Analysis and Simulation of Switchgrass Harvest Systems for Large-scale Biofuel Production

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ABSTRACT

In the United States, the Energy Independence and Security Act of 2007 mandates the annual production of 136 billion liters of renewable fuel in the US by 2022 (US Congress, 2007). As the nation moves towards energy independence, it is critical to address the current challenges associated with large-scale biofuel production. The biomass logistics network considered consists of three core operations: farmgate operations, highway-hauling operations, and receiving facility operations. To date, decision-making has been limited in post-production management (harvesting, in-field hauling, and storage) in farmgate operations.

In this thesis, we study the impacts in the logistics network resulting from the selection of one of four harvest scenarios. A simulation model was developed, which simulated the harvest and filling of a Satellite Storage Location (SSL), using conventional hay harvest equipment, specifically, a round baler. The model evaluated the impacts of four harvest scenarios (ranging from short, October-December, to extended, July-March), on baler equipment requirements, baler utilization, and the storage capacity requirements of round bales, across a harvest production region. The production region selected for this study encompassed a 32-km radius surrounding a hypothetical bio-crude plant in Gretna, VA, and considered 141 optimally selected SSLs. The production region was divided into 6 sub-regions (i.e. tours). The total production region consisted of 15,438 ha and 682 fields. The fields ranged in size from 6 to 156 ha.

Of the four scenarios examined in the analysis, each displayed similar trends across the six tours. Variations in the baler requirements that were observed among the tours resulted from variability in field size distribution, field to baler allocations, and total production area. The available work hours were found to have a significant impact on the resource requirements to fulfill harvest operations and resource requirements were greatly reduced when harvest operations were extended throughout the 9-month harvest season. Beginning harvest in July and extending harvest through March resulted in reductions in round balers ranging from 50-63%, as compared to the short harvest scenario, on a sub-regional basis. On a regional basis, beginning harvest in July and extending harvest through March resulted in baler reductions up to 58.2%, as compared to the short harvest scenario. For a 9-month harvest, harvesting approximately 50% of total switchgrass harvest in July-September, as compared to harvesting approximately 50% in October-December, resulted in reductions in round balers ranging from 33.3- 43.5%. An extended (9-month) harvest resulted in the lowest annual baler requirements, and on average lower baler utilization rates. The reduced harvest scenarios, when compared to the extended harvest scenarios, resulted in a significant increase in the number of annual balers required for harvest operations. However, among the reduced harvest scenarios (i.e. Scenario 3 and 4), the number of annual balers required for harvest operations showed significantly less variation than between the extended harvest scenarios (i.e. Scenarios 1 and 2). As a result, an increased utilization of the balers in the system, short harvest scenarios resulted in the highest average baler utilization rates. Storage capacity requirements were however found to be greater for short harvest scenarios. For the reduced harvest scenario, employing an October-December harvest window, approximately 50% of harvest was completed by the end of October, and 100% of total harvest was completed by the third month of harvest (i.e. December).

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CHAPTER ONE

INTRODUCTION

1.1 Motivation and Background

As the United States moves toward energy independence, biofuels stand at the forefront of promising renewable alternatives. Currently, renewable energy represents a small share of the nation's energy supply, accounting for approximately 8% of total consumption. Biomass supplies approximately 2% of total consumption (US Energy Information Administration, 2011). While biofuel energy consumption is low today, regulatory, legislative and policy efforts indicate biofuel consumption will increase rapidly within the next decade (US Department of Energy, 2011). The Energy Independence and Security Act of 2007 mandates the annual production of 136 billion liters of renewable fuel in the US by 2022 (US Congress, 2007). Advanced biofuels will account for 79 billion liters, with 60 billion liters derived from cellulosic biofuels. In recent years, the American Reinvestment and Recovery Act of 2009 provided grant funds to accelerate commercialization of advanced biofuels and integrated biorefinery projects (US Congress, 2009). As the nation transitions to renewable fuels, it is critical to address challenges associated with large-scale biofuel production.

Prior to the development of current government legislation, the United States Department of Energy, in the late 1980s, began an assessment of herbaceous species. These studies identified switchgrass (*Panicum virgatum L.*), a warm-season prairie grass, as a model species for further research because of its perennial growth, high yield potential, soil improvement capabilities and compatibility with conventional farming practices (Wright, 2007). Conclusions in the Department of Energy study prompted a 10-year development program to assess switchgrass as a dedicated energy crop. Research suggested switchgrass produced for energy would compete as a fuel and an agricultural crop (McLaughlin and Kszos, 2005).

Due to extensive research conducted on the genetic and agronomic aspects of switchgrass, implications pertaining to crop production are well understood. However, genetic and agronomic aspects of switchgrass production account for a fraction of the efforts required to successfully develop switchgrass into a viable bioenergy enterprise. A biorefinery logistics network, structured to supply switchgrass year-round, consists of farmgate operations, highway-hauling operations, and receiving facility operations. Research to date is very limited regarding post-production management (harvesting, in-field hauling, and storage) in farmgate operations.

The potential of switchgrass to make a vast impact on large-scale biofuel production relies heavily on proper harvest and post-harvest management strategies. Furthermore, proper management decisions are critical to ensure preservation of biomass and minimize cost, throughout the complex logistics network.

The biorefinery aims to meet plant demands, streamline storage and handling, and preserve the quality of the biomass for final conversion. Alternatively, the primary objective of the landowner is to maximize the harvestable quantity of biomass, minimize harvest related resources (e.g. fertilizer inputs and harvest equipment), and minimize interference with alternative competing harvest enterprises. The logistics of switchgrass supply is characterized by vast amounts of biomass distributed across expansive regions, limited harvest windows, and time and weather-sensitive harvest operations. Efforts to achieve the mutual objectives of the biorefinery and the landowner, within in this complex network, have prompted this study.

A simulation model was developed in this study, which simulated the harvest and filling of a Satellite Storage Location (SSL), using conventional hay harvest equipment, specifically, a round baler. The model was used to evaluate the impacts of the employed harvest scenario, on baler equipment requirements, across a harvest production region. Four harvest scenarios were examined, and applied to the 32-km radius surrounding Gretna, VA. The output from the simulation model was used to generate baler equipment utilization rates, annual baler equipment requirements, and assess storage implications, across the examined harvest scenarios. Although an initial attempt, the use of this simulation tool, provided insight, on the field level, of the implications of harvest scenarios, as well as a resource beneficial to both the biorefinery and the landowner.

1.2 Research Objectives

The overall objective of this research is to determine the impacts of four harvest scenarios on an integrated biofuel logistics network. These scenarios envision four different harvest windows (months when harvest can proceed). The specific objectives of this research are:

1. Using a discrete event simulation model, determine total annual balers required to fulfill harvest demands, baler utilization, the storage capacity requirements of biomass, in the logistics network, for each of the four harvest scenarios.

2. Determine the impacts in the logistics network resulting from the selection of one of the four scenarios.

1.3 Thesis Organization

The thesis is divided into several chapters that illustrate the biomass logistics network, define the scope of this study, and present key issues for future study. Chapter 2 provides a review of literature on hay harvest. In particular, Chapter 2 presents a detailed review on the harvest, storage, and transportation of herbaceous biomass. The chapter concludes by providing a review of a select simulation studies that modeled harvest operations. Chapter 3 describes the dataset and parameters used in this study. Chapter 4 provides a detailed description of the simulation model, and the model developmental process. Chapter 5 presents the results from the simulation model. Chapter 6 summarizes the conclusions from the simulation model. Finally, Chapter 7 offers recommendations for future work.

CHAPTER TWO

LITERATURE REVIEW

Literature on hay harvest, as well as herbaceous biomass harvest, was reviewed for application to current switchgrass harvest management practices in the Southeastern United States. It is useful to divide the discussion of literature into the following categories: (1) Harvest of Herbaceous Biomass, (2) Storage of Herbaceous Biomass, (3) Transport of Herbaceous Biomass, and (4) Simulation of Harvest Operations.

2.1 Harvest of Herbaceous Biomass

2.1.1 Harvest Frequency

As a perennial, switchgrass can be harvested annually, with a stand lasting 10 years or more (Fike et al., 2006). Annual harvest is typically managed with either a one- or two-cut strategy. Harvests of more than two-cuts were found to significantly reduce total biomass yields (Sanderson et al., 1999).

Fike et al. (2006) evaluated the response of upland and lowland switchgrass cultivars to one- and two-cut harvest management strategies in the upper Southeastern United States. Upland and lowland switchgrass cultivars were harvested over a 3-year period, at eight sites, in five states (North Carolina, Kentucky, Tennessee, Virginia, and West Virginia). Among all sites and cutting strategies, throughout the entire study, they reported higher yields for lowland cultivars (15.8 Mg/ha) compared to upland cultivars (12.6 Mg/ha). Positive yield responses were observed with two-cut management of both lowland and upland cultivars; although yield response was significantly greater for upland cultivars (36% increase in biomass) than lowland cultivars (8% increase in biomass). The study concluded that two-cuts might be less advantageous than a one-cut harvest strategy, for biomass yield with lowland cultivars. Furthermore, Fike et al. (2006) recommended further exploration of fuel quality and economic outcomes for a two-cut harvest strategy to determine if such management is warranted.

Similarly, researchers have suggested that the increase in yield might not offset the cost of an additional harvest (Cundiff, 1996; Sanderson et al., 1996).

Sanderson et al. (1999) evaluated yield potential and adaptability of switchgrass cultivars in five ecologically different locations in Texas. Contrary to Fike et al. (2006), Sanderson et al. (1999) reported large yield reductions with a two-cut harvest strategy in the lowland cultivars. Sanderson et al. (1999) determined a single harvest in the fall maximized biomass yields and maintained switchgrass stands.

In Virginia, average total biomass yield was estimated at 13.9 Mg/ha on a yearly basis (McLaughlin and Kszos, 2005), with yields projected to increase to support large-scale bioenergy production, through the advancement of breeding switchgrass cultivars (McLaughlin et al., 2006). For sustainable high yields, Parrish and Fike (2005) suggested a single harvest at the end of the season or later, and they recommended low nitrogen inputs as the optimal harvest management strategy. Regardless of harvest cut strategy, it has been common practice to leave 15.24 cm of stubble height on the stand to aid in regrowth, reduce tire damage, and reduce soil erosion among other benefits (USDA-NCRS, 2009).

2.1.2 Harvest Window

The harvest window for warm-season perennials, such as switchgrass, can begin as early as July (Ogden et al., 2010), following plant maturity, and end as late as March (Larson et al., 2010), prior to plant regrowth. Ogden et al. (2010) performed harvest operations in West Lafayette, Indiana from July to November. Chariton Valley Biomass Project (2002) began harvest operations in Iowa from September, following a killing frost, to November, prior to inclement weather (snow cover on fields). Larson et al. (2010) assumed harvest from November 1 to March 1 to evaluate operations in the Southeastern United States.

McLaughlin and Kszos (2005) reviewed a 10-year evaluation and developmental program of switchgrass as a bioenergy crop, sponsored by the US Department of Energy. Data indicated that improved feedstock quality was realized by delaying harvest dates until nutrients were retranslocated from leaf tissue, and mineral ash became a smaller fraction of total harvested biomass. Furthermore, final harvests whether in single or double-cut systems were found to be best applied either by mid-September, to maximize yields, or after the first frost to maximize retranslocation.

Multiple studies indicated a reduction in yields and moisture content when delaying harvest of switchgrass (Christian et al., 2002; Adler et al., 2006; Ogden et al., 2010). Christian et al. (2002) reported that delayed harvest reduced yield over the study period in Southern England. Adler et al. (2006) reported that delayed harvest reduced yields approximately 40% in winters with above average snowfall. Moisture contents decreased in spring versus fall-harvested switchgrass, and moisture content only reached levels safe for storage in spring-harvested switchgrass. Ogden et al. (2010) reported a maximum yield in August of 9.56 Mg/ha and reductions in October and November to 7.92 and 7.34 Mg/ha respectively. The highest moisture content was reported in the first month of harvest (July) and the lowest moisture content in the final month of harvest (November). Ogden et al. (2010) projected the high moisture contents experienced in the summer months would require 3-4 additional days of field drying before baling. Shinners et al. (2006) similarly reported moisture contents suitable for baling after 3 days of field drying.

Throughout a given harvest window, the changes that occur in the compositional makeup (structural and non-structural) of switchgrass were reported to affect quality of final bioenergy conversion (Ogden et al., 2010). Ogden et al. (2010) reported a significant increase of oxygen content in the fall versus summer months, which would translate to a better burn during combustion. Adler et al. (2006) reported five-C carbohydrates were more affected by harvest time than six-C carbohydrates; therefore, predicted ethanol yield tended to increase in spring harvested switchgrass. Adler et al. (2006) concluded delayed harvest reduced ash and water concentration, which thereby increased the energy content of the biomass for all conversion systems.

2.1.3 Probability Work Day

Harvest operations are weather dependent; therefore, location specific weather patterns must be considered to generate estimates on the available work days for harvest operations.

Hwang et al. (2009) determined the number of suitable field workdays in which switchgrass could be mowed and the number of days that mowed material could be baled for nine counties in

Oklahoma. Empirical distributions of the days available for mowing and baling switchgrass were determined for each month and two potential harvest seasons (October–December and July–February). Hwang et al. (2009) assumed the following conditions for safe baling: 1) the soil can be trafficed, and 2) the moisture content of the mowed switchgrass must be at levels safe for storage (< 15% m.c). Suitable field workdays for harvesting were predicted daily, based on meteorological information. Sequences of workdays (i.e. days weather and field conditions allow field operations) and non-workdays (i.e. days when field conditions do not permit field operations) were grouped, and then summed for each month. Results from the study indicated the difference in suitable harvest days among the potential harvest season.

Cundiff et al. (2011) provided estimates on the number of suitable field workdays in which switchgrass could be harvested using a round baler, compared to a square baler, in Virginia. Probability workday estimates are provided for each month, and baler system, during the non-growing season of switchgrass, July-March. Data indicated a decrease in the number of suitable field workdays during winter months, due to inclement weather and trafficability issues for both the round and square baler systems.

Grisso et al. (2012) determined the impact of switchgrass harvest scenarios, utilizing the probability workday estimates, generated by Cundiff et al. (2011). Harvest scenarios ranged from a short window (October – December), to an extended window (July – March). The estimates of the probability workdays available were found to have a significant impact on the equipment needs. The study concluded an extended harvest window would require 30% less balers, as compared to a short harvest window. Additionally, the short harvest was found to require 75% inventory space within the storage locations, as compare to 42% when utilizing the alternative scenarios.

2.1.4 Harvest Operation

Harvesting was reported the single most expensive annual operation in the production of herbaceous feedstocks (Khanna et al., 2010). An increased baling efficiency coupled with a more informed understanding of farm specific best practices can prevent the costs from increasing. The total delivered cost of switchgrass was sensitive to the method of harvest, storage, and handling. Harvesting operations are as follows: 1) mowing, which cuts the biomass from the stand, 2) conditioning, which macerates the biomass to a specified degree to promote field drying, 3) drying, which allows the biomass to reach the acceptable moisture content for safe storage, 4) raking, which gathers the biomass into windrows, and 5) collection of biomass. It should be noted that conditioning and drying could be omitted from the harvest operations if the biomass is ready for safe baling. Harvest is executed in one of two ways: 1) single-pass harvesting, which executes several harvest operations simultaneously with a single equipment unit, or 2) multiple-pass harvesting, where the harvest operations are performed by multiple dedicated equipment units. Larson et al. (2010) estimated the cost for a round and square bale multiple-pass harvesting (mowing, raking, and baling) of switchgrass $31.47 and $22.38/Mg, respectively. Cost estimates for single-pass harvesting of switchgrass is not widely available in literature, as technologies are still under development. However, it has not been widely acknowledged that single-pass harvesting systems offer many advantages over multiple-pass harvest systems including reduced cost. Yu et al. (2011) projected the cost for a single-pass harvesting (chopping using a forage harvester) of switchgrass is approximately $5.51/Mg lower than multiple-pass harvesting (mowing, raking, and chopping). Shinners et al. (2003) evaluated cost for a single-, two-, and three-pass harvesting system of corn stover and estimated a 26% reduction in cost for a single-pass harvesting system.

The harvest methods used for switchgrass are the same used for the harvest of forage for livestock. It can be baled (round or rectangular) or chopped directly in the field and hauled as size-reduced material.

Large round and large rectangular balers are two well-known and widely available harvesting technologies (Reynolds and Frame, 2005), which offer a range of advantages and disadvantages for farmgate operations. The differences between these harvest methods, and the resulting bale properties, greatly impacts investment in equipment, transportation, and storage infrastructure. Round balers are widely accessible on farms in the Southeastern United States, thus allowing a farmer to utilize conventional farm equipment for baling operations (Lindh et al., 2005; Lotjonen, 2008) and thereby reduce capital investment cost for new equipment. The round baler was roughly one-third the cost of the large rectangular baler; but, the round baler had less throughput capacity (Mg/h) than the rectangular baler (Cundiff and Marsh, 1996). The round baler was required to stop, wrap and eject the bale, whereas, the square baler operated continuously. Cundiff and Marsh (1996) simulated switchgrass harvest of large rectangular bales and round bales to compare total harvest cost across yields of 4.5, 9, and 18 dry-Mg/ha. The lowest-cost (1.8 m dia. x 1.5 m long) round bale, as recommended by Cundiff (1996), was selected and compared with the (1 m x 1.2 m x 2.4 m) rectangular bale. Forward speed of the mower-conditioner, and baler was adjusted for each yield and windrow density to ensure that the equipment operated at design capacity. The study determined that per-dry-Mg harvest cost decreased for the rectangular bale system, as the yield increased. Conversely, harvest costs increased for the round bale system at higher yields, due to higher bailing and hauling cost. For the round bale system, as yields doubled from 9 to 18 dry-Mg/ha, bale mass was 34% less, baling cost increased 18% and harvest cost increased 20% per-dry-Mg. Cundiff (1996) simulated five large round bale harvest systems and reported a decreased bale mass, increased baling cost, and increased harvest cost at higher yields when utilizing the round bale system versus the rectangular baler. Not taking into account any dry matter storage losses, the least cost method of switchgrass harvest was reported to be the rectangular bale, with the use of conventional hay equipment (Larson et al., 2010). Kemmerer and Liu (2011) reported an actual material capacity of 13 Mg/ha for the New Holland large square baler. Kemmerer and Liu (2011) found the large square bales could be handled and transported at more than twice the rate at which the bales were produced, thus the baling operation limited the efficiency of the entire harvest system.

Baling of switchgrass has generally been accomplished using conventional hay equipment. Perennials, such as switchgrass, have greater yields than forage crops. Concern has been raised on the capability of conventional hay equipment to harvest switchgrass when managed as a bioenergy crop. High yields were found to cause considerable difficulty with baling operations (Bransby et al., 1996). Shinners et al. (2006) experienced limited baler productivity because of the volume of the windrows and higher yields. A Pennsylvania study assessed switchgrass yields with delayed harvest until spring, and found that switchgrass yields decreased almost 40% (Adler et al., 2006). Nearly 10% of switchgrass yield reduction was due to a decreased tiller mass; nearly 90% of switchgrass reduction was the result header losses due to lodged material. A similar analysis of field studies also shows similar findings, suggesting the need for improvement of the baler pickup mechanism to retain yields over the harvest season (Sokhansanj et al., 2008).

An alternative to the baling harvest methods has been to chop the material in the field and haul the loose chopped material. Due to limited literature addressing the harvest of loose chopped switchgrass, a proposed corn stover logistics system by Morey et al. (2010) was found to have potential application for switchgrass harvest management.

2.1.5 Moisture Content

The moisture content of switchgrass directly affects the feasibility of employing either a single-pass or a multiple-pass harvest system, and it has also been a key factor in determining a suitable harvest collection method (Shinners et al., 2006; Sokhansanj et al., 2009). As the harvest season progresses, the moisture content of biomass will decrease. Initial moisture content when switchgrass was cut before a killing frost ranged from 66-46% (w.b.) (Shinners et al., 2006). The study indicates that acceptable baling moisture content (<20% w.b.) can be achieved in a single day when biomass was placed in a wide swath using a tedder. It should be noted, that while Shinners et al. (2006) suggests less than 20% w.b. for baling, numerous studies recommended less than 15% w.b. (Cundiff and Marsh, 1996; McLaughlin et al., 1996; Hwang et al., 2009). Furthermore, when considering the baling harvest collection methods, moisture content at baling was more critical for the rectangular bale (Cundiff and Marsh, 1996). If round bales are harvested at greater than 20% moisture content, there will be a temperature increase in the bale during the first month of storage. If the bales are in single layer ambient storage, this temperature rise will not be detrimental. With large rectangular bales placed in a stack several bales high, the temperature increase can get large enough for the stack to catch fire.

If the harvest collection method is in the form of loose chopped biomass, there is greater flexibility in moisture content, as either a wet chop (>40% w.b) or a dry chop (<15% w.b) can be performed. However, it has been preferred in the logistics network to have low moisture content. Higher moisture content means added weight to transport, and limits storage options.

2.2 Storage of Herbaceous Biomass

The seasonality of switchgrass harvest requires an adequate storage to ensure year-round operation of the biorefinery. Storage of switchgrass has ranged between 3-12 months, depending on the harvest window. In general, the investment in storage increases, as the harvest window decreases.

The preservation of the physical and chemical condition of switchgrass during the storage period was noted a critical factor in ensuring the quality and quantity of final feedstock conversion (Wiselogel et al., 1996). Feedstock losses, onset by weathering and biochemical reactions, are categorized in terms of dry matter loss and compositional changes (structural and non-structural). The literature gives various post-harvest storage methods as a means to reduce losses of biomass. Post-harvest storage methods are either covered or uncovered, on one of three storage surfaces: 1) well-drained ground, 2) a gravel surface, or 3) a wooden pallet. Location of storage can be on the production field or at an intermediate storage site. During the period of storage, harvest collection method greatly influenced the preservation of biomass. Dry matter storage losses are far greater for covered rectangular bales than uncovered round bales (Larson et al., 2010). Round bales have the ability to shed water, which reduces the need for costly covered storage (Cundiff and Grisso, 2008). Larson et al. (2010) conducted a study, which analyzed the cost of switchgrass post-harvest storage methods, using covered and uncovered storage, on well-drained ground, a graveled surface, and a wooden pallet. Similar to findings in literature, Larson et al. (2010) determined that protecting the bales using a tarp cover, pallet, or gravel surface increased the delivered cost, compared to non-protective storage options (i.e. uncovered storage). Larson et al. (2010) suggests that it was, in fact, more economical to select large uncovered round bales when considering the cost incurred due to biomass storages losses. Sanderson et al. (1997) conducted three experiments on losses of switchgrass stored in the form of large round bales, in protected and unprotected conditions. While average biomass losses for unprotected storage was 5% dry weight loss, biomass losses were reported up to 13% dry weight loss for round bales stored unprotected outside on grass sod. Storage losses were found to be negligible for bales stored inside in protected conditions. Dry matter storage losses in switchgrass bales are, greater for outside bale storage compared to inside bale storage (Sanderson et al., 1997; Shinners et al., 2006; Larson et al., 2010). Wiselogel et al. (1996) also analyzed switchgrass losses of large round bales stored unprotected, outside. The study, however, expanded the previous analysis to include structural and non-structural compositional changes. Results show decreases (8-11%) in extractives content. Brunback et al. (1995) analyzed dry matter losses and compositional changes in string-wrapped and net-wrapped round bales (1.8 m dia. x 1.2 m wide), of two switchgrass varieties, stored outside for 12 months. The study determined that net-wrapped bales shed more precipitation, and as a result were drier than string-wrapped bales.

Due to the limited storability of loose chopped switchgrass, studies have proposed the direct transport of the loose chopped biomass, or loose chopped biomass that has undergone a densification process, directly to the biorefinery (Larson et al., 2010).

Several researchers discuss the use of an intermediate storage location between the production field and the biorefinery. The question of how to flow the chopped material into storage, and then how to empty it from storage for delivery, is unresolved.

2.3 Transport of Herbaceous Biomass

Switchgrass is lower in energy density and bulk density, in comparison to solid and liquid fuel sources. Due to the bulky nature of the raw material, transport cost of switchgrass is relatively high per unit mass. Mode of transporting switchgrass is largely influenced by haul distance. Modes of transporting switchgrass include truck, rail, ship, and pipeline. Searcy et al. (2007) calculated the relative cost for three biomass feedstocks via truck, rail, ship, and pipeline. The study analyzed transportation cost by two components: 1) distance variable cost (DVC), the cost component directly dependent on travel distance, and 2) distance fixed cost (DFC), the cost component independent of the distance traveled. Searcy et al. (2007) suggested it was more economical to consider transport by truck for shorter haul distance, followed by transport via rail, then ship. Sokhansanj et al. (2009) reported truck transport was the least expensive option for distances less than 160-km, and rail was the least for distances greater than 160-km. Concerning the transport of biomass by ship, long distances (1,500-km) were required to offset the high DFC for loading and unloading. Pipelining was determined uneconomical at small scale; furthermore, pipeline transport of biomass was only suitable for specific conversion processes (Searcy et al., 2007; Sokhansanj et al., 2009). Consistent with Searcy et al. (2007), Kumar et al. (2004) concluded transport of chopped biomass, by a carrier medium in a pipeline, was determined to only be economical at either large capacities or medium to long distances (75-km for a one-way pipeline and 470-km for a two-way pipeline).

In addition to the relatively high transportation cost per unit mass for highway hauling, the low bulk density of switchgrass presents challenges in transport and handling switchgrass following harvest, an operation we will refer to as “in-field” hauling. The chosen harvest collection method impacts bulk density. Huisman (2003) and Sokhansanj et al. (2009) determined bulk densities as follows among the three harvest collection methods: 1) for loose chopped biomass, 60-80 kg/m^3, 2) for round baled biomass, 100-130 kg/m^3, and 3) for square baled biomass, 130-160 kg/m^3. In the case of switchgrass, volume is the limiting factor in the allowable transportable load, due to low bulk density. Chariton Valley Biomass Project (2002) advocates the use of the large rectangular bale and highlights successful case studies, due to the large rectangular bale hauling advantage.

Chariton Valley Biomass Project (2002) reported a flatbed trailer (16.15 m long) capable of transporting 42 large rectangular bales (0.91 m x 1.22 m x 2.44 m), or approximately 19 Mg of switchgrass. Kemmerer and Liu (2011) reported that every percent increase in bale density corresponded to a percent increase in the material capacity of the handling and transportation equipment. Densification (pelleting, cubing, or briquetting) is a proposed alternative to reduce transportation cost by increasing the bulk density of switchgrass. Judd (2012) found that densification was not cost effective for transportation distances less than 81-km. Morey et al. (2010) proposed a system that collected and transported round bales to local storage sites. These bales were then ground in a tub grinder and the ground material passed through a roll press to produce briquettes. A key advantage found in this system, over other systems that harvest loose chopped biomass, was the increased bulk density for highway hauling. In addition, the Morey et al. (2010) system specifies that the equipment that processes the bales at the local storage sites be mobile, so that it can move from one storage site to the next. This led to a reduced investment in equipment because it was used over a longer period (more operating hours per year), and equipment cost per Mg was less.

