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Chapter 5 Switchgrass Harvest and Storage

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Chapter 5
Switchgrass Harvest and Storage

Rob Mitchell and Marty Schmer

Abstract The feedstock characteristics of the conversion platform will influence the optimal harvest and post harvest management practices for switchgrass. However, many of the harvest management practices are tied to plant phenology and will be similar across platforms. Proper harvest and storage of switchgrass will help provide a consistent and high-quality feedstock to the biorefinery. Bioenergy-specific switchgrass strains are high-yielding and in most cases can be harvested and baled with commercially available haying equipment. Many options are available for packaging switchgrass for storage and transportation, but large round bales or large rectangular bales are the most readily available and are in use on farms. Large round bales tend to have less storage losses than large rectangular bales when stored outside, but rectangular bales tend to be easier to handle and load a truck for transport without road width restrictions. Although there is limited large-scale experience with harvesting and storing switchgrass for bioenergy, extensive research, as well as a history of harvesting hay crops for livestock in many agroecoregions, makes harvesting and preserving switchgrass for bioenergy feasible at the landscape scale.

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5.1 Introduction

Switchgrass is not a new crop and switchgrass research is not a new phenomenon. The USDA location in Lincoln, Nebraska, USA has been conducting switchgrass research continually since 1936. Although the first 50 years of research focused on switchgrass for livestock and conservation, the research since 1990 within USDA-ARS, numerous universities, and more recently private industry, has emphasized bioenergy [1, 2]; see also Chap. 1). Although there is limited large-scale experience with harvesting and storing switchgrass for bioenergy, more than 20 years of bioenergy research from small plots to on-farm trials provides experience and critical insights.

Switchgrass is native to the North American tallgrass prairie and is broadly adapted to habitats east of the Rocky Mountains and south of 55°N latitude [3]. Switchgrass plants are generally caespitose or with short rhizomes and reproduce both sexually and asexually. Switchgrass has two primary ecotypes (upland and lowland) and two primary ploidy levels (tetraploid and octoploid) [2]. Switchgrass genotypes are largely self-incompatible and seed production results from cross-pollination by wind [1]. Switchgrass generally grows 1–3 m tall depending on location and genetic background and can develop extensive root systems to a depth of 3 m [1]. The aboveground growth and root structure makes switchgrass well-suited for dual use as a biomass crop and vegetative filter strips which have removed 47–76% of the total reactive P in surface runoff water in areas treated with manure [4].

Morphology and phenological development are important to understand when managing switchgrass for bioenergy. The growth form of both the caespitose and rhizomatous plants is erect with leaf blade length ranging from 10 to 60 cm depending on genotype, environment, and location within the plant [2]. Switchgrass plants tend to be less prone to lodging than other warm-season grasses. Switchgrass is photoperiod sensitive and requires shortening day length for floral induction, which helps explain why switchgrass morphology is strongly correlated to day of the year (DOY) and growing degree days (GDD) [5]. Switchgrass has a determinate growth habit where most vegetative growth terminates with inflorescence development [5, 6], which has implications for regrowth following harvest. Following floral induction, tillers advance to the seed ripening stages, growth stops, and tiller senescence occurs. In switchgrass swards in eastern Nebraska, there were no vegetative tillers present by DOY 196 and 100% of the tillers had elevated apical meristems [7]. Any regrowth following a harvest at or after this stage will occur only from retillering. In eastern Nebraska, sufficient regrowth to warrant a second harvest after a killing frost occurs about one year out of four [8]. For a more complete review of the morphology and tiller dynamics of warm-season grass swards, see Mitchell and Moser [9].

Canopy architecture affects the physiology of growing plants and compositional characteristics of harvested biomass [10] and breeding for increased biomass and digestibility changed the canopy architecture of switchgrass [11]. Canopy architectural traits such as tiller density, phenology, and leaf area index (LAI) are in a continual state of flux and functions of tiller morphology and the growth stage distribution of tillers within the tiller population [11, 12]. In Trailblazer switchgrass, there was an inverse relationship between advancing phenology and tiller density, with tiller density declining by an average of 9.4 tillers m^{-2} d^{-1} and an average tiller density of 1,525 tillers m^{-2} during the 2 year study [7]. Quantifying the phenology of tiller populations provides information for understanding these architectural changes in the grass sward. For example, switchgrass phenology advanced linearly with DOY and GDD across six environments in Nebraska and Kansas [5]. The predictability of switchgrass development in response to DOY and GDD indicates switchgrass management recommendations for adapted cultivars may be made based on DOY within a region [5]. Switchgrass LAI increased as phenology advanced and varied across years with maximum LAI ranging from 4.9 to 7.7, with at least 95% of the variation in LAI explained by DOY [7]. If the selected conversion platform targets feedstock material harvested after senescence, there will be less variability in the phenologic stage of the swards at harvest and may provide a more uniform product to the biorefinery. However, the morphological status during the growing season will have implications for other management decisions.

