Advances in Bioscience and Biotechnology, 2024, 15, 112-128
https://www.scirp.org/journal/abb
ISSN Online: 2156-8502
ISSN Print: 2156-8456

Harvesting Technologies and Costs for Switchgrass Production

Hana Toth, Jude Liu

Department of Agricultural and Biological Engineering, The Pennsylvania State University, University Park, USA
Email: jxl79@psu.edu

How to cite this paper: Toth, H. and Liu, J. (2024) Harvesting Technologies and Costs for Switchgrass Production. *Advances in Bioscience and Biotechnology*, **15**, 112-128.
https://doi.org/10.4236/abb.2024.152008

Received: November 17, 2023
Accepted: February 5, 2024
Published: February 8, 2024

Abstract

As today's society searches for renewable energy sources that could be an alternative to fossil fuels, biomass and biofuels provide a promising solution. Switchgrass is one of feedstocks that can be utilized as a renewable energy source. When farming, one of the most important considerations is efficiency. This consists of several factors, including time, fuel use, economic and power efficiencies of equipment. Inefficient field operations could increase harvesting costs and in turn could cause hesitation when a farmer decides to participate in biomass production. This literature review will cover the main elements of biomass and biomass handling relating to determining harvesting efficiency and biomass quality for switchgrass round bales. Specifically, the following sections include past research activities relating to biomass harvesting, biomass bale quality during outdoor storage, logistics models, and data collection methods during biomass harvesting. The objective of this review is to examine status and needs for switchgrass round bale harvesting operations and the expenses that come with it.

Keywords

Biomass, Baling, Energy Crop, Logistics

1. Introduction

While today's society searches for renewable energy as an alternative to fossil fuels, biofuels offer a promising alternative. Biofuels developed from non-food biomass or a dedicated energy crop, are potential alternatives or compliments to the current utilization of biodiesel and corn ethanol usually seen in the renewable energy field. A dedicated energy crop's sole purpose is to be converted into various forms of energy. This lessens the burden of determining if a crop, such as corn or soybeans, should be used for feed or energy. Promoting the application of biofuels can help reduce greenhouse gas (GHG) emissions, develop fuel security for transportation and improve a local economy [1]. The production of warm-season grasses provides the opportunity to utilize marginal lands, where may not be suitable to produce high yield food or forage crops but can produce a high yield for dedicated energy crops. As the world population continues to grow, there will be less land to grow crops for food and energy. This opportunity to utilize marginal lands may reduce the amount of land that will be developed from agricultural to residential or commercial land in the future.

Switchgrass is a dedicated energy crop and a warm-season perennial grass that can be grown in marginal lands. It can grow 1 - 3 m tall contingent upon its environment and genetic traits and has the potential to develop an extensive root system that can reach a depth of 3 m [2]. In addition to being planted in marginal lands, switchgrass may be planted and harvested annually with minimal upkeep. This makes it inexpensive and an ideal crop for energy production. A farmer may plant switchgrass on formerly unusable or marginal land for extra income [3]. According to studies by Hancock [4], Wolf and Fiske [5] as cited by Mitchell [6], found that the benefit of growing switchgrass as biomass is that many farms in the United States have an extensive past of harvesting and storing hay for farm animals. Therefore, the transition to biomass harvesting can be relatively simple. Due to widespread research and farming practices performed on switchgrass, guidelines that outline the most beneficial management practices have been developed for regions within the United States. These guidelines are available online in state university extension and USDA webpages [7] [8] [9] [10].

After harvesting, switchgrass may be used in combustion processes to generate steam, heat, or electricity [2]. Focusing on switchgrass electricity, the most important parameter besides switchgrass energy yield is electricity generating efficiency for bioelectricity. Since there is a wide range of crop yields, there are three scenarios that vary by crop yield, low, medium, and high yield. It was observed that generation efficiency is 30% for all crop yield types, but energy yield (as electricity) ranges from 43 - 86 GJ/ha from low to high energy yield respectively [11].

Forage harvesting methods such as baling, and chopping are currently used to harvest switchgrass. Large rectangle and round balers are the primary types of equipment used in switchgrass harvesting [12]. Chopping can be utilized in regions where the weather may require the need for wet storage methods or chopping. Since switchgrass is harvested through traditional forage methods, it is likely if a farmer already has equipment for a certain type of harvesting method, they will utilize that method.

When farming, one of the most important considerations is field efficiency. This consists of several factors, including time, fuel use, economic and power efficiencies of equipment. Inefficient field operations would increase harvesting costs that could cause hesitation when a farmer decides to participate in biomass production. This literature review will discuss the main elements of biomass and biomass handling related to determining harvesting efficiency and biomass quality for switchgrass round bales. Specifically, the following sections include past research activities relating to biomass harvesting, biomass bale quality during outdoor storage, logistics models, and data collection methods during biomass harvesting. The objective of this review is to examine status and needs for switchgrass round bale harvesting operations and the expenses that come with it.

2. Switchgrass Harvesting Equipment

When a field crop is grown, it needs to be removed and transferred into a form that is easy to store and transport. Harvesting is defined as the sequence of operations that are completed to remove a crop from the field and into storage. This step accounts for more than half of the biomass procurement costs [13]. These steps for harvesting biomass may include mowing and conditioning, baling, bale collection, in-field transportation, and bale storage.