2.4 Simulation of Harvest Operations

Simulations are used extensively to represent the behavior of a system (or some component thereof). Cundiff (1996), Nilsson (1999a; 1999b), and Sokhansanj et al. (2006) have successfully applied simulation tools to model and analyze different operations within the biomass logistics network. Most common in literature are simulation models analyzing independent operations within the logistics network. For example, Cundiff (1996) simulated the performance of five large round bale harvest systems to predict the harvest cost of hay yields above 12 dry Mg/ha. The following baler sizes were utilized: 1.8 m x 1.5 m, 1.8 m x 1.2 m, 1.5 m x 1.2 m, and paired with equipment sets to form a harvest system. Three variations of the 1.8 x 1.5 baler, and a single harvest system of the 1.8 x 1.2, and the 1.5 x 1.2 baler were modeled. The model assumed a fixed field efficiency of the equipment, and accounted for no weather or maintenance delays.

Nilsson (1999a; 1999b) developed a simulation model, Straw Handling Model (SHAM), to analyze harvesting and transportation operations for three districts in Sweden. Performance analysis was achieved with a dynamic simulation model, using SIMAN language in Arena; while, energy and cost were determined statically with a spreadsheet program using Excel. The dynamic simulation model was divided into three core submodels: 1) location, 2) weather and field drying, and 3) harvesting and handling.

Geographical locations (e.g. field and intermediate storage) and site specific data (e.g. straw yields, and area) were established in the location submodel. Field selection randomly assigned fields, uniform straw distributions were assumed. Transportation distances were also included in the location submodel and calculated using the Euclidian distance formula, multiplied by a winding factor to represent the existing road patterns. Data from the location submodel was then retrieved by the harvesting and handling model to determine working capacities for harvesting machinery.

The weather and field-drying submodel continuously exchanged information with the harvest and handling submodel, to determine if the conditions are suitable to perform harvest operations. Field arrival for harvest was described using a Poisson process.

The simulation model represented each field as an entity, with each entity containing the following attributes: field location, field size, straw yield, straw type, initial moisture content, and harvest time. Entities are routed to multiple queues to wait for servicing by the different resources in the system. Attributes of the entity change dynamically as the entities are serviced.

Nilsson and Hansson (2001) modified SHAM to include a daily fuel use, soil moisture content, and early crop growth submodels, for handling of reed canary grass.

The simulation model developed by Sokhansanj et al. (2006) was, perhaps, the first fully integrated model in literature to simulate the biomass logistics network. Sokhansanj et al. (2006) developed the Integrated Biomass Supply Analysis and Logistics (IBSAL) model, using an event-oriented simulation language EXTEND. An Excel spreadsheet was used to import data into the model and generate model output data. IBSAL is a dynamic simulation that models the flow of biomass from field to a biorefinery, through collection, transport, storage and preprocessing. Estimates are given for delivered cost of biomass to a biorefinery ($/Mg) and for energy consumption (MJ/Mg).

ISBAL was structured using a network of operational modules and mathematical equations, which represent a process (e.g. drying, wetting, dry matter loss) or an event (e.g. baling, loading, transporting, stacking, storing) in the biomass supply chain. The model accounts for climatic and operational constraints, and quantifies resource allocations for operations in the biomass supply chain. The main input components featured in the model are spatial information, schedule, daily yield function, daily moisture content function, machine data, and daily weather data. The model generates the following output: Cost, energy input, carbon emission, biomass shrinkage, final quantity of delivered biomass, number of days for each operation, and final biomass moisture content. Hourly weather data from a national database was used to generate daily weather and field conditions. Based on the weather and field conditions, field operations are delayed or permitted. A gamma distribution function in the Excel Solver toolkit was used to estimate the daily percentage of farms harvested.

Several authors have successfully developed models, for various crops of interest, on the IBSAL framework (Kumar and Sokhansanj, 2007; Ebadian et al., 2011; Mobini et al., 2011).

CHAPTER THREE

INPUT

3.1 Harvest Production Region

The production area selected for this study encompasses a 32-km radius surrounding a hypothetical bio-crude plant in Gretna, VA. The harvest region database used to supply the simulation model was originally developed by Resop et al. (2011), and later optimized by Judd (2012). Judd (2012) utilized a mathematical programming-based approach to achieve the following:

1. Optimize the selection of Satellite Storage Locations (SSLs),
2. Establish the optimum order to "load-out" and transport round bales from the SSLs, and
3. Define the number of equipment sets required to load-out and deliver all the biomass stored in SSLs across the region.

The 32-km, (Judd, 2012) dataset considered two equipment systems for handling biomass at the SSLs; the equipment set was either stationed permanently at the SSL, or mobile and thereby traveled from one SSL to another. The study determined the mobile equipment set was the best solution, resulting in a 39.3% reduction in the total transportation distance (from the field to the SSL), as compared to the uniform distribution of SSLs assigned by Resop et al. (2011). Judd (2012) determined the 32-km region required a minimum of 6 sets of load-out equipment (i.e. 6 tours). The database resulted in 141, optimally selected SSLs, within the 32-km radius of Gretna, VA. Figure 3.1.1 displays an image of the load-out schedule for the Judd dataset.

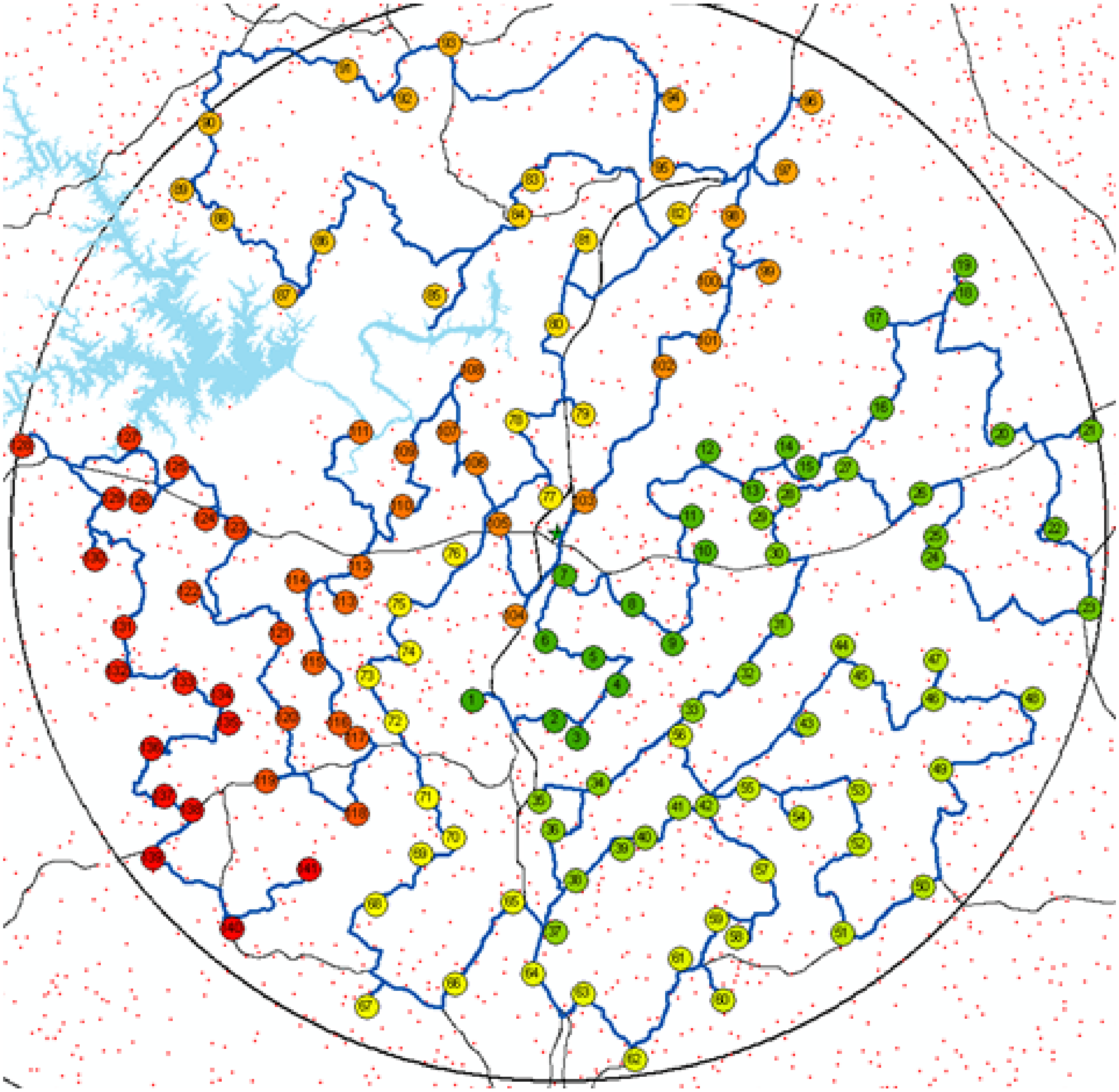

Figure 3.1.1 SSL load out schedule for production region surrounding Gretna, VA.

The 6 sets of load-out equipment translate into six independent tours, which each vary in total production area, number of fields, and number of SSLs (See Appendix A for load-out schedule). The six tours contain 15,438 ha of production area. While there is slight variation in the number of fields, SSLs, and production area of each tour, the tours were arranged such that each tour would contain approximately the same production area. Data for each tour is presented in Table 3.1.1.

Table 3.1.1 Distribution of Tours in Region

	No. of SSLs	Total No. of Fields	Production Area (ha)	% of Total Production Area
Tour 1	21	115	2,513	16.3
Tour 2	23	118	2,650	17.2
Tour 3	25	103	2,669	17.3
Tour 4	23	111	2,552	16.5
Tour 5	25	126	2,579	16.7
Tour 6	24	109	2,475	16.0

Tour 6 contains the smallest production area, and consists of approximately 16% of the total production area. In Tour 6, field sizes range from 6 to 97 ha. Tour 1, is the next smallest tour, following Tour 6. Field sizes in Tour 1 range from 6 to 153 ha. Tour 4 and Tour 5 are closely proportioned in production area, and consists of 16.5% and 16.7% of the total production area in the region, respectively. Field sizes range in Tour 4 from 6 to 156 ha. Field sizes in Tour 5 range from 6 to 105 ha. Tour 2 is the next to the largest tour, in terms of production area. Field sizes in Tour 2 range from 6 to 86 ha. Tour 3 contains the largest production area, and consists of approximately 17.3% of the total production area. Field sizes in Tour 3 range from 6 to 88 ha. Across all six tours in the region, the minimum field size is 6 ha, with each of the six tours containing at least one field of size 6 ha. The maximum field size is 156 ha, contained in Tour 4. The distribution of field sizes is displayed within each tour in Figure 3.1.2. Field sizes are displayed on the y-axis, and the field number is displayed on the x-axis.

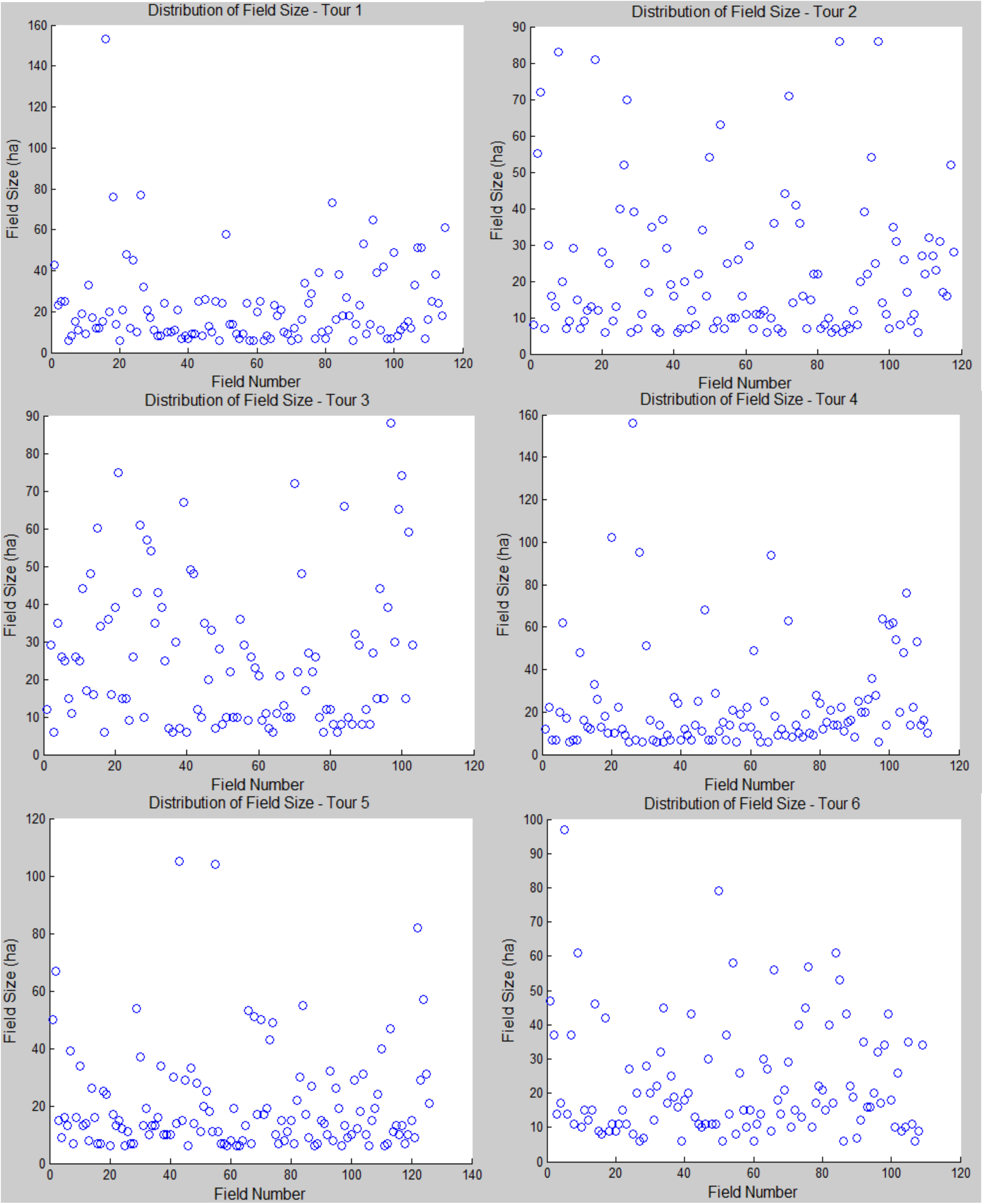

Figure 3.1.2 Field Size distributions for Tours 1-6.

3.2 Harvest Input Parameters

3.2.1 Probability Work Day

As suggested by Cundiff et al. (2011), the assumed probability of work day (PWD), and available work hours for each month is given in Table 3.2.1.1. The PWD featured in Table 3.2.1.1 account for the limited harvest period during winter months, when field conditions are such that less than 7 days are available for baling, as well as the increased harvest opportunity in the earlier period of the harvest season (July, August, and September). In the earlier period of the harvest season, there are potentially more than 14 work days available. The PWD does not consider harvest operations during the period of plant regrowth, April – June.

Table 3.2.1.1 Available work hours for the round baler.

	Round Baler	
Harvest Month	PWD	Available Work Hours (h)
#1-Jul	0.51	150
#2-Aug	0.48	150
#3-Sep	0.46	150
#4-Oct	0.42	120
#5-Nov	0.34	90
#6-Dec	0.43	56
#7-Jan	0.19	41
#8-Feb	0.20	49
#9-Mar	0.23	49

3.2.2 Harvest Scenarios

The four harvest scenarios do not represent all available options, but they do show the impact of harvest on number of units required to complete the harvest operations within a given time frame. Based on tradeoffs associated with the selection of a harvest window, as discussed in Chapter 2, this analysis considered four harvest scenarios, briefly described as follows:

1. Scenario-1 , a heavy summer, extended harvest,
2. Scenario-2, a light summer, extended harvest
3. Scenario-3 a delayed, short winter harvest, and
4. Scenario-4, a delayed, extended harvest.

The decimal quantity of total harvest completed during each month, in Scenarios 1-4, is given in Table 3.2.2.1.

Table 3.2.2.1 Harvest schedule for Harvest Scenarios 1-4.

	Harvest Scenario			
Harvest Month	1	2	3	4
#1-Jul	0.19	0.01	0	0
#2-Aug	0.179	0.06	0	0
#3-Sep	0.166	0.13	0	0
#4-Oct	0.141	0.21	0.46	0
#5-Nov	0.098	0.17	0.32	0.31
#6-Dec	0.07	0.13	0.22	0.22
#7-Jan	0.05	0.09	0	0.14
#8-Feb	0.047	0.09	0	0.14
#9-Mar	0.06	0.1	0	0.18
#10-Apr	0	0	0	0
#11-May	0	0	0	0
#12-Jun	0	0	0	0

Harvest Scenario-1 is described as a “heavy summer, extended harvest” scenario. This scenario assumes that all of the available hours shown in Table 3.2.1.1 can be effectively used for harvest operations and the monthly harvest of the land area follows a near approximate percentage as the available work days. During the summer months (July through September), over half of the total production area is scheduled for harvest. The remaining half is scheduled during the late fall and winter months. Harvest Scenario 1 contains a total of 855 available work hours.

Harvest Scenario-2 is described as a “light summer and spring, extended harvest” scenario. Approximately half of the harvest operations take place October through December, with the remaining harvest during the summer months (July through September) and late winter, early spring months (January through March) accounting for the remainder of the harvest operations. Harvest Scenario 2 contains a total of 855 available work hours.

Harvest Scenario-3 is described as a “delayed, short winter harvest” scenario. Scenario 3 is designed to accomplish all of the harvest in the late fall, thus avoiding the yield reduction that results from winter weather degradation of the crop. During the month of October, roughly half (46%) the total production area is scheduled for harvest. Harvest Scenario 3 contains a total of 266 available work hours.

Harvest Scenario-4 is a delayed summer, extended harvest. It is expected that fields using Scenario 4 will not require as much replacement fertilizer, and this is a cost benefit to the farmer that helps offset some of the yield loss that results from the Nov-Mar harvest. In addition, Scenario 4 represents less time competition with other farming activities for the available machinery and labor use. Harvest Scenario 4 contains a total of 285 available work hours.

The analysis assumed the annual yield rate of switchgrass to be 13.4 Mg/ha (Judd, 2012).

3.2.3 Equipment Capacity

The operational parameters assumed for the round baler is given in Table 3.2.3.1.

Table 3.2.3.1 Field capacity and field efficiency for the round baler (Cundiff et al., 2011).

Harvest System	Field Capacity (Mg/h)	Field Efficiency	Maximum Annual Hours of Use, A
Round Baler	12.25	0.694	420

3.2.4 Simulation Length

The total simulation time of the model is 901 hours. This level of resolution allows the user to capture the flow of biomass from the field to the storage location throughout the entire harvest season with a reasonable level of detail. Table 3.2.4.1 shows the simulation time steps and the corresponding simulation completion time for Months 1-12. Note, simulation time step is indicated by a lowercase “s”, while simulation time is indicated by an uppercase “S”. Each time step in the simulation model represents one hour. Additional detail is provided on the model simulation time components in Section 4.1.1.

Table 3.2.4.1 Simulation Time Steps for Months 1-12.

Harvest Month	Simulation Time Step, s, (h)	Simulation Time, S, (h)
#1-Jul	0-149	150
#2-Aug	150-299	300
#3-Sep	300-449	450
#4-Oct	450-569	560
#5-Nov	560-659	660
#6-Dec	660-715	716
#7-Jan	716-756	757
#8-Feb	757-805	806
#9-Mar	806-854	855
#10-Apr	855-870	871
#11-May	871-885	886
#12-Jun	886-900	901

CHAPTER FOUR

MODEL DESCRIPTION

The Field Harvest System (FHS) simulation model was designed and executed in MATLAB/Simulink/SimEvents, Version 4.0 (R2011b). The Simulink/SimEvents environment was chosen to provide the user maximum utility of the model. SimEvents, the discrete-event simulation and component library for Simulink, was used to develop the core structural components of the FHS model; however, a combination of discrete and continuous time elements was integrated to achieve the desired model behavior. The FHS model simulates the impacts of the employed harvest scenario, on baler equipment requirements, across a harvest production region. The harvest and filling of a Satellite Storage Location (SSL) is simulated using conventional hay harvest equipment, specifically, a round baler.

As discussed in Chapter 2, the logistical operations surrounding the harvest of switchgrass are quite complex. Currently, no standard tools exist which generate estimates for baler equipment requirements, at the field level, while simultaneously accounting for the factors associated with the seasonality of switchgrass. Grisso et al. (2012) offered global baler estimates to harvest a production region, which considered total regional production area and baler capacity data. This simulation tool will provide enhanced detail, as compared to the global estimates previously derived, to define baler requirements. A range of field sizes contained in the harvest region are accounted for in the simulation. The simulation tool used for this study provides a resource that can benefit both the biorefinery and the landowner.

The FHS model is divided into three core subsystems: (1) the Demand Generation Subsystem (DGS), (2) the Farmgate Operation Subsystem (FOS), and (3) the SSL Operation Subsystem (SOS). Each of the three subsystems contains smaller operational modules, which support the functionality of the core subsystem. In particular, the Resource Management Subsystem (RMS), is contained in the FOS, and is a key component in the model. A schematic of the interaction between the core subsystems, and operational modules, of the FHS model are highlighted in Figure 4.1.

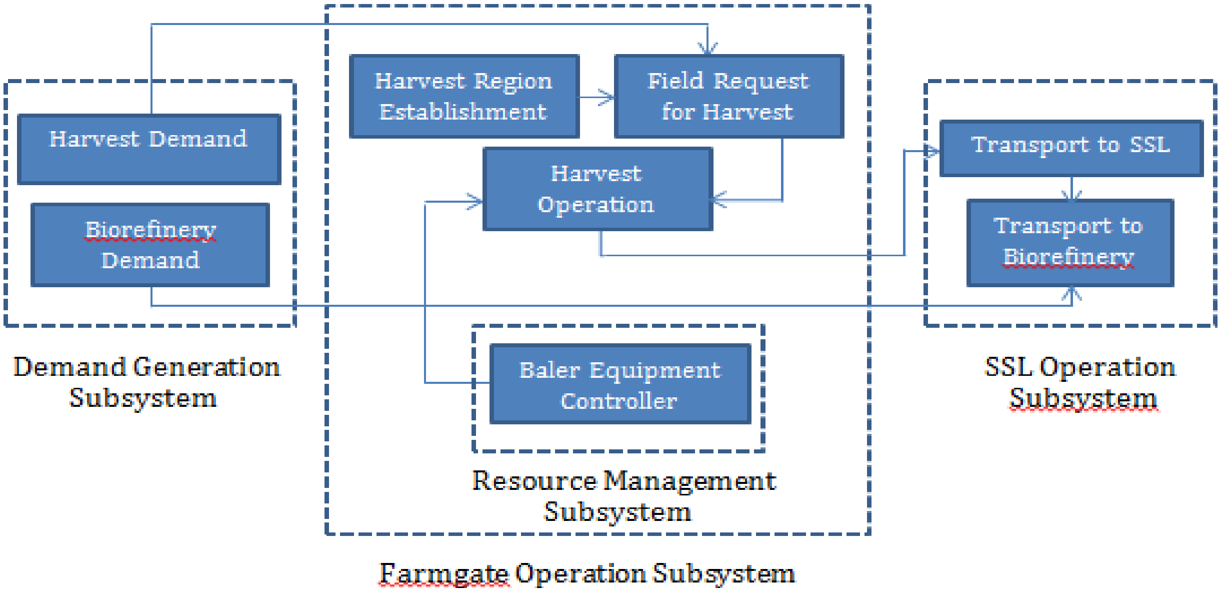

Figure 4.1 Components of simulation model.

The input data is defined prior to the start of the simulation. This input dataset defines the key parameters of the harvest region. Input data was imported from Microsoft Excel spreadsheets into MATLAB. A combination of MATLAB M-files and signals were supplied to the simulation model, either directly or indirectly via the MATLAB workspace. Model inputs and outputs are summarized in Figure 4.2. More detail on these inputs and outputs will be given later.

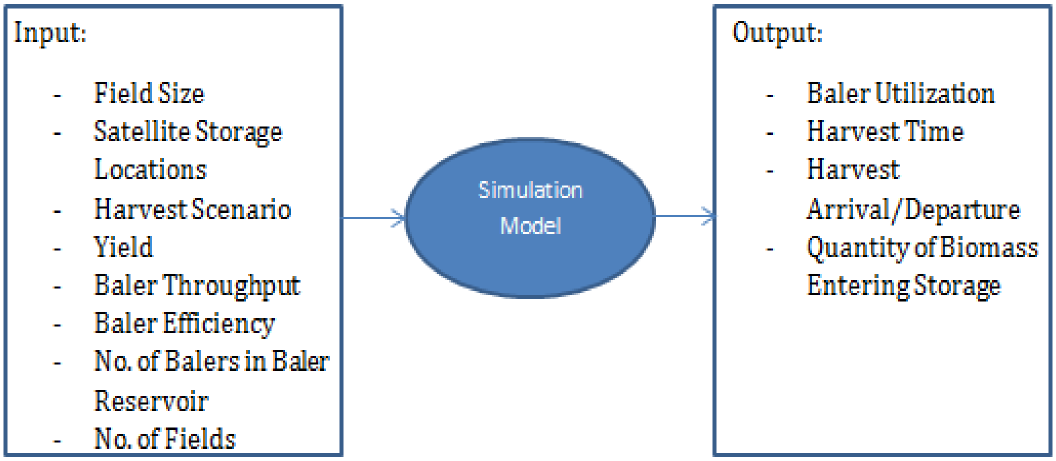

Figure 4.2 Model inputs and outputs.

In addition to input parameters (described in Chapter 3), the following assumptions were used in the development of the model:

1. The SSL unload scheduling sequence, previously established by Judd (2012), is used. (This sequence is hereafter referred to as the "load-out" sequence.)
2. In the scheduling of field harvest operations, priority is given to fields that supply the next SSL in the load-out sequence.
3. Partial field harvest is not permitted. Once harvest of an individual field begins, harvest operations are not permitted to stop.
4. Harvest operations are simulated using one, two, three or four balers per field.
5. No considerations are given to scheduled routine maintenance, equipment breakdowns, or mobilization time to move between fields.
6. The FHS model monitors a single baler per field harvest operation.