5.2 Harvest Management

The bioenergy conversion platform likely will determine the optimal harvest and post harvest management practices for switchgrass [2]. However, many of the harvest management practices will be similar for all conversion platforms. Many agroecoregions in the US have a history of harvesting and preserving hay for livestock, so making adjustments to harvesting for bioenergy production will be an easy transition. Due to the extensive research conducted on switchgrass, best management practices and extension guidelines have been developed for many regions [8, 13, 14]. High-yielding switchgrass fields (>12 Mg ha^{-1}) can be harvested and baled with commercially available haying equipment, but some important items must be considered [8]. For example, self-propelled swathers with rotary heads (disc mowers) will be required to optimize efficiency and handle the volume of material harvested from switchgrass bioenergy production fields [8]. Cutting height is easily adjusted and in most cases will be 10–15 cm, which keeps the windrows elevated above the soil surface to facilitate air movement and more rapid drying to less than 20% moisture content prior to baling [2]. After harvest, switchgrass can be packaged for storage and transportation in large round bales or large rectangular bales [2, 8]. Large round bales tend to have less storage losses than large rectangular bales when stored outside, but rectangular bales tend to be easier to handle and load a truck for transport without road width restrictions [8]. These technologies are in use on farms to harvest and package forages for livestock and are discussed in more detail in later sections.

5.2.1 Timing and Frequency

Maximum biomass yield with high lignocellulose content is the primary objective of most herbaceous bioenergy feedstock harvests [8, 15]. Depending on ecoregion, switchgrass biomass can be maximized with a one-cut or multi-harvest system [13, 16–18]. Most research supports a single annual harvest for optimizing biomass and energy inputs, as well as maintaining stands. For example, Sanderson et al. [17] concluded a single harvest near DOY 260 maximized biomass yield in the south-central USA. In most rainfed environments of the Great Plains and Midwest USA, maximum first-cut yields and long-term stand maintenance can be achieved by harvesting switchgrass once during the growing season to a 10-cm stubble height when panicles are fully emerged to the post-anthesis stage, near DOY 215 [8, 18, 19]. However, harvesting after frost minimizes nutrient removal, especially N [13]. With upland ecotypes, plant material senesces rapidly and is completely dormant within 7 days of killing frosts. However, lowland ecotypes grown in northern latitudes senesce and enter dormancy slowly after exposure to killing frost. This difference in response by ecotype is illustrated by upland and lowland plants harvested 27 days after the first killing frost and exposed to low temperatures of less than 0°C on 17 of the 27 days. The completely dormant material is Shawnee, whereas the material with green stem bases is a lowland strain selected from Kanlow (Fig. 5.1).

This delay in entering dormancy may be one explanation for the winter injury susceptibility of lowland ecotypes. However, harvest strategies for upland and lowland ecotypes have not been compared in agro-ecoregions where both ecotypes occur, so harvest strategies may vary [8]. Proper harvest timing, cutting height and maintaining adequate N fertility are important management practices required to maximize yield and ensure persistent switchgrass stands [2, 8]. As previously mentioned, time of harvest research generally indicates a single harvest at post-anthesis maximizes yield, but harvesting after a killing frost ensures stand persistence and productivity, especially during drought [2, 8]. For example, Vogel et al. [18] reported switchgrass biomass increases up to anthesis, then decreases by 10–20% until killed by frost. This fits well with recommendations by Mitchell et al. [8] who reported switchgrass should not be harvested within 6 weeks of the first killing frost or below a 10-cm stubble height to ensure carbohydrate translocation to the plant crowns for setting new tiller buds and maintaining stand productivity.

