0.02	0.06
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	N/A	11.0	173.1	106.1	N/A	N/A

3.3.3.2 Cost Sensitivity Analysis

A histogram of the handling and transportation cost (Figure 3-40) for the round bale corn stover scenario shows that the cost of the unit operation with 90% confidence ranges between $15.17 and $18.50 per DM ton. Further, the mean and standard deviation of this range is $16.78 ± 1.01 per DM ton, and a mode value of $16.95 per DM ton. This value closely represents the result of the static model, $16.17 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

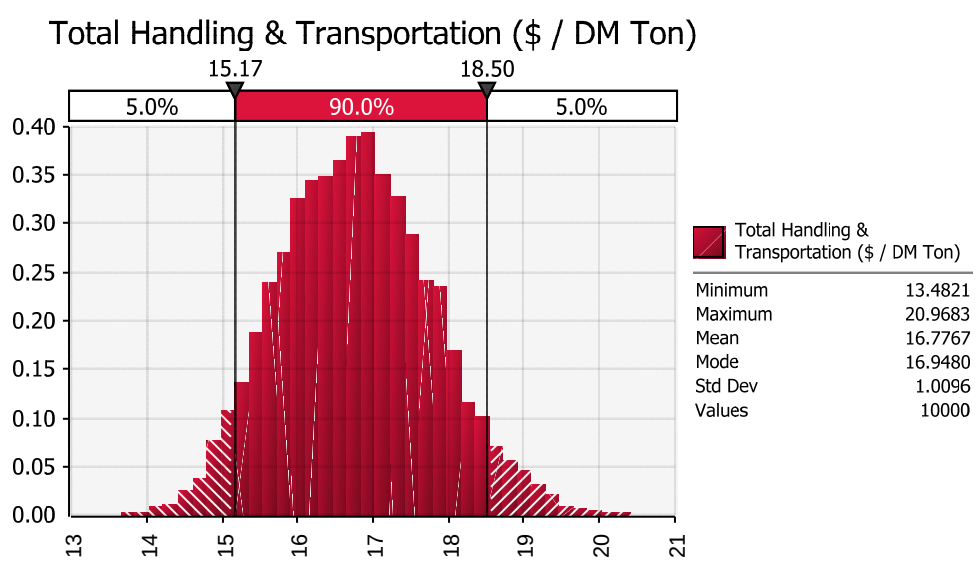

Figure 3-40. Pioneer Uniform handling and transportation cost distribution histogram from @Risk analysis for the round bale corn stover scenario.

Looking at square bales, a histogram of the handling and transportation cost (Figure 3-41) for corn stover shows that with 90% confidence the cost of the unit operation ranges between $10.72 and $13.12 per DM ton, with a the mean and standard deviation of $11.88 ± 0.73 per DM ton. The mode value of the handling and transportation cost is $11.87 per DM ton. This value closely represents the result of the static model, which is $9.20 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

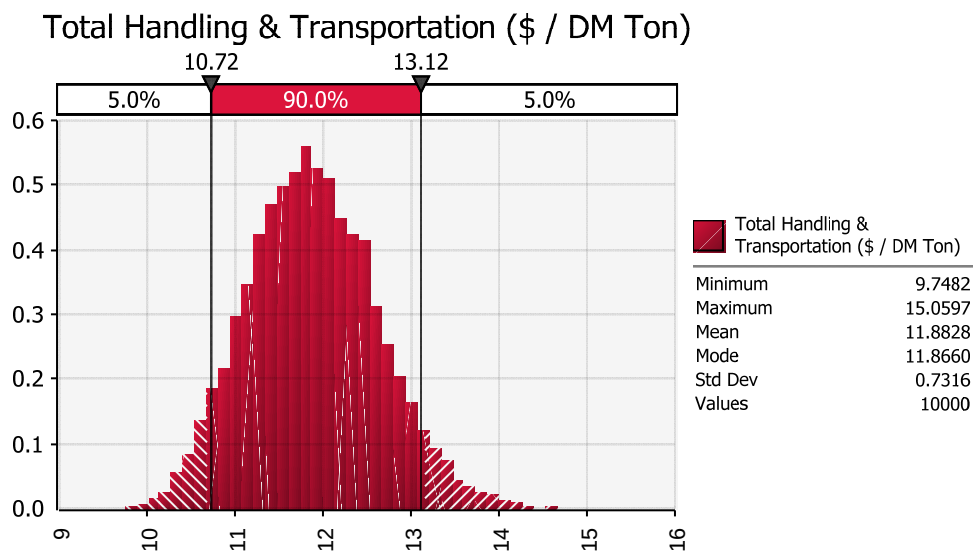

Figure 3-41. Pioneer Uniform handling and transportation cost distribution histogram from @Risk analysis for the square bale corn stover scenario.

Similarly, a histogram of the handling and transportation cost (Figure 3-42) for round bale switchgrass shows that with 90% confidence the cost of the unit operation ranges between $ 14.10 and $ 17.12 per DM ton with a mean and standard deviation of this range of $ 15.56 ± 0.92 per DM ton. The mode value of this cost range is $ 15.56 per DM ton, which closely represents the result of the static model of $ 15.68 per DM ton.

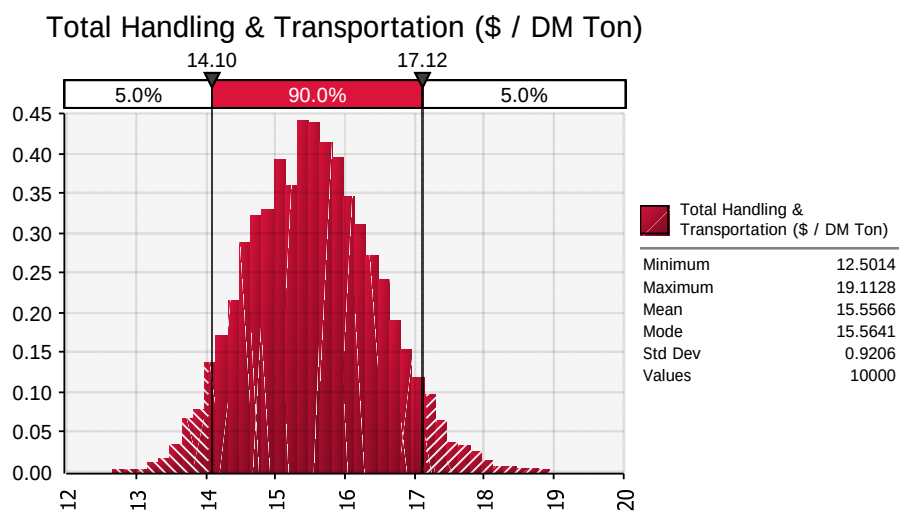

Figure 3-42. Pioneer Uniform handling and transportation cost distribution histogram from @Risk analysis for the round bale switchgrass scenario.

Looking at the square bales, a histogram of the handling and transportation cost (Figure 3-43) for switchgrass shows that with 90% confidence the cost of the unit operation ranges between $ 10.01 and $ 12.38 per DM ton with the mean and standard deviation of this range being $ 11.14 ± 0.72 per DM ton. The mode value of this cost range is $ 11.38 per DM ton, which closely represents the result of the static model of $8.53 per DM ton.

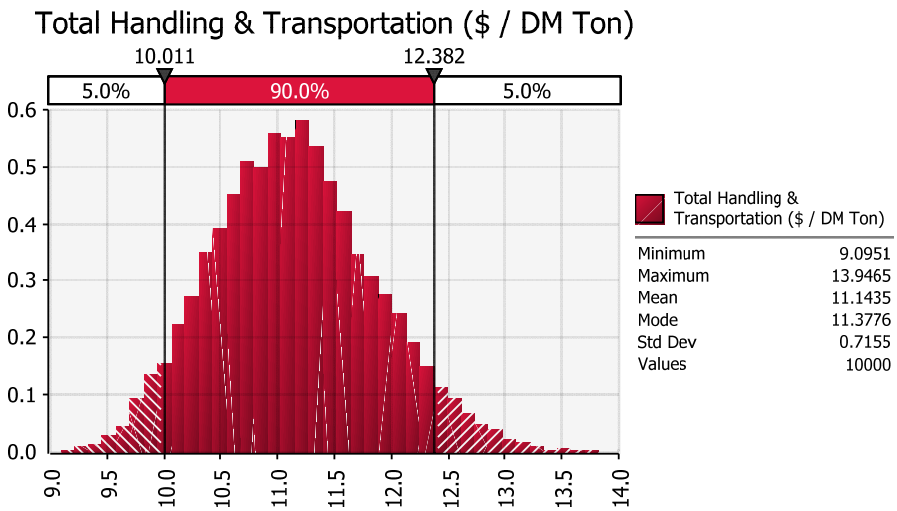

Figure 3-43. Pioneer Uniform handling and transportation cost distribution histogram from @Risk analysis for square bale switchgrass.

A histogram of the preprocessing cost (Figure 3-44) for round bale corn stover shows that with 90% confidence the cost of the unit operation ranges between $12.73 and $17.64 per DM ton. Further, the mean and standard deviation of this range is $14.75 ± 1.64 per DM ton. The mode value of the preprocessing cost is $14.23 per DM ton. This value closely represents the result of the static model, which is $12.97 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

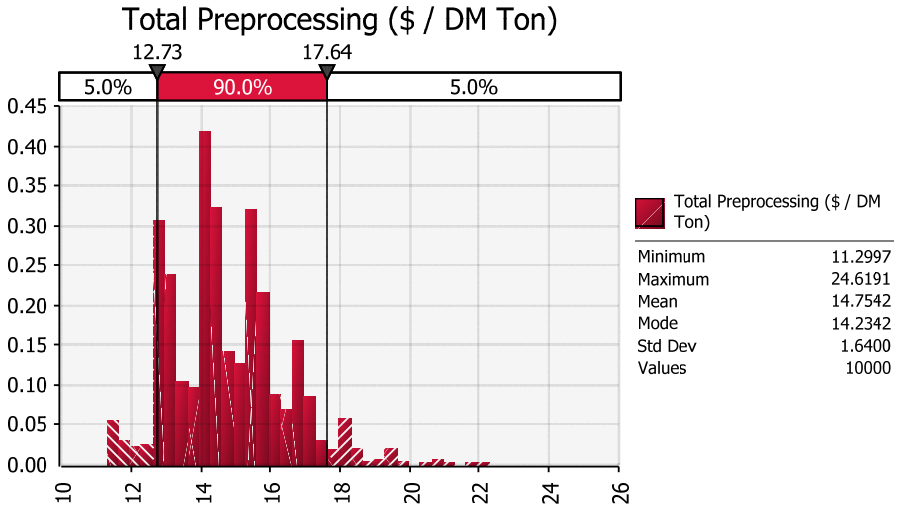

Figure 3-44. Pioneer Uniform preprocessing cost distribution histogram from @Risk analysis for the round bale corn stover scenario.

A histogram of the preprocessing cost (Figure 3-45) for the square bale corn stover case shows that the cost of the unit operation ranges between $12.71 and $17.62 per DM ton with 90% confidence, with a mean and standard deviation of $14.75 ± 1.64 per DM ton. The mode value of the preprocessing cost is $14.20 per DM ton, which is close to the static model result of $12.97 per DM ton. This is expected, as the defined value of the parameter distributions was set equal to the static value in the model.

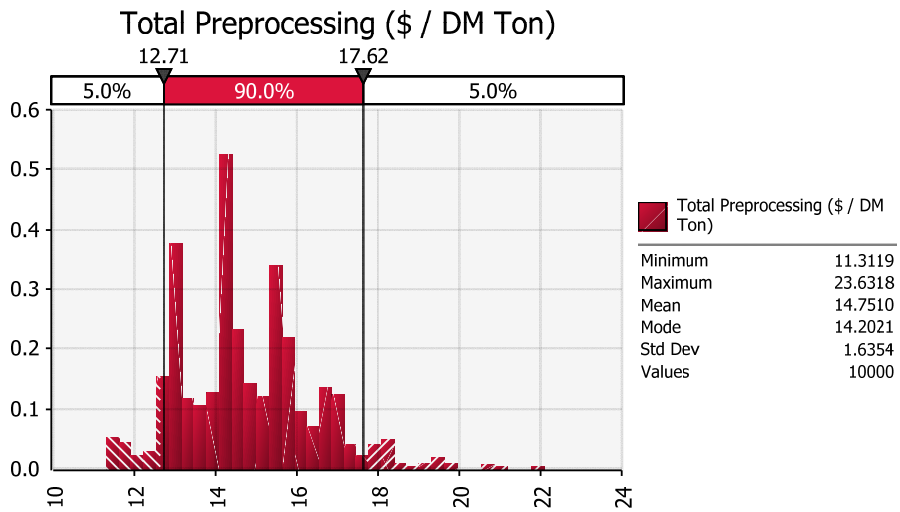

Figure 3-45. Pioneer Uniform preprocessing cost distribution histogram from @Risk analysis for the square bale corn stover scenario.