2.1. Mowing and Conditioning Switchgrass

The first step to removing switchgrass from the field is the mowing operation. Mowing removes most of the above-ground segment of the plant. Two of the most common mowers used are the sickle-bar mower and disc mower or discbines. **Figure 1** shows a disc mower blade. A sickle-bar mower works with reciprocating triangular mower blades that are in the middle of stationary blades. Each movement back and forth will shear any plant stem that is in the middle of these stationary blades [14]. Discbines have several small discs that are mounted on top of a cutter bar and these discs rotate at high speeds. Similar to the sickle-bar the cutter bar of the discbines travel parallel to the ground, this bar is what controls the cutting height [14].

Farming practices have demonstrated that the most efficient way to harvest switchgrass is with a self-propelled swather equipped with disc header. These kinds of mowers will lay the cut switchgrass into windrows where it may dry in the field. The mowing height of the switchgrass is around 10 to 15 cm above the ground surface. Switchgrass is cut at this height because it allows the windrows to be raised above the soil surface to assist with drying. The biomass in these windrows needs to be dried to a moisture content less than 20% d.b. [12].

As mentioned previously, the moisture content of the switchgrass should be less than 20% d.b. [12]. The importance of conditioning done during mowing is to accelerate drying. When switchgrass is conditioned, the plant stem is crushed without altering its structure. Conditioning systems fall into either impeller/tine-type or roll-type conditioners [15]. Roll type conditioners consist of two rolls that force the crop between them to break the stems. Flail Type conditioners use metal flails to hit the crop after it is mowed to break the stems. As the crop is fed through the flails it is also rubbed against the conditioning hood which wears away at the stem's surface allowing moisture to escape more easily [15].

Figure 1. Disc mower blade.

Switchgrass drying rate can be improved through a combination of intensive conditioning and wide swath drying. This method of roll conditioning crushes and scuffs the stems which disturbs the plants' cutin layer and flattens the stem nodes. This provides a better way for water vapor to leave the stem and dry faster. Although, wide swath drying decreases field drying time, it requires an additional field operation to rake wide swaths into windrows that can be picked up with commercially available balers [16].

Switchgrass is normally harvested and baled with commercially available forage equipment, but a few significant items should be considered. From previous field harvesting studies, it was found that self-propelled swathers with a mower and conditioner head are utilized because they are not only efficient, but they can handle different volumes of switchgrass to be harvested [3] [6] [17].

2.2. Baling Switchgrass

Once the crop is mowed, conditioned, and windrowed, it is ready for the final step in harvesting, baling and collection. Switchgrass can either be baled or chopped. Large square and round balers are the primary types of balers used in switchgrass harvesting [12]. **Figure 2** shows a picture of a large square and round baler. Small square bales are not produced since there is a lack of market for them and biorefineries have trouble handling these bales [6]. A baler consists of a pickup head to pick up the crop and is fed into a compression chamber. The crop is then compressed and tied or net-wrapped to form a bale that can easily be transported. After bales are made, they are collected and transported to a storage location or biorefinery. Harvesting methods that differ to baling may be used in regions where the weather may require the need for wet storage methods.

Round balers typically have lower capital costs than large square balers, but their field capacity tends to be lower because the baler and tractor combination needs to stop moving to wrap and release the bale. Some agricultural machinery companies have released non-stop or continuous round balers that eliminate the need to stop when ejecting a round bale. Additionally, these bales are wrapped with plastic wrap to protect them from precipitation post-harvesting. Some farm

Figure 2. Large Square Baler (left), Round Baler (right).

machinery manufacturers developed new equipment continuous round balers, which could wrap and drop the round bale without stopping. Other companies developed large square balers, which could bale constantly without interruption and are estimated to have a lower cost per unit of harvested area [6]. One downside to utilization of balers is the inability to completely collect all biomass that has been mowed, resulting in losses.

2.3. Chopping Switchgrass

Harvesting methods different from baling may be used in areas where climate conditions and existing harvesting systems allow for substitute harvesting scenarios. Wet storage methods have been applied to areas where drying conditions for baling operations are not feasible due to high relative humidity and increased precipitation after harvest. Like baling, a swather harvester is used to mow the switchgrass. After mowing, the switchgrass is chopped utilizing a self-propelled forage harvester. Using a forage chopper to remove biomass crops from a field is currently a fairly uncommon practice; however, sometimes it is still performed in situations where compressed pellets are the end product. Crop can both be chopped while still standing or it can be picked up and chopped after being mowed.

This harvester has a rotary head that blows the material into an adjacent trailer [6] [18] [19]. This harvesting system is a one-pass system, compared to bailing which requires many steps or operations to get the switchgrass off the field [18] [20] [21].

A disadvantage associated with chopping is if it is chopped at a moisture content that is too low, excessive heating and mold growth can run the risk of self-combustion [18] [19]. A forage harvester is not designed to harvest dry matter meaning that dust has the potential to cause environmental and mass loss issues and the possibility to cause machine fires as observed by [22]. Another disadvantage is the higher equipment and storage structure costs compared to a conventional baling system [6] [23].

2.4. Switchgrass Collection and Storage

After baling is completed, the bales can be collected or left in the field. Dependent on a producer's storage availability and capacity, bales can be collected and stacked in-field. These bales either remain at the edge of the field or are transported elsewhere for storage [6]. During bale loading from field to storage, it takes double the time to load round bales on semi-trailers than large square bales [6] [24]. If the switchgrass is large square baled, they are stacked in-field and transported off-field to an indoor storage facility or under-roof storage. This is because, when precipitation occurs, the flat surface of the bale does not shed water and as a result dry matter losses can be substantial [6] [23]. After round bales are baled, they can be left in-field for storage or under-roof storage, like square bales. Round bales may be left in-field because of their sloped surface, water penetration is less likely, especially if they are net wrapped [6] [24].