Wullschleger et al. [20] compiled a database comprised of switchgrass biomass production studies conducted at 39 field sites in 17 states which supported the single harvest for bioenergy. They reported the switchgrass mean biomass yield across all locations was 8.7 ± 4.2 Mg ha^{-1} for upland cultivars and 12.9 ± 5.9 Mg ha^{-1} for lowland cultivars and the yield difference between ecotypes was significant. Additionally, they reported that there was no evidence that small plots biased switchgrass yield when compared to field-scale sites and stressed the importance of single harvest systems for biomass energy.

Several studies throughout the Great Plains and Midwest have evaluated switchgrass harvest management. Phenologic stage at first harvest did not affect

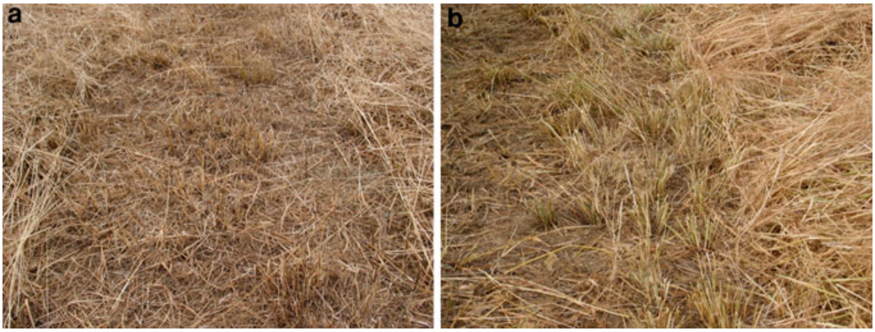

Fig. 5.1 Upland and lowland ecotypes of switchgrass enter dormancy at different rates when grown in the same environment. Both photographs were taken following field-scale switchgrass harvest in eastern Nebraska on 15 November, 2011. Notice that the upland cultivar **a** 'Shawnee' is completely dormant, whereas the lowland experimental strain **b** still has *green* stem bases (photos by Rob Mitchell)

switchgrass persistence, but regrowth potential decreased as first harvest was delayed to later stages of development and later DOY [21]. Harvesting switchgrass two or three times each year resulted in the greatest stand reductions [22]. Switchgrass harvested once at anthesis in Nebraska and Iowa had greater biomass than areas harvested twice [18]. Biomass was maximized with a single harvest during anthesis and yields ranged from 10.5 to 12.6 Mg ha^{-1} yr^{-1} with no stand reduction [18]. In Texas, Sanderson et al. [17] harvested several switchgrass strains once or twice per growing season from multiple environments and concluded that a single harvest in autumn maximized biomass and maintained stands.

In general, delaying harvest until after a killing frost reduces yield, but ensures stand productivity and persistence, especially during drought, and reduces N fertilizer requirements for the following year by about 30% [2, 8]. Post-frost harvests allow N and other nutrients to be mobilized into roots for storage during winter and use for new growth the following spring, but will reduce the amount of snow captured during winter and will limit winter wildlife habitat value [8]. Harvesting after a killing frost is a logical management decision for thermo-chemical conversion platforms and biopower because N, Ca, and other plant nutrients that function as contaminants in the thermo-chemical process are minimized in the plant tissue. Another alternative harvest time is to leave switchgrass standing in the field over winter and harvest the following spring [23]. Delaying harvest until spring reduced yield by 20–40% compared with harvesting in autumn after a killing frost, but had no effect on gasification energy yield [23]. Yield losses associated with delaying harvest until spring may be acceptable if wildlife cover during winter is critical [23].

These studies from a broad geographic range in the USA support a single annual harvest will maximize biomass and maintain stand persistence, but harvest timing needs to be considered for optimizing biofuel production. Additionally, the conversion process is an important consideration when determining the optimum harvest date. With good harvest and fertility management, productive stands can be maintained indefinitely and certainly for more than 10 years [8].

5.2.2 Nutrient Removal

Harvesting biomass, whether crop residue or dedicated herbaceous perennial feedstocks such as switchgrass, removes large quantities of nutrients from the system [19]. In most agro-ecoregions, nitrogen (N) is the most limiting nutrient for switchgrass production and is the most expensive annual production input. Consequently, reducing N removal from the switchgrass production system has a positive effect on the economic and environmental sustainability of the system. For example, harvesting 10 Mg ha^{-1} of switchgrass DM with whole-plant N concentration of 1% will remove 100 kg of N ha^{-1}, whereas if harvest is delayed until after senescence, N concentration can decline to 0.6%, resulting in the removal of only 60 kg of N ha^{-1}. Depending on conversion platform and a predictable harvest window in autumn or winter, this 40 kg of N ha^{-1} reduction in N removal may be an acceptable trade-off for the yield losses associated with delaying harvest.