The structural components of the model, model behavior, and the underlying mathematical components of the model are detailed in this chapter.

4.1 FHS Model Construct

The three major components of a discrete event system, as described by Chung (2004), are as follows:

- Entities,
- Queues, and
- Resources.

The FHS model was constructed using the following two entities: (1) a field entity, and (2) a baler entity. Queues were used to provide waiting and holding areas for the entities, and to sort the entities by field size, as needed. Resources in the FHS model consisted of single servers, and infinite servers. The infinite servers were used to service (i.e. harvest) the field/baler entity. The infinite servers delayed field/baler entities for a period of time, which corresponded to the harvest time of the field undergoing service. Single servers were required in certain sequences of block operations to ensure the simulation behavior was executed correctly. This was a feature of the software. It should be noted, an alternate model construct would have been to model balers as resources (i.e. servers). In the FHS model, it was determined to be most suitable to model balers as entities, given the field/baler assignments, quantity of balers, and the level of detail that was required.

Figures 4.1.1 and 4.1.2 are organized according to the subsystems in the model, and show the movement of the field and baler entity throughout the FHS model. In addition, the rectangular blocks are used to represent processes, the orange diamonds represent decisions that are made in the system, the orange arrows represent the flow of an entity, and the black dashed lines represent the flow of data. In Figure 4.1.1 harvest demand data is supplied from the DGS to the production region. A field entity remains in the production region until requested for harvest. The harvest demand is the driver of the initial movement of the field entity. The harvest demand triggers the field entity request, and a release gate permits the subsequent arrival for harvest. Following the field entity arrival for harvest, the field entity waits for a baler assignment. After a baler entity is assigned, the field/baler entity proceeds with the scheduling of harvest. The number of balers required (one, two, three or four) to complete harvest of a given field, prior to the end of the user specified demand interval, is determined. The field/baler entity harvest takes place. Finally, the biomass from the harvested field is transported to its assigned SSL, where it waits in storage.

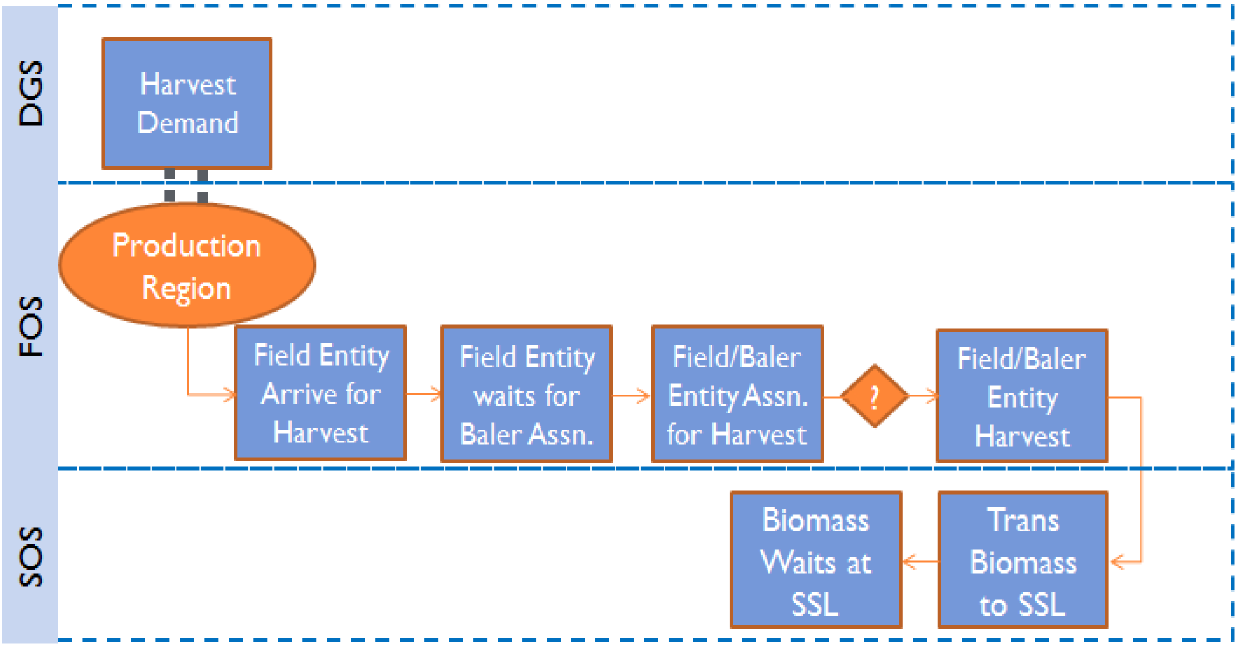

Figure 4.1.1 Field entity movement in the FHS model.

In Figure 4.1.2 baler equipment controller data is supplied from the RMS, to the Variable Capacity (VC) queue. The VC queue controls the initial release of additional baler entities in the system, above the quantity specified by the baler equipment controller. (Additional discussion is provided on the VC queue in Section 4.6.2). As stated, the Baler Reservoir is the establishment location of all the balers in the harvest region. A baler entity remains in the Baler Reservoir until it is released by the VC queue, and assigned a field entity. Following the assignment of a baler to a field entity, the field/baler entity proceeds with the scheduling of harvest. The number of balers required to complete harvest, prior to the end of the user specified demand interval, is determined. The field/baler entity harvest takes place. Following harvest, it is determined if the baler will be assigned any additional fields, before being returned to the Baler Reservoir. Alternatively, if the baler has exceeded its annual use, it will be *Down*, and receive no additional field assignments (Figure 4.1.2).

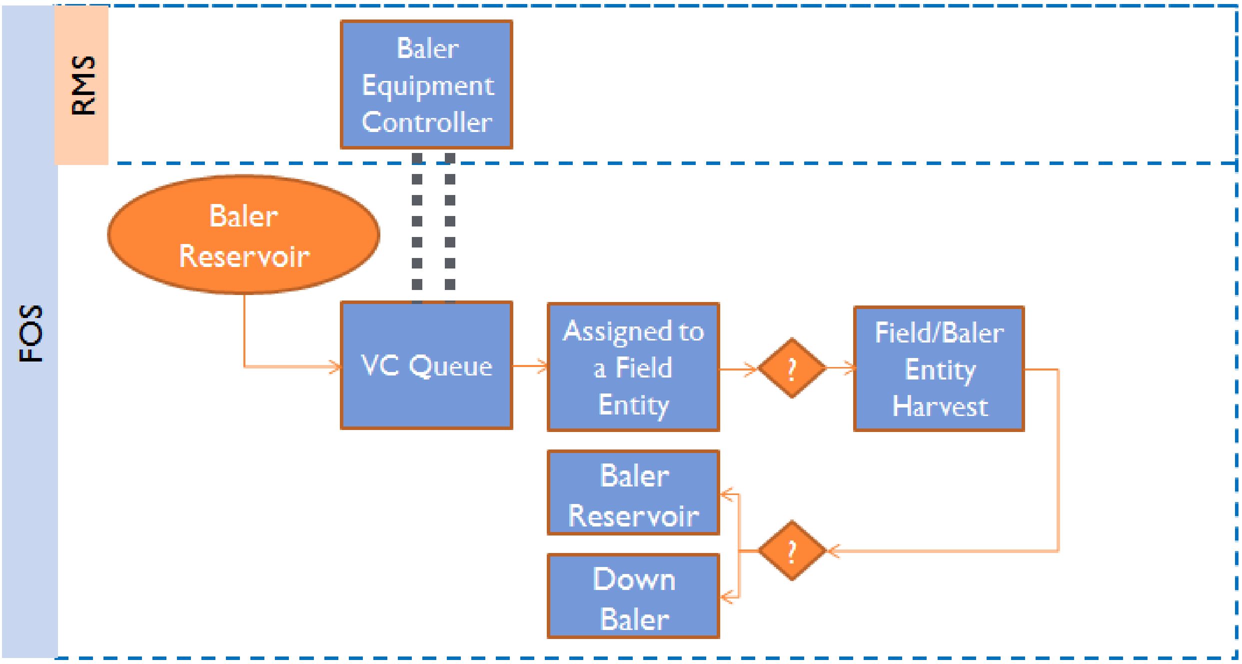

Figure 4.1.2 Baler entity movement in the FHS model.

The movement of the field and baler entities, highlighted in Figures 4.1.1 and 4.1.2, prompt the occurrence of events to take place. The key events in the FHS model are as follows:

1. Event 1- Assignment of a baler entity to a field entity for servicing (i.e. harvesting), and

2. Event 2- Server completion of the field/baler entity.

Between Events 1 and 2, the field entity transforms from being classified as an unharvested field to a harvested field. Simultaneously, the occurrence of Events 1 and 2 prompt a state change of the baler entity. The FHS model identifies the following four baler entity states:

1. *Idle* – a baler, previously used in the system, awaits field assignment in the Baler Reservoir.

2. *Busy* – a baler entity is assigned a field entity, and is engaging in, or scheduled to engage in harvest.

3. *Down* – a baler entity is prevented from receiving any additional field assignments, due to the baler exceeding its maximum annual use (A).

4. *Standby* – an unused baler is on reserve for potential use in the Baler Reservoir, in the event that field assignments cannot be achieved using the current number of *Idle* balers.

Note, both *Standby* and *Idle* balers are in the Baler Reservoir. However, *Standby* indicates a new, unused baler entity, while *Idle* indicates the baler has previously been used in the system, but has no current field assignment.

Event 1 prompts the state change of the baler entity from either *Standby* to *Busy*, or from *Idle* to *Busy*, provided a baler is accessible. However, the rate at which the baler entity state changes from either *Standby* to *Busy*, or from *Idle* to *Busy*, depends on the conditions of the model. Model conditions include: (1) the total number of baler entities in the region, (2) the number of field entities waiting for a baler entity assignment, (3) the number of *Idle* baler entities, (4) the number of current field/baler entity assignments, and (5) number of balers estimated by the baler equipment controller. When a field/baler completes harvest, Event 2 prompts the state change of the baler entity from either *Busy* to *Down*, or *Busy* to *Idle*. The rate at which the state change occurs, following Event 2, is immediate. However, if a baler enters into an *Idle* state, the amount of time the baler entity remains in the *Idle* state, again depends on the conditions of the model. Following a baler entity state change to *Down*, the baler remains in this state for the remainder of the simulation run.

Figures 4.1.3 and 4.1.4 describe the process flow of the FHS model. The FHS model retrieves the parameters that were initialized by the user (see Figure 4.2 for model input) to establish the production region, and the Baler Reservoir. The harvest demand is generated at the interval(s) specified by the user. Following which, the system determines if the harvest demand has been met. If the demand has not been met, and there are field entities in the region that have not been requested for harvest, an additional field entity is requested for harvest and the number of field entities requested for harvest increments by one. Once the demand is met, and/or all of the field entities in the region have been requested for harvest, the field entity waits to be assigned a baler for harvest. If a baler is not accessible, the field entity waits until a baler becomes accessible. If a baler is accessible, the field entity is assigned a baler entity, and the field/baler entity proceeds with the scheduling of harvest. It is next determined if additional balers are required, above the quantity generated by the baler equipment controller. For each field/baler entity scheduled for harvest, it is determined, if one, two, three, or four times the baler capacity will be required to complete harvest, prior to the end of the user specified demand interval. Harvest takes place, using the determined number of balers required. The field entity is routed to its assigned SSL, where is waits in storage. The baler is returned to the Baler Reservoir, to await field reassignment, if the baler has remaining use. The baler entity is routed to a containment area, to prevent reassignment to an additional field, if it is determined that the baler has exceeded its maximum annual use.

Figures 4.1.1 and 4.1.2, which detail the field and baler entity movement, provide useful insight in understanding the triggering mechanisms of the processes highlighted in Figure 4.1.3 and 4.1.4. By examining Figure 4.1.1, it is shown that the harvest demand, generated in the DGS, triggers the initial movement of the field entity. Movement of each field entity begins at the field request for harvest, and ends at the placement of the field harvested biomass into the assigned SSL (Figures 4.1.3 and 4.1.4, Steps 4-19). By examining Figure 4.1.2, it is shown that the baler equipment controller, generated in the RMS, triggers the initial movement of the baler entity. Movement of the baler entity begins at the baler entity assignment to a field entity for harvest (Figure 4.1.3, Step 10). In contrast to the field entity, each baler entity utilized in the system, has the potential to be reused throughout the entire simulation model. Each field entity has a discrete finish time, following the completion of field harvest and transport of bales to the SSL.

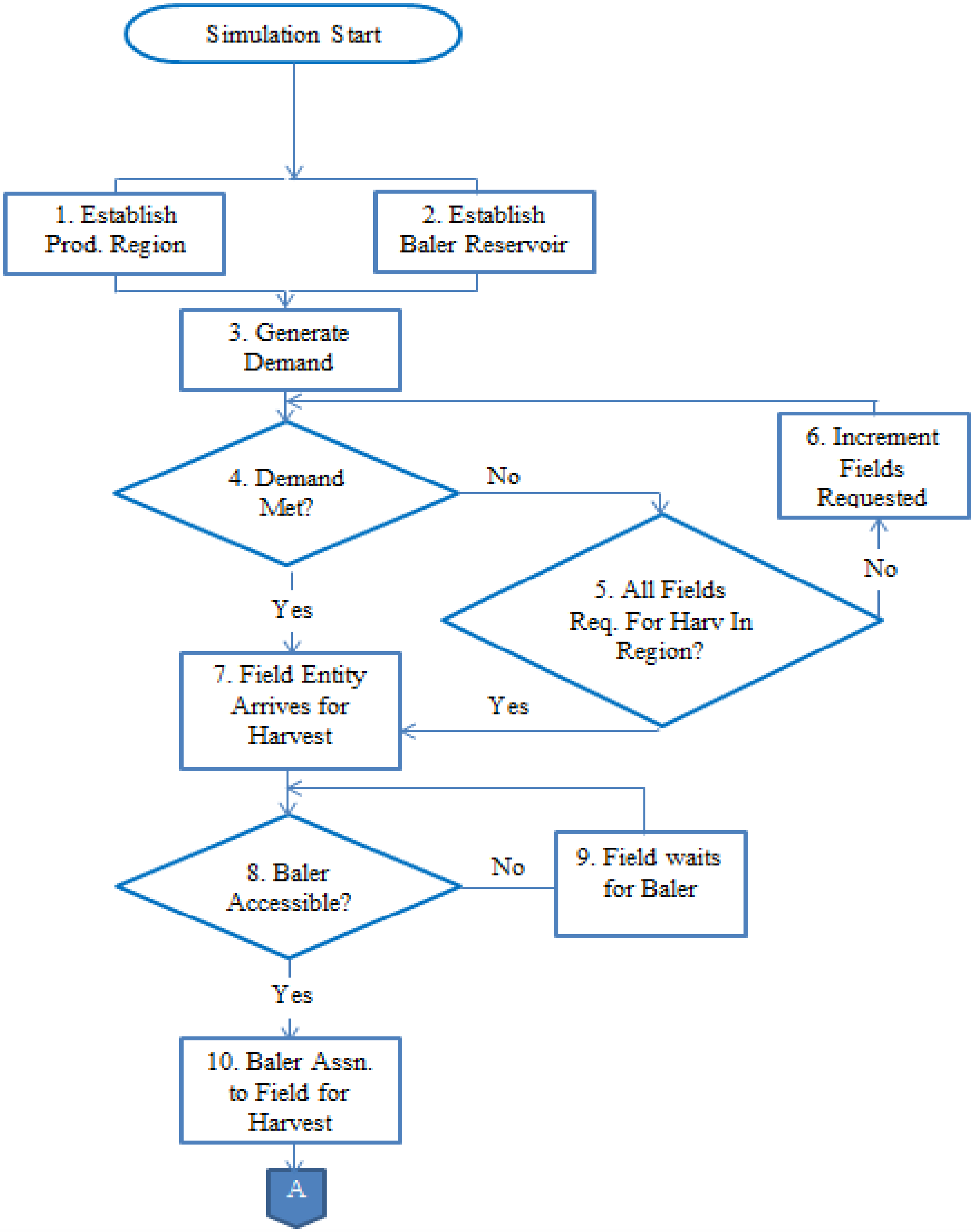

Figure 4.1.3 Simulation flowchart.

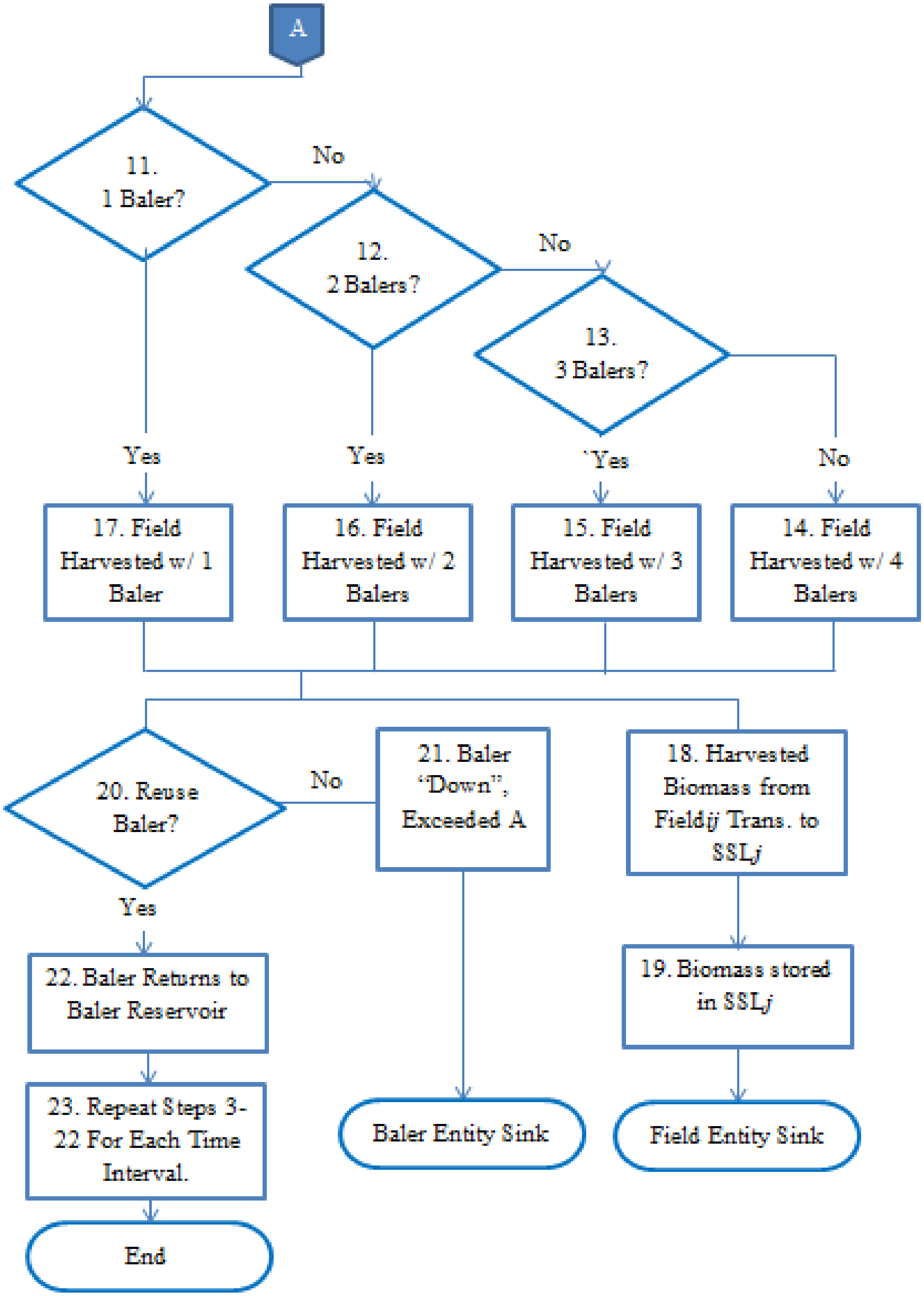

Figure 4.1.4 Figure 4.1.3 continued.

Up to this point, figure representations have been used to describe the model behavior. In the sections to follow, the mathematical representation of the model components will be presented to further guide the reader on the FHS model behavior. Figures 4.2 and 4.1.1-4.1.4 will be used as aides to orient the reader. Each of the processes presented in the preceding figures is described in the following sections.

4.1.1. Simulation Time Parameters

To facilitate discussion, the description of the model will use the units defined in the input parameters (refer to Chapter 3) in Sections 4.6 to 4.10. It is appropriate to recap the time parameters. The total simulation time of the model is 901 hours. The time interval t in the simulation is one month. The time step in the simulation, s, is one hour. It should be noted that time step in the FHS simulation model is used to govern the available time in time interval time interval t, $T_{av,t}$ and to calculate the remaining work time in the simulation model, $T_{rem,t}$. Figure 4.1.1.1 displays the simulation time, S, for each month in the simulation model. In the FHS model, harvest demands are supplied from the beginning of July to the end of March. Recall, the beginning of April to the end of June is the regrowth period and no harvest operations take place during this time. Throughout the harvest period (July to March), harvest operations can and do occur at a fraction of an hour. The available time in time interval t, $T_{av,t}$, corresponds to the simulation time length of each time interval t. The available time in time interval t, $T_{av,t}$, is used throughout the simulation run to determine the accumulated available work time, $T_{c,t}$, (Equations (4-14) and (4-15)). The accumulated available work time, $T_{c,t}$, and the available time in time interval t, $T_{av,t}$, are used to calculate the remaining work time at simulation time step s, $T_{rem,s}$ (Equation (4-16)).

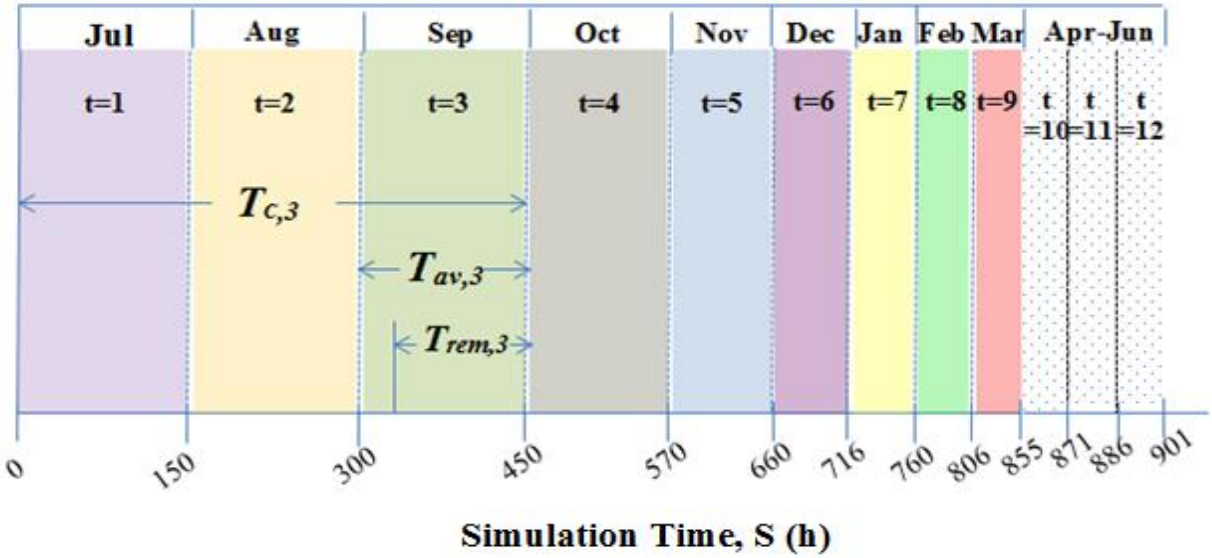

Figure 4.1.1.1 Simulation Time Parameters

4.2 Production Region Establishment

Data for each harvest sub-region (i.e. tour), includes SSLs, number of fields assigned to each SSL, and field sizes, was supplied to the model by a MATLAB function file (M-file). Using data generated in the M-file, the simulation model established the harvest region by the Entity Pre-Allocation simulation method. The Entity Pre-Allocation method, pre-allocated all of the field entities in the production region. Given that the production region was previously established and defined, this was straightforward At the start of the simulation, F fields are generated as entities, and grouped according to the N SSL assignments, which are arranged in the order of the SSL load-out sequence. (Appendix A gives the SSL load-out sequence.) The number of fields pre-allocated to a given SSL was defined by a script in the M-file. The script contained a MATLAB function, which counted the number of fields assigned to each of the N SSLs. The function was supplied to a Function-Call Generator, found in the Simulink/SimEvents toolbox. The field attributes assigned included field number, field size, SSL assignment, and field efficiency for baling (assigned based on field shape and size). A priority queue scheduling discipline, which permitted the departure of the largest fields first, was applied to each field grouping. This means that the largest field assigned to an SSL was harvested first, then the next largest, and so forth until all fields were harvested.

4.3 Harvest Equipment Establishment

The Baler Reservoir establishes the location of all the balers in the harvest sub-region. The Baler Reservoir is a queue, which contains *K* finite harvest equipment resources (i.e. balers), generated at the start of the simulation model. The scheduling discipline is first-in, first-out (FIFO). Each baler is modeled as a single entity, using the Entity Pre-Allocation method described in Section 4.2. The *K* quantity of balers, specified at the start of the simulation model, is a fixed parameter, and services the harvest sub-region for the duration of the simulation model. Preferably, the number of baler entities generated is a large quantity to ensure there is an adequate number of balers to service the entire harvest sub-region. Any additional balers, above the quantity of balers required to service the harvest sub-region remain in the Baler Reservoir, and are not included in any of the utilized baler calculations. The FHS model consists of *K* balers subject to the following operational constraints:

1. A baler is assigned a maximum annual use, (A).
2. Harvest operations are not subject to interruption, after a baler begins to service a field.

4.4 Demand Generation Subsystem

As displayed in Figure 4.2, the DGS is responsible for generating the harvest demand, and the biorefinery demand. While the current edition of the FHS model, does not activate the biorefinery demand operational module, it is useful to understand the behavior of the module. Sections 4.4.1 and 4.4.2 mathematically describe the behavior of the harvest and biorefinery demands, respectively.

4.4.1. Harvest Demand

As stated above, the harvest demand is the driving component of the initial field movement in the FHS. The Harvest Demand module generates, Hd_t, the harvest schedule demand for the time interval(s) specified by the user in the FHS model (e.g. daily, weekly, monthly, etc.), using the following equation:

$$Hd_t = P_t R\,Y \tag{4-1}$$

Where, Hd_t = harvest schedule demand (Mg) for time interval *t*, *t* = {1, …, T},

P_t = proportion of harvest demanded from procurement region (dec) for time interval *t*, *t* = {1, …, T},

R = total procurement area (ha), and

Y = average yield (Mg/ha).