2.5. Switchgrass Harvesting Seasons

Switchgrass can be either harvested in the spring or fall, depending on what time a producer chooses to harvest is dependent upon field conditions, equipment availability, and end-use energy generation [6] [25]. Although it has been found that yield decreases by 20% - 40% if the crop spends the winter in the field, the content of ash and water concentrations reduced. Thus, increasing the energy content of switchgrass for all conversion systems [6] [12] [25].

When harvest is delayed, the lowered concentration of choice minerals reduces the potential for fusible ash which can result in slagging and fouling or deposits in the boilers used for direct combustion [12] [25]. In this case, switchgrass intended to be used for direct combustion should be harvested in the spring rather than the fall. If the end-use is to be used for ethanol fermentation or gasification systems, a fall harvested crop may be better suited because of their lignocellulose yield [9] [25].

Improved methods for optimizing switchgrass harvest, storage, and transportation are required to better the financial and net energy economics of switchgrass production. These optimal methods will vary with the type of bioenergy conversion that is to be utilized and aim to reduce the quantity of switchgrass that is left in the field during harvesting.

3. Biomass Quality and Outdoor Storage of Round Bales

When under roof storage facilities are not available or limited, round bales may be stored in-field because of their ability to shed water. As these bales are stored outside, directly on soil, losses of dry matter (DM) can range from 3% to 40% and these losses are directly related to storage time [26]. In the past, many studies [27]-[37] have studied different bale wrap methods (twine or net wrap) with different storage conditions (in-field or under-roof). These studies have concluded that factors like the storage method, storage time, type of forage, and climate can affect both DM recovery and nutritional value. From these studies, it has been recommended and mentioned that an effective way to improve DM recovery is to physically separate the bottom of the bale from the soil or grass sod to facilitate air flow [26] [38] [39] [40] [41] and to utilize a plastic net to wrap the bale to sustain a more uniform surface during in-field storage [29] [40] [41].

For switchgrass, nutritional value is not as an important factor; since it will not be used as animal feed, DM losses are more important. Bales that are left in-field are traditionally stored on soil with no separation between the ground surface and the bottom of the bale [42]. During outdoor storage during the winter, DM losses occur through leaching and microbial activity from being stored directly on the ground [26] [42]. These losses could be extensive in the northern U.S. during the winter season. An in-field bale storage study in central Wisconsin determined that when they are in outdoor storage for nearly a year; by raising bales on a pallet, to separate the bale from the ground, it has been found that breaking the contact between the soil surface and the bale has improved the recovery of DM by 3.1% for hay [42], making this an effective management option.

A study on switchgrass by [43] conducted in Oklahoma, has found that tarped round bales that were stored on pallets and gravel showed the least amount of DM losses and changes to the bales' composition. This finding suggests that tarping may be an alternative to barn storage. More farmers may opt to use a tarping method during in-field storages to reduce losses during storage since it proves to be just as effective as under-roof storage.

A study by [44] developed a dynamic cost model for three storage methods; indoor, outdoor tarped and outdoor open with two biomass bale types, large square bale and round to estimate the storage costs for switchgrass. The study concluded that the outdoor-tarped large square bales option was the least costly (\$16/dry Mg) and that indoor storage of round bales was costly due to establishment and use costs. This cost could be potentially reduced if it is used more than once a year. The cost for tarping round bales during in-field storage would add to the overall cost of biomass production and this model estimates this added cost to be \$16.11/dry Mg when in storage for 10 months.

A study done by [45], studied three different round bale stacking configurations for hay, single, pyramid, and mushroom. From these methods, it was determined which method had the lowest DM loss when stored outside during the winter months in Montana. These stacking methods can be seen below in **Figure 3**.

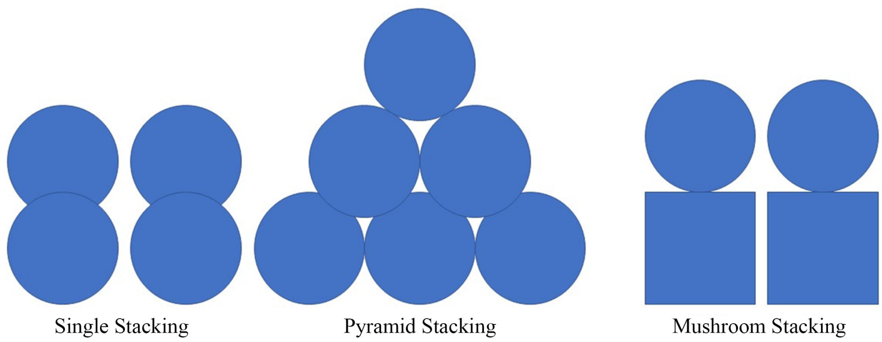

Figure 3. Different round bale stacking methods adapted from [45].

Recently, the mushroom stacking formation has become a popular hay storage technique practiced in the mid-western U.S. [45]. Although it was concluded that single stacking has the most consistent forage quality and DM for Montana conditions, switchgrass bales are traditionally stored through pyramid stacking. It would be valuable to perform the same stacking method at the same location for switchgrass round bales with different ground separation techniques to determine which ground separation has the least amount of DM loss.