Similarly, a histogram of the preprocessing cost (Figure 3-46) for the round bale switchgrass case shows that the cost of the unit operation ranges between $ 12.84 and $ 19.66 per DM ton with 90% confidence, with the mean and standard deviation of this range being $ 15.72 ± 2.23 per DM ton. The mode value of this cost range is $ 14.21 per DM ton, which closely represents the result of the static model of $ 12.97 per DM ton.

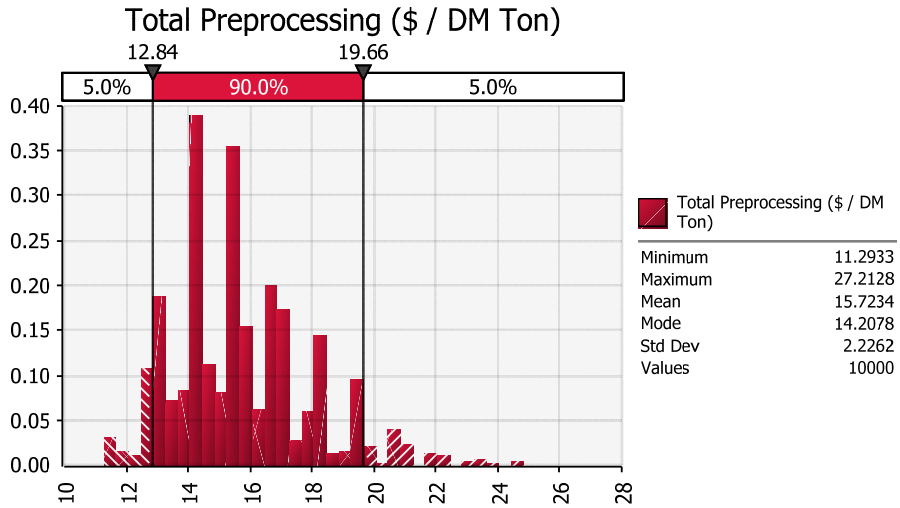

Figure 3-46. Pioneer Uniform preprocessing cost distribution histogram from @Risk analysis for the round bale switchgrass scenario.

Similarly, a histogram of the preprocessing cost (Figure 3-47) for square bale switchgrass shows that the cost of the unit operation ranges between $ 12.83 and $ 19.64 per DM ton with 90% confidence, with a mean and standard deviation of this range of $ 15.72 ± 2.24 per DM ton. The mode value of this cost range is $ 14.18 per DM ton, which closely represents the result of the static model of $12.96 per DM ton.

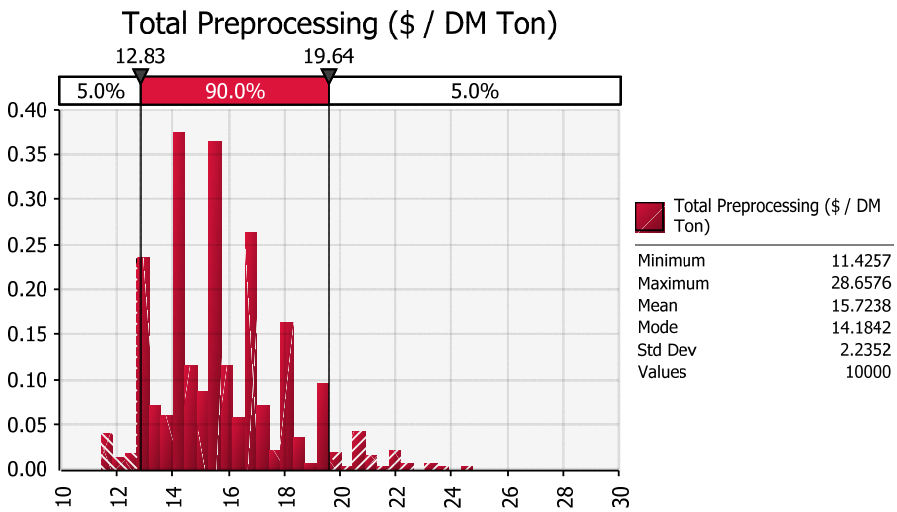

Figure 3-47. Pioneer Uniform preprocessing cost distribution histogram from @Risk analysis for the square bale switchgrass scenario.

Finally, a histogram of the storage cost for corn cobs (Figure 3-48) shows that with 90% confidence the cost of the unit operation ranges between $14.00 and $24.14 per DM ton with the mean and standard deviation of this range being $18.96 ±3.04 per DM ton. The mode value of this cost range is $17.26 per DM ton, which closely represents the result of the static model of $18.92 per DM ton.

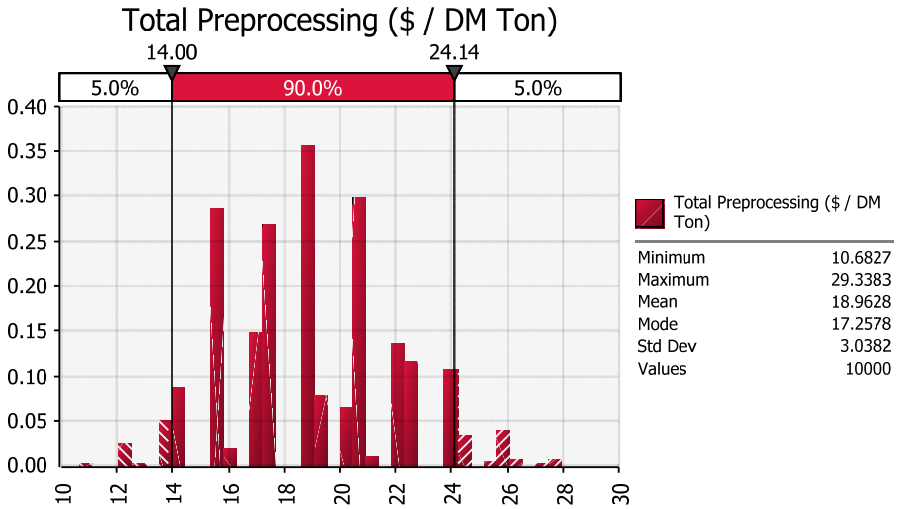

Figure 3-48. Pioneer Uniform preprocessing cost distribution histogram from @Risk analysis for corn cobs.

The overall costs associated with the Pioneer Uniform preprocessing and transportation unit operation for corn stover, switchgrass, and corn cobs are provided in Tables 3-27, 3-28, and 3-29 and on a per-DM-

ton and per-bale basis. These costs, reported in terms of a mean and standard deviation, come as a result of 10,000 model iterations of the simulated Pioneer Uniform feedstock supply system.

Table 3-27. Bale and bulk transportation cost summary for the Pioneer Uniform corn stover and switchgrass scenarios.

		Load and Unload	Transport to Depot	Receiving and Queue for Preprocessing	Queue for Transport	Transport to Biorefinery	Total Round Bale Transport
Equipment		Telehandler	Kenworth T800 3-axle Day Cab with Fontaine Phantom 53-ft Flatbed Trailer	Scales Unlimited, Inc. Model AGETS-11711-NTEP Semi-truck Scale and Asphalt Pad	Surge Bin, Foreign Material Eliminators and other Conveying Equipment	Peerless Roadrunner 53-ft Chip Transport and Kenworth T800 3-axle day cab	
Corn Stover	Modeled Cost Totals[a]	4.46 ± 0.35 $/DM ton	8.43 ± 0.56 $/DM ton	0.20 ± 0.00 $/DM ton	0.05 ± 0.006 $/DM ton	16.78 ± 1.01 $/DM ton	3.88 ± 0.46 $/DM ton
		1.88 ± 0.09 $/bale	3.55 ± 0.10 $/bale	0.001 ± 0.00 $/bale	0.03 ± 0.004 $/bale	5.44 ± 0.19 $/bale	0.02 ± 0.002 $/bale
		15.16 ± 0.51 $/mi	9.13 ± 0.26 $/mi			27.05 ± 0.77 $/mi	2.75 ± 0.07 $/mi
Switchgrass	Modeled Cost Totals[a]	4.02 ± 0.30 $/DM ton	7.60 ± 0.47 $/DM ton	0.20 ± 0.00 $/DM ton	0.04± 0.005 $/DM ton	15.56 ± 0.92 $/DM ton	3.93 ± 0.53 $/DM ton
		1.88 ± 0.09 $/bale	3.55 ± 0.10 $/bale	0.001 ± 0.00 $/bale	0.03 ± 0.004 $/bale	5.45 ± 0.19 $/bale	0.02 ± 0.003 $/bale
		15.17 ± 0.51 $/mi	9.13 ± 0.26 $/mi			27.00 ± 0.77 $/mi	2.70 ± 0.07 $/mi

a. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

		Cob Transport			Bulk Transport	
Equipment		Load and Unload	Transport to Depot	Receiving and Queue for Preprocessing	Queue for Transport	Transport to Biorefinery
		TH220B Telehandler	Kenworth T800 3-axle Day Cab with Trinity Trailer Eagle Bridge 42-ft, 29-in./4-ft side	Scales Unlimited, Inc. Model AGETS-11711-NT EP Semi-truck Scale	Surge Bin, Foreign Material Eliminators and other Conveying Equipment	Kenworth T800 3-axle day cab with Western Trailer 48-ft Flat Floor Chip Trailer
	Modeled Costs	2.73± 0.31 $/DM ton	8.99 ± 0.82 $/DM ton	± $/DM ton	0.03 ± 0.00 $/DM ton	6.53 ± 0.75 $/DM ton
		0.01 ± 0.00 $/unit	0.03 ± 0.00$/unit	± $/unit	0.03 ± 0.00 $/unit	0.05 ± 0.01$/unit
		4.77 ± 0.36 $/mi	6.46 ± 0.37 $/mi			2.58 ± 0.06 $/mi

Table 3-28. Preprocessing cost summary for the Pioneer Uniform corn stover and switchgrass scenarios.

Equipment		Grinder Loader from Bale Queue	Grinder Infeed System	Grinder	Dust Collection	Bale and Twine Disposal	Total Preprocessing – Round Bale	Total Preprocessing – Square Bale
		Caterpillar TH220B Telehandler	Schuon conveyor	Vermeer HG6000 Horizontal Grinder	Cyclone, Baghouse, Conveying Equipment	Dump Truck		
Corn Stover	Modeled Cost Totals[a]	2.17 ± 0.36 $/DM ton	1.66 ± 0.23 $/DM ton	8.48 ± 1.06 $/DM ton	2.10 ± 0.25 $/DM ton	0.30 ± 0.05 $/DM ton	14.75 ± 1.64 $/DM ton	14.75 ± 1.63 $/DM ton
		0.92 ± 0.16 $/bale	0.70 ± 0.11 $/bale	3.58 ± 0.50 $/bale	1.20 ± 0.16 $/unit	0.09 ± 0.01 $/unit	6.52 ± 0.79 $/unit	8.58 ± 1.05 $/unit
Switchgrass	Modeled Cost Totals[a]	2.42 ± 0.48 $/DM ton	1.65 ± 0.21 $/DM ton	9.11± 1.44 $/DM ton	2.18 ± 0.28 $/DM ton	0.33± 0.07 $/DM ton	15.72 ± 2.23 $/DM ton	15.72 ± 2.24 $/DM ton
		1.13 ± 0.24 $/bale	0.77 ± 0.11 $/bale	4.27 ± 0.72 $/bale	1.64 ± 0.22 $/unit	0.11 ± 0.02 $/unit	7.95 ± 1.17 $/unit	10.40 ± 1.54 $/unit

a. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

Table 3-29. Preprocessing cost summary for Pioneer Uniform corn cob scenario.

		Grinder Loader from Queue	Grinder Infeed System	Grinder	Dust Collection	Surge Bin	Waste Disposal
		Phelps 40-ft Corn Hopper	12,000 BPH, 180-ft En Masse conveyor	Vermeer HG6000 Horizontal Grinder	Cyclone, Baghouse, and other Conveying Equipment	Sukup, hopper bottom surge bin	Truck Scale, moisture meter, electro magnet
	Modeled Costs	4.24 ± 0.87 $/DM ton	0.27 ± 0.03 $/DM ton	9.89 ± 1.49 $/DM ton	2.37 ± 0.33 $/DM ton	0.03 ± 0.002 $/DM ton	2.16 ± 0.32 $/DM ton
		0.02 ± 0.003 $/unit	0.001 ± 0.00 $/unit		2.12 ± 0.31$/unit	0.03 ± 0.001 $/unit	

3.4 Pioneer Uniform Receiving and Handling

Because preprocessing operations have already occurred, the biorefinery receives a feedstock that has been processed to a known uniform-format specification that includes particle size and distribution, moisture, and bulk density. Since biorefinery receiving and handling systems are designed according to this specification, these systems are broadly replicable regardless of feedstock variety and harvesting methods specific to geographical regions. The receiving and handling systems at a biorefinery consist of weighing and unloading incoming bulk transport trucks, storing bulk feedstock in short-term queuing, and feeding bulk feedstock into the conversion process (Figure 3-49). Thus, this section presents a receiving and handling design that can be widely replicated in association with conversion facilities within the

varied climatic and regulatory constraints that may be encountered across diverse geographic areas. As such, this design may not necessarily represent lowest cost methods or common practices.