The accumulated scheduled demand, Td_t, at each time interval, is given by:

$$Td_t = Td_{t-1} + Hd_t \tag{4-2}$$

Where, Td_t = accumulated harvest scheduled at the *t* time interval (Mg), and

Td_{t-1} = accumulated harvest scheduled at the *t*-1 time interval (Mg), and

Hd_t = harvest schedule demand for time interval *t* (Mg).

The accumulated harvest schedule demand at the end of each time interval, Td_t, is supplied to the Farmgate Operation module to govern field request and subsequent assignments. Specifically, the FHS model supplies the demand values to the storage locations (i.e. SSLs), which contain the field entities in the harvest production region. The FHS model cycles through all the SSLs, in the order of the SSL load-out sequence, to transfer any potential unmet harvest schedule demands to subsequent SSLs in the production region (as explained in Equations (4-3) to (4-9).

The mass quantity of biomass on a field *i* in SSL *j* is given by the following:

$$Q_{fld,ij} = ha_{ij}Y \tag{4-3}$$

Where, $Q_{fld,ij}$ = mass quantity of biomass on field *i* in SSL *j* (Mg), ∀i = 1,…, F_j, ∀j = 1,…, *N*,

ha_{ij} = size of production field *i* in SSL *j* (ha) ∀i = 1,…, F_j, ∀j = 1,…, *N*, and

Y = average yield (Mg/ha).

Using the mass quantity on a field, $Q_{fld,ij}$, the total mass storage quantity of biomass for each SSL is given by:

$$Q_{tot,j} = \sum_{i=1}^{F_j} Q_{fld,ij} \tag{4-4}$$

Where, $Q_{tot,j}$ = total mass quantity of biomass for SSL *j* (Mg), ∀*j* = 1,…, *N*.

(F_j is the total number of fields assigned to SSL*j*.)

The total quantity of biomass for each SSL is calculated at the beginning of the simulation. This value is a constant, and does not change throughout the simulation. All fields in the production region are generated at the start of the simulation, and grouped according to the SSL assignment. As demands are supplied to the FOS, the total mass quantity of fields that are requested for harvest is deducted from the total mass quantity of biomass for its assigned SSL. The result is the remaining amount of biomass, that is unharvested, for any given SSL.

During time interval *t*, f_{Rj} fields in SSL*j* are requested for harvest. The total mass quantity of biomass on fields, assigned to SSL *j*, that have been requested for harvest during time interval *t*, is given by:

$$Q_{req,jt} = \sum_{i=1}^{F_j} ha_{R,ijt} Y \tag{4-5}$$

Where, $Q_{req,jt}$= total mass quantity of biomass on fields, assigned to SSL *j*, that have been requested for harvest during time interval *t*, *t* = {1, …, T}, (Mg), and

$ha_{R,ijt}$ = size of production field *i* in SSL *j* requested for harvest during time interval *t*, *t* = {1, …, T}, (ha).

(field *i* is the next largest unharvested field assigned to SSL*j*.)

For *t*=1, the total remaining mass quantity of biomass on fields that have not been requested for harvest (i.e. this represents all unharvested fields), for SSLj, is given by:

$$Q_{rem,j1} = Q_{tot,j} - Q_{req,j1} \qquad (4\text{-}6)$$

Where, $Q_{rem,j1}$= total remaining mass quantity of biomass on fields, assigned to SSL *j*, at that have not been requested for harvest, at time interval *t* =1 (Mg).

For *t*>1, the total remaining mass quantity of biomass on fields that have not been requested for harvest (i.e. this represents all unharvested fields), for SSL *j*, is given by:

$$Q_{rem,jt} = Q_{rem,jt-1} - Q_{req,jt} \qquad (4\text{-}7)$$

Where, $Q_{rem,jt}$ = total remaining mass quantity of biomass on fields, assigned to SSL *j*, at that have not been requested for harvest, at time interval *t*, *t* = {2, …, T}, (Mg).

$Q_{rem,jt-1}$= total remaining mass quantity of biomass on fields, assigned to SSL *j*, at that have not been requested for harvest, at time interval *t*-1 (Mg).

In the case of SSL *j*=1, the incoming harvest schedule demand is provided by the accumulated harvest schedule demand, Td_t. For SSL *j*=1, the remaining unmet harvest scheduled demand, $S_{dem,jt}$, at time interval *t*, is given by:

$$S_{dem,1t} = \begin{cases} 0, & if\ Q_{rem,1t} \geq Td_t \\ Td_t - Q_{rem,1t}, & if\ Q_{rem,1t} < Td_t \end{cases} \qquad (4\text{-}8)$$

In the case of SSL *j* >1, the incoming harvest schedule demand is provided by the unmet harvest schedule demand, from the previous SSL, $S_{dem,j-1,\mathrm{t}}$. As described, the accumulated harvest schedule demand values are supplied to the SSLs, which contain the fields in the harvest production region. The FHS model cycles through the SSLs, to transfer any potential unmet harvest schedule demands to subsequent SSLs in the production region.

For SSL j >1, $S_{dem,jt}$, is given by:

$$S_{dem,jt} = \begin{cases} 0, & if\ Q_{rem,jt} \geq S_{dem,j-1,t} \\ S_{dem,j-1,t} - Q_{rem,jt}, & if\ Q_{rem,jt} < S_{dem,j-1,t} \end{cases} \tag{4-9}$$

4.4.2. Biorefinery Demand

The Biorefinery Demand module generates, Pd_t, the plant demand for the time interval(s) specified by the user in the FHS model (e.g. daily, weekly, monthly, etc.), using the following equation:

$$Pd_t = \frac{R\,Y}{T} \tag{4-10}$$

Where, Pd_t = biorefinery demand (Mg) for time interval t, t = {1, …, T},

T = number of time intervals (integer),

R = total procurement area (ha), and

Y = average yield (Mg/ha).

Note that Equation (4-10) generates a constant value throughout the entire simulation run. When enabled, Pd_t, governs the release of harvested biomass to be transferred from the SSLs to the biorefinery. Therefore, it is assumed equal amounts of biomass will be transferred from the SSLs to the biorefinery every demand interval. The Biorefinery Demand value is an integrated subsystem, but inactive component of the current model. This feature will be enabled in future editions of the model.

4.5 Demand Fulfillment

In the FHS, all field entities requested for harvest proceed to be scheduled for harvest, and classify as having contributed towards meeting the harvest schedule demand. Immediately following a field entity's request for harvest, the field waits for a baler assignment. The number of field entities requested for harvest, f_{Rj}, is governed by the demand values (refer to Equations (4-3) to (4-9) for demand value calculations). As displayed in Figure 4.1.3, if it is determined that the scheduled harvest demand has not been fulfilled, and there are fields in the harvest region that have not been requested for harvest, the number of fields requested for harvest is incremented by one. The number of fields requested for harvest continues to be incremented, until the harvest demand is fulfilled, or there are no fields remaining in the harvest region that have not been requested for harvest. In the model this is achieved by the release of one field, using a release gate. The gate permits the release of a field while the quantity of biomass requested for harvest, is less than the scheduled harvest demand.

For SSL j=1, field request for harvest is permitted while the quantity of biomass requested for harvest from SSL j, $Q_{req,jt}$, is less than the cumulative harvest schedule demand, Td_t ($Q_{req,1t} < Td_t$). For SSL *j* >1 field request for harvest is permitted while the quantity of biomass requested for harvest from SSL j, $Q_{req,jt}$, is less than the unmet harvest schedule demand, from the previous SSL, $S_{dem,j-1,\mathrm{t}}$, ($Q_{req,jt} < S_{dem,j-1,\mathrm{t}}$).

As described above, fields are requested for harvest, while the harvest requested amount is less than the harvest demand. As a result, in most cases, $Q_{req,t}$, the total mass quantity of biomass on all fields that are to be harvested during time interval *t*, is greater than the incoming harvest demand. The total mass quantity of biomass on all fields that are to be harvested, $Q_{req,t}$, is determined by the following:

$$Q_{req,t} = \sum_{i=1}^{F_t} ha_{R,it} \tag{4-11}$$

Where, $Q_{req,t}$ = total mass quantity of biomass on all fields that are to be harvested (Mg) for time interval t, t = {1, …, T},

$ha_{R,it}$ = total mass quantity of biomass on field *i* requested for harvest (Mg) in time interval t, t = {1, …, T}.

4.6 Resource Management Subsystem (RMS)

The two main components of the RMS are the baler equipment controller, and the variable capacity queue. The RMS is structured utilizing Equations (4-12) to (4-17), in the

MATLAB/Simulink environment to estimate the baler equipment requirements for the harvest sub-region. As observed in Figure 4.1.2, the RMS governs the baler entity movement throughout the FHS model. Sections 4.6.1 and 4.6.2 describe the behavior of the baler equipment controller, and the variable capacity queue, respectively.

4.6.1. Baler Equipment Controller

As stated, the global baler estimates generated are used as a guiding parameter to control the release of balers in the FOS. The estimate for the number of single balers required, $B_{est,t}$, are generated at the time the field entity arrives in the holding queue, to wait for a baler assignment (Equation (4-12)) . The baler estimates are global estimates, and are assumed to be the minimum number of single balers required to harvest the subset of the production region scheduled for harvest. The global baler estimate considers the total available time, at each time interval, *t*, in the simulation model. Baler equipment controller data is supplied to the Variable Capacity (VC) queue. The FHS model generates the global baler estimates, using the following equation:

$$B_{est,t} = \frac{Q_{req,t}}{T_{av,t}\, B_c\, F_{e,i}} \tag{4-12}$$

Where, $B_{est,t}$ = total number of global balers estimated for month *t*,

B_c = the baler throughput capacity (Mg/h),

$T_{av,t}$ = available time in time interval *t* (h), and

$F_{e,i}$ = field efficiency of the baler for field *i* (dec).

As stated previously, available harvest time in time interval *t*, $T_{av,t}$, is determined by the user.

4.6.2. Variable Capacity Queue

The VC queue provides a continuous monitor of active balers operating in the FHS model. At the arrival of a field entity into the holding queue, to await baler assignment, the baler equipment controller generates the global estimate for the number of single balers required to fulfill harvest operations during the current time interval, *t*, $B_{est,t}$ (see Section 4.6.1). Provided there are balers in the Baler Reservoir, the baler releases an initial quantity of active balers, $B_{act,s}$, such that $B_{act,s} \leq B_{est,t}$. $B_{act,s}$ represents the active quantity of balers engaging in harvest in the model. $B_{est,t}$ represents the global baler estimate, which is the estimated quantity of balers required for harvest. A quantity of baler entities, $B_{act,s}$, are initially assigned to fields awaiting harvest in the holding queue. The FHS model determines, on a per field basis, if additional balers are required to complete harvest, prior to the end of the current time interval, *t*. This is determined by using Equations (4-13) to (4-17). If determined that additional balers are required, $B_{act,s}$, adjusts to represent the actual quantity of balers required for harvest. Throughout the simulation run, the VC queue enables and prohibits the release of balers in the system. If $B_{act,s}$ reaches a quantity greater than the $B_{est,t}$, because it has been determined that additional balers are required to complete harvest prior to the end of the current time interval, the VC queue will prohibit the release of any additional balers (i.e. prohibit any additional field assignments), until balers currently in the system are finished with the fields they are harvesting. Following the completion of a harvest activity, the baler returns to the Baler Reservoir. $B_{act,s}$ adjusts accordingly as harvest activities start and finish.

4.7 Baler Entity Assignment

The baler/field assignment takes place following: (1) the accessibility of a baler, (2) the field entity awaiting harvest in the holding queue. As discussed previously, the accessibility of a baler depends upon the conditions of the model. Following an accessible baler, the baler entity is assigned to the next field awaiting harvest in the FIFO queue. Recall, field entity arrival is such that the largest fields, for each SSL assignment, arrive first. Following arrival, field/baler assignments are FIFO. In addition, all baler entities are granted field assignments according to the following:

1. All *Idle* balers are assigned first.
2. Among the *Idle* balers in the system, the balers that have been *Idle* for the longest periods are the first to receive field assignments.
3. If no *Idle* balers are present in the system, and the RMS has supplied a signal granting baler release, *Standby* balers will be assigned to field entities.

4.8 Harvest Requirements

As displayed in Figure 4.1.4, harvest can take place in one of four harvest operation modules. The harvest operation is executed in the model by an infinite server. The server block delays the field in the block for a specified time, in an effort to simulate the time the field would undergo harvest operations. The model is capable of modifying the service time based upon the field size attribute with the use of an Attribute Function block. Prior to the field exiting the harvest operation subsystem, the total quantity of biomass is summed to generate a total quantity harvested value. The duration of the harvest operation is described by the following equation.

The harvest time for field i, $\forall i = 1,\ldots, F$, is given by:

$$T_{har,i} = \frac{Q_{fld,ij}}{H_{cap,i} B_c \, F_{e,i}} \tag{4-13}$$

Where, $T_{har,i}$ = the time to harvest field i (h), and

$H_{cap,i}$ = the additional harvest capacity required for field i (integer). [See Equation (4-17) presented at the end of this section.]

The harvest time is calculated for each field, following baler assignment. This calculation is then compared to the remaining work time, $T_{Rem,t}$, to determine if any additional balers (one, two, three, or four balers) are required. $T_{c,t}$, the accumulated available work time is calculated throughout the simulation model, and is used to calculate $T_{Rem,t}$.

For t=1, the accumulated available work time, $T_{c,1}$, is given by:

$$T_{c,1} = T_{av,1} \tag{4-14}$$

For t >1, the accumulated available work time, $T_{c,t}$, is given by:

$$T_{c,t} = T_{c,t-1} + T_{av,t} \tag{4-15}$$

Where, $T_{c,t}$ = the accumulated available work time, in time interval t (h),

$T_{c,t-1}$ = the accumulated available work time, for the previous time interval *t*-1 (h), and

$T_{av,t}$ = available time in time interval *t* (h).

The remaining work time, $T_{Rem,s}$, is determined by:

$$T_{Rem,s} = T_{c,t} - s \tag{4-16}$$

Where, $T_{Rem,s}$ = the remaining work time at simulation time *s* (h), and

s = the simulation time step (h).

It should be noted, the simulation time step, s, is monitored by a simulation block, which starts at the beginning of the simulation run. The simulation step, s, is structured to increment by one each hour, to correspond to the current simulation time. Throughout the simulation run, the current simulation time step is subtracted from the accumulated available work time, $T_{c,t}$, to determine the remaining work time (Equation 4-17). Because Equation 4-16 is only determined on an hourly interval, the remaining work time, $T_{Rem,s}$, remains constant throughout the hourly interval, until $T_{Rem,s}$, is recalculated at the start of the next hour during the simulation run. As a result, if $T_{Rem,s}$ is calculated anytime during the hourly interval, $T_{Rem,s}$, will assume the value calculated at the start of the current hourly interval.

The FHS model determines if additional harvesting capacity is required to complete harvest operations by the end of the current time interval, using the following:

$$H_{cap,i} = \begin{cases} 1, & if \quad T_{har,i} \leq T_{Rem,s} \\ 2, & if\ T_{har,i} > \ T_{Rem,s}\ \&\ \ 2T_{har,i} \leq T_{Rem,s} \\ 3, & if\ T_{har,i} > 2T_{Rem,s}\ \&\ 3T_{har,i} \leq T_{Rem,s} \\ 4, otherwise, & if\ T_{har,i} > 3T_{Rem,s} \end{cases} \tag{4-17}$$

4.9 Baler Reuse

Following the completion of harvest, the model determines if the baler is permitted to harvest any additional fields. In Figure 4.1.4, this decision is shown at Step 20. If it is determined that the baler has not exceeded its maximum annual use, it is routed to the Baler Reservoir, where it waits for the next field assignment. If the baler has exceeded its maximum annual use (*A*), it is routed to an Entity Sink (*Down*), to prohibit any additional field assignments. The mathematical representation of this decision is presented below.

The FHS monitors the accumulated harvest time of each baler, following the completion of each harvest activity, to ensure that each baler is not exceeding its maximum annual use. When a baler is first removed from the reservoir a remaining time is assigned. Following the completion of the first field (*i*=a), the remaining time on baler k is:

$$T_{Ba,ki=a} = A - T_{har,ki=a} \tag{4-18}$$

Following the completion of the next field (*i*=b), the remaining annual use of a baler is calculated by the following:

$$T_{Ba,ki=b} = T_{Ba,ki=a} - T_{har,ki=b} \tag{4-19}$$

Where, $T_{Ba,ki}$ = amount of time remaining for baler *k* at simulation time s following the completion of field *i* (unit time), and

$T_{har,ki}$= total harvest time using baler *k* at simulation time s following the completion of field *i* (unit time).

Balers that have depleted the annual harvesting use (when $T_{Ba,ki}$ <=0) are termed as *Down*, and are removed from the Baler Reservoir, balers are not permitted to perform any additional harvest operations. Baler removal is determined by the following:

$$B_{rem,k} = \begin{cases} 1, & if\ T_{Ba,ki} > 0 \\ 0, & if\ T_{Ba,ki} \leq 0 \end{cases} \tag{4-20}$$

Where, $B_{rem,k}$= 1, indicates the maximum annual baler use of the baler has not been reached, and

$B_{rem,k}$= 0, indicates the baler has reached the maximum annual baler use.

4.10 Transport to SSL

Transport of bales to the SSL is the last operation for each field entity. In Figure 4.1.4, this process is shown at Step 18. Following transport to the assigned SSL, the biomass remains in storage. The time component associated with the in-field hauling of the harvested field is represented in Equations (4-21) to (4-24).

In-field hauling consists of the time to load, transport the baled biomass to the SSL, unload, and return to the field. Loading time is defined by the following:

$$T_{l,ij} = T_{Bl} \frac{Q_{fld,ij}}{Q_B} \tag{4-21}$$

Where, $T_{l,ij}$ = loading time of biomass for field *i* in SSL *j* (h),

T_{Bl} = bale loading rate (Bales/h), and

Q_B = average bale mass (Mg).

Next, unloading time is defined by the following:

$$T_{ul,ij} = T_{Bul} \frac{Q_{fld,ij}}{Q_B} \tag{4-22}$$

Where, $T_{ul,ij}$ = unloading time of biomass for field *i* in SSL *j* (h), and

T_{Bul} = bale unloading rate (Bales/h).

Transport time of biomass is given by:

$$T_{tp,ij} = \frac{Q_{fld,ij} D_{ij}}{H_c v} \tag{4-23}$$

Where, $T_{tp,ij}$ = transport time of biomass for field *i* to SSL *j* (h),

D_{ij} = average transport distance to from field *i* to SSL *j* (km),

H_c = hauling capacity (Mg/load), and

v = transport velocity (km/h).

Thus, the time for in-field hauling field *i* to SSL j, $T_{hal,ij}$, is given by:

$$T_{hal,ij} = T_{l,ij} + 2T_{tp,ij} + T_{ul,ij} \tag{4-24}$$

Where, $T_{hal,ij}$ = cycle time of hauling of biomass for field *i* to SSL *j* (h).

4.11 Simulation Output

The analysis consisted of running the simulation six times, once for each tour. Each tour was simulated four times, using the four different harvesting scenarios defined in Chapter 3.

The FHS model was capable of measuring traditional discrete-event simulation metrics, such as service time (i.e. harvest time), the number of fields serviced, harvest arrival and departure times. Because the resources were constructed in the form of an entity, additional calculation was required to determine baler resource utilization (Equation (4-25)).

The following output data was generated: (1) Baler Usage, (2) Harvest Time per Field, and (3) Harvest Quantity. In addition, baler and field attributes, which included field number, field size, and baler number, were retrieved from all output data. Baler utilization was derived, using the output data generated, following the completion of each simulation run. In particular, the monthly utilization rate for a baler was defined as follows:

$$U = \frac{(Total\ Baler\ Operation\ hours)}{(Total\ Potential\ Operation\ Hours * Number\ of\ Balers)} \tag{4-25}$$

Where, U = baler utilization.

Utilization rates were calculated for each month of the harvest season, in terms of the total collective baler usage. Individual baler utilization rates were not accessible, due to the current structure of the model, as briefly mentioned above in the model assumptions. As stated in model assumptions, the FHS model is currently capable of monitoring one physical baler per field, for each harvest operation. For example, if Field *i* requires two balers to fulfill harvest operations, one physical baler is monitored and will retain attributes of Field *i* (e.g. harvest time, field number, field size, etc.). The model adjusts accordingly to compensate for the addition baler(s) required, and output is provided on baler requirements. While the implications that resulted from this limitation of the model were assumed to not present significant impacts on the analysis results, an analysis was conducted to evaluate the accuracy of the baler allocation requirements generated in the model, for Tour 6, Scenario 1. Following the baler analysis, results from the FHS model are presented.

To construct the manual assessed baler allocations, the following attributes were examined from each harvest operation in Tour 6, Scenario 1:

- Field harvest start and finish time
- Baler allocated to designated field
- Number of balers required to fulfill harvest operations during time interval *t*

Figure 4.11.1 displays the manually assessed baler allocation, for Tour 6, Scenario 1. The x-axis represents simulation time, and is divided by harvest month. The rows are organized such that each row is an individual baler, with each bar representing a harvest operation performed by that baler. The light blue bars represent each additional baler allocated for a single field in the system. This includes any additional baler(s) required to fulfill harvest operations, and/or required to compensate for competing harvest operations.

The number of balers manually allocated in the system, for each month in Tour 6, Scenario 1, is presented in Table 4.11.1.

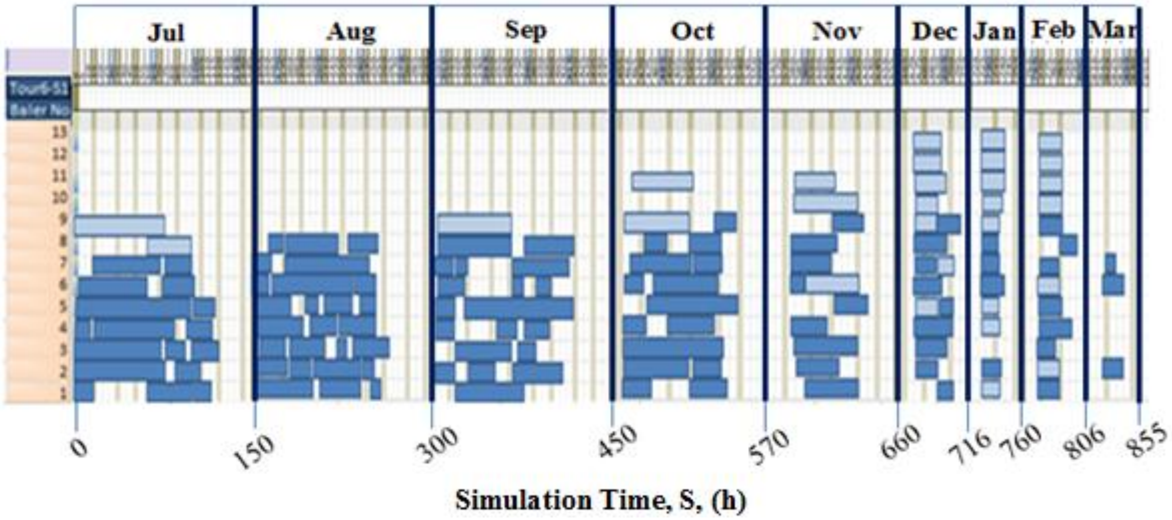

Figure 4.11.1 Manually Assessed Baler Analysis Tour 6, Scenario 1.

Table 4.11.1 presents the number of balers estimated for each month using the model simulated baler allocations and the manually assessed baler allocation. The largest variation in the model estimated baler allocation was found to be in Month 5. In Month 5, the estimated baler allocation totaled 9 balers while the manual assessed allocation indicated 11 balers were required. In the manual allocation, it was determined that while 9 balers were capable of completing harvest operations, when considering the available harvest time during the season, the balers were engaged in other harvest operations and thus prevented the reuse of all but 1 baler. The most frequent variation between the derived estimates was by a value of one. In Months 1, 3, and 4, the model estimates were one less than the manual estimates. Five months (Months 2, 6, 7, 8, and 9) out of the nine month harvest season were found to have no variation between the model estimated allocation and the manual baler allocation. Thus, the model estimated baler allocations were typically underutilizing what might be required, but were found to be a suitable parameter for this analysis.

Table 4.11.1 Comparison of Simulated versus Manual Assessed Baler Allocation Methods

	#1-Jul	#2-Aug	#3-Sep	#4-Oct	#5-Nov	#6-Dec	#7-Jan	#8-Feb	#9-Mar
Model	8	8	8	9	9	13	12	13	3
Manual	9	8	9	10	11	13	12	13	3

Figures 4.11.2 and 4.11.3 show the potential operational activity of balers and fields in the FHS model, organized according to field number and the SSL load-out sequence, respectively. The horizontal axis displays the transition of field harvest operations over time. The vertical axis indicates the number assigned to an individual baler (i.e. Baler #). In Figures 4.11.2 and 4.11.3, transitions over one time interval are displayed. A dark blue bar is used to represent a field harvest operation, currently utilizing a single baler in the specified row. For example, Baler #2 harvests two fields during this time interval, one of which is Field #5. Each light blue bar featured in the figure indicates an additional baler that was required to complete the field harvest operation (refer to Equations (4-13) and (4-17)). Note from Equation (4-17), the maximum number of balers present on any individual field does not exceed 4 balers. As a result, no more than 3 light blue bars will correspond to a single field. As displayed in Figure 4.11.2, 9 balers

operate during this time interval (i.e. month *t*). At the beginning of the simulation, 7 balers are operating simultaneously, including one additional baler required on Field #5. Following the completion of the first harvest operation by Baler #4, Baler #4 returns to the Used Baler Reservoir, after it was determined that Baler #4 had annual baler use remaining (see Section 4.9). When Baler #4 returned to the Used Baler Reservoir, this allowed Baler #7 to begin field harvest operations. As described in Section 4.6, balers are permitted to be assigned a field waiting in queue for harvest, provided that the actual quantity of balers in the system, $B_{act,ts}$, is less than or equal to the global estimated $B_{est,t}$. After a field has been allocated a baler, if it is determined that the baler will not be able to harvest the field prior to the deadline, an additional baler is permitted to assist in fulfilling the harvest demand. This is displayed in Fields #14 and 5. Prior to the harvest of Field #14, a large lag time was observed. In this case, Baler #1, reengaged in harvest operation, following the completion of harvest operation by Baler #6. This indicates that the $B_{est,t}$, at this time in the simulation model was reached, and a baler was required to complete harvest operations prior to the entry of another baler into the system for field harvest. The measure was imposed to restrict excess entry of balers in the system. In this particular case, the 9 balers operate across 17 fields, and 4 SSLs (Figure 4.11.3). The arrival pattern featured in this case, enabled the fields to arrive simultaneously, in groups, across each of the four SSLs harvested. Thus, size variation across the SSLs did not fully retain the field size prioritizing as previously described. While not structured to do such, 6 out the 9 balers (Baler #'s 1,5,6,7,8, and 9) harvested fields for the same SSL. It is also observed in Figure 4.11.3, that while harvest was structured such that SSLs were prioritized for harvest according to the SSL load-out schedule, this prioritizing was not retained. Rather, the model ensured that harvest, for each time interval, would be prioritized according to the SSL load-out sequence.