4. Biomass Production Logistics Models

Models are important in many industries because they provide a way to predict future events, costs, or a framework of the best way to complete a task. Biomass logistics models attempt to encompass every operation, from seeding the plant to the time it reaches the biorefinery. For a successful model, detailed information must be recorded about every step of the process in between. The foundation of these models is based on the soil type, seeding rate, establishment time, equipment required and equipment costs, labor cost, and weather data. The information collected helps develop the initial parameters for cost and maintenance to establish the stand.

The second element of the model involves the harvesting of the biomass. This consists of machinery required, costs to operate the machinery, plant composition (moisture content, yield), harvest date, time spent harvesting and other associated operational costs after harvesting, the storage and transportation of biomass post-harvesting needs to be considered. Again, considering the fuel costs, bale densities, travel distance, storage information, and labor cost. Finally, the last part of the model entails the production of biofuel. These costs include, the materials required for production, machine operation cost, labor cost, production time, transportation cost, and the cost of storage. This detailed information used for the model is primarily collected from field testing.

4.1. MILP Models

Recently, the mixed-integer linear programming (MILP) models are being developed and, in some cases, used in conjunction with the Greenhouse gasses, Regulated Emissions, and Energy use in Technologies (GREET) model created by the Argonne National Laboratory, to estimate greenhouse gas emissions based on these model outputs [1] [46]. When these models were developed, field tests were completed, and specific data was recorded so that predictions can be made about how changing specific conditions will alter the outcome of the models. Recent developments in biomass logistics models incorporate the sporadic availability of biomass throughout areas of interest, uncertainties of supply, GIS, emissions from logistics operations, and traffic congestion caused by biomass transportation. Current models focus mainly on economic objectives rather than emissions from logistics activities [47].

The incorporation of the GREET model with a logistics model [1] has been utilized to calculate the greenhouse gas emissions for the logistics model outputs. This model when used with the GREET model presents an output that determines the energy consumption, costs, and emissions. The logistics model is made up of two sub-models: the harvesting operations and the post-harvesting transportation model. The model can be used for switchgrass and loblolly pine production. This model examines four forms of biomass harvesting methods: whole tree woodchip, clean woodchip, round bale and square bale [1]. Not only does the model produce the biomass collection radius, number of machines required, cost and energy consumption from the inputs, but it also presents the emissions of the entire operation from biomass production to biorefinery.

This model does not consider an agricultural field size or shape, and this may alter the outcome of the model. The model does consider tractors and implements used, bale accumulators, and typical bale sizes for large square (0.9 × 1.2 × 2.4 m) and round bales (1.7 × 2 m). The fuel consumption was estimated by equations from two previous publications: [48] [49]. Turhollow [1] used ASABE Standards EP496.3 [50] [51] when Nebraska Tractor Test Laboratory data was not available.

4.2. IBSAL Model

The integrated biomass supply analysis and logistics model (IBSAL) model is a well-developed model that considers the collection, storage, and transportation of biomass (Sokhansanj *et al.*, 2006). The IBSAL emphasizes weather and the affects it can have on harvest and supply to the biorefinery. It also can predict the date that specific operations will be accomplished. This is based on the equipment available and utilization of weather data.

4.3. Economic Evaluation of Switchgrass Harvesting Systems

Some publications use a cost evaluation uses the standards ASAE EP496.3 and ASAE D497.7 [50] [51] and the equations within them to determine how much the harvesting cost is in $/dry Mg. These costs are determined from the equipment use, equipment travel, fuel consumption, labor costs for harvesting operations. These publications usually utilize data from field observations and the material and field capacities from field tests [52].

4.4. Biomass Model Inputs and Comparisons

Models like the MILP/GRREET [1] and the IBSAL [53] have inputs needed for the model and are listed below in **Table 1**.

Different harvesting costs for large square and round bale harvesting system for switchgrass are summarized in **Table 2**. These prices were determined by using a logistics model or an economic evaluation. A cost evaluation uses the ASAE standards [50] [51] and equations in there to determine how much the harvesting cost is in $/dry Mg. The publications that used a logistics model to determine the prices were: [1] [52] [54]-[60].

Table 1. Switchgrass harvesting cost model inputs.

Input	Source
Bulk Density	[1]
Dry Matter Loss	[1]
Final Bale Form (Large Square/Round)	[1]
Machine Capacity and Efficiency	[1] [53]
Machine Purchase Price	[1] [53]
Moisture Content	[1] [53]
Number of Machines Required	[53]
Size of Field	[1] [53]
Transportation Distances and Mode	[1] [53]
Weather Data	[53]
Yield	[1] [53]

Table 2. Comparison of switchgrass harvesting costs from different publications for large square and round baling systems.

Baling System	Cost ($/dry Mg)	Harvest Season	Location	Source
Large Square	4.10	Fall	USA	[1]
	12.25	Fall	VA	[59]
	10.41	Spring	PA	[62]
	15.73	Fall/Spring	OK	[54]
	19.34	Spring	Italy	[52]
	23.72	Fall	USA	[57]
	32.72	Fall	Midwestern US	[60]
Average Cost	**16.90**	-	-	-
Round	3.90	Fall	USA	[1]
	8.72	Spring	PA	[62]
	13.10	Spring	Italy	[52]
	15.90	Fall	VA	[59]
	31.03	Fall	Midwestern US	[60]
Average Cost	**14.53**	-	-	-

There is a large variation in harvesting cost ranging from $4/dry Mg to $32/dry Mg for both large square and round bales. Possible reasoning for this would be because different cost evaluations used or excluded different inputs or factors. One model considers weather conditions and the number of machines [52], whereas one does not consider either and the number of machines required is an output of the model [1].