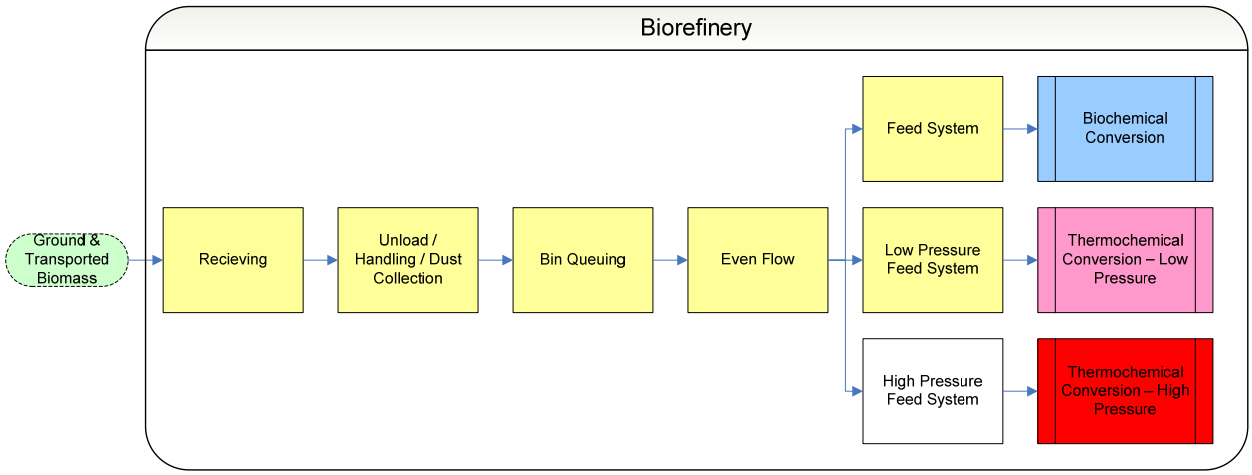

Figure 3-49. Receiving and handling supply logistic processes and biomass format intermediates.

(Note: Green ovals represent biomass format intermediates, tan ovals represent potential waste streams, yellow rectangles represent processes modeled in this report, and white rectangles represent processes not modeled in this report. The blue, pink, and red rectangles represent different conversion processes.)

3.4.1 Pioneer Uniform Receiving Format Intermediates

The feedstock format does not change at this point in the Pioneer Uniform design. Instead, the variables that impact the selection of receiving and handling equipment are based on the bulk format that is produced in the biomass depots (Table 3-30). The receiving and handling processes are largely impacted by the size of the feedstock inventory that is maintained to supply the conversion process in the event costly disruptions in the supply chain occur, such as weather delays.

Table 3-30. Attributes of receiving and handling format intermediates for corn stover, switchgrass, and corn cobs.

	Receiving, Handling, and Queuing	Dust Collection		Receiving, Handling, and Queuing	Dust Collection		Receiving, Handling, and Queuing	Dust Collection
Biomass Output	Corn Stover	Corn Stover		Switchgrass	Switchgrass		Corn Cobs	Corn Cobs
Yield (DM tons/day)	2,600			2,600			2,600	
Format Output	Bulk (1 in. minus)			Bulk (1 in. minus)			Bulk (1 in. minus)	
Bulk DM Density Output	7.4 lb/ft^3			10.3 lb/ft^3			14 lb/ft^3	
Output Moisture (% w.b.)	12			12			12	

3.4.1.1 Biomass Deconstruction, Fractionation, and Physical Property Changes

In the Pioneer Uniform design, the received feedstock has been preprocessed according to the specifications and particle size distribution discussed in Section 3.3.1.2. These feedstock characteristics may ultimately need to be improved based on conversion process requirements and material handling and

flowability constraints. As for the Conventional Bale design, a general mean particle size target for the Pioneer Uniform system of 1/4-in. minus, with no range constraint or lower size limit, is being used as a baseline. However, it is generally true that smaller particle-size requirements will mean lower grinder capacities and higher preprocessing costs. Figure 3-1 in Section 2.4.1 show the mean particle size and particle-size distribution for corn stover and switchgrass at various moisture contents.

3.4.1.2 Format and Bulk Density Impact on Supply System Processes

The handling and queuing of bulk feedstock formats are functions of the physical properties of the material and the design of the equipment used in the various processes. Conducting these processes is complicated because most existing handling and conveying technologies are designed for operation with granular materials, such as food grains or minerals. These materials typically have small, uniform particle sizes, high densities, and are not compressible. In contrast, the herbaceous feedstocks proposed for use in biofuel production may have large particle size variations, low densities, and can be highly compressible.

In order to achieve cost targets, the ground Pioneer Uniform feedstock must be able to flow through conventional feeder, conveyor, transportation, and storage systems. In particular, due to limited harvest windows and the large amount of feedstocks needed to continuously operate biorefineries, storage systems are especially sensitive to cost increases caused by feedstock handling issues. The low bulk density of loose feedstocks dictates the use of large storage volumes and possibly customized structures. Storage in large piles can require labor-intensive means of retrieving the feedstocks, and they may also incur significant losses due to weathering. On the other hand, high-capacity storage structures require large capital expenditures to site and build and, due to the cohesive nature of loose feedstocks, may require large active bridge-breaking devices to assist material conveyance and flow, resulting in additional costs to build and operate the facilities.

The most economical way to convey, feed, and store biomass feedstocks is in standard systems that use gravity flow. The ability of the feedstock to flow through a particular assembly system is a function of the feedstock physical properties and the design of the structure. The material properties that determine how easily a feedstock will flow through a structure include its bulk density, its tendency to bridge, and the frictional forces it exerts on itself and the structure wall. These properties are, in turn, impacted by the feedstock's particle size and distribution, particle shape and distribution, moisture content, temperature, and the pressure it has experienced as a function of time.

Conventional feedstock conveying and storage systems generally consist of cylindrical or rectangular structures integrated with a hopper that allows the material to converge and flow through the opening. As it converges, the material may experience a number of problems, ranging from unsteady flow to no flow. The controllable, steady flow from a bin or hopper depends on the slope angle and shape of the hopper, and the frictional forces within the material and the structure wall. The no-flow condition is generally caused by the material forming a stable arch, or bridge, within the structure that acts an obstruction to flow. This bridge is a result of the cohesive strength of the material and the pressure exerted by the weight of the material lying above it in the facility. In general, the longer the material is in storage, the more cohesive it becomes. The combined influence of cohesive strength, internal friction, and bulk density of the material, determines the diameter of the storage facility needed to allow unassisted flow.

In order to identify a feedstock format that will readily flow through low-cost, conventional feedstock conveying and storage systems, feedstock flowability properties are tested and selected based on criteria developed by Jenike. In these criteria, the yield strength of the material, measured as a function of consolidating stresses, is used to develop a flow function and determine the frictional properties of the material. Jenike then proposes using the ratio of the maximum consolidating stress at steady state flow to the unconfined yield strength, which is also the inverse slope of the flowability graph (Figure 3-25), to produce a value known as the flow function, ff_c. Table 3-31 provides the relationship between the flow

function and the flowability classification of the material. Five flowability categories are identified ranging from hardened and non-flowing to free-flowing material. Figure 3-25 shows this same relationship graphically and highlights the region where material can be considered gravimetrically flowable. It was determined from these flowability categories that the target flow function is a value greater than four (green highlight in Figure 3-50).

Table 3-31. Flow function value ranges and the corresponding flowability classification

Flow Function (ff_c)	Flowability Classification
ffc ≤ 1	Hardened and non-flowing
1 < ffc ≤ 2	Very cohesive
2 < ffc ≤ 4	Cohesive
4 < ffc ≤ 10	Easy flowing
ffc > 10	Free flowing

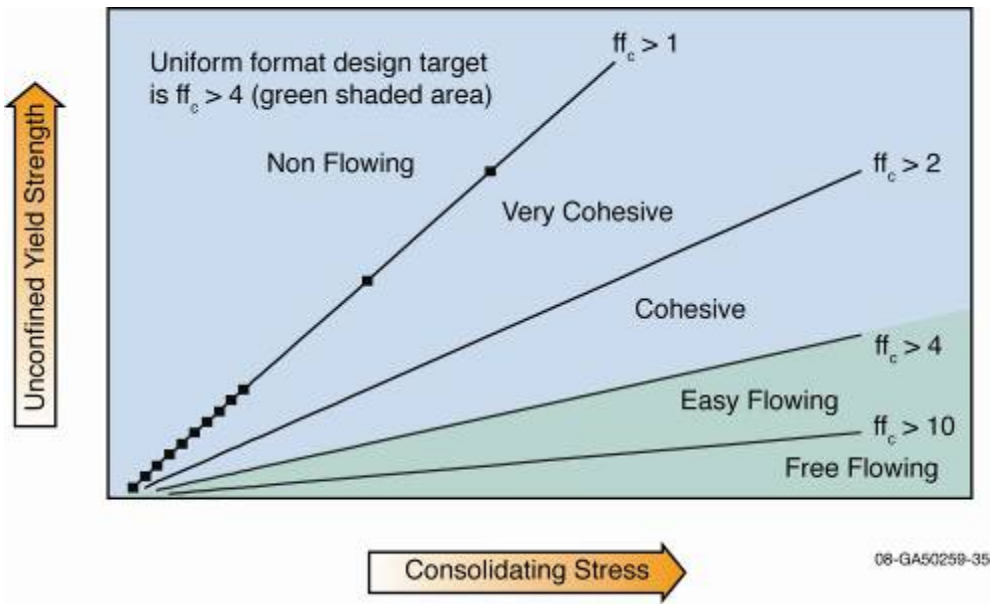

Figure 3-50. Flowability classification ranges. Uniform-Format design target is $ff_c > 4$.

The material properties of the feedstock will need be tailored to have a flow function, ff_c of greater than four (easy flowing), at the maximum consolidation stress produced within standard, silo-structures under the most extreme environmental conditions expected during handling and storage. This criterion should result in a material that would be unlikely to form stable bridges or create other flow problems. If flow problems did occur, they could be addressed through common remediation techniques, such as the use of low friction coatings or liners, drag chains, or aeration or vibration systems.

3.4.1.3 Biomass Moisture Impact on Supply System Processes and Material Stability

Material arriving at the biorefinery has passed through the biomass depot and is therefore a relatively consistent and stable material (<20% moisture). Nevertheless, moisture and other quality parameters will be tested at the biorefinery to verify established standards. In addition, the received material is unloaded directly into the queuing structure (in this case, a Eurosilo bulk storage structure), where it is subsequently fed into the conversion process with little opportunity for significant changes in moisture content.

3.4.2 Pioneer Uniform Receiving and Handling Equipment

Material received in the Pioneer Uniform design was preprocessed into a uniform format at a biomass depot such that different feedstocks handle similarly and different equipment is not necessary for receiving corn stover, switchgrass, and corn cobs. As with the Conventional Bale design, the Pioneer Uniform receiving component includes equipment and systems for accepting truckloads of bulk biomass at the biorefinery and conducting a transaction between the buyer (the biorefinery) and the producer based solely on moisture and weight. However, quality assessment laboratories may be added as part of the receiving system as biomass trading quality factors become better understood. After the material arrives and is assessed, it is unloaded into Eurosilos, where it is queued for the conversion process. The equipment specifications for the receiving and handling operation are outlined in Table 3-32.

Table 3-32. Receiving equipment specifications for the Pioneer Uniform Design.

	Receiving	Unloading and Handling	Dust Collection	Bin Queuing and Even Flow
Equipment	Scales Unlimited, Inc. Model AGETS-11711-N TEP Semi-truck Scale	Phelps drive-through full-truck tipper and hopper	Cyclone Separator and Baghouse	Eurosilo
Capacity (wet ton/hr)	137.7 ton/hr	137.7 ton/hr	137.7 ton/hr	1,507,064 ft^3
Operational Efficiency (%)[a]	41 [b]	76[b]	100	95 [b]
Dry Matter Loss (%)	0	0	0	0
Operational Window				
hrs/day	24	24	24	24
days/year	300	300	300	350

a. Estimate of the operating time that is actually spent working and the amount of capacity used.

b. Published efficiency input into the analysis model (Appendix A).

Weighing

One drive-on truck scale will be used to weigh the trucks as they enter the plant and again as they leave to determine the amount of feedstock delivered to the plant. The truck scale implemented in this design scenario is the AGETS-11711-NTEP model from Scales Unlimited, Inc. and is shown previously in Figure 2-40.