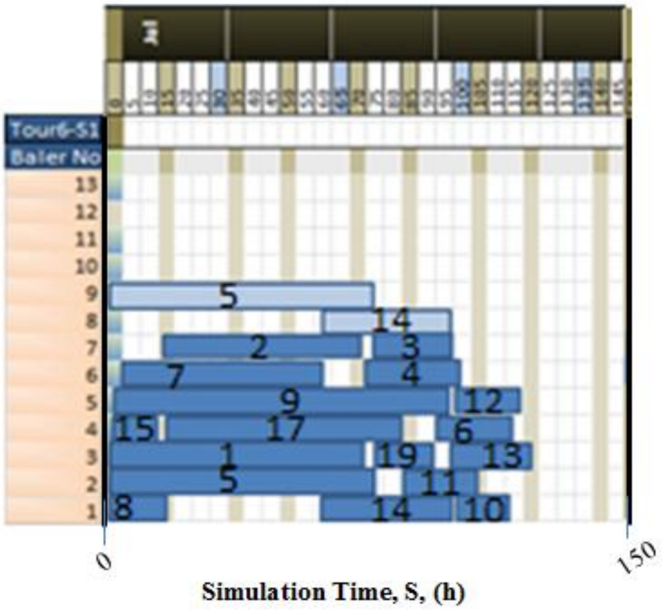

Figure 4.11.2 Potential operational activity of balers and fields (labeled by Field Number).

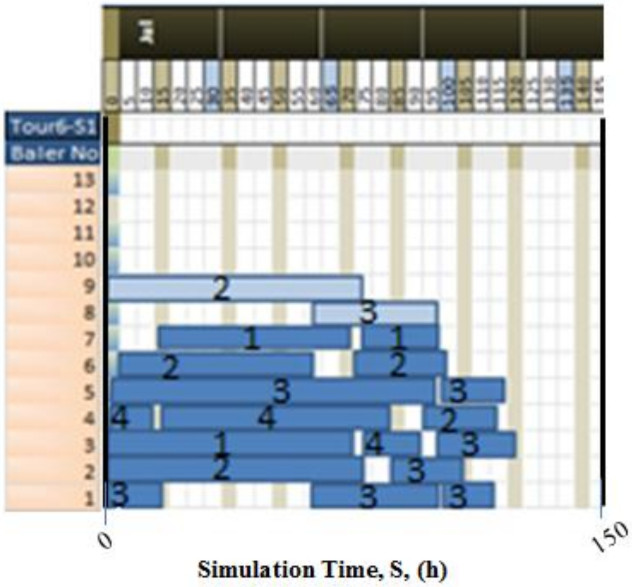

Figure 4.11.3 Potential operational activity of balers and fields (labeled by SSL load-out sequence).

CHAPTER FIVE

RESULTS

This study developed a hybrid simulation model to estimate the harvest requirements for baling of switchgrass using four potential harvesting scenarios. The analysis consisted of running the simulation six times, once for each of the six sub-regions. Harvest in each sub-region was simulated four times, using four different harvesting scenarios and the input parameter values provided in Chapter 3.

The simulation model was ran on a 2.1 GHz dual-core processor with 4 GB of RAM. Each simulation run took approximately less than 3 minutes. The model output data was retrieved from the workspace, and imported into Microsoft Excel spreadsheets.

In the sections to follow, a brief overview of the results from Scenarios 1-4, Tours 1-6, is provided to offer additional information on individual tour harvest characteristics, as well as provide insight on the equipment requirements estimated by the FHS model.

5.1 Round Bale Scenario-1

5.1.1 Tour 1-Scenario 1

Table 5.1.1.1 displays the monthly harvest distribution in Tour 1, Scenario 1. As seen, in Harvest Months 1, 3, 5, 7, and 8, the production area harvested (i.e. actual harvest) is greater than the requested monthly demand. In contrast, the production area harvested in Months 2, 4, 6, and 9, appears to be less than the requested monthly demand. As discussed, the FHS model is not permitted to harvest partial fields, and the harvest demand is satisfied when the actual harvest area either meets or exceeds the minimum harvest demand. Harvest months, in which the actual harvested amount exceeds the monthly demand, will compensate for any potential months lacking in harvest. The resulting cumulative actual harvest (not displayed) is greater than or equal to the cumulative demand requested. This is common among all tours (i.e. Tours 1-6) and all scenarios (Scenarios 1-4). The harvested production area in Months 1, 2, and 3 account for approximately 55.4% of the total production area in Tour 1. The greatest percentage of the total production area in Tour 1 is harvested in Month 1, approximately 20.2%. The minimum harvested is in Month 9, approximately 3.1% of total production area. The largest number of fields are harvested in Month 3, with 27 fields harvested. The minimum number of fields harvested was Month 9, with 2 fields harvested. The limited production area of Tour 1 is the result of the small harvest in Month 9. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 846 h, in the simulation model. Due to the limited size of the production area in Tour 1, the cumulative harvest demand was not achieved.

Table 5.1.1.1 Monthly Harvest Distribution Tour 1, Scenario 1

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Fields Harvested
#1-Jul	488.9	488.9	507	20.2	17
#2-Aug	949.4	460.6	446	17.7	23
#3-Sep	1,376.6	427.1	440	17.5	27
#4-Oct	1,736.8	360.2	346	13.8	16
#5-Nov	1,988.9	252.2	264	10.5	11
#6-Dec	2,169.0	180.1	174	6.9	10
#7-Jan	2,297.7	128.7	135	5.4	3
#8-Feb	2,418.6	120.9	122	4.9	6
#9-Mar	2,573.0	154.4	79	3.1	2

*Percent of total production area for this tour.

Table 5.1.1.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 1, Scenario 1. Approximately 63.8% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 17.3%, 9.2%, and 9.7% of the total harvest area, respectively.

Table 5.1.1.2 Baler Distribution per Field Tour 1, Scenario 1

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Production Area
Single	6	58	99	1603	63.8
Two	24	77	7	435	17.3
Three	38	153	3	230	9.2
Four	33	61	5	245	9.7

5.1.2 Tour 2-Scenario 1

Table 5.1.2.1 displays the monthly harvest distribution in Tour 2, Scenario 1. Harvest in Months 1, 2, and 3 accounts for approximately 53.3% of the total production area in Tour 2. The greatest percentage of the total production area in Tour 2 is harvested in Month 1, approximately 19%. The minimum harvested is in Month 7, approximately 4.4% of total production area. The largest number of fields were harvested in Month 2, with 25 fields harvested. The minimum number of fields harvested was Months 8 and 9, each harvesting 6 fields. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 848 h, in the simulation model. Due to the large size of the production area in Tour 2, the cumulative harvest demand was exceeded.

Table 5.1.2.1 Monthly Harvest Distribution Tour 2, Scenario 1

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Fields Harvested
#1-Jul	488.9	488.9	491	19.0	18
#2-Aug	949.4	460.6	474	18.3	25
#3-Sep	1,376.6	427.1	414	16.0	23
#4-Oct	1,736.8	360.2	365	14.1	16
#5-Nov	1,988.9	252.2	245	9.5	10
#6-Dec	2,169.0	180.1	197	7.6	7
#7-Jan	2,297.7	128.7	113	4.4	7
#8-Feb	2,418.6	120.9	122	4.7	6
#9-Mar	2,573.0	154.4	166	6.4	6

*Percent of total production area for this tour.

Table 5.1.2.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 2, Scenario 1. Approximately 63.7% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 19.3%, 8.4%, and 8.7% of the total harvest area, respectively.

Table 5.1.2.2 Baler Distribution per Field Tour 2, Scenario 1

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	72	94	1648	63.7
Two	8	83	14	498	19.3
Three	23	39	7	217	8.4
Four	52	86	3	224	8.7

5.1.3 Tour 3-Scenario 1

Table 5.1.3.1 displays the monthly harvest distribution in Tour 3, Scenario 1. Harvest in Months 1, 2, and 3 accounts for approximately 53.2% of the total production area in Tour 3. The greatest percentage of the total production area in Tour 3 is harvested in Month 1, approximately 19.4%. The minimum harvested is in Month 8, approximately 3.2% of total production area. The largest number of fields was harvested in Month 4, with 19 fields harvested. The minimum number of fields harvested was Months 8 and 9, each harvesting 3 fields. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 850.4 h, in the simulation model. Due to the large size of the production area in Tour 3, the final harvest demand was exceeded.

Table 5.1.3.1 Monthly Harvest Distribution Tour 3, Scenario 1

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#1-Jul	488.9	488.9	509	19.4	17
#2-Aug	949.4	460.6	460	17.5	15
#3-Sep	1,376.6	427.1	429	16.3	17
#4-Oct	1,736.8	360.2	354	13.5	19
#5-Nov	1,988.9	252.2	244	9.3	15
#6-Dec	2,169.0	180.1	192	7.3	8
#7-Jan	2,297.7	128.7	155	5.9	4
#8-Feb	2,418.6	120.9	84	3.2	3
#9-Mar	2,573.0	154.4	198	7.5	3

*Percent of total production area for this tour.

Table 5.1.3.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 3, Scenario 1. Approximately 62.4% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 18.3%, 4.2%, and 15.1% of the total harvest area, respectively.

Table 5.1.3.2 Baler Distribution per Field Tour 3, Scenario 1

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	67	80	1638	62.4
Two	15	75	13	480	18.3
Three	39	72	2	111	4.2
Four	44	88	6	396	15.1

5.1.4 Tour 4-Scenario 1

Table 5.1.4.1 displays the monthly harvest distribution in Tour 4, Scenario 1. Harvest in Months 1, 2, and 3 accounts for approximately 57.5% of the total production area in Tour 4. The greatest percentage of the total production area in Tour 4 was harvested in Month 1, approximately 19.2%. The minimum total area harvested is in Month 7, approximately 3.4% of total production area. The largest number of fields was harvested in Month 3, with 26 fields harvested. The minimum number of fields harvested was Month 8, with 2 fields harvested. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 845.4 h, in the simulation model. Due to the limited size of the production area in Tour 4, the cumulative harvest demand was not met.

Table 5.1.4.1 Monthly Harvest Distribution Tour 4, Scenario 1

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Total Area*	No. Field Harvest
#1-Jul	488.9	488.9	490	19.2	22
#2-Aug	949.4	460.6	468	18.3	17
#3-Sep	1,376.6	427.1	510	20.0	26
#4-Oct	1,736.8	360.2	280	11.0	17
#5-Nov	1,988.9	252.2	250	9.8	13
#6-Dec	2,169.0	180.1	213	8.3	5
#7-Jan	2,297.7	128.7	88	3.4	3
#8-Feb	2,418.6	120.9	124	4.9	2
#9-Mar	2,573.0	154.4	129	5.1	6

*Percent of total production area for this tour.

Table 5.1.4.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 4, Scenario 1. Approximately 62% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 11.8%, 9.8%, and 16.4% of the total harvest area, respectively.

Table 5.1.4.2 Baler Distribution per Field Tour 4, Scenario 1

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	61	64	3	1582	62.0
Two	20	102	5	302	11.8
Three	94	156	2	250	9.8
Four	48	76	7	418	16.4

5.1.5 Tour 5-Scenario 1

Table 5.1.5.1 displays the monthly harvest distribution in Tour 5, Scenario 1. Harvest in Months 1, 2, and 3 accounts for approximately 54.4% of the total production area in Tour 5. The greatest percentage of the total production area in Tour 5 is harvested in Month 1, approximately 20.9%. The minimum total area harvested is in Months 7 and 9, each harvesting approximately 5.2% of the total production area in Tour 5. The largest number of fields were harvested in Month 1, with 27 fields harvested. The minimum number of fields harvested was in Months 8 and 9, each harvesting 5 fields. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 842.8 h, in the simulation model. Due to the large size of the production area in Tour 5, the cumulative harvest demand was exceeded.

Table 5.1.5.1 Monthly Harvest Distribution Tour 5, Scenario 1

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#1-Jul	488.9	488.9	540	20.9	27
#2-Aug	949.4	460.6	425	16.5	19
#3-Sep	1,376.6	427.1	439	17.0	22
#4-Oct	1,736.8	360.2	375	14.5	16
#5-Nov	1,988.9	252.2	219	8.5	15
#6-Dec	2,169.0	180.1	173	6.7	10
#7-Jan	2,297.7	128.7	134	5.2	7
#8-Feb	2,418.6	120.9	141	5.5	5
#9-Mar	2,573.0	154.4	133	5.2	5

*Percent of total production area for this tour.

Table 5.1.5.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 5, Scenario 1. Approximately 73.4% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 16.6%, 1.2%, and 8.8% of the total harvest area, respectively.

Table 5.1.5.2 Baler Distribution per Field Tour 5, Scenario 1

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	67	111	1893	73.4
Two	12	105	10	429	16.6
Three	31	31	1	31	1.2
Four	40	82	4	226	8.8

5.1.6 Tour 6-Scenario 1

Table 5.1.6.1 displays the monthly harvest distribution in Tour 6, Scenario 1. Harvest in Months 1, 2, and 3 account for approximately 55.7% of the total production area in Tour 6. The greatest percentage of the total production area in Tour 6 is harvested in Month 1, approximately 20%. The minimum total area harvested is in Month 9, harvesting approximately 1.1% of the total production area in Tour 6. The largest number of fields are harvested in Month 2, with 26 fields harvested. The minimum number of fields harvested was in Month 9, with 3 fields. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 836.5 h, in the simulation model. Due to the limited size of the production area in Tour 6, the cumulative harvest demand was not met.

Table 5.1.6.1 Monthly Harvest Distribution Tour 6, Scenario 1

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#1-Jul	488.9	488.87	495	20.0	17
#2-Aug	949.4	460.567	467	18.9	26
#3-Sep	1,376.6	427.118	415	16.8	19
#4-Oct	1,736.8	360.22	362	14.6	15
#5-Nov	1,988.9	252.154	252	10.2	9
#6-Dec	2,169.0	180.11	202	8.2	9
#7-Jan	2,297.7	128.65	114	4.6	4
#8-Feb	2,418.6	120.931	142	5.7	7
#9-Mar	2,573.0	154.38	26	1.1	3

*Percent of total production area for this tour.

Table 5.1.6.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 6, Scenario 1. Approximately 65.9% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 25.1%, 6%, and 3.1% of the total harvest area, respectively.

Table 5.1.6.2 Baler Distribution per Field Tour 6, Scenario 1

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	61	89	1629	65.9
Two	16	97	14	622	25.1
Three	34	43	4	147	6.0
Four	34	43	2	77	3.1

5.1.7 Summary Scenario 1

Figure 5.1.7.1 displays the baler usage for Tours 1-6, in Scenario 1. This figure indicates the number of balers operating simultaneously, at each time interval during the harvest season. Baler usage shows minor variations, in the earlier portion of the harvest season, from July to September. In the latter portion of the harvest season, the baler requirements show significant variations among the six tours. The maximum number of balers required, for a full operational month was 14 balers (Tour 4, Month 6). As the figure shows, baler usage declines to zero towards the end of every harvest month, following the completion of all harvest operation.

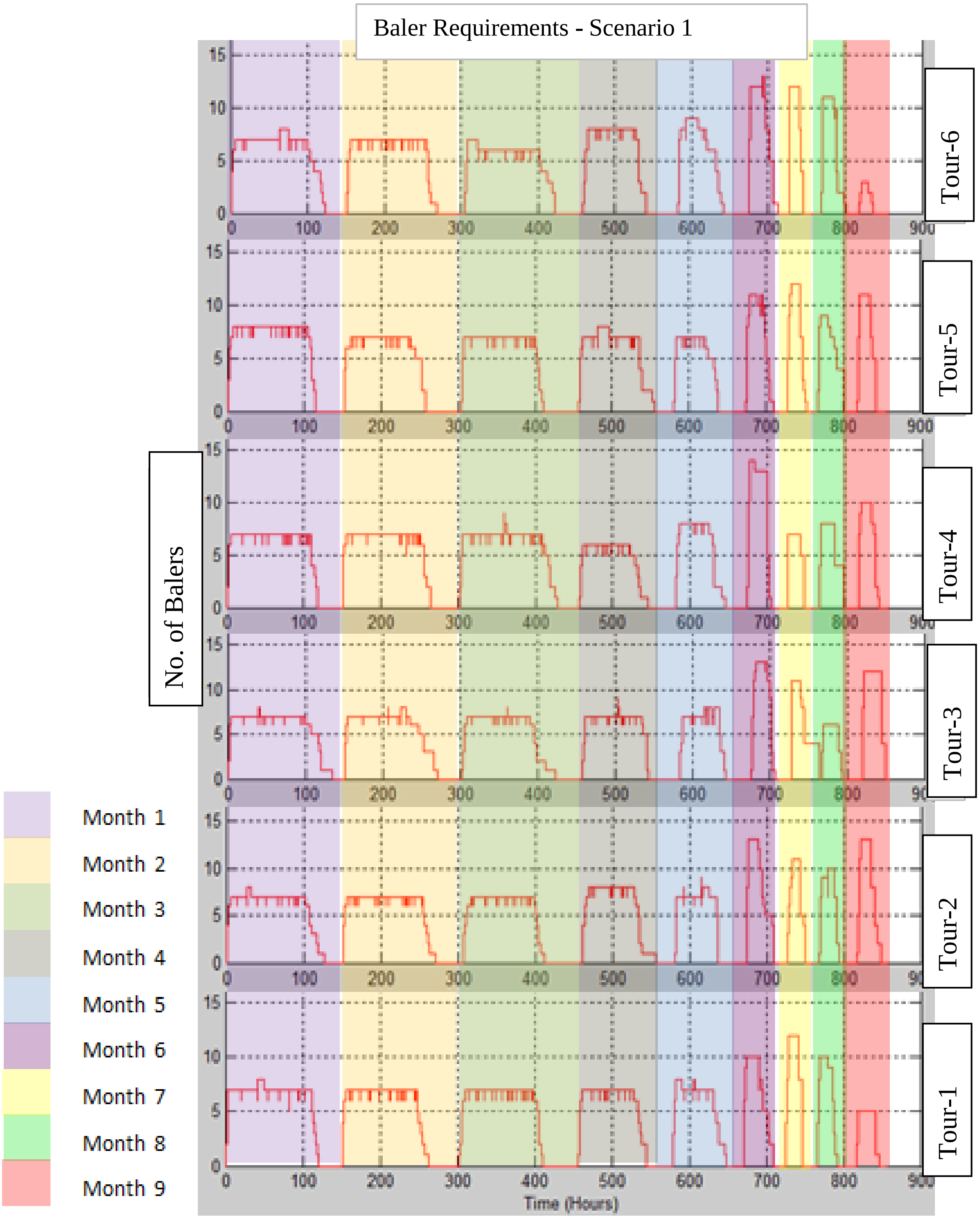

Figure 5.1.7.1 Baler Usage, Scenario 1

The variations in the estimated baler requirements observed among the six tours are thought to be attributed to the variability in field size distributions, and incoming sequence selected for the harvest of the fields.

Table 5.1.7.1 Monthly Average Harvest Time per Field for Scenario 1.

	Monthly Average Harvest Time per Field by Month (h)								
	#1 - Jul	#2 - Aug	#3 - Sept	#4 - Oct	#5 - Nov	#6 - Dec	#7 - Jan	#8 - Feb	#9 - Mar
Tour 1	40.1	29.4	25.8	32.2	29.8	18.4	17.8	19.3	25.0
Tour 2	38.9	30.0	28.5	34.0	22.8	24.0	13.8	16.1	17.5
Tour 3	44.7	42.8	37.7	26.7	20.3	21.7	22.3	22.2	26.1
Tour 4	33.7	37.0	28.8	24.6	30.4	24.1	19.9	24.5	20.4
Tour 5	31.6	33.6	31.3	34.9	23.1	18.3	16.3	24.8	19.1
Tour 6	41.2	28.4	32.8	33.7	33.2	20.0	15.0	18.7	13.7

Table 5.1.7.1 shows the average monthly harvest time for Tours 1-6 in Scenario 1. As displayed, Tour 3 was found to have overall, the maximum average harvest time. Table 5.1.7.1 shows a decline in harvesting time as the harvest season progresses. As presented in Section 4.8, field harvest time is directly correlated to field size. While the field size does not change as the harvest season progresses, the data presented in Table 5.1.7.1 supports Table 5.1.7.2, which indicates there is an increase in multiple balers harvesting on the field in the later portion of the harvest season (when PWD are decreased). As a result, the harvest time declines, on a per field basis, due to the multiple balers operating on the field.

Table 5.1.7.2 Number of Fields Requiring Additional Balers, Scenario 1

	Fields Requiring Additional Balers by Month								
	#1 - Jul	#2 - Aug	#3 - Sept	#4 - Oct	#5 - Nov	#6 - Dec	#7 - Jan	#8 - Feb	#9 - Mar
Tour 1	2	1	0	1	3	2	3	3	1
Tour 2	2	0	0	1	4	3	4	4	6
Tour 3	1	2	1	1	4	4	3	2	3
Tour 4	1	2	1	1	0	3	2	2	2
Tour 5	0	1	1	1	0	5	2	2	3
Tour 6	2	0	1	2	3	5	4	3	0

The utilization rate for a baler is the ratio of the total balers operating hours by the total possible operating hours. Table 5.1.7.3 presents the monthly utilization rates of balers for Tours 1-6, in Scenario 1. Overall, the maximum baler utilization rate was 71.2% (Month 1, Tour 5), and the minimum utilization rate was 28% (Month 9, Tour 6). Across all six tours, the maximum utilization rates for Months 1 through 9, were 71.2%, 64.1%, 67.3%, 61.8%, 55%, 49.2%, 54.4%, 50.6%, and 53.3%, respectively. Utilization rates, in Scenario 1, were found to be higher in the earlier portion of the harvest season, with a decline in rates as the harvest season progressed. This is confirmed in Figure 5.1.7.2. In fact, baler utilization can be best described by examining Figure 5.1.7.2. As seen, baler utilization is far greater in the earlier portion of the harvest season. This time in the harvest season is characterized by the highest PWD, which translates to an increased amount of time to perform harvest operations. This allows for a larger window of opportunity for harvest operations, as well as for reuse of the baler. In many cases, larger quantities of biomass can be harvested, with no fields requiring additional balers to be present on the field. As the harvest season progresses, balers are reused less frequently, due to lack of time for the harvest of an additional field, and/or a missed window of opportunity while the baler is assigned to other field harvest activities. As indicated in the figure, the latter portion of the harvest season is marked by an increased number of balers due to limited harvest window, large field sizes, and the balers inability to reuse current balers in the system (due to the limited harvest window). This is displayed by the increase in the light blue bars in Figure 5.1.7.2. Recall, the light blue bar represents an additional baler required to complete a harvest operation. Month 9 of Tour 6 has the lowest monthly utilization in the harvest season. The least amount of biomass is harvested. A small number of fields are harvested, and each field is assigned a single baler. The average harvest time is 13.7 h. Following the harvest of the 3 fields in Tour 6, the baler is not assigned any additional hours. It should be noted, that while Tour 6 received the lowest monthly utilization, and the least number of fields were harvested, this is solely a result of the limited size of the production area.

The challenges displayed in Figure 5.1.7.2, while specific for Tour 6, also reflect similar trends in the entire region. Consider Month 4 of Tour 4 (Table 5.1.7.1), average harvest time is low, and Tour 4 harvested the least amount of biomass during this month. Due to the limited operation of the allocated balers, Tour 4 has the lowest monthly utilization in Month 4. This is consistent with Month 9 of Tour 6.

The maximum baler utilization rate overall in Scenario 1 was found in Tour 5, Month 1 (Table 5.1.7.3). During Month 1, Tour 5 harvested the largest amount of biomass, across a large number of fields. In addition, Tour 5, Month 1 had the minimum average harvest time (Table 5.1.7.1), and required no additional balers on the fields (Table 5.1.7.2). Tour 5 also had the maximum monthly baler utilization rate in Month 4 (Table 5.1.7.3). In Month 4, Tour 5 harvested the largest amount of biomass, across an average amount of fields. Tour 3 had the maximum monthly utilization rate in Month 9 (Table 5.1.7.3). While a small number of fields are harvested, Tour 3 harvests the maximum amount of biomass for Month 3. Tour 3 also had the maximum baler utilization rate in Month 7 (Table 5.1.7.3).