Although there have been many cost evaluations of switchgrass baling harvesting systems, these evaluations fail to consider field shapes when creating a logistics model. Recently, there has been empirical proof that planting perennial grasses like switchgrass on marginal parts of fields can provide sustainability benefits, but can be difficult and costly to harvest [61]. By optimizing or altering field designs that incorporate annual crops (e.g., corn, soybeans, small grains) and switchgrass, has the opportunity to improve a producer's willingness to participate in switchgrass production [61]. Another possibility to incorporating existing agricultural field shapes into cost and or logistics models is the opportunity for producers to utilize these models as a decision-making tool. For example, those who own these marginal lands may calculate if they should sell the land to be developed or continue to be in agricultural production. Although this may be tedious, the benefit of a user-friendly, decision-making tool could help producers determine the most optimal harvesting scenario dependent on the availability of equipment, field size and shape.

4.5. Field Harvesting Data Collection Methods

To collect all the necessary information to run a logistics model for switchgrass harvesting, a variety of different data collection methods have been used by researchers. Many aspects of data recording can be done manually using stopwatch and video recording devices. New technologies utilizing Global Positioning Systems (GPS), Controller Area Network Bus (CAN Bus), unmanned aerial vehicles (UAVs or drones), data loggers and other technologies are available to aid in the data collection. Manually collected field harvesting data often is used to verify that the information is collected properly.

During field harvesting data collection, it is important to determine the path of the equipment to and from a field, its path through a field, and where the bales are being dropped during the harvesting operations. By attaching a GPS receiver to the farming equipment (on-board GPS) that is moving through the field, different aspects of the field can be captured. For example, time spent turning, stopping, or idling may be mapped along with bale drop coordinates. The information provided by the GPS data will help to verify field size, bale locations, travel speed, and distance traveled [5]. Additional verification may be done by hand using hand-held GPS devices or other surveying tools to plot various ground control points (GCPs) at field boundaries or bale drop locations.

In addition to on-board GPS receivers, drones and associated mapping software have become more popular for utilization in mapping and surveying in environmental and agricultural applications. One agricultural application of drones is determining a removal system for biomass bales from a stationary position [63]. As the baler moves throughout the field, it drops them in a non-uniform pattern, making the task of bale collection tedious and labor-intensive. The utilization of drones during bale collection presents an opportunity to determine bale location within a field, distances between bales and the best strategy for collecting the bales to reduce collection time.

In a recent study by [63], researchers developed an UAV-based image system to scan an entire field through utilizing drone photogrammetry, which was later used to determine bale locations in a field. Drone images were processed to explore the best approach for bale collection. That study concluded that the higher flight velocity does not suggest there is higher inaccuracy, since the software used automatically adjusts velocity in accordance with weather conditions. Similarly, a higher flight height improved field coverage capacity [63]. If flight velocity and height do not significantly affect the precision of bale locating, then one could take field pictures at a faster velocity and higher flight elevation, making this action alone quicker to do leaving more time to determine bale location.

The disadvantage of just using a drone for data collection is the following data will not be collected: bale weights, moisture content, and fuel usage. A combination of utilizing a drone and in-field data collection methods may exclude some manual data verification methods like using a tape measure to measure distances between bales. Instead, one may use a drone and a handheld GPS. Most commercial handheld GPS's have a horizontal accuracy up to 3 m if the unit receives a wide area augmentation system (WAAS) signal, if not the accuracy is 10 m [64].

5. Conclusions

Biomass and biofuels play an important role in the renewable energy movement as fossil fuel supplies continue to lessen and use increases. There needs to be a well-developed foundation for alternative energy sources before the fossil fuel reserves run out completely. Switchgrass production is a possible solution to the renewable energy movement. However, the most efficient way to harvest switchgrass and storage in-field in the northeastern U.S. has not been clearly determined. Even though most farmers with commercial haying equipment tend to use equipment they have already purchased, it may not be the most efficient harvesting method. The benefit of a user-friendly, decision-making tool has the potential to aid producers in determining the most optimal harvesting scenario dependent on the availability of equipment, field size and shape.

After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command and use the naming convention prescribed by your journal for the name of your paper. In this newly created file, highlight all the contents and import your prepared text file. You are now ready to style your paper.

Acknowledgements

This work is supported by USDA National Institute of Food and Agriculture Federal Appropriations under Project PEN04872 and Accession #7005726. This research was supported by Agriculture and Food Research Initiative Competitive Grant No. 2020-68012-31881 from the USDA NIFA.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Lu, X., Withers, M.R., Seifkar, N., Field, R.P., Barrett, S.R.H. and Herzog, H.J. (2015) Biomass Logistics Analysis for Large Scale Biofuel Production: Case Study of Loblolly Pine and Switchgrass. *Bioresource Technology*, **183**, 1-9. https://doi.org/10.1016/j.biortech.2015.02.032

[2] Vogel, K.P. (2004) Switchgrass. In: Moser, L.E., Burson, B.L. and Sollenberger, L.E., Eds., *Warm-Season (C4) Grasses*, ASA-CSSA-SSSA, Madison 2. https://acsess.onlinelibrary.wiley.com/doi/book/10.2134/agronmonogr45

[3] Redcay, S., Koirala, A. and Liu, J. (2018) Effects of Roll and Flail Conditioning Systems on Mowing and Baling of *Miscanthus* × *giganteus* Feedstock. *Biosystems Engineering*, **172**, 134-143. https://doi.org/10.1016/j.biosystemseng.2018.06.009

[4] Hancock, D.W. (2017) The Management of Switchgrass in Georgia. Georgia Cooperative Extension Bulletin, No. 1358.