Collins et al. [24] reported the average yield for three switchgrass cultivars irrigated in the Pacific Northwest ranged from 14.5 to 20.4 Mg dry matter ha^{-1} yr^{-1}. They reported each kg of N produced 83 kg of biomass and the macronutrient export averaged 214 kg N ha^{-1}, 40 kg P ha^{-1}, 350 kg K ha^{-1}, 15 kg S ha^{-1}, 60 kg Ca ha^{-1}, 38 kg Mg ha^{-1}, and 6 kg Fe ha^{-1}. Averaged across cultivars, switchgrass removed less than 1 kg ha^{-1} of B, Mn, Cu, and Zn. Additionally, delaying harvest until spring reduced ash content and leached nutrients from the vegetation [23]. Although management of all nutrients in the system is important, N is the most expensive, has the greatest potential for environmental contamination, and has the greatest influence on life cycle assessment.

Nitrogen removal in switchgrass production systems is a function of biomass yield and N concentration, with biomass N concentration increasing as N fertilization rates increase [18]. In a multi-environment study evaluating numerous N rates and harvest dates, biomass was optimized when switchgrass was harvested at the boot to post-anthesis stage and fertilized with 120 kg N ha^{-1} [18]. At this harvest date and fertility level, the amount of N removed at harvest was similar to the amount of N applied, and soil NO_3-N did not increase throughout the study [18]. Consequently, it is important to consider the interaction of N rate and harvest date to only replace the N needed for the production system to prevent over-fertilization and soil N accumulation.

5.2.3 Soil Carbon

As mentioned previously, switchgrass has an extensive perennial root system which protects soil from erosion and sequesters carbon (C) in the soil profile [25]. Soil organic carbon (SOC) typically increases rapidly when annual cropland is converted to switchgrass [26, 27]. The amount of C sequestered depends on the climate, soil type, original soil C content, time, and placement depth of C [28, 29].

For example, switchgrass grown and managed for bioenergy on three marginally productive cropland sites in Nebraska resulted in an average SOC increase of 2.9 Mg C ha^{-1} yr^{-1} in the top 1.2 m of soil in just 5 years [30]. In South Dakota, switchgrass grown in former cropland enrolled in CRP stored SOC at a rate of 2.4–4.0 Mg ha^{-1} yr^{-1} at the 0–90 cm depth [31]. McLaughlin et al. [32] reported an average of 1.7 Mg C ha^{-1} yr^{-1} sequestered in the Southeast U.S. on switchgrass experimental plots. Soil carbon levels on low-input switchgrass fields have been shown to increase over time, across soil depths, and are higher than adjacent cropland fields in the Northern Plains [25]. A similar result was found between switchgrass and a corn (*Zea mays* L.)-soybean (*Glycine max* (L.) Merr.)-alfalfa (*Medicago sativa* L.) rotational system in Iowa [33]. Switchgrass managed for bioenergy on multiple soil types in the Northern Plains was carbon-negative, sequestering 4.42 Mg C ha^{-1} yr^{-1} into the soil profile [34]. In the Southeast U.S.A., an estimated 0.17–0.21 Mg C ha^{-1} yr^{-1} was sequestered on switchgrass plots, managed as a bioenergy crop, based on SOC that was near steady state [35]. Nitrogen applications on switchgrass plots did not alter root C storage when compared with non-fertilized plots in a 2 year study [36]. However, fertilization of grasslands increased the amount of C sequestered by 0.30 Mg ha^{-1} yr^{-1} on 42 studies throughout the world [28]. Microbial biomass carbon increased after establishment of switchgrass and carbon mineralization increased by 112 and 254% at depths of 0–0.15 m and 0.15–0.30 m, respectively [36]. Soil organic C increased at rates ranging from 1.7 to 10.1 Mg C ha^{-1} yr^{-1} after switchgrass establishment throughout North America [31, 34, 35, 37].