Unloading

After the trucks arrive in the receiving area and are weighed, the bulk material is unloaded into a below-ground hopper using a Phelps drive-through full-truck tipper. This truck tipper and hopper system have a combined 138 ton/hour field capacity (Figure 3-51).

Figure 3-51. Receiving processes within the Pioneer Uniform design: Phelps drive-through truck tipper.

Dust Collection

A high-efficiency dust collection system, similar to the one used in the Conventional Bale design (Section 2.4.2, Figure 2-44), will be integrated with the conveying system leading from the truck tipper hopper to the Eurosilo queuing bins. Dust collection will be sized to handle only airborne particles released during the unloading and conveying processes.

Conveying Systems

The conveying system between the truck tipper hopper and the Eurosilo consists of several En Masse conveyors and a 120-ft bucket elevator. Since one Euro Silo will be feeding the conversion process while the other is receiving from the truck tippers, the conveying system is capable of switching between silos for both the fill and discharge process (Figure 3-52).

(Photo to be inserted)

Figure 3-52.

Queuing and Even Flow

Bulk flowability is a key characteristic of the Pioneer Uniform design. The general risk imposed by biomass feedstocks is their lack of flowability characteristics. While the goal is to engineer material that is flowable in gravimetric systems, the Pioneer Uniform design uses an active flow system to queue feedstock for the conversion process. This system is a 530,000-ft^3 (3,000 wet ton/day) Eurosilo that is capable of actively filling and discharging the silo volume through a reversible screw-type sweep auger that rotates in a helical pattern up and down the interior of the silo (Figure 3-53). This system eliminates the risks associated with arching and rat holing, which occur in standard bins and hoppers with the

proposed feedstock. To meet the needed capacity and provide a reasonable queue time for the biorefinery, two Eurosilos are implemented in the Pioneer Uniform design (Figure 3-52).

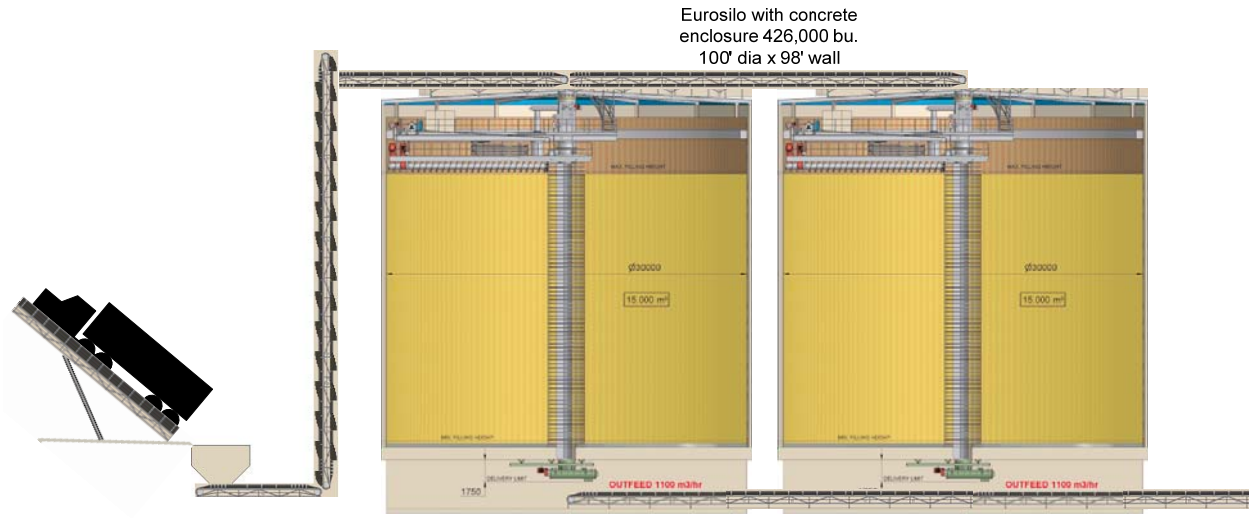

Figure 3-52. Receiving and cueing processes within the Pioneer Uniform design: bulk material being unloaded by tipper truck and being conveyed into the Eurosilo.

3.4.2.1 Equipment Capacity and Operational Efficiency

The Pioneer Uniform receiving and handling system must have a capacity of just under 2,300 DM ton/day. Key to the efficiency of this system is the cycle time of the transportation system and the capacity of the conveying system feeding two 530,000-ft^3 Eurosilos.

Receiving and weighing the feedstock as it arrives from the biomass depots is the first process within the plant gate. Both electronic and mechanical drive-over scales can be used to weigh incoming bulk feedstock. Mechanical scales are less expensive to purchase and maintain compared to electronic scales, but electronic scales can weigh trucks in 3 to 4 minutes compared to 10 minutes for mechanical scales (Badger, 2002). Given the need for low cycle times in large-scale processing plants, electronic scales are preferred despite their higher costs. Further, bar codes or radio frequency identification (RFID) tags can be used to automatically record truck weights and to automate payments for deliveries to improve the efficiency of the process.

Once the trucks are weighed, they move to the unloading area. The design of the truck unloading process is largely based on the required truck unloading time, which becomes increasingly more important as the size of the biorefinery increases. Self-unloading trucks, such as those with live-bottom trailers that have a belt or chain conveyor in the bottom of the trailer, require no additional equipment for unloading and are generally capable of unloading in 5 to 10 minutes. Walking-floor trailers are slower than live-bottom trailers and are capable of unloading in about 15 to 20 minutes, depending on the load Data from INL unpublished data). Standard semi-trailer vans require hydraulic truck dumpers. Trailer-only dumpers require detaching the trailer from the tractor to tilt the trailer on end for unloading, while whole-truck dumpers can tilt the entire tractor trailer unit. Trailer-only dumpers unload in 15 to 20 minutes, while whole-truck dumpers can unload in half the time (7 to 10 minutes) (Badger, 2002). The Pioneer Uniform design uses a drive-through, whole-truck tipper to take advantage of the use of standard, high-volume trailers and a 7 to 10-minute unload time.

The proper selection of conveying systems to provide adequate and reliable material transport is critical to the performance of receiving and handling operations. In fact, the conveying system should be

one of the most important considerations, because, unlike the rest of the supply system where many pieces of equipment provide ample redundancy if a single piece of equipment goes down, a failure in the plant conveying system could cause costly production delays. There are many methods used to convey bulk materials, generally combining mechanical, inertial, pneumatic, and gravity forces (Srivastava et al., 2006). Mechanical conveyors use belts, drag chains, or screws to move material while vibratory or oscillatory conveyors rely on inertial and frictional forces. Pneumatic conveyors use aerodynamic drag forces on an air-entrained solid to move material. The proper conveyor selection depends on the following considerations (Dreier, 1990):

- Material properties—Material property considerations include particle size, homogeneity, shape, moisture, and bulk flow properties.
- Capacity requirement—Capacity is important not only for conveyor sizing, but some conveyors can inherently handle higher capacities than others.
- Process configuration—Changes in elevation and conveyance distance are of primary importance.
- Processing efficiency—Some conveying methods are chosen for the ability to process the material while conveying. For example, screw conveyors are good if mixing is desired, while vibratory conveyors are good for sizing/sieving while conveying.

Table 3-33 describes the advantages and disadvantages of the different conveying equipment with regards to the conveying of woody bulk materials (Badger, 2002), but it is broadly applicable to bulk biomass materials in general.

Table 3-33. Advantages and disadvantage of wood fuel conveying systems (Badger, 2002).

Type	Cost	Advantage	Disadvantage
Belt conveyors	Highest capital cost/energy efficient	Any type of material	Limited to 20-degree incline, light dry particles, easily blown off
Screw conveyors	High capital cost/energy efficient	When site space is a premium, easily used on inclines	Not applicable for large pieces or stringy wood
Chain/drag conveyors	Medium capital cost/energy efficient	Rugged and adaptable to plant conditions	High maintenance, possible fire hazard, limited to 18 degree inclines
Bucket conveyors	Medium capital cost	Applicable for inclines and vertical transport	Not suitable for long horizontal runs
Oscillating conveyors	Low capital cost/energy efficient	Dense, bulky and stringy wood fuels, horizontal transport	Not applicable for small light fuels such as sawdust limited incline
Pneumatic conveyors	High operating (energy) cost	Small, lighter fuels, i.e., finely hogged dry waste, sawdust and sander dust, long distances	Not applicable for larger particles, fugitive dust problems

The selection of conveying equipment for the Pioneer Uniform design is based on the physical characteristics of the received bulk feedstock. Using the characteristics of the feedstock format described previously, the following considerations are presented in support of the conveying system design:

- The dry matter bulk density of the Pioneer Uniform system will likely be in the range of 20 to 30 lb/ft^3. To achieve this density the biomass must be compacted or densified in some fashion. While the durability of this compacted mass must be sufficient to withstand the forces associated with material handling, material handling systems that minimize damage must be chosen to reduce the durability requirement. Pneumatic and screw conveyors are both known to damage grain (Srivastava, 2006), and for this reason are not considered for primary conveying from the unloading pit hopper to short-term storage.
- Oscillating conveyors are considerably slower that other options, and because sizing is not required, they are not considered in the Pioneer Uniform design.
- As discussed in the following section, storage systems will likely consist of bins and hoppers. In this case, vertical transport is required. Because screw conveyors and pneumatic conveyors have been omitted due to their tendency to damage the conveyed biomass, a bucket elevator remains a viable option.
- Belt and drag chain conveyors remain the best options for horizontal conveying. Because the receiving and plant handling operations described in this design resemble the grain industry, this design is following the grain model with the use of drag chain conveyors.

Options for short-term storage (queuing) of bulk biomass feedstocks consist of open, uncovered piles; covered piles; and storage structures such as bins, hopper, or silos. Open, uncovered piles are the lowest cost, but they are prone to wind and moisture losses. Covered storage such as a shed, a covered bunker, or a fully enclosed building, will help mitigate these losses, but can add significant cost. While a partially covered pile may be adequate to protect the feedstock from precipitation and wind and meet regulatory requirements for wind-blown debris, the extra protection afforded by complete enclosure is warranted to protect against extreme weather conditions.

Because the Pioneer Uniform design does not assume the feedstock is fully flowable but that it is still prone to arching and rat holing, which are difficult to control in large capacity bins because of the high static pressures and the cohesive nature of the feedstock, a fully active storage system that uses augers rather than gravity to load and unload the bins must be used. Thus, the Pioneer Uniform design uses two Eurosilos to queue feedstock for the conversion process. These silos are capable of actively moving materials that are prone to flowability problems. These two silos function so that one silo is being filled while the other is being emptied into the conversion process. Each silo contains enough material for 25 hours of operation. The silos also act as metering bins and control the flow into the conversion process.

3.4.2.2 Dry Matter Losses

Dry matter losses include material that is not recovered from dust emissions and spillage, and cause economic, environmental, and air quality issues. Dust emissions and equipment leaks within the Pioneer Uniform design are controlled with a cyclone separator and baghouse that reintroduces captured material into the queuing system, as were used in the Conventional Bale design. Thus, no dry matter losses are modeled in the Pioneer Uniform design.

3.4.2.3 Operational Window

The receiving operation at the biorefinery will not operate on the same schedule as the conversion process. Instead, it will match the bulk transportation schedule (24 hours a day, 6 days a week) of the biomass depots. This schedule will allow receiving to provide bulk biomass to the queuing system at a rate that will maintain a minimum of 25-hour inventory for the conversion process. The queuing system, on the other hand, is an integral part of the conversion process and will match the biorefinery schedule.

The Eurosilo queuing bins will provide a steady flow of feedstock to the conversion process 24 hours a day, 7 days a week, for 350 days a year.

3.4.3 Pioneer Uniform Receiving and Handling Cost and Sensitivity Analysis

3.4.3.1 Static Model Cost Summary

A breakdown of the costs associated with each piece of equipment used in the Receiving and Handling unit operation identifies significant cost components that are valuable for making individual comparisons and identifying areas of research potential (Table 3-34). These costs are reported in terms of DM tons entering each process.

Table 3-34. Static model costs for major receiving and handling equipment in the Pioneer Uniform corn stover, switchgrass, and corn cob scenarios.