[5] Wolf, D.D. and Fiske, D.A. (1995) Planting and Managing Switchgrass for Forage Wildlife, and Conservation. Virginia Cooperative Extension Pub. No. 418-013, Blacksburg.

[6] Mitchell, R., Schmer, M. and Monti, A. (2012) Switchgrass: A Valuable Biomass Crop for Energy. Green Energy and Technology, Vol. 94, Springer, Berlin, 113-127. https://doi.org/10.1007/978-1-4471-2903-5

[7] Douglas, J., Lemunyon, J., Wynia, R. and Salon, P. (2009) Planting and Managing Switchgrass as a Biomass Energy Crop. USDA-NRCS: Plant Materials Program, Technical Note No. 3. https://forages.ca.uky.edu/files/opennonwebcontent1.pdf

[8] Jacobson, M. (2013) NEWBio Energy Crop Profile: Switchgrass. Penn State Extension. https://extension.psu.edu/newbio-energy-crop-profile-switchgrass

[9] Pennington, D. (Michigan S.U.E.) (2015) When to Harvest Switchgrass. https://www.canr.msu.edu/news/when_to_harvest_switchgrass

[10] Renz, M., Undersander, D. and Casler, M. (2009) Establishing and Managing Switchgrass. In UW Extension Factsheet. https://fyi.extension.wisc.edu/forage/establishing-and-managing-switchgrass/

[11] Sands, R.D., Malcolm, S.A., Suttles, S.A. and Marshall, E. (2017) Dedicated Energy Crops and Competition for Agricultural Land. USDA Economic Research Service, Economic Research Report No. (ERR-223) 72. https://www.ers.usda.gov/publications/pub-details/?pubid=81902

[12] Vogel, K.P., Sarath, G., Saathoff, A.J. and Mitchell, R.B. (2010) Switchgrass. In: Halford, N.G. and Karp, A., Eds., *Energy Crops*, The Royal Society of Chemistry, London, 341-380. https://doi.org/10.1039/9781849732048-00341

[13] Lin, T., Mathanker, S.K., Rodriguez, L.F., Shastri, Y.N., Hansen, A.C. and Ting, K. (2013) Impact of Harvesting Technologies on Biomass Feedstock Logistics. *American Society of Agricultural and Biological Engineers Annual International Meeting* 2013, Kansas City, 21-24 July 2013, 1-6. https://doi.org/10.13031/aim.20131592212

[14] Goodwin, P. (2015) Buyer's Guide to Hay Equipment. Tractor Tools Direct. https://www.extension.iastate.edu/smallfarms/buyers-guide-hay-equipment

[15] Redcay, S. and Liu, J. (2023) The Effect of Mechanical Conditioning on Physical Conditions of Miscanthus Plants. *American Journal of Plant Sciences*, **14**, 77-88.

[16] Shinners, K.J. and Friede, J.C. (2017) Enhancing Switchgrass Drying Rate. *Bioenergy Research*, **10**, 603-612. https://doi.org/10.1007/s12155-017-9828-5

[17] U.S. Department of Energy (2011) U.S. Billion-Ton Update: Biomass Supply for a

Bioenergy and Bioproducts Industry. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, 227 p.

[18] Adkins, A.B. (2014) Switchgrass Harvest Timing & Harvest/Storage Method Influence Quantity, Quality & Sustainability Aspects of a Lignocellulosic Ethanol Production System in the Northern Corn Belt/Great Lakes Region. Michigan State University, East Lansing.

[19] Schroeder, J.W. (2013) Haylage and Other Fermented Forages. Quality Forage AS1252, 1-8.

[20] Chen, Y., Sharma-Shivappa, R.R. and Chen, C. (2007) Ensiling Agricultural Residues for Bioethanol Production. *Applied Biochemistry and Biotechnology*, **143**, 80-92. https://doi.org/10.1007/s12010-007-0030-7

[21] Digman, M.F., Shinners, K.J., Muck, R.E. and Dien, B.S. (2010) Full-Scale On-Farm Pretreatment of Perennial Grasses with Dilute Acid for Fuel Ethanol Production. *Bioenergy Research*, **3**, 335-341. https://doi.org/10.1007/s12155-010-9092-4

[22] Brownell, D., Liu, J., Hilton, J.W., Richard, T.L., Cauffman, G.R. and Macafee, B.R. (2012) Evaluation of Two Forage Harvesting Systems for Herbaceous Biomass Harvesting. *ASABE Annual International Meeting* 2009, **55**, 1651-1658.

[23] Collins, M. and Owens, V.N. (2003) Preservation of Forage as Hay and Silage. In: Barnes, R.F., Nelson, C.J., Collins, M. and Moore, K.J., Eds., *Forages*: *An Introduction to Grassland Agriculture*, 6th Edition, Iowa State University Press, Ames, 443-471.

[24] Hess, J., Kenney, K., Ovard, L., Searcy, E. and Wright, C. (2010) Uniform-Format Bioenergy Feedstock Supply System: A Commodity-Scale Design to Produce and Infrastructure-Compatible Bulk Solid from Lignocellulosic Biomass (Issue September).