5.3 Storage Management

Substantial amounts of switchgrass biomass will need to be safely stored on a year-around basis to supply a cellulosic biorefinery. Cellulosic biorefineries in the U.S. are expected to keep only a 72 h feedstock inventory with the remaining feedstock inventory at the edge of field or at satellite storage facilities [38]. At present, there is uncertainty on the overall capacity of cellulosic biorefineries but techno-economic models have evaluated refinery sizes ranging from 535 to 8,000 dry Mg feedstock per day [39–41]. Offsite storage management will be critical to maintain desirable composition characteristics and to ensure feedstock access under variable weather conditions. Storage infrastructure requirements will need to be cost effective, maintain desirable quality characteristics depending on conversion technology, provide an aerobically stable environment, and have flexible delivery schedules depending on regional weather factors [42].

Storage requirements and management will be dependent on how switchgrass is harvested. In the near-term switchgrass will be harvested and baled using commercial hay equipment. Self-propelled mower/conditioners (swather) with rotary heads are effective in harvesting high-yielding (>12 Mg ha^{-1}) switchgrass fields (U.S. [43]). The conditioner component on a swather accelerates switchgrass drying by crushing plant stems but not altering plant structure and consolidates the switchgrass into a windrow [38]. After harvest, the baling step bundles switchgrass into a more condensed form to ease handling, transport and storage. Variable chamber round balers or rectangular balers will likely be used to consolidate and bundle switchgrass. Round balers will typically make a bale that is 1.2–1.8 m in diameter and 1.2–1.8 m in length. Large rectangular bale size ranges from 0.9 to 1.2 m in height and width and 1.8–2.4 m in length. Round balers and large rectangular balers require switchgrass moisture levels to be $\leq$18 and $\leq$16%, respectively, at time of baling to reduce storage losses. Bale moisture content in excess of these respective values may result in composition degradation or spontaneous combustion. Field drying prior to baling is required to meet safe moisture levels for baling which may be hindered depending on the region and harvest date. Balers can be modified to spray preservatives (e.g. propionic acid) onto hay limiting microbial growth and removing excess moisture for hay with 20–25% moisture content [44].

The density of a round bale or a large rectangular bale will vary depending on harvest period with anthesis harvest bales having a greater density than post-killing frost harvest bales. There are advantages and disadvantages for the round baling or large rectangular baling methods but both are capable of processing switchgrass and are commercially available to producers. The round baler is one-fourth to one-third the capital cost as a large rectangular baler [45] but the field capacity of a round baler is lower because the baler needs to be stopped to wrap and release the bale. Large rectangular balers continuously bales without the need for stopping and is estimated to cost less per unit of harvested area [46]. Smaller bioenergy producers may opt for the round baler methods because of the lower capital costs or may outsource harvest and baling to custom harvesting enterprises that are equipped with large rectangular balers. Rectangular bales need to be removed from the field soon after baling and protected from precipitation events because the flat surface of the bale does not shed water and resultant DM losses can be large [44].

Commercially available self-propelled or pull-type round or rectangular bale stacking equipment collect bales within the field and are able to place bales at the edge of field for short-term or long-term storage until feedstock delivery to a biorefinery. These stacking systems significantly lower energy use and increase field capacity efficiency when compared with a single bale loader system. Switchgrass round bales have less storage losses than large rectangular bales when stored outside as they are less prone to water penetration especially when net wrapped [38]. Net wrapped round bales had 60–70% lower DM losses when compared with round bales tied with plastic twine [47]. Rectangular bales tend to be easier to handle and load a truck for transport without road width restrictions. The time required to load bales onto semi trailers is double for round bales than it is for rectangular bales [38]. Unless cellulosic biorefineries stipulate a certain baling method or alternative harvest method, both baling methods will likely occur for a given region.

Consolidation methods other than baling may be implemented in regions where weather conditions or existing infrastructure enterprises allow for alternative harvesting scenarios [19, 48–51]. Wet storage methods have been proposed for switchgrass in regions where drying conditions for baling operations are not possible because of high relative humidity and increased chance of a precipitation event after harvest [50]. Switchgrass harvested using wet storage methods include either a swather harvest and then chopped using a self-propelled forage harvester with a windrow pickup or directly cut with a self-propelled forage harvester with an attached rotary head that blows the material into adjacent semi bulk trailers.