		Receiving		Dust Collection	Biochem Feed System	
	Equipment	Truck Scales	Phelps Full Truck Tipper/Hopper	Baghouse and Cyclone	Conveyors	Eurosilos
Corn Stover	Quantity of Equipment	1	1	1	1	3
	Installed Capital[a]	0.07	1.24	0.36	0.80	17.44
	Ownership Costs[b]	0.01	0.14	0.05	0.09	6.64
	Operating Costs[c]	0.19	0.38	0.13	0.23	1.88
	Labor	0.19	0.19	0.00	0.00	1.11
	Non-Labor	0.00	0.18	0.13	0.23	0.78
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	N/A	N/A	8.1	7.7	N/A
Switchgrass	Quantity of Equipment	1	1	1	1	1
	Installed Capital[a]	0.07	1.24	0.36	0.80	5.81
	Ownership Costs[b]	0.01	0.14	0.05	0.09	2.21
	Operating Costs[c]	0.19	0.38	0.13	0.23	1.37
	Labor	0.19	0.19	0.00	0.00	1.11
	Non-Labor	0.00	0.18	0.13	0.23	0.26
	Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
	Energy Use (Mbtu/DM ton)	N/A	N/A	8.1	7.7	N/A
Corn Cobs	Quantity of Equipment	1	2	1	1	2
	Installed Capital[a]	0.07	2.49	0.36	0.80	11.63

Equipment	Receiving		Dust Collection	Biochem Feed System	
	Truck Scales	Phelps Full Truck Tipper/Hopper	Baghouse and Cyclone	Conveyors	Eurosilos
Ownership Costs[b]	0.01	0.27	0.05	0.09	4.43
Operating Costs[c]	0.19	0.39	0.13	0.23	1.63
Labor	0.19	0.19	0.00	0.00	1.11
Non-Labor	0.00	0.19	0.13	0.23	0.52
Dry Matter Loss Costs	N/A	N/A	N/A	N/A	N/A
Energy Use (Mbtu/DM ton)	N/A	N/A	8.1	7.7	N/A

3.4.3.2 Cost Sensitivity Analysis

A histogram of the receiving and handling cost (Figure 3-54) for the round bale corn stover case shows that the cost of the unit operation ranges between $3.03 and $3.05 per DM ton with 90% confidence. Further, the mean and standard deviation of this range is $3.04 ± 0.01 per DM ton. The mode value of the receiving and handling cost is $3.04 per DM ton. This value equals the result of the static model, since the defined value of the parameter distributions was set equal to the static value in the model.

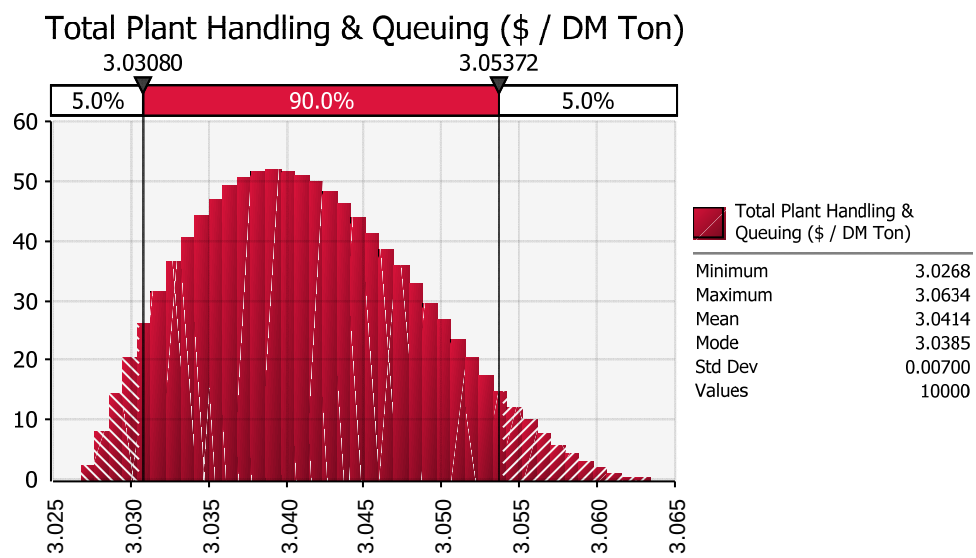

Figure 3-54. Pioneer Uniform receiving and handling cost distribution histogram from @Risk analysis for the round bale corn stover scenario.

A histogram of the receiving and handling cost (Figure 3-55) for the square bale corn stover case shows that with 90% confidence the cost of the unit operation ranges between $2.81 and $2.94 per DM ton,. The mode value of the receiving and handling cost is $2.93 per DM ton. This value closely represents the result of the static model, which is $2.94 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model. As the results are bi-modal,

reflecting the step function of costs when moving to a second expensive piece of equipment, the distribution is not normal and it is not meaningful to report a mea or standard deviation.

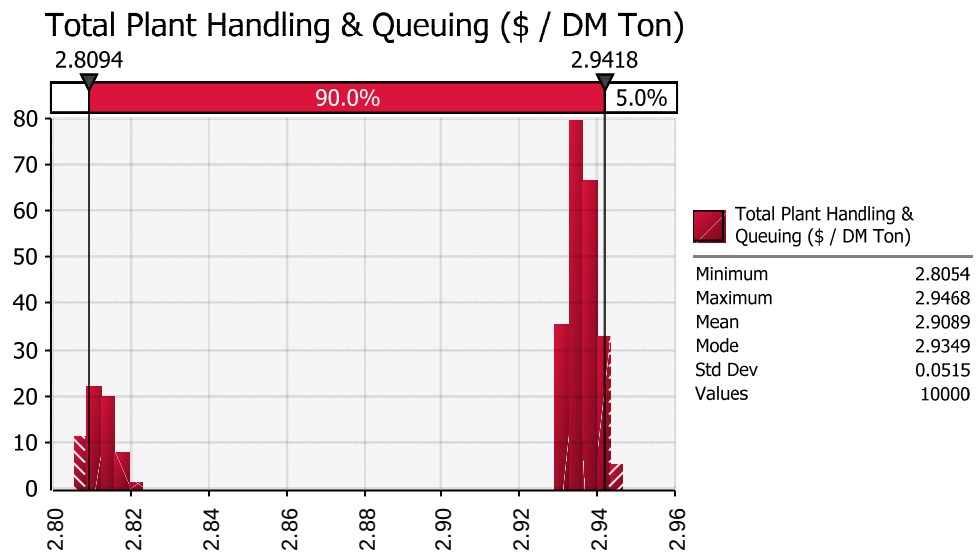

Figure 3-55. Pioneer Uniform receiving and handling cost distribution histogram from @Risk analysis for square bale corn stover.

Similarly, a histogram of the receiving and handling cost (Figure 3-56) for round bale switchgrass shows that the cost of the unit operation ranges between $1.97 and $1.99 per DM ton with 90% confidence, with the mean and standard deviation of this range being $1.98 ± 0.01 per DM ton. The mode value of this cost range is $1.98 per DM ton, which is the same as the result of the static model.

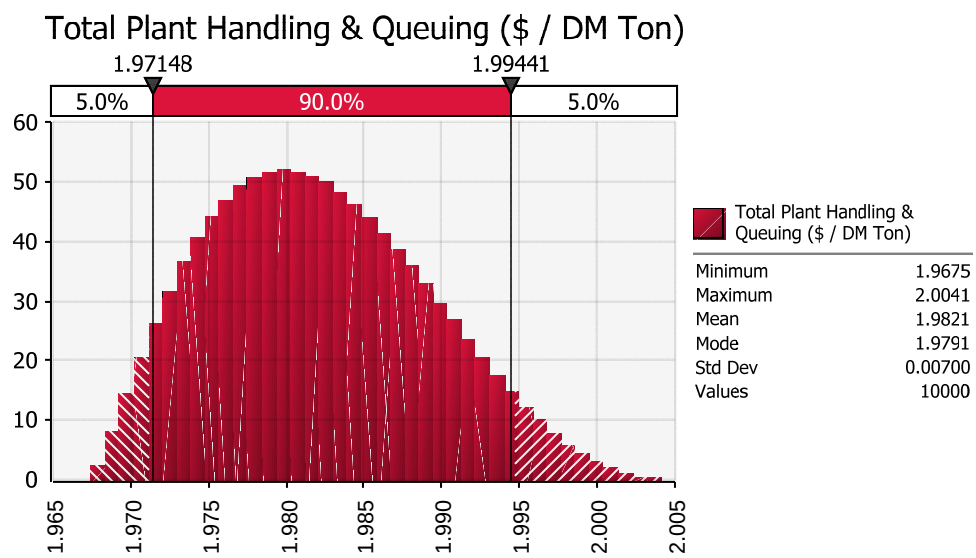

Figure 3-56. Pioneer Uniform receiving and handling cost distribution histogram from @Risk analysis for the round bale switchgrass scenario.

Looking at square bales, a histogram of the receiving and handling cost (Figure 3-57) for switchgrass shows that with 90% confidence the cost of the unit operation ranges between $2.81 and $2.94 per DM

ton. The mode value of this cost range is $2.81 per DM ton, which is equal to the result of the static model. As the results are bi-modal, reflecting the step function of costs when moving to a second expensive piece of equipment, the distribution is not normal and it is not meaningful to report a mean or standard deviation.

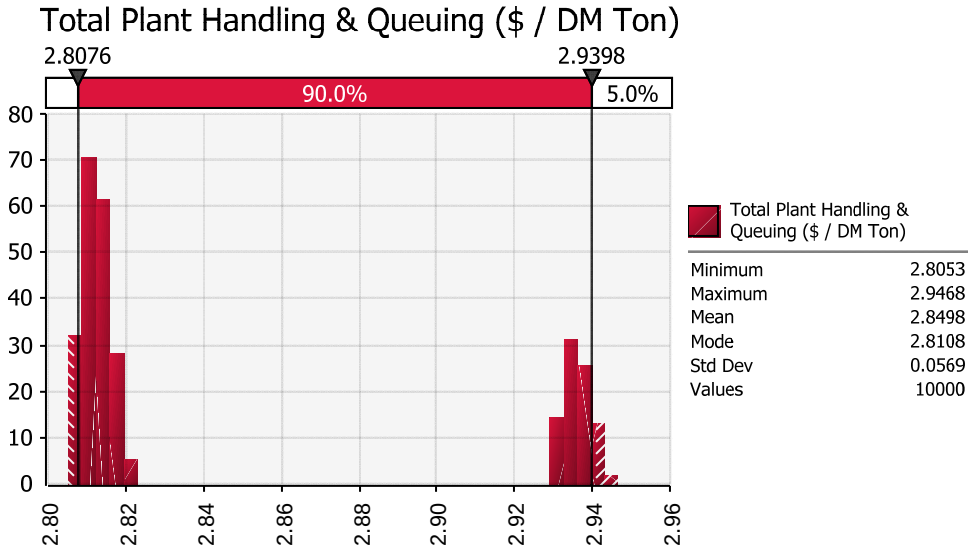

Figure 3-57. Pioneer Uniform receiving and handling cost distribution histogram from @Risk analysis for the square bale switchgrass scenario.

Finally, a histogram of the receiving and handling cost for corn cobs (Figure 3-58) shows that with 90% confidence the cost of the unit operation ranges between $2.51 and $2.67 per DM ton. The mode value of this cost range is $2.65 per DM ton, which closely represents the result of the static model of $2.66 per DM ton. As the results are bi-modal, reflecting the step function of costs when moving to a second expensive piece of equipment, the distribution is not normal and it is not meaningful to report a mean or standard deviation.

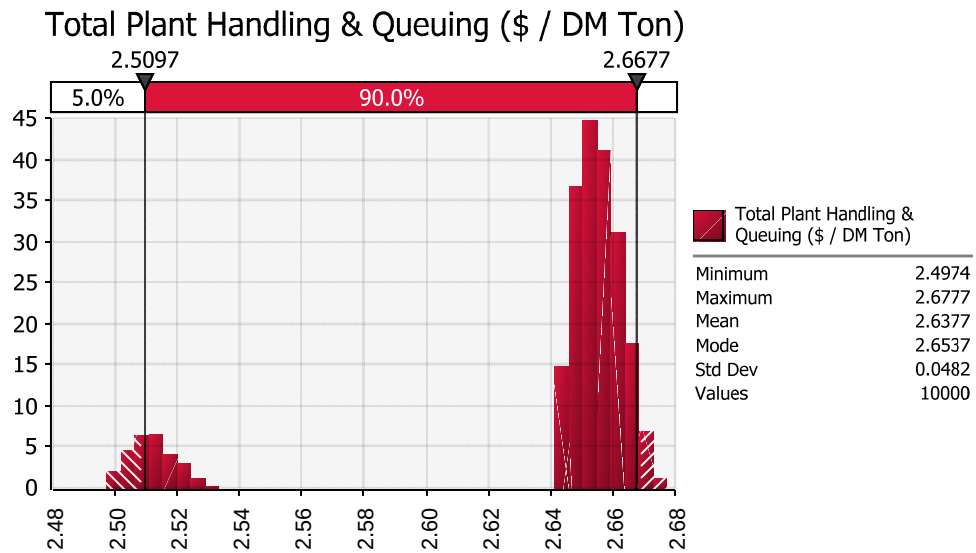

Figure 3-58. Pioneer Uniform receiving and handling cost distribution histogram from @Risk analysis for corn cobs.

The overall costs associated with the Pioneer Uniform receiving and handling unit operation for both corn stover and switchgrass are provided in Table 3-35 on a per-DM ton and per-bale basis. These costs, reported in terms of a mean and standard deviation, come as a result of 10,000 model iterations of the simulated Conventional Bale feedstock supply system.