[25] Adler, P.R., Sanderson, M.A., Boateng, A.A., Weimer, P.J. and Jung, H.J.G. (2006) Biomass Yield and Biofuel Quality of Switchgrass Harvested in Fall or Spring. *Agronomy Journal*, **98**, 1518-1525. https://doi.org/10.2134/agronj2005.0351

[26] Rotz, C.A. and Muck, R.E. (1994) Changes in Forage Quality during Harvest and Storage. In: Fahey Jr., G.C., Ed., *Forage Quality*, *Evaluation*, *and Utilization*, American Society of Agronomy Inc., Madison, 828-868. https://doi.org/10.2134/1994.foragequality.c20

[27] Anderson, P.M., Kjelgaard, W.L., Hoffman, L.D., Wislon, L.L. and Harpster, H.W. (1981) Harvesting Practices and Round Bale Losses. *Transactions of the ASAE*, **24**, 841-842. https://doi.org/10.13031/2013.34349

[28] Collins, M., Paulson, W.H., Finner, M.F., Jorgensen, N.A. and Keuler, C.R. (1986) Moisture and Storage Effects on Dry Matter and Quality Losses of Alfalfa in Round Bales. *Paper—American Society of Agricultural Engineers*, **30**, 913-917. https://doi.org/10.13031/2013.30498

[29] Collins, M., Swetnam, L.D., Turner, G.M., Hancock, J.N. and Shearer, S.A. (1995) Storage Method Effects on Dry Matter and Quality Losses of Tall Fescue Round Bales. *Journal of Production Agriculture*, **8**, 507-514. https://doi.org/10.2134/jpa1995.0507

[30] Harrigan, T.M. and Rotz, C.A. (1994) Net, Plastic, and Twine-Wrapped Large Round Bale Storage Loss. *Applied Engineering in Agriculture*, **10**, 189-194. https://doi.org/10.13031/2013.25840

[31] Huhnke, R.L. (1988) Large Round Bale Alfalfa Hay Storage. *Applied Engineering in Agriculture*, **4**, 316-318.

[32] Huhnke, R.L. (1990) Round Bale Bermudagrass Hay Storage Losses. *Applied Engi-*

neering in Agriculture, **6**, 569-574. https://doi.org/10.13031/2013.26430

[33] Huhnke, R.L. (1993) Round Bale Orientation Effects on Alfalfa Hay Storage. *Applied Engineering in Agriculture*, **9**, 349-351.

[34] Russell, J.R., Yoder, S.J. and Marley, S.J. (1990) The Effects of Bale Density, Type of Binding and Storage Surface on the Chemical Composition, Nutrient Recovery and Digestibility of Large Round Hay Bales. *Animal Feed Science and Technology*, **29**, 131-145. https://doi.org/10.1016/0377-8401(90)90099-T

[35] Shinners, K.J., Huenink, B.M., Muck, R.E. and Albrecht, K.A. (2009) Storage Characteristics of Large Round Alfalfa Bales: Dry Hay. *Transactions of the ASABE*, **52**, 409-418.

[36] Taylor, R.K., Blasi, D.A. and Shroyer, J.P. (1994) Storage Losses in Net-Wrapped, Large Round Bales of alfalfa. *Applied Engineering in Agriculture*, **10**, 317-320. https://doi.org/10.4148/2378-5977.2099

[37] Turner, J.E., Poore, M.H. and Benson, G.A. (2007) Dry Matter Recovery, Nutritive Value, and Economics of Cool-Season Grass Hay Stored for Seven or Fifteen Months in the Southern Appalachian Mountains. *The Professional Animal Scientist*, **23**, 686-695. https://doi.org/10.15232/S1080-7446(15)31041-X

[38] Ball, D.M., Bade, D.H., Lacefield, G.D., Martin, N.P. and Pinkerton, B.W. (1998) Minimizing Losses in Hay Storage and Feeding. National Forage Information Circular 98-1.

[39] Coblentz, W.K., Jennings, J.A., Davis, G.V., Hellwig, D.H. and Cassida, K.A. (2002) Management of Hay Production. Arkansas Cooperative Extension Service, #MP434.

[40] Collins, M. (1995) Hay Preservation Effects on Yield and Quality. In: Moore, K.J. and Peterson, M.A., Eds., *Post-Harvest Physiology and Preservation of Forages*, American Society of Agronomy Inc., Madison, Vol. 22, 67-89. https://doi.org/10.2135/cssaspecpub22.c4

[41] Pogue, D.E., Ivy, R.L., Evans, R.R. and Bagley, C.P. (1996) The Dollars and Sense of Hay Production. 1-24.

[42] Coblentz, W.K. (2009) Effects of Wrapping Method and Soil Contact on Hay Stored in Large Round Bales in Central Wisonsin. *ASABE*, **25**, 835-850.