Moisture content for switchgrass at time of pickup under wet storage methods are >40%. Advantages to wet storage methods include reduced harvest costs, lower DM losses during storage, improved switchgrass cell wall recovery during enzymatic hydrolysis and lower potential risk of fire during storage [50]. Disadvantages for the wet storage method include higher equipment and storage structure costs than a conventional baling system [44]. The wet storage method was found to be more expensive than other collection and storage methods for cellulosic refinery sizes greater than 1,500 Mg switchgrass per day because of the high cost of the ensiling pit and transportation of wet material by truck [51].

Regions where silage harvesting is common would likely have increased participation in storing switchgrass under wet conditions. Field chopping using a forage harvester can be done at moisture levels similar to baling in less humid regions. Field chopping has an added advantage to baling in that particle size is much smaller which may eliminate a preprocessing step at the biorefinery [19]. Estimated delivery costs for chopped switchgrass biomass are less than for a conventional baling system [51]. Chopped biomass requires specific storage areas either at farm site or at a satellite storage facility. Chopped biomass has the lowest bulk density and densification may be an issue for long-term storing and transporting the material [19]. Southeastern U.S. researchers have proposed increased densification of chopped switchgrass by using modulizing technology developed for the cotton industry [48, 49].

A loafer stacker system has also been proposed as a cost effective method to collect switchgrass for biomass production [52]. The loafing system is similar to the field chopping system (dry storage) with the exception that instead of blowing switchgrass material into a semi trailer the loaf stacker picks up switchgrass from the windrow and makes a biomass stack approximately 2.4 m wide, 6 m long, and 3.6 m high [51]. The roof of the loafer stacker has a dome shape which creates a biomass stack that resembles a bread loaf and is designed to shed water. Field capacity of a loafer stacker is lower than either conventional baling system or a forage chopper. Once the loafer stacker is full, the operator needs to immediately transport the biomass stack to the edge of field or use specialized trailers to transport the biomass stack after harvest. Biomass stacks are also susceptible to large biomass loss in regions with significant wind velocities if placed perpendicular to prominent wind direction.

The U.S. Department of Energy has proposed a uniform-stacking feedstock supply design that can pre-process switchgrass and other cellulosic materials regardless of collection method for use in a large-scale cellulosic biorefinery ($\geq$4,535 Mg d^{-1}) which would increase regional and producer flexibility to harvest and collect switchgrass [38].

5.3.1 Desirable Storage Characteristics

The ideal storage management procedures are to preserve switchgrass so that it enters and leaves the storage phase in an unaltered state [53]. Key factors in minimizing storage loss for bales are to ensure low moisture levels prior to storage and protection from moisture during the storage phase. Low relative humidity and low ambient temperatures during storage also reduce DM loss and composition degradation. Maintaining low biological activity during storage to reduce microbial growth and subsequent storage loss is also important.

Switchgrass with higher levels of N or with increased soluble sugars have increased potential for microbial growth and degradation during bale storage [38]. Harvest dates determine overall N and soluble sugar content in switchgrass [54]. Storage conditions that reduce the potential for spreading crop diseases, low rodent populations, and mold spore formation are also desirable [38].

5.3.2 Storage Platforms

Although there is limited research on switchgrass storage platforms for specific bioenergy purposes, there is significant storage research on forages that offer insights into the advantages and disadvantage of different storage options. Near-term storage strategies include placing bales outside on well-drained surfaces (i.e. gravel, crushed rock), tarping, bale wrapping in plastic and indoor placement. Optimal storage platforms are dependent on expected bale storage losses and projected storage costs to offset these losses. For example, enclosed buildings are the most expensive storage platform but also ensure the greatest switchgrass value and lowest storage loss [55]. Proper storage of wet material or ensiling has been well documented for a number of feedstocks including switchgrass [38, 44, 56]. Pre-processing steps such as pelletizing or briquetting switchgrass provides decreased storage losses and decreased transportation costs [57]. Estimated capital costs for a pellet mill or briquettor, however, potentially offset any near-term savings in storage or transportation costs [41].