Table 3-35. Receiving and handling cost summary for the Pioneer Uniform corn stover, switchgrass, and corn cob scenarios.

Equipment		Receiving			Dust Collection	Biochem Feed System	Total Receiving, Queuing, and Feed
		Truck Scales	Truck Tipper and unloading hoppers	Eurosilos		Surge Bin and Conveying Equipment	
Corn Stover	Modeled Cost Totals[a]	0.20 ± 0.00 $/DM ton	0.51 ± 0.00 $/DM ton	1.83 ± 0.00 $/DM ton	0.18 ± 0.004 $/DM ton	0.32 ± 0.003 $/DM ton	3.04 ± 0.01$/DM ton
		0.001 ± 0.00 $/unit	0.002 ± 0.00 $/unit		0.18 ± 0.004 $/unit	0.001 ± 0.00 $/unit	0.19 ± 0.004 $/unit
Switchgrass	Modeled Cost Totals[a]	0.20 ± 0.00 $/DM ton	0.51± 0.00 $/DM ton	0.77± 0.00 $/DM ton	0.18 ± 0.004 $/DM ton	0.32 ± 0.003 $/DM ton	1.98 ± 0.01 $/DM ton
		0.001 ± 0.00 $/unit	0.003 ± 0.00 $/unit		0.18 ± 0.004 $/unit	0.002 ± 0.00 $/unit	0.19 ± 0.004 $/unit
Corn Cobs	Modeled Cost Totals[a]	0.20 ± 0.00 $/DM ton	0.64 ± 0.05 $/DM ton	1.30 ± 0.00 $/DM ton	0.18 ± 0.003 $/DM ton	0.32 ± 0.003 $/DM ton	2.64 ± 0.05 $/DM ton

Equipment	Receiving			Dust Collection	Biochem Feed System	Total Receiving, Queuing, and Feed
	Truck Scales	Truck Tipper and unloading hoppers	Eurosilos		Surge Bin and Conveying Equipment	
	0.001 ± 0.00 $/unit	0.004 ± 0.00 $/unit		0.18 ± 0.003 $/unit	0.002 ± 0.00 $/unit	0.19 ± 0.004 $/unit

a. Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario.

3.5 Summary of Costs for the Pioneer Uniform Feedstock Supply System

The objectives of the sensitivity analysis are:

1. To evaluate the effects of variability and uncertainty on supply system economics
2. To identify the probability of meeting the DOE feedstock cost target with this supply system design
3. To identify key feedstock barriers for improvement and optimization of supply system economics.

3.5.1 Selection and Definition of Input Parameters

A single-point sensitivity analysis (a straightforward analysis to represent variations of a single variable) was conducted on the Pioneer Uniform design to identify and rank all input factors that affect the delivered feedstock cost (Table 3-36). This analysis is the first step of the sensitivity analysis for the purpose of input variable selection and preliminary variable assessment, and it is performed by uniformly varying each identified variable by ±10% of the base value. The results of this analysis provide a ranking of input parameters according to the magnitude of their influence on the delivered feedstock cost.

Based on the ranking of input variables, resulting from the single-point sensitivity analysis, we then defined each parameter's uncertainty using a probability distribution. The probability distribution represents either the inherent variability or the uncertainty of the input variables, as determined by the variability in collected field data, published data (e.g., field efficiency and field speed ranges published by ASABE (ASAE D497.5, 2006), or a range of operating parameters suggested by skilled operators of the equipment. The most likely value included in each distribution is the benchmark value input to the feedstock model.

Table 3-36. Input parameter distributions for sensitivity analysis.

Yield	Grain Yield (bu/acre)[b]	Pert	140	220	180
	Feedstock Yield[d]	Pert	3	8	5
Harvest Input	Harvest Window (wks/yr)	Static			=6*Harvest_Window
	Shredder Speed (mph)[c]	Pert	3	6	5
	Shredder Field Efficiency (%)[c]	Pert	0.75	0.85	0.8
	Harvest Collection Efficiency (%)[c]	Pert	0.667	0.75	0.71
	Harvest Collection Efficiency (%)[d]	Pert	0.75	0.9	0.77
	Harvest Collection	Pert	0.15	0.20	0.18

Yield	Grain Yield (bu/acre)[b]	Pert	140	220	180
	Efficiency (%)[c]				
	Mower/Conditioner[d]	Pert	5	12	7
	Mower/Conditioner Field Efficiency (%)[d]	Pert	0.75	0.9	0.8
Harvest Window	Harvest_Window	Pert	0.5	1.5	1
	FDI_CDI_Multiplier	Pert	0.5	2	1
Bailing Input	Baling Window (wks/yr)	Static			=6*Harvest_Window
	Baling Collection Efficiency (%)[c]	Pert	0.33	0.65	0.54
	Baling Collection Efficiency (%)[d]	Pert	0.8	0.95	0.86
	Baling Moisture (%)	Pert	0.1	0.2	0.12
	Round Baler (bales/hr)[c]	Pert	18	57	26
	Round Baler Field Efficiency (%)	Pert	0.55	0.75	0.65
	Bale Bulk Density (lb/ft^3)[c]	Pert	8	11	9
	Bale Bulk Density (lb/ft^3)[d]	Pert	9	12	10
Roadsiding Input	Roadsiding Window (wks/yr)	Static			=6*Harvest_Window
	Roadsiding Distance (miles)	Pert	0.25	1	0.5
	Stinger Load (sec/bale)	Pert	12	25	15
	Stinger Unload (sec/bale)	Pert	1	3	1.5
	Stinger Field Speed (mph)	Pert	10	25	15
	Stinger Road Speed (mph)	Pert	45	55	50
Storage Input	Storage Dry Matter Loss (%)	Pert	0.01	0.08	0.05
	Bale Wrapper (bales/hr)	Pert	60	120	80
Transport Input	Winding Factor	Pert	1.2	1.5	1.2
	Transporter Semi (mph)	Pert	40	55	50
	Transport Loader (round bale/hr)	Pert	22	42	40
	Transport Unloader (round bale/hr)	Pert	22	42	40
Receiving Input	Feeder Density (DM lb/ft^3)[c]	Static			=7.4*FDI_CDI_Multiplier
	Bin Density (DM lb/ft^3)[c]	Static			=9.1*FDI_CDI_Multiplier
	Feeder Density (DM lb/ft^3)[d]	Static			=10.3*FDI_CDI_Multiplier
	Bin Density (DM lb/ft^3)[d]	Static			=11.9*FDI_CDI_Multiplier
	Feeder Density (DM lb/ft^3)[e]	Static			=12*FDI_CDI_Multiplier
	Bin Density (DM lb/ft^3)[e]	Static			=17*FDI_CDI_Multiplier

a. Harvest Window, Baling Window, and Roadsiding Window are tied into the same distribution function.

b. ASABE, ASAE D497.5, 2006 - Table 3.

c. Corn stover only parameter

d. Switchgrass only parameter

3. Corn cob only parameter

3.5.2 Monte Carlo Analysis

A more sophisticated uncertainty analysis is conducted by allowing the input parameters to change over their respective probability distributions simultaneously, thus representing the combined impacts of the system uncertainty and the interdependence of input parameters. This analysis is conducted using @Risk, which interfaced directly with the Excel-based feedstock model. The simulation consisted of 10,000 iterations. For each iteration, all of the parameters were randomly varied according to the defined probability distributions presented above (Table 3-36), and the resulting total delivered feedstock cost as well as the incremental feedstock costs throughout each stage (five stages: harvest and collection, storage, transportation, receiving, and preprocessing) of the supply chain was recorded. Only the results of the total delivered feedstock cost are presented in this section of the report; the incremental cost analyses are presented in Appendix A-2.5, "Pioneer Uniform Sensitivity Analysis."

A histogram of the final cost for the round bale corn stover scenario, delivered to the throat of the conversion reactor at a biorefinery (Figure 3-59) for the Pioneer Uniform shows that with 90% confidence the cost ranges between $54.19 and $69.20 per DM ton. Further, the mean and standard deviation of this range is $61.27 ± 4.57 per DM ton. The mode value of the final cost is $60.61 per DM ton. This value closely represents the result of the static model, which is $57.01 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

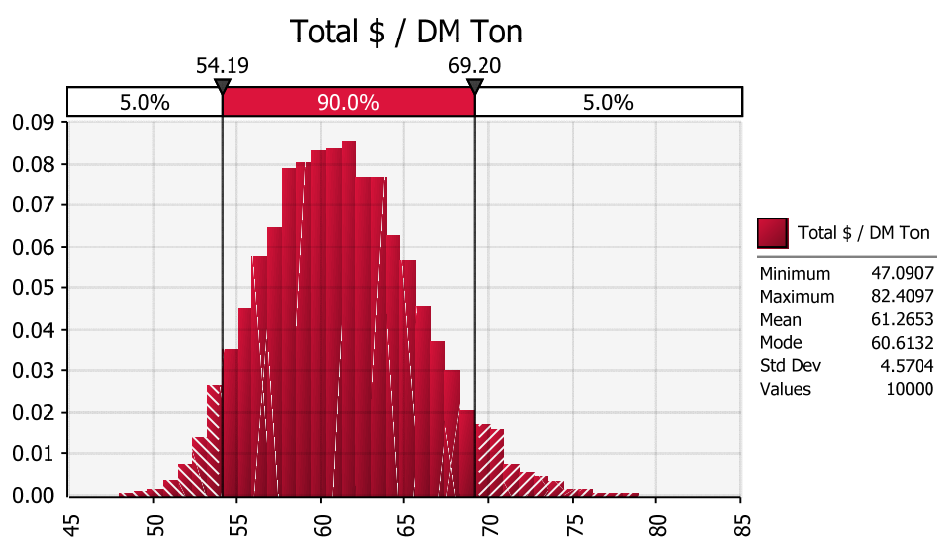

Figure 59. Total Pioneer Uniform supply system design cost distribution histogram from @Risk analysis for the round bale corn stover scenario.

Similarly, a histogram of the final delivered cost for the square bale corn stover scenario to the throat of the conversion reactor at a biorefinery (Figure 3-60) for the Pioneer Uniform shows that with 90% confidence the cost ranges between $52.18 and $64.19 per DM ton. Further, the mean and standard deviation of this range is $57.78 ± 3.72 per DM ton. The mode value of the final cost is $55.83 per DM ton. This value closely represents the result of the static model, which is $53.35 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

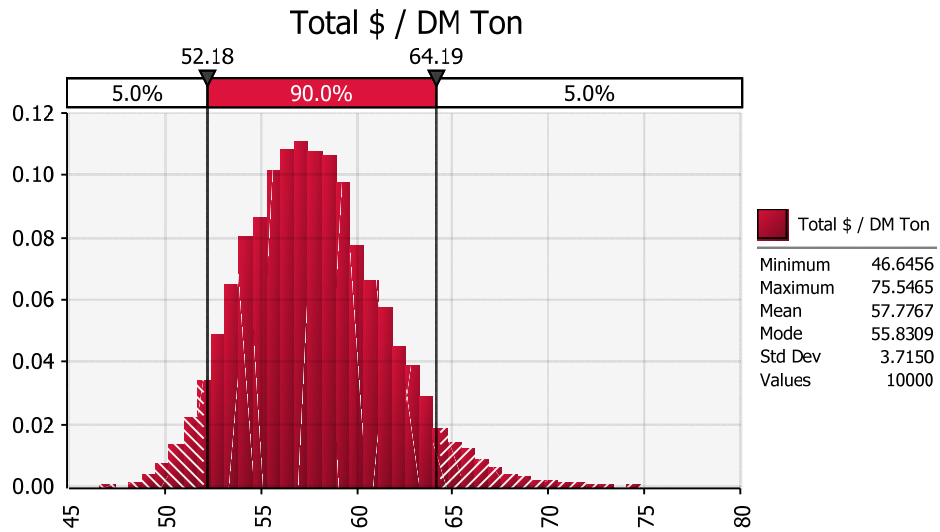

Figure 3-60. Total system cost summary for the Pioneer Uniform square bale corn stover scenario.