Table 5.1.7.3 Monthly Average Baler Utilization, Scenario 1

Monthly Average Baler Utilization by Month (%)									
	#1 - Jul	#2 - Aug	#3 – Sept	#4 - Oct	#5 - Nov	#6 – Dec	#7 - Jan	#8 - Feb	#9 - Mar
Tour 1	66.9	58.8	58.0	57.0	58.0	49.2	43.4	39.4	51.0
Tour 2	64.8	62.5	54.6	53.5	47.9	42.8	39.6	39.4	41.2
Tour 3	67.1	53.9	50.3	51.9	47.7	41.7	54.4	45.2	53.3
Tour 4	64.6	61.7	67.3	46.2	54.9	43.0	48.5	50.1	41.7
Tour 5	71.2	64.1	66.2	61.8	55.0	44.4	43.1	50.6	39.0
Tour 6	65.3	61.6	54.7	53.0	49.2	43.9	36.7	41.7	28.0

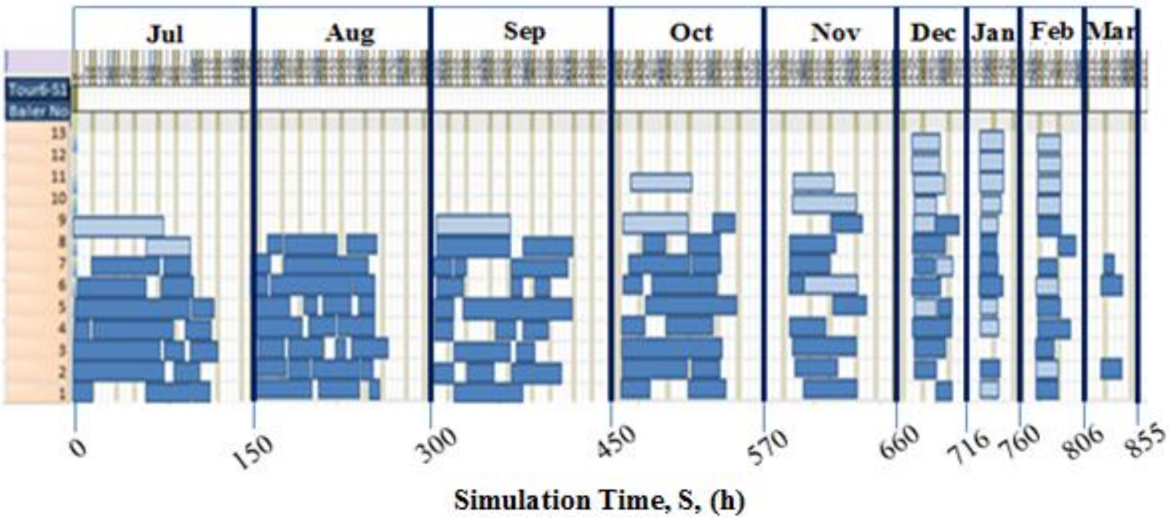

Figure 5.1.7.2 Manually Assessed Baler Analysis Tour 6, Scenario 1

Table 5.1.7.4 indicates the accumulated harvest percentage, per tour, in the 9-month harvest season. The "% Har" column indicates the percentage of the total harvested amount per tour in each of the harvest months. The "% Sto" column indicates the accumulated harvested biomass entering storage in each of the harvest months. The differences observed in the harvested amount, across the 6 tours, are a result of the variations in field size. In Scenario 1, the accumulated harvest is at least 50% of the total harvested amount by Month 3 (September). The SSL accumulates 100% of the total harvested amount per tour in Month 9 (March).

Table 5.1.7.4 Accumulated Harvest in Storage, Scenario 1

	Tour											
	1		2		3		4		5		6	
	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto
#1-Jul	20.2	20.2	19.0	19.0	19.4	19.4	19.2	19.2	20.9	20.9	20.0	20.0
#2-Aug	17.7	37.9	18.3	37.3	17.5	36.9	18.3	37.5	16.5	37.4	18.9	38.9
#3-Sep	17.5	55.4	16.0	53.3	16.3	53.2	20.0	57.5	17.0	54.4	16.8	55.7
#4-Oct	13.8	69.2	14.1	67.4	13.5	66.7	11.0	68.5	14.5	68.9	14.6	70.3
#5-Nov	10.5	79.7	9.5	76.9	9.3	76.0	9.8	78.3	8.5	77.4	10.2	80.5
#6-Dec	6.9	86.6	7.6	84.5	7.3	83.3	8.3	86.6	6.7	84.1	8.2	88.7
#7-Jan	5.4	92.0	4.4	88.9	5.9	89.2	3.4	90.0	5.2	89.3	4.6	93.3
#8-Feb	4.9	96.9	4.7	93.6	3.2	92.4	4.9	94.9	5.5	94.8	5.7	99.0
#9-Mar	3.1	100.0	6.4	100.0	7.5	100.0	5.1	100.0	5.2	100.0	1.0	100.0

5.2 Round Bale Scenario-2

5.2.1 Tour 1-Scenario 2

Table 5.2.1.1 displays the monthly harvest distribution in Tour 1, Scenario 2. Harvest in Months 1, 2, and 3 account for approximately 20.7% of the total production area in Tour 1, with 52.9% of the production area harvested in Months 4, 5, and 6. The greatest percentage of the total production area in Tour 1 is harvested in Month 4, approximately 22.1%. The minimum total area harvested is in Month 1, harvesting approximately 1.7% of the total production area in Tour 1. The largest number of fields are harvested in Month 4, with 27 fields harvested. The minimum number of fields harvested was in Month 1, with 1 field harvested. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 846.6 h, in the simulation model. Due to the limited size of the production area in Tour 1, the cumulative harvest demand was not met.

Table 5.2.1.1 Monthly Harvest Distribution Tour 1, Scenario 2

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#1-Jul	25.7	25.7	43	1.7	1
#2-Aug	180.1	154.4	154	6.1	8
#3-Sep	514.6	334.5	325	12.9	9
#4-Oct	1,054.9	540.3	555	22.1	27
#5-Nov	1,492.3	437.4	421	16.8	30
#6-Dec	1,826.8	334.5	352	14.0	14
#7-Jan	2,071.3	244.4	224	8.9	9
#8-Feb	2,315.7	244.4	250	9.9	10
#9-Mar	2,573.0	257.3	189	7.5	7

*Percent of total production area for this tour.

Table 5.1.5.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 1, Scenario 2. Approximately 51.7% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 17.6%, 10.1%, and 20.6% of the total harvest area, respectively.

Table 5.2.1.2 Baler Distribution per Field Tour 1, Scenario 2

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	48	87	1,300	51.7
Two	11	77	14	442	17.6
Three	25	153	4	254	10.1
Four	33	73	10	517	20.6

5.2.2 Tour 2-Scenario 2

Table 5.2.2.1 displays the monthly harvest distribution in Tour 2, Scenario 2. Harvest in Months 1, 2, and 3 account for approximately 20.4% of the total production area in Tour 2, with 51.2% of the production area harvested in Months 4, 5, and 6. The greatest percentage of the total production area in Tour 2 is harvested in Month 4, approximately 21.2%. The minimum total area harvested is in Month 1, harvesting approximately 3.1% of the total production area in Tour 2. The largest number of fields are harvested in Month 4, with 26 fields harvested. The minimum number of fields harvested was in Month 1, with 2 fields harvested. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 848.6 h, in the simulation model. Due to the large size of the production area in Tour 2, the cumulative harvest demand was exceeded.

Table 5.2.2.1 Monthly Harvest Distribution Tour 2, Scenario 2

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#1-Jul	25.7	25.7	80	3.1	2
#2-Aug	180.1	154.4	271	10.5	10
#3-Sep	514.6	334.5	175	6.8	8
#4-Oct	1,054.9	540.3	549	21.2	26
#5-Nov	1,492.3	437.4	429	16.6	23
#6-Dec	1,826.8	334.5	346	13.4	17
#7-Jan	2,071.3	244.4	287	11.1	11
#8-Feb	2,315.7	244.4	202	7.8	12
#9-Mar	2,573.0	257.3	248	9.6	9

*Percent of total production area for this tour.

Table 5.2.2.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 2, Scenario 2. Approximately 48.6% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 27.5%, 10.7%, and 13.1% of the total harvest area, respectively.

Table 5.2.2.2 Baler Distribution per Field Tour 2, Scenario 2

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	72	82	1,258	48.6
Two	8	83	22	712	27.5
Three	16	71	8	278	10.7
Four	22	86	6	339	13.1

5.2.3 Tour 3-Scenario 2

Table 5.2.3.1 displays the monthly harvest distribution in Tour 3, Scenario 2. Harvest in Months 1, 2, and 3 account for approximately 20.8% of the total production area in Tour 2, with 49.4% of the production area harvested in Months 4, 5, and 6. The greatest percentage of the total production area in Tour 3 is harvested in Month 4, approximately 19.7%. The minimum total area harvested is in Month 1, harvesting approximately 1.8% of the total production area in Tour 3. The largest number of fields are harvested in Month 5, with 20 fields harvested. The minimum number of fields harvested was in Month 1, with 2 fields harvested. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 850.4 h, in the simulation model. Due to the large size of the production area in Tour 3, the cumulative harvest demand was exceeded.

Table 5.2.3.1 Monthly Harvest Distribution Tour 3, Scenario 2

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#1-Jul	25.7	25.7	47	1.8	2
#2-Aug	180.1	154.4	348	13.3	13
#3-Sep	514.6	334.5	150	5.7	3
#4-Oct	1,054.9	540.3	518	19.7	17
#5-Nov	1,492.3	437.4	431	16.4	20
#6-Dec	1,826.8	334.5	348	13.3	17
#7-Jan	2,071.3	244.4	252	9.6	13
#8-Feb	2,315.7	244.4	249	9.5	10
#9-Mar	2,573.0	257.3	282	10.7	6

*Percent of total production area for this tour.

Table 5.2.3.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 3, Scenario 2. Approximately 51.8% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 20%, 7.4%, and 20.9% of the total harvest area, respectively.

Table 5.2.3.2 Baler Distribution per Field Tour 3, Scenario 2

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	75	71	1,359	51.8
Two	12	67	15	525	20.0
Three	17	54	6	193	7.4
Four	32	88	9	548	20.9

5.2.4 Tour 4-Scenario 2

Table 5.2.4.1 displays the monthly harvest distribution in Tour 4, Scenario 2. Harvest in Months 1, 2, and 3 accounts for approximately 25.3% of the total production area in Tour 4, with 46.7% of the production area harvested in Months 4, 5, and 6. The greatest percentage of the total production area in Tour 4 is harvested in Month 4, approximately 17.4%. The minimum total area harvested is in Month 1, harvesting approximately 2.9% of the total production area in Tour 1. The largest number of fields are harvested in Month 4, with 23 fields harvested. The minimum number of fields harvested was in Month 1, with 2 fields harvested. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 850.5 h, in the simulation model. Due to the limited size of the production area in Tour 4, the cumulative harvest demand was not met.

Table 5.2.4.1 Monthly Harvest Distribution Tour 4, Scenario 2

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#1-Jul	25.7	25.7	74	2.9	2
#2-Aug	180.1	154.4	285	11.2	11
#3-Sep	514.6	334.5	287	11.2	10
#4-Oct	1,054.9	540.3	444	17.4	23
#5-Nov	1,492.3	437.4	414	16.2	22
#6-Dec	1,826.8	334.5	334	13.1	19
#7-Jan	2,071.3	244.4	250	9.8	11
#8-Feb	2,315.7	244.4	259	10.1	6
#9-Mar	2,573.0	257.3	205	8.0	7

*Percent of total production area for this tour.

Table 5.2.4.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 4, Scenario 2. Approximately 45.6% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 21.4%, 8.2%, and 24.7% of the total harvest area, respectively.

Table 5.2.4.2 Baler Distribution per Field Tour 4, Scenario 2

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	62	81	1,164	45.6
Two	14	102	16	547	21.4
Three	26	156	3	210	8.2
Four	20	94	11	631	24.7

5.2.5 Tour 5-Scenario 2

Table 5.2.5.1 displays the monthly harvest distribution in Tour 5, Scenario 2. Harvest in Months 1, 2, and 3 accounts for approximately 17.5% of the total production area in Tour 5, with 53.5% of the production area harvested in Months 4, 5, and 6. The greatest percentage of the total production area in Tour 5 is harvested in Month 4, approximately 20.5%. The minimum total area harvested is in Month 1, harvesting approximately 1.9% of the total production area in Tour 5. The largest number of fields are harvested in Month 4, with 25 fields harvested. The minimum number of fields harvested was in Month 1, with 1 field harvested. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 851.6 h, in the simulation model. Due to the large size of the production area in Tour 5, the cumulative harvest demand was exceeded.

Table 5.2.5.1 Monthly Harvest Distribution Tour 5, Scenario 2

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#1-Jul	25.7	25.7	50	1.9	1
#2-Aug	180.1	154.4	146	5.7	5
#3-Sep	514.6	334.5	344	13.3	21
#4-Oct	1,054.9	540.3	529	20.5	25
#5-Nov	1,492.3	437.4	434	16.8	18
#6-Dec	1,826.8	334.5	329	12.8	17
#7-Jan	2,071.3	244.4	253	9.8	16
#8-Feb	2,315.7	244.4	243	9.4	15
#9-Mar	2,573.0	257.3	251	9.7	8

*Percent of total production area for this tour.

Table 5.2.5.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 5, Scenario 2. Approximately 52.8% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 16.8%, 13.1%, and 17.2% of the total harvest area, respectively.

Table 5.2.5.2 Baler Distribution per Field Tour 5, Scenario 2

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	67	90	1,363	52.8
Two	9	53	19	434	16.8
Three	14	105	9	339	13.1
Four	18	104	8	443	17.2

5.2.6 Tour 6-Scenario 2

Table 5.2.6.1 displays the monthly harvest distribution in Tour 6, Scenario 2. Harvest in Months 1, 2, and 3 accounts for approximately 21.1% of the total production area in Tour 6, with 53.8% of the production area harvested in Months 4, 5, and 6. The greatest percentage of the total production area in Tour 6 is harvested in Month 4, approximately 24.4%. The minimum total area harvested is in Month 1, harvesting approximately 1.9% of the total production area in Tour 6. The largest number of fields are harvested in Month 4, with 30 fields harvested. The minimum number of fields harvested was in Month 1, with 1 field harvested. All harvest operations were complete prior to the end of each harvest month. The last field completed harvest operations at 848.8 h, in the simulation model. Due to the limited size of the production area in Tour 6, the cumulative harvest demand was not met.

Table 5.2.6.1 Monthly Harvest Distribution Tour 6, Scenario 2

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#1-Jul	25.7	25.7	47	1.9	1
#2-Aug	180.1	154.4	148	6.0	3
#3-Sep	514.6	334.5	326	13.2	16
#4-Oct	1,054.9	540.3	604	24.4	30
#5-Nov	1,492.3	437.4	382	15.4	17
#6-Dec	1,826.8	334.5	347	1.4	15
#7-Jan	2,071.3	244.4	221	8.9	7
#8-Feb	2,315.7	244.4	250	10.1	11
#9-Mar	2,573.0	257.3	150	6.1	9

*Percent of total production area for this tour.

Table 5.2.6.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 6, Scenario 2. Approximately 55.2% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 21.7%, 12%, and 11.1% of the total harvest area, respectively.

Table 5.2.6.2 Baler Distribution per Field Tour 6, Scenario 2

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	61	78	1366	55.2
Two	12	97	16	538	21.7
Three	20	45	9	297	12.0
Four	17	61	6	274	11.1

5.2.7 Summary Scenario 2

Figure 5.2.7.1 displays the baler usage for Tour 1-6, in Scenario 2. Baler requirements follow a similar trend among all tours in Scenario 2. The latter portion of the harvest season, accounts for the majority of the allocated baler requirements in Scenario 2. The maximum number of balers required, for a full operational month was 23 balers (Tour 2, Month 7). As the figure shows, larger idle periods are observed in the early portion of the harvest season. This is indicated in Figure 5.2.7.1 when the baler usage drops to zero, towards the end of the harvest month. As the harvest season progresses, the lag times in between harvest months, when baler usage drops to zero is minimal. Tours 2, 3 and 4, harvest a greater percentage of biomass in Month 2, in comparison to Tours 1, 5, and 6. This was determined to be the result of a signal error in the simulation model.

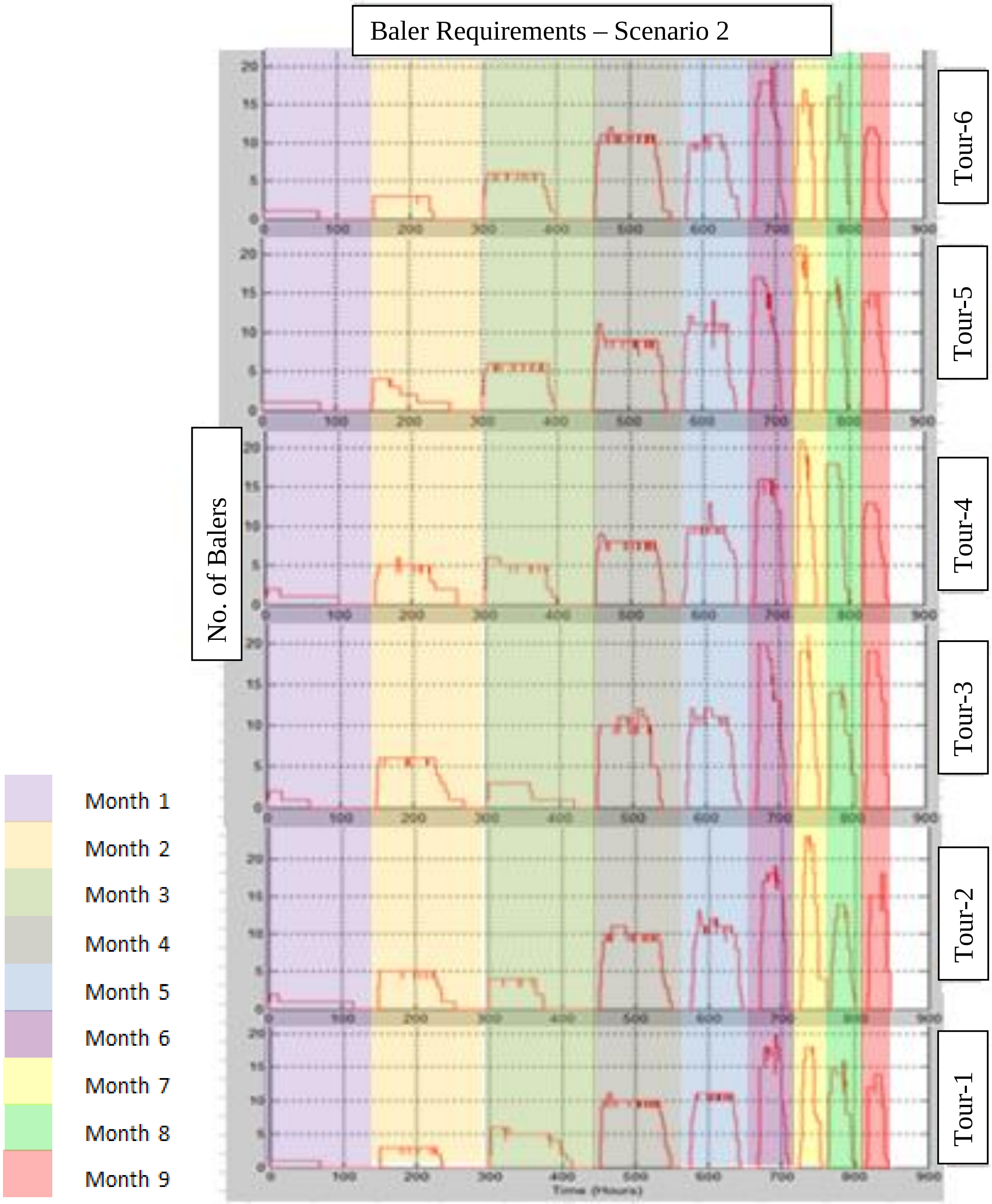

Figure 5.2.7.1 Baler Usage, Scenario 2

Table 5.2.7.1 shows the occurrence of additional balers per field, in Scenario 2. Due to the limited number of harvest operations that take place in the earlier portion of the harvest season, as confirmed in Figure 5.2.7.1, combined with the larger PWD, the number of additional balers required in Months 1, 2, and 3 are very limited. The data presented in Table 5.2.7.1 follows a similar trend to the baler requirements featured in Figure 5.2.7.1, showing a peak in the winter months and then gradually declining towards the end of the harvest season.

Table 5.2.7.1 Number of Fields Requiring Additional Balers, Scenario 2

	Month								
	#1 - Jul	#2 – Aug	#3 - Sept	#4 - Oct	#5 - Nov	#6 - Dec	#7 - Jan	#8 - Feb	#9 - Mar
Tour 1	0	0	2	2	0	9	6	5	4
Tour 2	0	1	1	1	4	7	8	5	9
Tour 3	0	0	0	4	3	6	7	5	5
Tour 4	0	1	1	2	2	8	7	6	3
Tour 5	0	0	0	1	5	6	12	6	6
Tour 6	0	1	0	1	4	9	6	7	3

Table 5.2.7.2 presents the monthly utilization rates of balers for Tours 1- 6, in Scenario 2. Overall, the maximum baler utilization rate was 66.4% (Month 4, Tour 5), and the minimum utilization rate was 24.8% (Month 1, Tour 3). Across all six tours, the maximum utilization rates for Months 1 through 9 were 49.6%, 52.4%, 57.1%, 66.4%, 66.2%, 59%, 51.2%, 57.4%, and 50.9%, respectively. As expected, utilization rates in Scenario 2, were found to be, on average, the greatest during the winter months of the harvest season. In particular, Months 4 and 5 were found to have the highest utilization rates. This corresponds to the time in the harvest season when the largest amounts of biomass are harvested. Across all tours in Scenario 2, the highest utilization rate was 66.4% (Tour 6, Month 4). Tour 6 harvested the largest amount of biomass, across the largest number of fields, and had the lowest average field size across all tours during Month 4. Additional balers were only required on 1 field. The lowest average baler utilization rate observed across all tours in Scenario 2 was in 24.8% (Month 1, Tour 3). Tour 3 was allocated a baler to each of the two fields harvested during this month. Due to the small amount of biomass harvested, baler utilization was low.

Because of the decline in the PWDs, in Month 5, Tour 1 was the only instance when additional balers were not required on any fields. Tour 1 harvested the smallest average field size (14 ha), and the largest number of fields (30), across all tours during Month 5.

Table 5.2.7.2 Monthly Utilization Summary, Scenario 2

	Month								
	#1 - Jul	#2 – Aug	#3 - Sept	#4 - Oct	#5 - Nov	#6 - Dec	#7 - Jan	#8 - Feb	#9 - Mar
Tour 1	45.4	40.6	57.1	61.0	61.7	49.7	48.0	50.5	43.6
Tour 2	42.2	47.7	30.8	65.8	58.0	51.5	48.2	46.6	44.5
Tour 3	24.8	52.4	52.7	56.9	63.2	49.2	51.2	57.4	47.9
Tour 4	39.0	50.1	50.5	58.6	56.0	59.0	45.9	46.5	50.9
Tour 5	52.7	30.8	51.8	63.4	63.6	54.7	46.5	49.0	54.0
Tour 6	49.6	52.0	49.1	66.4	56.0	49.0	50.2	50.5	40.4

Table 5.2.7.3 indicates the accumulated harvest percentage, per tour, in the 9-month harvest season. The “% Har” column indicates the percentage of the total harvested amount per tour in each of the harvest months. The “% Sto” column indicates the accumulated harvested biomass entering storage in each of the harvest months. The differences observed in the harvested amount, across the 6 tours, are a result of the variations in field size. However, a larger percentage of harvest is accumulated in Months 1 and 2, for Tours 2, 3, and 4. This is due to a signal error present in the simulation model. In Scenario 1, the accumulated harvest is approximately 20% of the total harvest per tour in Month 3 (September). The SSL accumulates 100% of the total harvested amount per tour in Month 9 (March).

Table 5.2.7.3 Accumulated Harvest in Storage, Scenario 2

	Tour											
	1		2		3		4		5		6	
	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto
#1-Jul	1.7	1.7	3.1	3.1	1.8	1.8	2.9	2.9	1.9	1.9	1.9	1.9
#2-Aug	6.1	7.8	10.5	13.6	13.3	15.1	11.2	14.1	5.7	7.6	6.0	7.9
#3-Sep	12.9	20.7	6.8	20.4	5.7	20.8	11.2	25.3	13.3	20.9	13.2	21.1
#4-Oct	22.1	42.8	21.2	41.6	19.7	40.5	17.4	42.7	20.5	41.4	24.4	45.5
#5-Nov	16.8	59.6	16.6	58.2	16.4	56.9	16.2	58.9	16.8	58.2	15.4	60.9
#6-Dec	14.0	73.6	13.4	71.6	13.3	70.2	13.1	72.0	12.8	71.0	1.4	74.9
#7-Jan	8.9	82.5	11.1	82.7	9.6	79.8	9.8	81.8	9.8	80.8	8.9	83.8
#8-Feb	9.9	92.4	7.8	90.5	9.5	89.3	10.1	91.9	9.4	90.2	10.1	93.9
#9-Mar	7.5	100.0	9.6	100.0	10.7	100.0	8.0	100.0	9.7	100.0	6.1	100.0

5.3 Round Bale Scenario-3

5.3.1 Tour 1-Scenario 3

Table 5.3.1.1 displays the monthly harvest distribution in Tour 1, Scenario 3. Harvest in Months 1, 2, and 3 do not occur, and 47.4% of the production area is harvested in Month 4. The minimum total area harvested is in Month 6, harvesting approximately 18.7% of the total production area in Tour 1. The largest number of fields are harvested in Month 4, with 53 fields harvested. The minimum number of fields harvested was in Month 6, with 20 fields harvested. All harvest operations were complete prior to the end of each harvest month. For Scenario 3, this indicated all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 709.9 h, in the simulation model. Due to the limited size of the production area in Tour 1, the cumulative harvest demand was not met.

Table 5.3.1.1 Monthly Harvest Distribution Tour 1, Scenario 3

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#4-Oct	1,183.6	1,183.6	1,191	47.4	53
#5-Nov	2,006.9	823.4	851	33.9	42
#6-Dec	257	566.1	471	18.7	20

*Percent of total production area for this tour.

Table 5.3.1.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 1, Scenario 3. Approximately 55.4% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 14.5%, 14.7%, and 15.4% of the total harvest area, respectively.

Table 5.3.1.2 Baler Distribution per Field Tour 1, Scenario 3

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	48	91	1,392	55.4
Two	12	77	11	365	14.5
Three	25	76	7	369	14.7
Four	33	153	6	387	15.4

5.3.2 Tour 2-Scenario 3

Table 5.3.2.1 displays the monthly harvest distribution in Tour 2, Scenario 3. Harvest in Months 1, 2, and 3 do not occur, 45.9% of the production area is harvested in Month 4. The minimum total area harvested is in Month 6, harvesting approximately 22.3% of the total production area in Tour 2. The largest number of fields are harvested in Month 4, with 52 fields harvested. The minimum number of fields harvested was in Month 6, with 25 fields harvested. All harvest operations were complete prior to the end of each harvest month. For Scenario 3, this indicated all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 712.2 h, in the simulation model. Due to the large size of the production area in Tour 2, the cumulative harvest demand was exceeded.

Table 5.3.2.1 Monthly Harvest Distribution Tour 2, Scenario 3

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#4-Oct	1,183.6	1,183.6	1,188	45.9	52
#5-Nov	2,006.9	823.4	823	31.8	41
#6-Dec	257	566.1	576	22.3	25

*Percent of total production area for this tour.

Table 5.2.3.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 2, Scenario 3. Approximately 42.9% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 32.6%, 12.3%, and 8.7% of the total harvest area, respectively.

Table 5.3.2.2 Baler Distribution per Field Tour 2, Scenario 3

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	55	78	1,109	42.9
Two	11	83	30	937	36.2
Three	22	71	7	317	12.3
Four	52	86	3	224	8.7

5.3.3 Tour 3-Scenario 3

Table 5.3.3.1 displays the monthly harvest distribution in Tour 3, Scenario 3. Harvest in Months 1, 2, and 3 do not occur, 45.7% of the production area is harvested in Month 4. The minimum total area harvested is in Month 6, harvesting approximately 21.4% of the total production area in Tour 3. The largest number of fields are harvested in Month 4, with 40 fields harvested. The minimum number of fields harvested was in Month 6, with 17 fields harvested. All but one field achieved harvest operations prior to the end of the harvest month. For Scenario 3, this would indicate all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 717.2 h, in the simulation model. Due to the large size of the production area in Tour 3, the cumulative harvest demand was exceeded with the harvest of the last remaining field.