5.3.3 Storage Losses

Limited research has been conducted on DM losses during switchgrass storage with most research evaluating storage loss using the baling method. In Texas, DM losses for large, round bales ranged from 1 to 5%, with larger losses occurring with drier material [58]. Switchgrass round bales stored for 6–12 months inside had 0–2% DM losses, whereas bales stored outside lost 5–13% of the original bale weight [58]. In southeastern U.S., round bales with higher initial moisture content and longer storage times caused increased DM loss when stored outside [59]. In Indiana, switchgrass round bales wrapped in twine had 13% DM loss on sod but bales stored on crushed rock had 5% DM loss after six months [60]. Switchgrass round bales stored outside on either sod or gravel showed similar DM losses 12 months after baling in Texas [58]. Estimated DM storage losses in excess of 16% are required to cover the initial cost of storage sites using crushed rock for improved drainage [38]. In southern Europe, switchgrass round and rectangular bales showed minimal storage loss and no visible microbial activity when stored under a sheltered roof [61]. Storage loss was found to be greater for tarped large rectangular bales than for tarped round bales and that delivery costs increased with larger storage times due to increased storage losses [62]. Tarped and untarped large rectangular bales had DM losses of 7% and up to 25%, respectively, six months after harvest in Nebraska [8]. Water and temperature together determines microbial damage for storage systems with regions having high relative humidity and having temperatures results in increased storage degradation on portions of biomass in direct contact with air [38]. In general, biomass stored dry should be kept at moisture levels below 15% to prevent biomass degradation by filamentous fungi and bacteria [63]. Additional physical factors that cause storage loses include wind erosion or handling losses, moisture partitioning, bulk settling, and dust accumulation [38].

5.3.4 Changes in Composition During Storage

Composition changes during storage will likely be more unfavorable for biochemical conversion than either thermo-chemical conversion technology or direct combustion for electrical generation. Switchgrass round bales stored unprotected outside lost up to 11% of ethanol extractables, which could significantly reduce conversion to ethanol [64]. Biomass quality heterogeneity will occur within bales with portions of the bale showing no signs of degradation while other portions having significant spoilage or composition degradation. Round bales can be segmented to four portions based on the potential for deterioration [65].

Approximately 33% of a round bale circumference contacts the ground after settling which can absorb moisture and result in spoilage [38]. The first round bale portion is where the round bale contacts the ground up to 15 cm. A transitional area above this portion (15–30 cm) can also be degraded depending on moisture conditions and length of storage. Sanderson et al. [58] noted that switchgrass round bales stored on sod had a large, black layer where the bale was in contact with sod whereas round bales stored on gravel did not have this layer of spoilage indicating outside storage method will influence composition heterogeneity of bales. The third portion of the round bale is the outer 15 cm of the round bale not in contact with the ground. This portion can also have compositional changes depending on weather factors, length of storage, and wrapping methods (i.e. plastic twine, plastic net-wrap). The final portion of the round bale is the core which is the least likely to

Fig. 5.2 Large rectangular bales are susceptible to spoiling on the *top* and *bottom* of the bale if not stored properly. This bale was cut in half to expose the spoilage on the bale interior (photo by Rob Mitchell)

have compositional changes during storage. Biomass degradation from weather and microbial activity can be as high as 42% by volume for a round bale [65]. For large rectangular bales, moisture can penetrate at the top of the bale or can be absorbed at the bottom of the bale. A large rectangular bale is comprised of a number of layers of switchgrass compressed together. Water channeling can occur within these layers causing heterogeneous spoilage ([38]; Fig. 5.2).

Large rectangular bales are typically stacked so water channels between layers can cause biomass degradation to adjacent bales as well. Chopped switchgrass in a dry form will have the most compositional changes around the outer surface layer (0–0.8 m) with the interior portions unaltered. The amount of compositional changes by volume from dry chopped switchgrass piles is a result of the overall stack size. Sulfuric acid pretreatment on switchgrass stored under wet conditions inhibited microbial activity and resulted in 7% higher ethanol conversion efficiency than untreated switchgrass [50].

5.4 Conclusions

This brief overview has scratched the surface of switchgrass harvest and storage management. Proper harvest and storage management is paramount to providing a consistent and high-quality feedstock to the biorefinery. Although the bioenergy conversion platform will guide the switchgrass harvest and post harvest management practices, proper handling will ensure optimum biofuel recovery. Continued research on the effects of harvest and storage management on feedstock characteristics is critical as landscape scale deployment of switchgrass for bioenergy moves forward. Important areas for continued research include the effects of compositional changes during storage on biofuel production; harvest timing effects on ecosystem services, especially SOC sequestration, wildlife, and pollinator habitat, and GHG emissions and mitigation; and long-term research evaluating harvesting effects on macronutrient and micronutrient removal, as well as developing strategies for maintaining soil nutrient status.

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