A histogram of the final cost for the round bale switchgrass scenario, delivered to the throat of the conversion reactor at a biorefinery (Figure 3-61) for the Pioneer Uniform shows that with 90% confidence the cost ranges between $49.74 and $65.88 per DM ton. Further, the mean and standard deviation of this range is $57.12 ± 4.92 per DM ton. The mode value of the final cost is $54.84 per DM ton. This value closely represents the result of the static model, which is $53.64 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

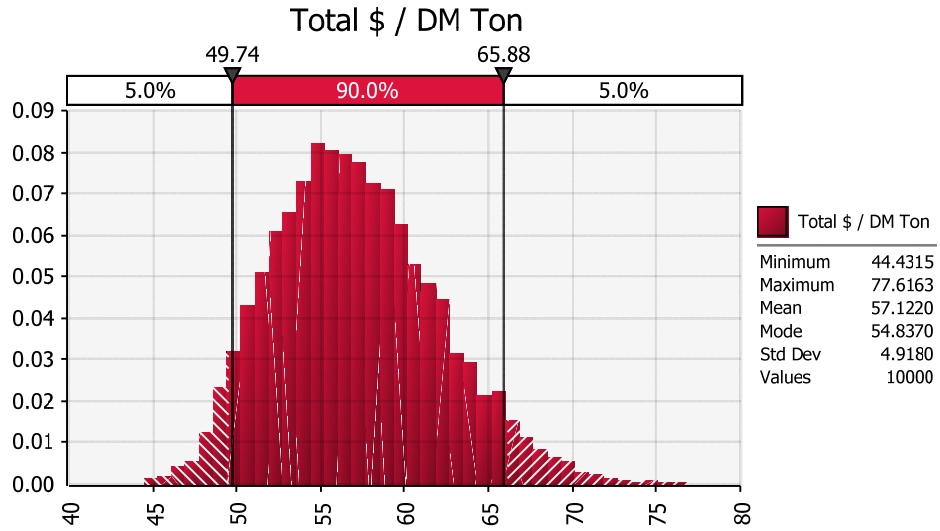

Figure 61. Total Pioneer Uniform supply system design cost distribution histogram from @Risk analysis for the round bale switchgrass scenario.

For the square bale switchgrass scenario, a histogram of the total cost of biomass delivered to the throat of the conversion reactor at a biorefinery (Figure 3-62) for the Pioneer Uniform shows that with 90% confidence the cost ranges between $46.05 and $58.51 per DM ton. Further, the mean and standard deviation of this range is $51.58 ± 3.79 per DM ton. The mode value of the final cost is $51.16 per DM

ton. This value closely represents the result of the static model, which is $46.45 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

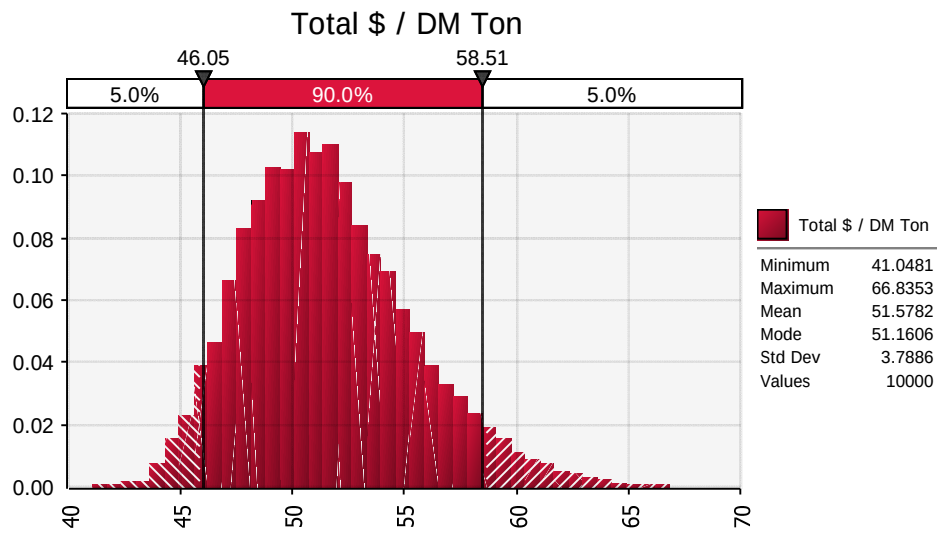

Figure 3-62. Total system cost summary for the Pioneer Uniform square bale switchgrass scenario.

Finally, for the corn cob scenario, a histogram of the total cost of biomass delivered to the throat of the conversion reactor at a biorefinery (Figure 3-63) for the Pioneer Uniform shows that with 90% confidence the cost ranges between $62.40 and $75.83 per DM ton. Further, the mean and standard deviation of this range is $68.91 ± 4.11 per DM ton. The mode value of the final cost is $68.50 per DM ton. This value closely represents the result of the static model, which is $66.93 per DM ton, since the defined value of the parameter distributions was set equal to the static value in the model.

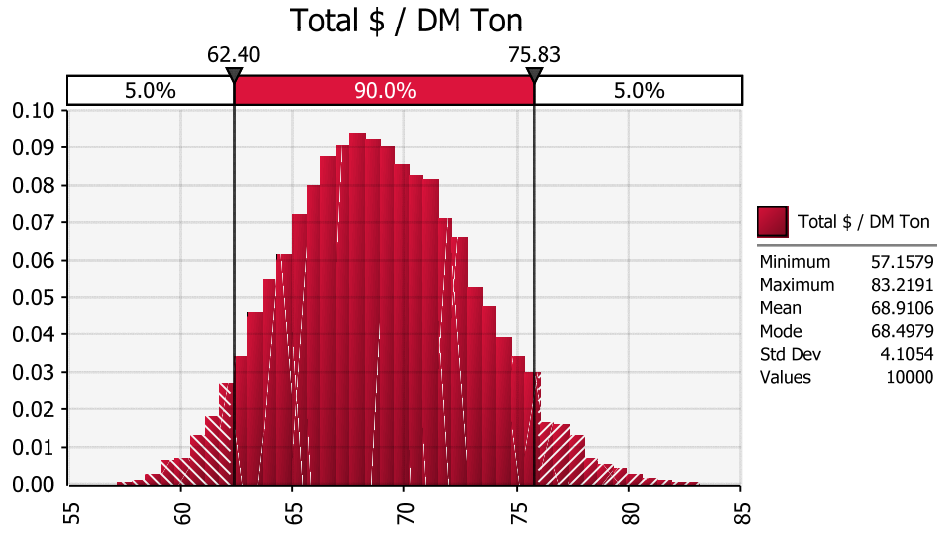

Figure 3-63. Total system cost summary for the Pioneer Uniform corn cob scenario.

The total costs (including all unit processes) are presented in Table 3-37. The square bale switchgrass scenario had the lowest cost per dry matter ton, and the corn cob scenario had the highest cost per dry matter ton.

Table 3-37. Summary of costs for the Pioneer Uniform feedstock supply systems, presented in $/DMton.

	Corn Stover	Switchgrass
Round Bale	61.27 ± 4.57 $/DM ton	57.12 ± 4.92 $/DM ton
Square Bale	57.78 ± 3.72 $/DM ton	51.58 ± 3.79 $/DM ton
Cob	68.91 ± 4.11 $/DM ton	N/A

3.5.3 Ranking of Input Parameters

The @Risk simulation also produced a ranking of input parameters based on the statistical relationship between each parameter and the delivered feedstock cost. The top fourteen parameters from this ranking were further analyzed to produce the correlations shown in Figure 3-64, which represents the response of feedstock cost changes to these top fourteen parameters. This analysis was conducted by incrementing each parameter throughout the defined distribution while randomly varying the remaining parameters according to their own defined probability distributions. Thus, the impact of each parameter is determined individually, while also capturing the interdependence of the input parameters.

This graph illustrates some interesting relationships (Figure 3-65). First, the slope of the response curve represents the statistical correlation (sensitivity) between the delivered feedstock cost and the input parameter. Second, the length (delta-X) of the response curve represents the magnitude of the variability or uncertainty (represented as the percentage change from the base value). Third, the delta-Y of the response curve represents the magnitude of the impact of the parameter on the delivered feedstock cost. Finally, the non-linearity of the response curve represents the interdependence of the input parameters, where more curvature of the response curve suggests broader interdependence.

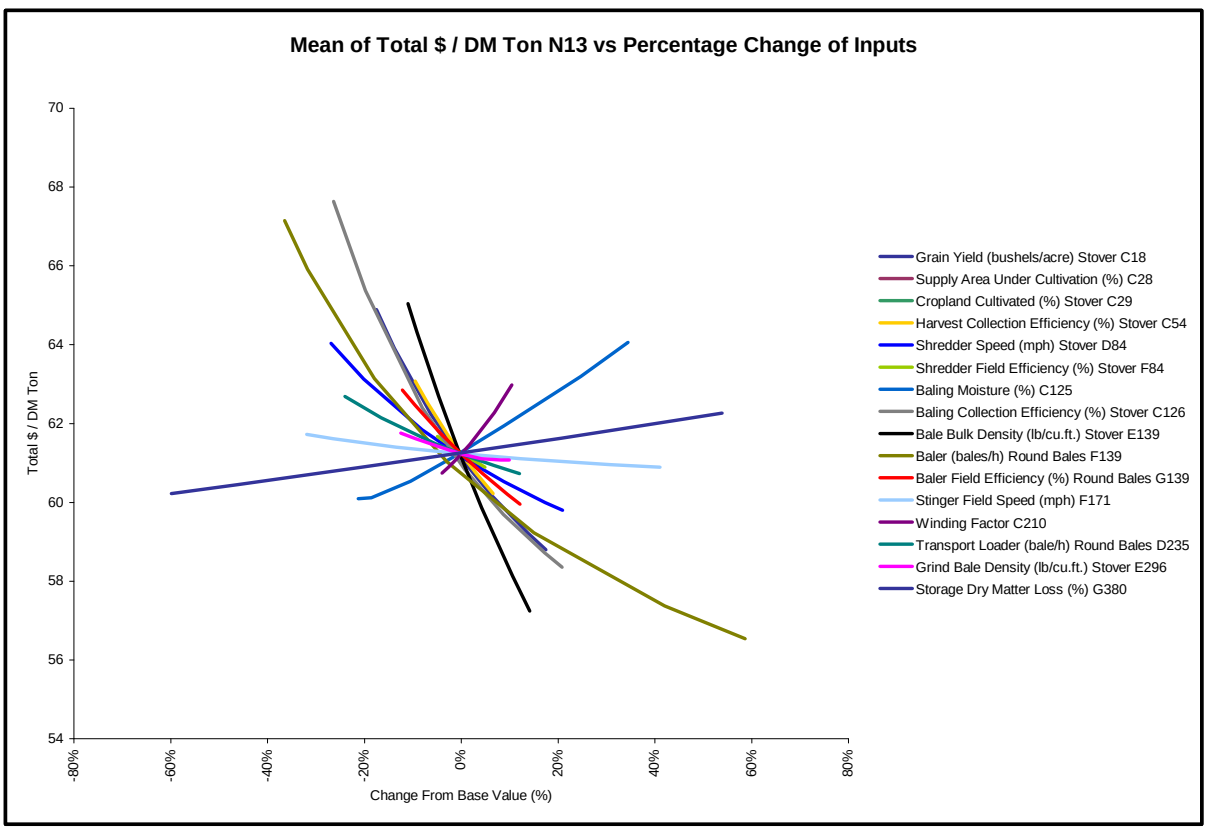

Figure 3-64. Percent change of variable to output.

To resolve the sensitivity rankings of these parameters, this graph was further analyzed to isolate the individual influences. Approximating the slope using a linear regression of each response curve, followed by normalization with respect to the highest slope (bale bulk density), provides a good relative sensitivity comparison (Figure 3-65). Similarly, normalizing the delta-Y with respect to the highest ranking parameter (baling efficiency) provides a clear comparison of the overall potential impact of each variable on the delivered feedstock cost (Figure 3-66).

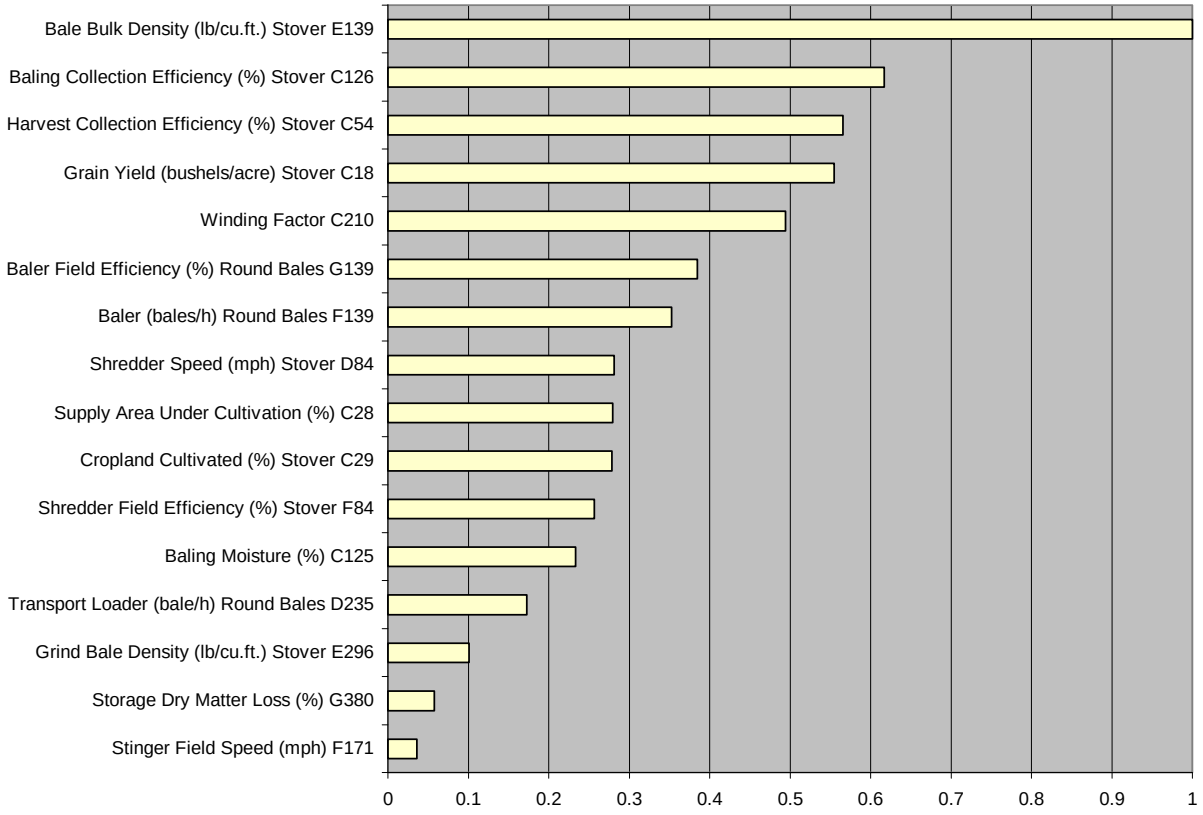

Figure 3-65. Relative sensitivity of individual supply system parameters.