Table 5.3.3.1 Monthly Harvest Distribution Tour 3, Scenario 3

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#4-Oct	1,183.6	1,183.6	1,199	45.7	40
#5-Nov	2,006.9	823.4	863	32.9	44
#6-Dec	257	566.1	563	21.4	17

*Percent of total production area for this tour.

Table 5.2.3.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 3, Scenario 3. Approximately 46.7% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 20.5%, 13%, and 19.8% of the total harvest area, respectively.

Table 5.3.3.2 Baler Distribution per Field Tour 3, Scenario 3

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	60	70	1,227	46.7
Two	16	75	13	538	20.5
Three	15	66	9	340	13.0
Four	30	88	9	520	19.8

5.3.4 Tour 4-Scenario 3

Table 5.3.4.1 displays the monthly harvest distribution in Tour 4, Scenario 3. Harvest in Months 1, 2, and 3 do not occur, 46.4% of the production area is harvested in Month 4. The minimum total area harvested is in Month 6, harvesting approximately 20.9% of the total production area in Tour 4. The largest number of fields are harvested in Month 4, with 53 fields harvested. The minimum number of fields harvested was in Month 6, with 15 fields harvested. All but one field achieved harvest operations prior to the end of the harvest month. For Scenario 3, this would indicate all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 716.9 h, in the simulation model. Due to the limited size of the production area in Tour 4, the cumulative harvest demand was not met.

Table 5.3.4.1 Monthly Harvest Distribution Tour 4, Scenario 3

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#4-Oct	1,183.6	1,183.58	1,184	46.4	53
#5-Nov	2,006.9	823.36	834	32.7	43
#6-Dec	257	566.06	534	20.9	15

*Percent of total production area for this tour.

Table 5.3.4.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 4, Scenario 3. Approximately 44% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 25%, 4.8%, and 26.2% of the total harvest area, respectively.

Table 5.3.4.2 Baler Distribution per Field Tour 4, Scenario 3

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	48	82	1,123	44.0
Two	11	95	18	639	25.0
Three	20	102	2	122	4.8
Four	48	156	9	668	26.2

5.3.5 Tour 5-Scenario 3

Table 5.3.5.1 displays the monthly harvest distribution in Tour 5, Scenario 3. Harvest in Months 1, 2, and 3 do not occur, 46.2% of the production area is harvested in Month 4. The minimum total area harvested is in Month 6, harvesting approximately 22.2% of the total production area in Tour 5. The largest number of fields are harvested in Month 4, with 55 fields harvested. The minimum number of fields harvested was in Month 6, with 26 fields harvested. All harvest operations were complete prior to the end of each harvest month. For Scenario 3, this indicated all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 713.3 h, in the simulation model. Due to the large size of the production area in Tour 5, the cumulative harvest demand was exceeded.

Table 5.3.5.1 Monthly Harvest Distribution Tour 5, Scenario 3

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#4-Oct	1,183.6	1,183.6	1,191	46.2	55
#5-Nov	2,006.9	823.4	816	31.6	46
#6-Dec	257	566.1	572	22.2	26

*Percent of total production area for this tour.

Table 5.3.5.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 5, Scenario 3. Approximately 55% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 25.6%, 7%, and 12.4% of the total harvest area, respectively.

Table 5.3.5.2 Baler Distribution per Field Tour 5, Scenario 3

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	54	96	1,419	55.0
Two	9	67	21	660	25.6
Three	15	104	4	180	7.0
Four	29	105	5	320	12.4

5.3.6 Tour 6-Scenario 3

Table 5.3.6.1 displays the monthly harvest distribution in Tour 6, Scenario 3. Harvest in Months 1, 2, and 3 do not occur, 49.5% of the production area is harvested in Month 4. The minimum total area harvested is in Month 6, harvesting approximately 17.8% of the total production area in Tour 5. The largest number of fields are harvested in Month 4, with 53 fields harvested. The minimum number of fields harvested was in Month 6, with 22 fields harvested. All harvest operations were complete prior to the end of each harvest month. For Scenario 3, this indicated all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 713.2 h, in the simulation model. Due to the limited size of the production area in Tour 6, the cumulative harvest demand was not met.

Table 5.3.6.1 Monthly Harvest Distribution Tour 6, Scenario 3

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#4-Oct	1,183.6	1,183.6	1,226	49.5	53
#5-Nov	2,006.9	823.4	808	32.6	34
#6-Dec	257	566.1	441	17.8	22

*Percent of total production area for this tour.

Table 5.3.6.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 6, Scenario 3. Approximately 51% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 35.3%, 10.2%, and 3.6% of the total harvest area, respectively.

Table 5.3.6.2 Baler Distribution per Field Tour 6, Scenario 3

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	47	77	1,262	51.0
Two	9	97	25	873	35.3
Three	35	79	5	253	10.2
Four	34	54	2	88	3.6

5.3.7 Summary Scenario 3

Figure 5.3.7.1 displays the baler usage for Tour 1-6, in Scenario 3. Baler requirements display a consistent trend among all tours in Scenario 3. In general, approximately the same quantities of biomass are harvested each month. This contributes to the large consistency between the tours. Baler requirements increase slightly in latter portion of the harvest season. The maximum number of balers required, for a full operational month was 35 balers (Tour 2, Month 6). As the figure indicates, idle time of the balers is nearly nonexistent. Balers are engaged in harvest the until the end of the harvest month. The greatest baler requirements are observed in Month 6. This is expected, as the time to complete harvest operations is further limited by the reduced PWD. In general, the number of balers are fairly consistent throughout the harvest period; slight variations are observed in the cumulative month of harvest.

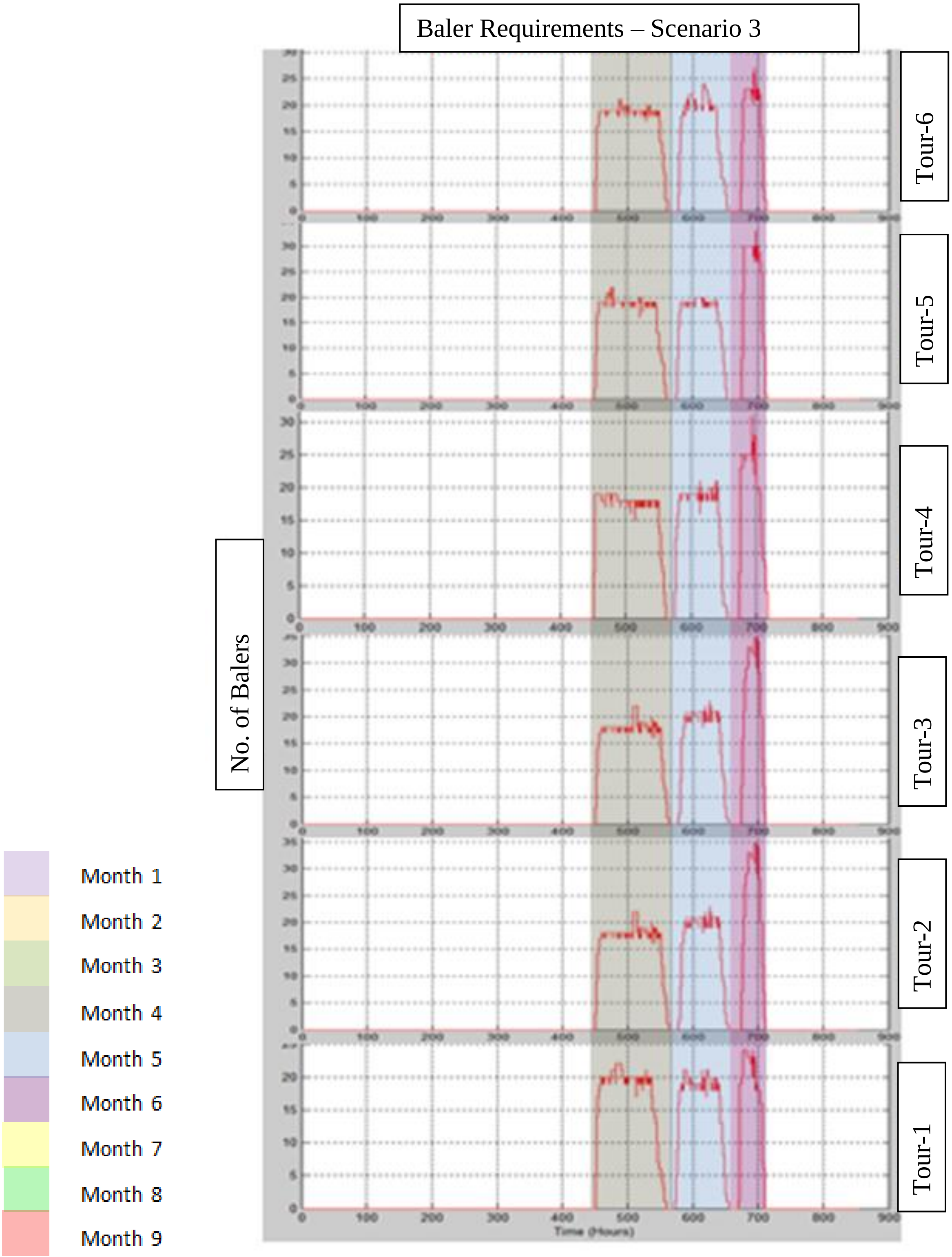

Figure 5.3.7.1 Baler Usage, Scenario 3

Table 5.3.7.1 shows the additional balers required per field in Scenario 3. The table indicates significant increases in the number of additional balers present in the system. Due to the limited harvest window (Months 4-6), the large amounts of biomass harvested, combined with the reduced PWD, additional balers are required across all tours and months, in Scenario 3. In general, the number of fields requiring an additional baler increased as the harvest season progressed. Month 6, Tours 2 and 5 have the maximum number of fields requiring additional balers (17 fields). Tour 2 corresponds to the lowest utilization rate for Month 6.

Table 5.3.7.1 Number of Fields Requiring Additional Balers, Scenario 3

	Month		
	#4 - Oct	#5 - Nov	#6 - Dec
Tour 1	5	10	9
Tour 2	11	12	17
Tour 3	12	8	11
Tour 4	6	11	12
Tour 5	4	9	17
Tour 6	7	11	14

Table 5.3.7.2 presents the monthly baler utilization rates for Tours 1-6, in Scenario 3. Overall, the maximum baler utilization rate was 86.7% (Month 4, Tour 4), and the minimum utilization rate was 46.5% (Month 6, Tour 2). Across all six tours, the maximum utilization rates for Month 4, 5, and 6, were 86.7%, 71.7%, and 63.3%, respectively. In general, there were slight variations in the utilization rates between Tours 1-6 in each month. Utilization rates on average were found to be the greatest during Month 4 of the harvest season. In Scenario 3, this time corresponds to an increased PWD, as compared to Months 5 and 6. Across all tours, in Scenario 3, the highest utilization rate was 86.7% (Month 4, Tour 4). Tour 4 harvested the least amount of biomass, and used the minimum number of balers during Month 4. The minimum utilization rate, displayed in Tour 2, Month 6, harvested the largest amount of biomass, and used the maximum number of balers. Month 6 also corresponded to the maximum number of fields requiring additional balers. No obvious trends, corresponding to average field size, average harvest time, etc., were observed in Scenario 3. This is likely the result of the large quantities of biomass harvested.

Table 5.3.7.2 Monthly Utilization Summary, Scenario 3

	Month		
	#4 - Oct	#5 - Nov	#6 - Dec
Tour 1	71.4	71.3	55.5
Tour 2	71.2	65.8	46.5
Tour 3	71.9	66.0	49.7
Tour 4	86.7	69.8	53.9
Tour 5	71.4	71.7	53.9
Tour 6	77.0	59.2	63.3

Table 5.3.7.3 indicates the accumulated harvest percentage, per tour, in the 3-month harvest season. The "% Har" column indicates the percentage of the total harvested amount per tour in each of the harvest months. The "% Sto" column indicates the accumulated harvested biomass entering storage in each of the harvest months. The harvest percentages, across the 6 tours, are very consistent. The minor differences observed are a result of the variations in field size. In Scenario 3, the accumulated harvest is approximately 50% of the total harvested amount in Month 4 (October). The SSL accumulates 100% of the total harvested amount per tour in Month 6 (December).

Table 5.3.7.3 Accumulated Harvest in Storage, Scenario 3

	Tour											
	1		2		3		4		5		6	
	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto
#4-Oct	47.4	47.4	45.9	45.9	45.7	45.7	46.4	46.4	46.2	46.2	49.5	49.5
#5-Nov	33.9	81.3	31.8	77.7	32.9	78.6	32.7	79.1	31.6	77.8	32.6	82.1
#6-Dec	18.7	100.0	22.3	100.0	21.4	100.0	20.9	100.0	22.2	100.0	17.8	100.0

5.4 Round Bale Scenario-4

5.4.1 Tour 1-Scenario 4

Table 5.4.1.1 displays the monthly harvest distribution in Tour 1, Scenario 4. Harvest in Months 1, 2, 3 and 4 do not occur; 55.3% of the production area is harvested in Months 5 and 6. Month 5 consists of the greatest percentage of the total production area harvested in Tour 1. The minimum total area harvested is in Month 9, harvesting approximately 12.6% of the total production area in Tour 1. The largest number of fields are harvested in Month 6, with 39 fields harvested. The minimum number of fields harvested was in Month 9, with 13 fields harvested. All harvest operations were complete prior to the end of each harvest month. For Scenario 4, this indicated all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 846.9 h, in the simulation model. Due to the limited size of the production area in Tour 1, the cumulative harvest demand was not met.

Table 5.4.1.1 Monthly Harvest Distribution Tour 1, Scenario 4

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#5-Nov	797.6	797.6	808	32.2	28
#6-Dec	1,363.7	566.1	585	23.3	39
#7-Jan	1,749.6	386.0	423	16.8	19
#8-Feb	2,109.9	360.2	380	15.1	16
#9-Mar	2,573.0	463.1	317	12.6	13

*Percent of total production area for this tour.

Table 5.4.1.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 1, Scenario 4. Approximately 39.7% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 16.6%, 11.3%, and 32.4% of the total harvest area, respectively.

Table 5.4.1.2 Baler Distribution per Field Tour 1, Scenario 4

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	45	75	997	39.7
Two	12	48	18	418	16.6
Three	18	77	8	283	11.3
Four	25	153	14	815	32.4

5.4.2 Tour 2-Scenario 4

Table 5.4.2.1 displays the monthly harvest distribution in Tour 2, Scenario 4. Harvest in Months 1, 2, 3 and 4 do not occur; 52.7% of the production area is harvested in Months 5 and 6. Month 5 consists of the greatest percentage of the total production area harvested in Tour 2. The minimum total area harvested is in Month 8, harvesting approximately 14.3% of the total production area in Tour 2. The largest number of fields are harvested in Month 6 and 7, each with 32 fields harvested. The minimum number of fields harvested was in Month 8, with 16 fields harvested. All harvest operations were complete prior to the end of each harvest month. For Scenario 4, this indicated all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 852.4 h, in the simulation model. Due to the large size of the production area in Tour 2, the cumulative harvest demand was exceeded.

Table 5.4.2.1 Monthly Harvest Distribution Tour 2, Scenario 4

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#5-Nov	797.6	797.6	800	30.9	32
#6-Dec	1,363.7	566.1	566	21.9	32
#7-Jan	1,749.6	386.0	471	18.2	20
#8-Feb	2,109.9	360.2	380	14.7	16
#9-Mar	2,573.0	463.1	370	14.3	18

*Percent of total production area for this tour.

Table 5.4.2.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 2, Scenario 4. Approximately 20% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 37.1%, 17.7%, and 25.2% of the total harvest area, respectively.

Table 5.4.2.2 Baler Distribution per Field Tour 2, Scenario 4

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	28	53	519	20.0
Two	7	72	40	959	37.1
Three	14	83	12	458	17.7
Four	22	86	13	651	25.2

5.4.3 Tour 3-Scenario 4

Table 5.4.3.1 displays the monthly harvest distribution in Tour 3, Scenario 4. Harvest in Months 1, 2, 3 and 4 do not occur; 52.1% of the production area is harvested in Months 5 and 6. Month 5 consists of the greatest percentage of the total production area harvested in Tour 3. The minimum total area harvested is in Month 8, harvesting approximately 11.5% of the total production area in Tour 3. The largest number of fields are harvested in Month 6, with 28 fields harvested. The minimum number of fields harvested was in Month 9, with 15 fields harvested. All harvest operations were complete prior to the end of each harvest month. For Scenario 4, this indicated all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 855 h, in the simulation model. Due to the large size of the production area in Tour 3, the cumulative harvest demand was exceeded.

Table 5.4.3.1 Monthly Harvest Distribution Tour 3, Scenario 4

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#5-Nov	797.6	797.6	827	31.5	28
#6-Dec	1,363.7	566.1	543	20.7	20
#7-Jan	1,749.6	386.0	452	17.2	22
#8-Feb	2,109.9	360.2	301	11.5	16
#9-Mar	2,573.0	463.1	502	19.1	15

*Percent of total production area for this tour.

Table 5.4.3.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 3, Scenario 4. Approximately 22.9% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 31.3%, 10.1%, and 35.7% of the total harvest area, respectively.

Table 5.4.3.2 Baler Distribution per Field Tour 3, Scenario 4

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	43	46	602	22.9
Two	9	61	30	821	31.3
Three	17	75	7	264	10.1
Four	29	88	18	938	35.7

5.4.4 Tour 4-Scenario 4

Table 5.4.4.1 displays the monthly harvest distribution in Tour 4, Scenario 4. Harvest in Months 1, 2, 3 and 4 do not occur; 53.8% of the production area is harvested in Months 5 and 6. Month 5 consists of the greatest percentage of the total production area harvested in Tour 4. The minimum total area harvested is in Month 8, harvesting approximately 13.3% of the total production area in Tour 4. The largest number of fields are harvested in Month 6, with 35 fields harvested. The minimum number of fields harvested was in Month 9, with 12 fields harvested. All harvest operations were complete prior to the end of each harvest month. For Scenario 4, this indicated all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 848.5 h, in the simulation model. Due to the limited size of the production area in Tour 4, the cumulative harvest demand was not met.

Table 5.4.4.1 Monthly Harvest Distribution Tour 4, Scenario 4

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#5-Nov	797.6	797.6	826	32.4	29
#6-Dec	1,363.7	566.1	548	21.5	35
#7-Jan	1,749.6	386.0	436	17.1	21
#8-Feb	2,109.9	360.2	340	13.3	14
#9-Mar	2,573.0	463.1	402	15.8	12

*Percent of total production area for this tour.

Table 5.4.4.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 4, Scenario 4. Approximately 33.7% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 21.6%, 8.4%, and 36.2% of the total harvest area, respectively.

Table 5.4.4.2 Baler Distribution per Field Tour 4, Scenario 4

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	33	70	860	33.7
Two	8	62	23	552	21.6
Three	15	95	5	215	8.4
Four	24	156	13	925	36.2

5.4.5 Tour 5-Scenario 4

Table 5.4.5.1 displays the monthly harvest distribution in Tour 5, Scenario 4. Harvest in Months 1, 2, 3 and 4 do not occur; 54.4% of the production area is harvested in Months 5 and 6. Month 5 consists of the greatest percentage of the total production area harvested in Tour 5. The minimum total area harvested is in Month 8, harvesting approximately 11.9% of the total production area in Tour 5. The largest number of fields are harvested in Month 5, with 40 fields harvested. The minimum number of fields harvested was in Month 7, with 17 fields harvested. All harvest operations were complete prior to the end of each harvest month. For Scenario 4, this indicated all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 852.6 h, in the simulation model. Due to the large size of the production area in Tour 5, the cumulative harvest demand was exceeded.

Table 5.4.5.1 Monthly Harvest Distribution Tour 5, Scenario 4

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#5-Nov	797.6	797.6	834	32.3	40
#6-Dec	1,363.7	566.1	570	22.1	28
#7-Jan	1,749.6	386.0	402	15.6	17
#8-Feb	2,109.9	360.2	307	11.9	21
#9-Mar	2,573.0	463.1	466	18.1	20

*Percent of total production area for this tour.

Table 5.4.5.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 5, Scenario 4. Approximately 41.3% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 23.9%, 9.2%, and 25.6% of the total harvest area, respectively.

Table 5.4.5.2 Baler Distribution per Field Tour 5, Scenario 4

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	39	84	1066	41.3
Two	9	67	23	617	23.9
Three	15	53	7	237	9.2
Four	17	105	12	659	25.6

5.4.6 Tour 6-Scenario 4

Table 5.4.5.1 displays the monthly harvest distribution in Tour 6, Scenario 4. Harvest in Months 1, 2, 3 and 4 do not occur; 55.6% of the production area is harvested in Months 5 and 6. Month 5 consists of the greatest percentage of the total production area harvested in Tour 6. The minimum total area harvested is in Month 8, harvesting approximately 12.7% of the total production area in Tour 6. The largest number of fields are harvested in Month 5, with 35 fields harvested. The minimum number of fields harvested was in Month 8, with 11 fields harvested. All harvest operations were complete prior to the end of each harvest month. For Scenario 4, this indicated all fields were harvested prior to the end of the harvest period. The last field completed harvest operations at 851.2 h, in the simulation model. Due to the limited size of the production area in Tour 6, the cumulative harvest demand was not achieved.

Table 5.4.6.1 Monthly Harvest Distribution Tour 6, Scenario 4

Harvest Month	Cumulative Demand (ha)	Month Demand (ha)	Actual Harvest (ha)	% of Tour Area*	No. Field Harvest
#5-Nov	797.6	797.6	810	32.7	35
#6-Dec	1,363.7	566.1	567	22.9	27
#7-Jan	1,749.6	386.0	419	16.9	17
#8-Feb	2,109.9	360.2	314	12.7	11
#9-Mar	2,573.0	463.1	365	14.7	19

*Percent of total production area for this tour.

Table 5.4.6.2 identifies the distribution of production fields that were assigned a single, two, three or four balers per field, to execute harvest operations for Tour 6, Scenario 4. Approximately 31.4% of harvest operations were achieved using a single baler. Two, three, and four balers were required per field, for 26.4%, 14.9%, and 27.4% of the total harvest area, respectively.

Table 5.4.6.2 Baler Distribution per Field Tour 6, Scenario 4

No. of Balers per Field	Min Field Size (ha)	Max Field Size (ha)	No of Fields	Total Harvest (ha)	% of Total Harvest
Single	6	37	58	778	31.4
Two	10	61	26	653	26.4
Three	13	97	10	366	14.9
Four	21	79	15	678	27.4

5.4.7 Summary Scenario 4

Figure 5.4.7.1 displays the baler usage for Tour 1-6, in Scenario 4. Baler requirements display a similar across all tours in Scenario 4. In general, approximately the same quantities of biomass are harvested each month, with the exception of the final harvest month. Baler requirements peak at Month 7, and decline in the final two months of harvest. The maximum number of balers required, for a full operational month was 36 balers (Tour 2, Month 7). As the figure indicates, idle time of the balers is nearly nonexistent. Balers are engaged in harvest until the end of the harvest month. The greatest baler requirements are observed in Month 7. This is expected, as the time to complete harvest operations is further limited by the reduced PWD.

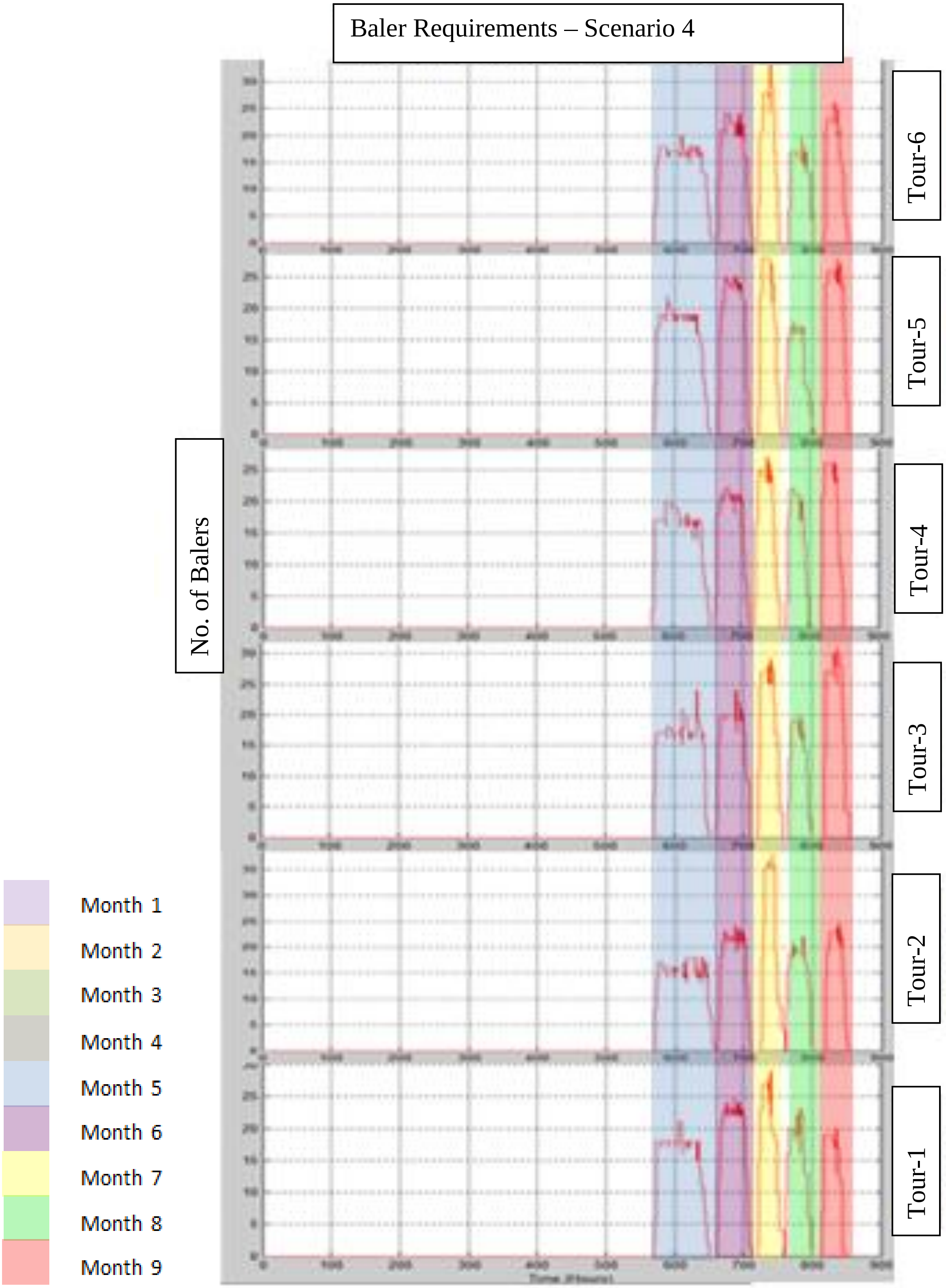

Figure 5.4.7.1 Baler Usage, Scenario 4

Table 5.4.7.1 shows the occurrence of additional balers per field, in Scenario 4. The table indicates significant increases in the number of additional balers present in the system; in particular, Month 7 has the largest number of additional baler occurrences. This is anticipated due to the large quantities of biomass harvested during this time in the harvest season, and the reduced number of PWDs available for harvest operations. Across all months, and tours in Scenario 4, Tour 2 has the maximum number of fields requiring additional balers.