[43] Khanchi, A., Jones, C.L., Sharma, B. and Huhnke, R.L. (2013) Characteristics and Compositional Change in Round and Square Switchgrass Bales Stored in South Central Oklahoma. *Biomass and Bioenergy*, **58**, 117-127. https://doi.org/10.1016/j.biombioe.2013.10.017

[44] Sahoo, K. and Mani, S. (2017) Techno-Economic Assessment of Biomass Bales Storage Systems for a Large-Scale Biorefinery. *Biofuels*, *Bioproducts and Biorefining*, **11**, 417-429. https://doi.org/10.1002/bbb.1751

[45] Staudenmeyer, D.M. (Montana S.U.-B.) (2017) Utilizing Gene Suppression Technology and Hay Storage Techniques to Improve Forage Quality and Animal Performance. https://scholarworks.montana.edu/xmlui/handle/1/13516

[46] Argonne National Labortory (2018) The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model. Argonne National Laboratory, Lemont. https://greet.es.anl.gov/

[47] Malladi, K.T. and Sowlati, T. (2018) Biomass Logistics: A Review of Important Features, Optimization Modeling and the New Trends. *Renewable and Sustainable Energy Reviews*, **94**, 587-599. https://doi.org/10.1016/j.rser.2018.06.052

[48] Akay, A.E. (1998) Estimating Machine Rates and Production for Selected Forest Harvesting Machines Operating in the Western United States and Determining the

Most Economical Machine Combinations under Representative Conditions in Turkey. Oregon State University, Corvallis.

[49] Turhollow, A.F., Wilkerson, E. and Sokhansanj, S. (2009) Cost Methodology for Biomass Feedstocks: Herbaceous Crops and Agricultural Residues (Issue December).

[50] ASABE (2005) ASAE EP496.3 FEB2006 (R2020) Agricultural Machinery Management.

[51] ASABE (2011) ASAE D497.7 MAR2011 Agricultural Machinery Management Data. Test, 2011, 9.

[52] Martelli, R., Bentini, M. and Monti, A. (2015) Harvest Storage and Handling of Round and Square Bales of Giant Reed and Switchgrass: An Economic and Technical Evaluation. *Biomass and Bioenergy*, **83**, 551-558. https://doi.org/10.1016/j.biombioe.2015.11.008

[53] Sokhansanj, S., Kumar, A. and Turhollow, A.F. (2006) Development and Implementation of Integrated Biomass Supply Analysis and Logistics Model (IBSAL). *Biomass and Bioenergy*, **30**, 838-847. https://doi.org/10.1016/j.biombioe.2006.04.004

[54] Griffith, A.P., Haque, M. and Epplin, F.M. (2014) Cost to Produce and Deliver Cellulosic Feedstock to a Biorefinery: Switchgrass and Forage Sorghum. *Applied Energy*, **127**, 44-54. https://doi.org/10.1016/j.apenergy.2014.03.068

[55] Grisso, R.D., Webb, E.G., Cundiff, J.S. and Sokhansanj, S. (2013) Parametric Study of Machinery Management Relationships on Forage Equipment. *American Society of Agricultural and Biological Engineers Annual International Meeting* 2013, *ASABE* 2013, Vol. 1, 26-37. https://doi.org/10.13031/aim.20131539003

[56] Langholtz, M., Stokes, B. and Eaton, L. (2016) 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy (Executive Summary). *Industrial Biotechnology*, **12**, 282-289. https://doi.org/10.1089/ind.2016.29051.doe

[57] Sokhansanj, S., Mani, S., Turhollow, A.F., Bransby, D., Lynd, L. and Laser, M. (2009) Large-Scale Production, Harvest and Logistics of Switchgrass (*Panicum virgatum* L.)—Current Technology and Envisioning a Mature Technology. *Biofuels, Bioproducts and Biorefining*, **6**, 124-141. https://doi.org/10.1002/bbb

[58] Wang, Y., Wang, J., Schuler, J., Hartley, D., Volk, T. and Eisenbies, M. (2020) Optimization of Harvest and Logistics for Multiple Lignocellulosic Biomass Feedstocks in the Northeastern United States. *Energy*, **197**, Article ID: 117260. https://doi.org/10.1016/j.energy.2020.117260

[59] Cundiff, J.S. and Marsh, L.S. (1996) Harvest and Storage Costs for Bales of Switchgrass in the Southeastern United States. *Bioresource Technology*, **56**, 95-101. https://doi.org/10.1016/0960-8524(95)00166-2

[60] Kaliyan, N., Morey, R.V. and Tiffany, D.G. (2015) Economic and Environmental Analysis for Corn Stover and Switchgrass Supply Logistics. *Bioenergy Research*, **8**, 1433-1448. https://doi.org/10.1007/s12155-015-9609-y

[61] Griffel, L.M., Vazhnik, V., Hartley, D.S., Hansen, J.K. and Roni, M. (2020) Agricultural Field Shape Descriptors as Predictors of Field Efficiency for Perennial Grass Harvesting: An Empirical Proof. *Computers and Electronics in Agriculture*, **168**, Article ID: 105088. https://doi.org/10.1016/j.compag.2019.105088

[62] Brownell, D.K. and Liu, J. (2011) Field Test and Cost Analysis of Four Harvesting Options for Herbaceous Biomass Handling. *International Journal of Agricultural and Biological Engineering*, **4**, 58-68. https://doi.org/10.3965/j.issn.1934-6344.2011.03.0-0

[63] Seyyedhasani, H., Digman, M. and Luck, B.D. (2021) Utility of a Commercial Unmanned Aerial Vehicle for In-Field Localization of Biomass Bales. *Computers and Electronics in Agriculture*, **180**, Article ID: 105898. https://doi.org/10.1016/j.compag.2020.105898

[64] USGS (2017) USGS Global Positioning Application and Practice. U.S. Department of the Interior|U.S. Geological Survey. https://water.usgs.gov/osw/gps/