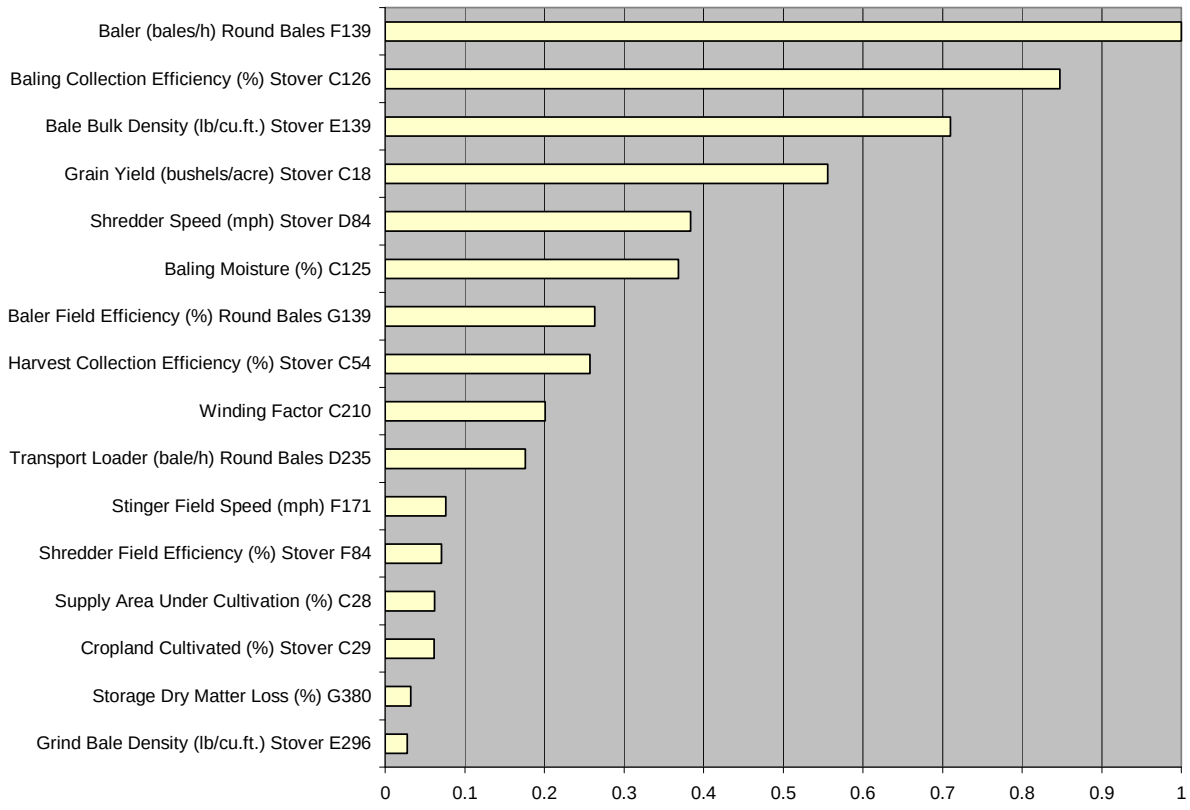

Figure 3-66. Relative cost impact of individual supply system parameters.

Comparing the rankings of these two figures shows that although the feedstock cost may be highly sensitive to changes in a specific variable (i.e., steep slope), the uncertainty or variability of that variable may be small (i.e., short line), and the corresponding impact on cost is likewise small (i.e., delta-Y); thus, the two rankings are not consistent. For example, harvest efficiency is ranked as the third highest parameter in terms of its potential influence on feedstock cost (Figure 3-65), but it ranks much lower (8th in Figure 3-66) in actual impact.

This reveals a dual-role of sensitivity analysis, and requires an important distinction in the objective of the analysis. If the objective is to optimize the Pioneer Uniform design, the rankings in Figure 3-65 would be most relevant. Design optimization is the driving force behind the Pioneer Uniform and the Advanced Uniform designs, so this will be discussed in detail in each section of this report. The objective of the sensitivity analysis of the Pioneer Uniform design is to quantify the uncertainty in the design, and thus the rankings shown in Figure 3-66 are most relevant. As such, the final ranking of input parameter for the Pioneer Uniform, expressed in a tornado chart that represents the uncertainty or variability in delivered feedstock cost, is shown in Figure 3-67. The tornado chart shows that baler field losses, bale bulk density, and bale moisture are the top three parameters in order of decreasing uncertainty.

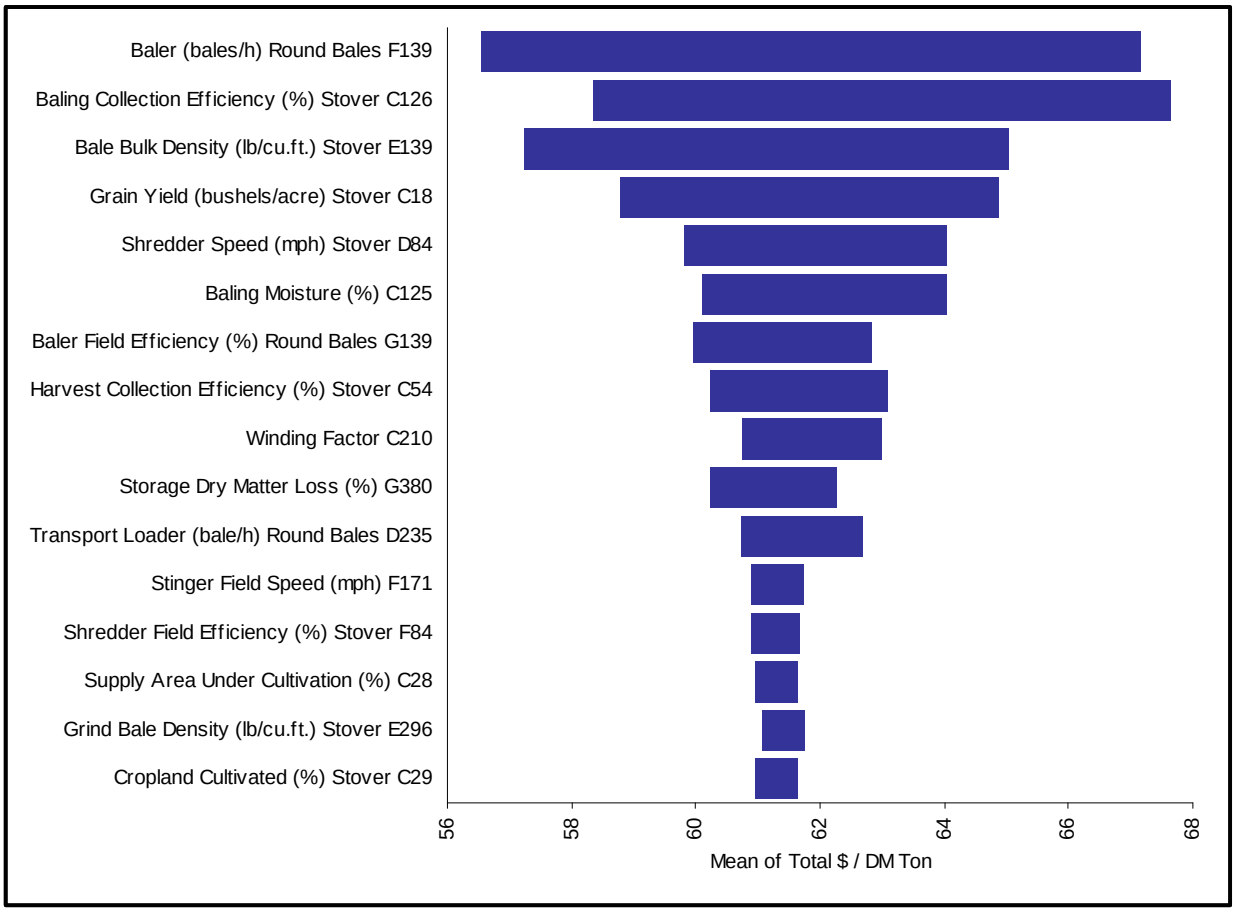

Figure 3-67. Tornado chart reflecting the final cost in dollars according to the distribution ranges defined.

Finally, additional analyses were conducted to examine the cause-and-effect relationship of the parameters shown in the tornado chart since this relationship is not necessarily intuitive. This was accomplished by evaluating and comparing the sensitivity of each unit process (harvest and collection, storage, transportation, and receiving and preprocessing) to each of the highest-ranking feedstock parameters (Figure 3-68).

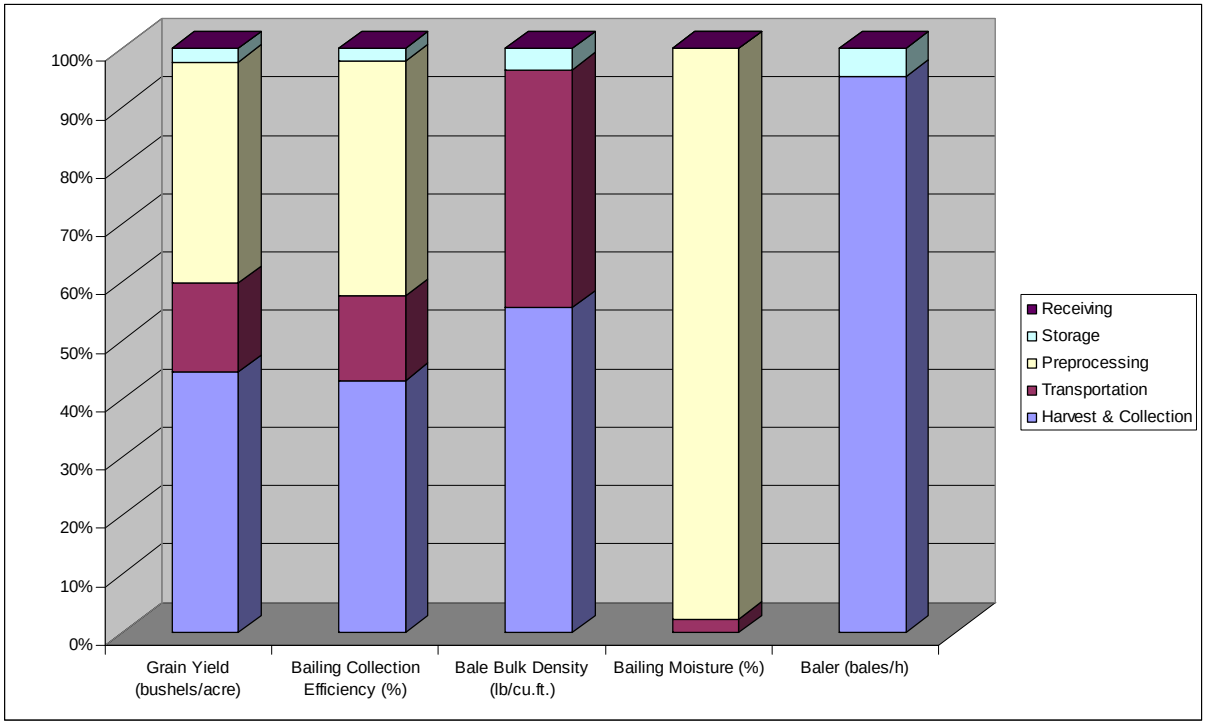

Figure 3-68. Variable impact on supply chain processes.