Table 5.4.7.1 Number of Fields Requiring Additional Balers, Scenario 4

	Month				
	#5 - Nov	#6 - Dec	#7 - Jan	#8 - Feb	#9 - Mar
Tour 1	5	10	10	7	8
Tour 2	15	16	12	9	13
Tour 3	12	11	16	7	9
Tour 4	8	5	12	6	10
Tour 5	4	9	11	5	13
Tour 6	10	11	12	9	9

Table 5.4.7.2 presents the monthly utilization rates of balers for Tours 1-6, in Scenario 4. Overall, the maximum baler utilization rate was 78.1% (Month 5, Tour 2), and the minimum utilization rate was 45.3% (Month 9, Tour 6). Across all six tours, the maximum baler utilization rates for Months 5, 6, 7, 8, and 9 were 78.1%, 70.4%, 55.4%, 58.3%, and 55.7%, respectively. Utilization rates on average, in Scenario 4, were found to be the greatest during Months 5 and 6 of the harvest season. Across all tours, the highest utilization rate was 78.1% (Month 5, Tour 2). In Month 5, Tour 2 harvested the least amount of biomass, and used the minimum number of balers. Additionally, Tour 2 contained the maximum number of fields requiring additional balers. Tour 3 had the lowest monthly utilization rate in Month 5. In Month 5, Tour 3 harvested the second to the largest quantity of biomass, and used the maximum number of balers.

Table 5.4.7.2 Monthly Utilization Summary, Scenario 4

	Month				
	#5 - Nov	#6 - Dec	#7 - Jan	#8 - Feb	#9 - Mar
Tour 1	67.7	68.9	56.3	53.4	51.2
Tour 2	78.1	66.6	50.5	55.8	49.8
Tour 3	60.6	63.9	62.3	54.0	54.0
Tour 4	72.6	70.4	60.1	49.9	48.1
Tour 5	69.8	64.4	55.4	58.3	55.7
Tour 6	71.2	66.8	49.0	49.0	45.3

Table 5.4.7.3 indicates the accumulated harvest percentage, per tour, in the 5-month harvest season. The “% Har” column indicates the percentage of the total harvested amount per tour in each of the harvest months. The “% Sto” column indicates the accumulated harvested biomass entering storage in each of the harvest months. The harvest percentages, across the 6 tours, are very consistent. The minor differences observed are a result of the variations in field size. In Scenario 4, the accumulated harvest is approximately 50% of the total harvested amount in Month 6 (December). The SSL accumulates 100% of the total harvested amount per tour in Month 9 (March).

Table 5.4.7.3 Accumulated Harvest in Storage, Scenario 4

	Tour											
	1		2		3		4		5		6	
	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto	%Har	%Sto
#5-Nov	32.2	32.2	30.9	30.9	31.5	31.5	32.4	32.4	32.3	32.3	32.7	32.7
#6-Dec	23.3	55.5	21.9	52.8	20.7	52.2	21.5	53.9	22.1	54.4	22.9	55.6
#7-Jan	16.8	72.3	18.2	71.0	17.2	69.4	17.1	71.0	15.6	70.0	16.9	72.5
#8-Feb	15.1	87.4	14.7	85.7	11.5	80.9	13.3	84.3	11.9	81.9	12.7	85.2
#9-Mar	12.6	100.0	14.3	100.0	19.1	100.0	15.8	100.0	18.1	100.0	14.7	100.0

5.5 Summary Scenarios 1-4

The percentage of tour area harvested using a single baler, in Tours 1-6, across Scenarios 1-4, are displayed in Table 5.5.1. Scenario 1 had the maximum percentage of fields harvested using a single baler on the field. This corresponds to a decreased number of balers required for the total annual harvest. Recall harvest operations are distributed throughout the entire 9-month harvest period, and roughly half of the harvest operations take place when there are larger amounts of available time. Scenario 4 had the smallest percentage of fields using a single baler on the field. As displayed in the previous sections, the number of fields requiring an additional baler increased as the harvest season progressed, due to limited time to complete the harvest operations. The percentage of fields that required a single baler on the field was comparable in Scenarios 2 and 3. Although Scenario 2 operated for an entire 9-month harvest period, only 20% of the tour production area was harvested during the period of increased PWD. Overall, Tour 5, Scenario 1 had the largest percentage of fields using a single baler. This is likely a result of the smaller field size distribution in Tour 5. Tour 5 also had the largest percentage of fields using a single baler, across all tours in Scenario 4. Scenario 4, Tour 2 had the smallest percentage of fields using a single baler on the field.

Table 5.5.1 Percentage of Tour Area Harvested Using Single Baler, Scenarios 1-4

	Scenario			
	1	2	3	4
Tour 1	63.8	51.7	55.4	39.7
Tour 2	63.7	48.6	42.9	20.0
Tour 3	62.4	51.8	46.7	22.9
Tour 4	62.0	45.6	44.0	33.7
Tour 5	73.4	52.8	55.0	41.3
Tour 6	65.9	55.2	51.0	31.4

Table 5.5.2 displays the annual baler requirements, in Tours 1-6, Scenario 1-4. Regional annual baler requirements, ordered from smallest to largest, are as follows: Scenario 1, Scenario 2, Scenario 3, and Scenario 4. Scenario 1 required the least number of balers (77 balers), across all scenarios (i.e. Scenarios 1-4). While both Scenario 1 and Scenario 2 were both 9-month harvest

scenarios, Scenario 1 required 37.4% fewer regional annual balers than Scenario 2. Across all scenarios, Scenario 4 resulted in the greatest baler requirements (184 balers). Scenario 3 and Scenario 4 were the two reduced scenarios, with harvest taking place over 3 months, and 5 months, respectively. However, Scenario 3 required 4.9% fewer regional annual balers than Scenario 4. Across all tours in Scenario 1, the maximum number of balers is 14, in Tour 4. In Scenario 2, the maximum number of balers was 23 balers in Tour 2. In Scenario 3, the maximum number of balers was 35 balers in Tour 2. In Scenario 4, the maximum number of balers was 36 balers in Tour 2.

Table 5.5.2 Annual Baler Requirements, Scenarios 1-4

	Scenario			
	1	2	3	4
Tour 1	12	20	24	29
Tour 2	13	23	35	36
Tour 3	13	20	32	30
Tour 4	14	21	28	28
Tour 5	12	21	30	28
Tour 6	13	18	26	33
Total	77	123	175	184

Figure 5.5.1 displays the average baler utilization rates in Tours 1-6, Scenario 1-4. Across all tours, the maximum average baler utilization is achieved in Scenario 3. The second highest baler utilization is achieved in Scenario 4, across all tours. The lowest average baler utilization was in Scenario 2, for Tours 1, 2, 3, 4, and 5. In Tour 6, Scenario 1 resulted in the lowest average baler utilization rate.

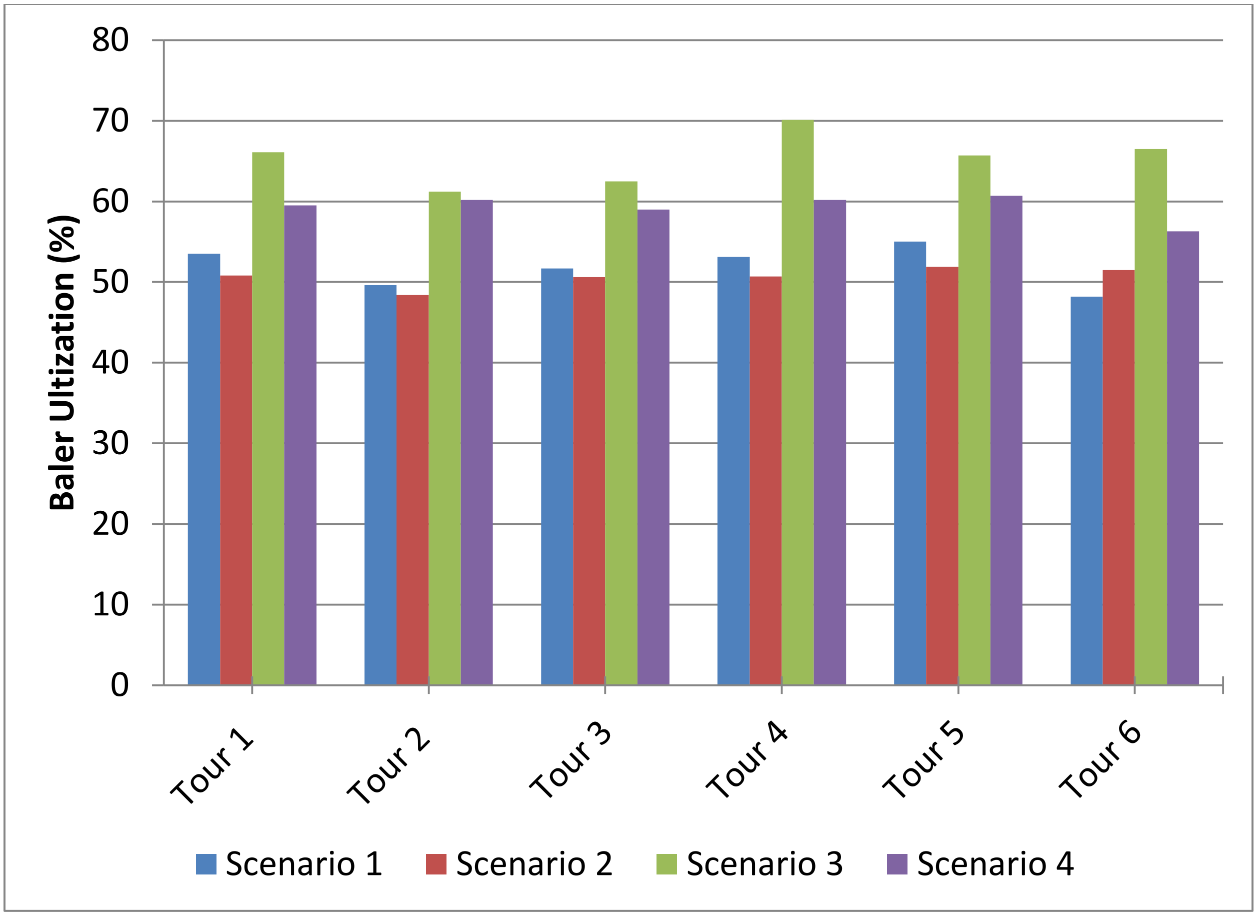

Figure 5.5.1 Average Baler Utilization, Scenarios 1-4

CHAPTER SIX

CONCLUSIONS

The simulation model developed in this study has shown to be an effective tool in estimating baler requirements for large-scale bioenergy production. The subsequent application of the model to a dataset representative of an existing region was found to further aid in the identification of several key considerations to address, prior to regional implementation.

The most interesting findings were the implications of field/baler scheduling for harvest. Field size, harvest time, harvest quantity, number of fields, and PWD were found to be critical in the management of harvest resources. It was concluded that a smaller number of larger field sizes, increased baler utilization rates towards the end of the harvest season, when PWD was greatly reduced. In general, harvesting large amounts of biomass from a larger number of smaller fields was determined to yield more favorable utilization rates when PWD was higher (i.e. earlier portion of the harvest season). However, the implications of field size, number of fields, and harvest time, in the earlier portion of the harvest season, was less critical. Direct trends in harvest parameters (i.e. field size, harvest time, harvest quantity, etc.) were not as obvious in the reduced harvest scenarios (i.e. Scenarios 3 and 4). It is undetermined whether this was a feature of the simulation model, or if there is a direct correlation between field size, harvest time, harvest quantity, and number of fields; as a result, additional studies are required.

Results from the analysis did not reveal any new insights on the implications of employing various harvest scenarios on the resource requirements; rather the analysis has confirmed many of the previously presented findings in literature. Consistent with Grisso et al. (2012), it was determined that the PWD has a significant impact of the resource requirements to fulfill harvest operations, and resource requirements were greatly reduced when harvest operations were extended throughout the 9-month harvest season, specifically in Scenario 1. Also consistent with Grisso et al. (2012), storage requirements were projected to be lower when harvest operations were extended throughout the harvest season. In Scenario 3, approximately 50% of harvest was completed in at the end of October, and 100% of total harvest was completed by the third month of harvest (i.e. December). Large quantities of biomass entered into the SSLs in a shorter period of time, and due to the reduced harvest season, round bales were projected to remain in storage for a longer period of time, when compared to the extended harvest scenarios. Although the scope of this study did not consider the removal of bales from the SSL, it is important to mention, that the only harvest scenario that would facilitate the removal of biomass from the storage facility, beginning in July, is Scenario 1. Recall no harvest took place in July for Scenarios 3 and 4. In July, for Scenario 2, due to the low quantity of biomass harvested, there would not be a sufficient quantity of biomass to achieve a full month's demand for removal.

In Scenario 1, over half of the harvest operations were executed in the earlier portion of the harvest season. Equipment requirements for Scenario 1 were found to be near constant throughout the harvest season, with slight increases as the available work hours (i.e. PWD) declined. The increase observed in the number of balers required (due to the additional balers required for harvest), while minimal, resulted in an overall increase in the annual number of balers required. Recall that Scenarios 1 and 2 were each 9-month harvest scenarios, and each scenario contained 855 available work hours (Section 3.2.2). When comparing Scenarios 1 and 2, Scenario 1 resulted in annual sub-regional balers reductions of 40%, 43.5%, 35%, 33.3%, 42.6%, and 27.8%, for Tours 1, 2, 3, 4, 5, and 6, respectively. When comparing the number of annual regional balers, Scenario 1 resulted in 37.4% fewer balers than in Scenario 2. This indicates that given the same available work hours, when approximately half of the harvest operations were executed in July-September (Scenario 1), as opposed to October-December, the quantity of biomass harvested following the decline in PWD significantly impacted the baler requirements.

Among the reduced harvest scenarios (i.e. Scenarios 3 and 4), the number of annual balers required for harvest operations showed significantly less variation than between the extended harvest scenarios (i.e. Scenarios 1 and 2). On the sub-regional level, when comparing Scenarios 3 and 4, Scenario 3 resulted in baler reductions of 17.2%, 2.8%, and 21.2%, for Tours 1, 2, and 6, respectively. Tours 3 and 5 resulted in baler increases of 6.3%, and 6.7%, respectively. Tour 4 baler requirements were the same in Scenarios 3 and 4. Although Scenario 3 had a shorter harvest window and less available work hours than in Scenario 4, Scenario 3 resulted in a 4.9%

reduction in the number of annual regional balers required. This was found to be the result of the increased quantity of harvest operations that took place following the decline in PWD.

The reduced harvest scenarios, when compared to the extended harvest scenarios, resulted in a significant increase in the number of annual balers required for harvest operations. Similar implications of the PWD were also observed when the extended harvest scenarios were compared to the reduced harvest scenarios. When comparing Scenarios 1 and 3, Scenario 1 resulted in annual sub-regional balers reductions of 50%, 62.6%, 59.4%, 50%, 60%, and 50%, for Tours 1, 2, 3, 4, 5, and 6, respectively. When comparing Scenarios 1 and 4, Scenario 1 resulted in annual sub-regional balers reductions of 58.6%, 63.9%, 56.7%, 50%, 57.1%, and 60.6%, for Tours 1, 2, 3, 4, 5, and 6, respectively. When comparing Scenarios 2 and 3, Scenario 2 resulted in annual sub-regional balers reductions of 16.7%, 34.3%, 37.5%, 25%, 30%, and 30.8%, for Tours 1, 2, 3, 4, 5, and 6, respectively. When comparing Scenarios 2 and 4, Scenario 2 resulted in annual sub-regional balers reductions of 31%, 36.1%, 33.3%, 25%, 25%, and 45.5%, for Tours 1, 2, 3, 4, 5, and 6, respectively. When comparing the number of annual regional balers, Scenario 1 resulted in 56% and 58.2% fewer balers, for Scenarios 3 and 4, respectively. When comparing the number of annual regional balers, Scenario 2 resulted in 29.7% and 33.2% fewer balers, for Scenarios 3 and 4, respectively. In general, the annual baler requirements increased as the harvest window decreased, across the harvest scenarios.

As expected, monthly baler utilization for the extended harvest scenarios were lower than baler utilization rates for the reduced harvest scenarios. The monthly baler utilizations in Scenario 2 contained the lowest utilization rates, except for in Tour 6. Recall, Tour 6 contained the smallest production area, which was believed to be a factor in the decreased utilization of Scenario 1. Scenario 1 resulted in the second lowest baler utilization rates. The decreased monthly baler utilization of the extended harvest scenarios were found to be the result of the following factors: the increased idle time of the baler in the extended harvest scenarios, the underutilization of the additional balers required for harvest, the reduced monthly harvest quantity, and reduced monthly baler operating hours. Balers utilized in the extended harvest scenarios, in particular during July-September, completed harvest activities prior to the end of the month, and remained idle during the remainder of the month. Following the decline of the PWD, the additional balers that were required for harvest, were underutilized. As a result, the baler operation hours were lower for the additional balers in the system. In general, the monthly baler operating hours were lower in the extended harvest scenarios, due the lower monthly harvest quantities. It should be noted, the large amounts of baler down time indicate the potential to reduce the number of balers and conduct harvest operations throughout the entire month.

The reduced Scenarios resulted in the highest monthly baler utilization rates. The increased baler utilization rates of the reduced harvest Scenarios were found to be the result of the following factors: the reduced idle time of the baler, the increased quantity of biomass harvested, and greater utilization of the additional balers required for harvest. In the reduced harvest Scenarios, due to the large quantities of biomass harvested and the reduced PWD, balers were engaged in harvest until the end of the harvest month; little to no idle time was observed in the reduced harvest Scenarios. In addition, the additional balers required for harvest were utilized more; again this was due to the increase quantity of biomass and the decline in the PWD. While both Scenarios required additional balers on the fields to complete harvest, because the monthly harvested quantity of biomass was much greater, the opportunity for the reuse of the additional balers was also greater. Baler utilization in Scenario 3 displayed the highest average monthly utilization rates, across all tours. The number of balers required for Scenario 3, throughout the harvest window (October-December), displayed the lowest variability. Sharp increases in the number of balers required to complete harvest throughout the harvest window was not observed in Scenario 3, as compared to the other harvest scenarios. This implies that the balers that were required for harvest were more frequently utilized, because the number of balers remained fairly constant throughout the harvest window. Baler utilizations in Scenario 4 overall contained the second highest utilization rates. It should be noted that while the reduced harvest scenarios resulted in higher monthly baler utilization rates, the individual baler utilization rates were expected to be greatly reduced. This is due to the fact that the balers that were required for harvest were utilized for a shorter period of time. In Scenarios 1 and 2, while unlikely, an individual baler has the potential to be utilized over a 9-month period (855 h). In Scenarios 3 and 4, the maximum available work hours are 266 and 285 h, respectively. It is not possible for an individual baler to reach the maximum baler utilization rate when considering the reduced harvest Scenarios.

Of the four Scenarios examined in the analysis, each displayed similar trends across the six Tours. Variations in the baler requirements that were observed among the Tours resulted from variability in field size distribution, field to baler allocations, and total production area. It was found that in the reduced harvest Scenarios (Scenarios 3 and 4), because the monthly harvested quantities were greater and the balers were used more throughout the harvest window, higher utilization rates were experienced. While obvious trends, in harvest time, number of fields harvested and average field size, which corresponded to either an increase or a decrease in utilization, were not observed with the reduced harvest Scenarios. The increased number of balers required for Tour 2, across Scenarios 3 and 4 suggest there may be a correlation; however, additional studies are recommended.

Conclusions on the best Scenario, among the four harvest Scenarios presented in this study were not determined. In fact, it is not fair to suggest one Scenario over another solely based on baler requirements, and baler utilization alone. The conclusion as to which harvest Scenario will be the most ideal, is likely to vary case by case. From the perspective of a landowner that has fewer obligations throughout the 9-month harvest season, in particular from July-September, and lower equipment investment funds, Scenario 1 may be ideal. From the perspective of the landowner that is engaged in other enterprises during the peak harvest season, Scenario 2 may be the most ideal harvest window. In such cases, if the landowner were to choose either Scenarios 1 or 2, the reduced monthly utilization has the potential to be offset by other harvest related activities the landowner participates in throughout the year. While Scenario 3 implies higher equipment investment cost and underutilized equipment (in terms of individual baler usage), all harvest operations are completed by the end of December, and harvest operations are completed prior to the sharp decline in PWD. Equipment investment cost were the highest for Scenario 4; however, this scenario may be ideal for a landowner that has additional obligations until November. It should also be noted, the selection of a harvest Scenario is also influenced by the end conversion, and other considerations that pertain to the needs of the biorefinery. As mentioned, storage aspects, and removal of biomass to supply the biorefinery is also a key consideration when selecting a harvest Scenario to employ.

CHAPTER SEVEN

FUTURE WORK

The FHS model is an initial attempt to quantify baler equipment requirements in a complex logistics network. The following recommendations are presented for future work.

- In the current model structure, the SSL Operation module and the Farmgate Operation module function as separate, independent operations. Additional work is required to quantify equipment requirements when the model accounts for the time of the in-field hauling operation.
- Additionally, the current model structure is only capable of simulating harvest operations for a single baler per field. While this was not found to cause significant impacts on the analysis results, for the purposes of this study, it is critical in future studies to provide estimates of the physical number of resources required to fulfill harvest operations.
- Removal of biomass from the SSL is a critical stage in the logistical operations to supply a biorefinery. In studies to follow, it would be useful to provide additional insight on the storage component of biomass. To date, this area has not been widely addressed in literature.
- To provide a more detailed view of the logistics system, and thus offer more accurate estimates, it will be useful to include delays (i.e. scheduled routine maintenance, equipment breakdowns, mobilization time, and field drying time), and variations in harvest parameters (e.g. field efficiency, yield, etc.) in later editions of the model.
- Lastly, results indicated potential areas of baler reductions. In future studies, it would be useful to enhance the capabilities of the model, such that the system will adjust the harvest parameters to balance the baler requirements.

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APPENDIX A

Table A1. Tour 1 Load-Out Sequence

	Tour 1 – Load-Out Sequence		
SSL	Sequence	No. of Fields	Size (ha)
236	1	7	145
8	2	6	101
7	3	6	290
245	4	4	87
260	5	3	132
267	6	5	89
292	7	6	84
283	8	5	40
265	9	10	209
307	10	9	120
321	11	4	44
355	12	9	133
21	13	4	99
361	14	9	218
25	15	4	96
375	16	8	194
409	17	4	81
418	18	5	169
429	19	3	79
367	20	2	42
28	21	1	61

Table A2. Tour 2 Load-Out Sequence

	Tour 2 – Load-Out Sequence		
SSL	Sequence	No. of Fields	Size (ha)
317	1	5	172
286	2	3	112
304	3	4	65
315	4	7	149
339	5	3	59
24	6	3	62
22	7	1	52
325	8	1	70
306	9	9	153
274	10	1	37
251	11	5	77
230	12	8	173
207	13	3	79
196	14	3	42
187	15	10	140
2	16	10	281
162	17	9	104
184	18	3	100
185	19	8	187
201	20	1	86
195	21	11	175
226	22	5	131
266	23	5	144

Table A3. Tour 3 Load-Out Sequence

	Tour 3 – Load-Out Sequence		
SSL	Sequence	No. of Fields	Size (ha)
250	1	4	82
238	2	5	103
259	3	2	69
235	4	3	81
210	5	7	266
160	6	4	65
143	7	5	225
179	8	3	117
203	9	4	68
192	10	7	199
205	11	1	35
220	12	3	60
168	13	2	36
147	14	5	88
150	15	2	38
116	16	2	49
134	17	3	41
95	18	4	45
122	19	4	105
125	20	6	162
156	21	6	54
119	22	7	161
109	23	4	62
157	24	5	216
177	25	5	242

Table A4. Tour 4 Load-Out Sequence

	Tour 4 – Load-Out Sequence		
SSL	Sequence	No. of Fields	Size (ha)
3	1	9	160
197	2	5	96
227	3	7	212
246	4	6	212
261	5	7	195
285	6	10	122
305	7	3	104
335	8	4	54
369	9	3	36
372	10	6	94
406	11	3	64
441	12	3	125
451	13	4	48
466	14	5	103
452	15	5	90
417	16	5	76
442	17	6	97
420	18	5	130
34	19	4	207
468	20	2	74
497	21	1	48
517	22	2	90
507	23	5	115

Table A5. Tour 5 Load-Out Sequence

	Tour 5 – Load-Out Sequence		
SSL	Sequence	No. of Fields	Size (ha)
521	1	4	141
506	2	3	68
475	3	7	118
503	4	7	102
473	5	4	46
448	6	4	79
426	7	9	165
423	8	5	169
400	9	8	156
392	10	6	176
333	11	10	133
278	12	7	246
319	13	5	51
350	14	3	44
368	15	4	111
390	16	2	33
354	17	5	78
329	18	3	53
366	19	4	38
297	20	6	106
14	21	3	58
290	22	6	124
256	23	3	30
225	24	5	145
217	25	3	109

Table A6. Tour 6 Load-Out Sequence

	Tour 6 – Load-Out Sequence		
SSL	Sequence	No. of Fields	Size (ha)
193	1	3	98
208	2	4	165
228	3	7	170
271	4	6	88
15	5	3	37
316	6	9	150
326	7	4	119
349	8	4	59
332	9	5	97
362	10	3	52
26	11	3	96
334	12	5	143
302	13	3	40
276	14	5	88
252	15	10	225
9	16	3	112
244	17	4	75
229	18	4	171
213	19	3	71
199	20	5	89
4	21	4	85
175	22	2	77
148	23	4	63
169	24	6	105