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Research paper

Optimized location of biomass bales stack for efficient logistics

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Producers often aggregate bales into stacks before transporting these bales to an outlet for consumption or delivery to industrial applications. Efficiency improvement in this infield bale logistics will be beneficial. To address this an R simulation program involving five methods for field stack location, namely field middle, middle data range, centroid, geometric median, and medoid, as well as origin (a direct aggregation method to outlet), were developed. These methods were evaluated against field areas, ranging from 0.5 to 520 ha, for infield bale logistics (aggregation, transport, and total) using Euclidean distances. The simulation used several input field variables, laid out bales based on yield variation, determined optimized bale stack locations of methods, and evaluated distances of aggregation to the stack, transport from the stack to the outlet, and total logistics. The origin method used 1-bale handling tractor for direct aggregation to the outlet, while others formed the bale stacks and transported bales to the outlet using 6-bales/trip equipment. Results indicated for aggregation that geometric median was the best, followed by field middle or centroid, middle data range, medoid, and finally origin. Methods aggregation were about 76% and transport about 24% of the total (for > 2 ha); and total distance were about 65% of the origin. ANOVA, excluding origin, indicated that all methods were not significantly different ($p < 0.05$) for the areas studied. The 'field middle' was recommended as an easy and practical method for locating field stacks. Fitted power models described well ($R^2 > 0.99$) all the logistics distances.

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1. Introduction

Infield logistics of collecting and moving biomass to a location suitable for further use represents a substantial field operation. Transport of biomass from the point of origin to the point of consumption was conceptually considered as a single logistics operation. However, a careful examination can reveal that the infield biomass logistics is a time-consuming operation involving several components. Biomass after harvest is usually made in a compacted form, such as bales and are initially left on the field. In a biomass supply chain, the compacted biomass (e.g., bales) has assumed to be transported to the final destination or grouped at a field edge or collected with self-loading wagons for off-site transport [1]. The aggregated bales are transported to a field outlet, such as a corner or edge of the field before moved to the point of final usage (e.g., biorefinery) or consumption (e.g., cattle feedlot). This logistics operation of land clearance for the next crop is essential for efficient crop production.

Producers often aggregate bales into several stacks in the field before transporting the bales to an outlet. The desire for forming bale stacks in the field is to utilize efficient multiple bale-hauling equipment from the stack to the outlet. Other motivations for the bale stacks formation that will lead to efficient logistics include (i) clearing the field for next crop, (ii) smoother mechanical crop management operations without bales hindrance, (iii) short window between harvest and next planting schedule, and (iv) field conditions may not allow for driving equipment. Thus, given the advantageous role of bale stacks in the infield bale logistics, it will be pertinent to investigate "where" to locate the bale stack so that the logistics will be efficient. Therefore, a study that focuses on the strategic location of the bale stacks, so that the bale aggregation and subsequent transport distances will be minimized, would improve the infield logistics efficiency.

Considering bales as points on a 2D plane, several mathematical grouping methods can be employed to simulate the aggregation of

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the bales into stacks. These methods of locating bale stack will lead to different locations in the field, based on their algorithm. Using these methods, the optimum bale stack location can be determined that gave the least aggregation or total distances, and the methods can be ranked based on these distances. Thus, it was hypothesized that the bale stack location methods will be significantly different from one another, from the viewpoint of infield logistics distances.

Several biomass logistics based studies addressing the biomass logistics in general, supply of biomass to the biorefinery, economics of biomass logistics, and patents related to bale forming and handling machinery were available. Studies involving biomass bale logistics include development of integrated biomass supply and logistics (IBSAL) model and its implementation for feedstock supply chain [2,3]; development of a MATLAB training tool on the timing and handling and storing round bales with a self-loading wagon [4]; biomass bales transport system based on cotton logistics as model and explored the difference and application [5]; herbaceous biomass bales transportation cost optimization [6]; large biomass modules logistics system to maximize legal highway loads and to minimize feedstock cost based on IBSAL [7]; hybrid genetic algorithm solution for the efficient bale collection routes with a 15- and 35-bales wagon [8]; and simulation of the bales layout mimicking the baler operation, and evaluation of several infield biomass bales aggregation strategies [9].

These studies demonstrate that biomass logistics simulation is a possible way to study the infield logistics and the various components of the supply chain from field to factory including the feedstock supply economics. However, literature on the infield bale logistics involving bale stacks were highly limited. Recently, a bale stack logistics study considered the bale collection logistics effect on the number of subfield bale stacks, locations of bale stack and field outlet, and the number of bales/trip in transport [10]. This study concluded that the best bale stacks location was the subfield middle compared to mid-edges or corners. Given the random layout of bales, it was expected that there could be better locations for the bale stack other than the field middle. Thus, in the present study, further exploration was performed around the field middle to obtain the optimum bale stack location. Several mathematical grouping strategies to obtain different bale stack locations using simulation, and the effect of field variables involved in the infield bale logistics with statistical analysis are proposed to be evaluated in this study.

The specific objectives of the study on the optimized bale stack location are: (i) simulate different bale aggregation methods that represent bale stack locations after simulating the layout of bales in the field from various field operation inputs; (ii) evaluate the aggregation, transport, and total infield bale logistics distances of different methods; (iii) determine the effect of area or number of bales on logistics distances and compare methods; and (iv) develop regression models for infield bale logistics distance as a function of area.

2. Materials and methods

2.1. Simulation of bales layout on field

In this study, the bale logistics simulation, data analysis, and data visualization codes were developed using the statistical analysis software R [11]. 'RStudio,' the integrated development environment that ran R, was used in this study. The bale layout algorithm [9], which mimicked the baling equipment actions of bale formation and layout on the field (Fig. 1A), was used in the simulation.

This algorithm simulated (1) collection of required quantity of biomass that go into the formation of a bale, (2) establishes the "collection length" of the windrow for a bale, (3) lays out the bale and records its coordinates, (4) continues the baling operation after turning at the field edge and keeps accumulating the biomass in the collection length for the next bale, (5) variation of biomass yield through variation factor limit, and random number generation within this limit, and (6) accounted for various input factors, such as field area, length/width ratio, swath of harvester, biomass yield, yield variation, and bale mass. The output of this algorithm will be the total number of bales and their coordinate locations (x_i, y_i) on the field. This Java-based algorithm was re-coded in R to simulate the bales layout on the field, along with simulation of different bale stack location methods.

2.2. Bales stack formation and transport

Once the bales layout was generated based on the various inputs to simulate different crops and field sizes, the bales need to be aggregated into field stacks. This bale stack formation makes the movement of bales from the stack to the outlet more efficient during transport. This was because the aggregation can handle only a few bales ($\leq$3) using a bale loader (tractor attached to bale grapple or spear) compared to wagons/trucks that can handle multiple bales ($\leq$32) during transport. In this study, it was assumed that 1 bale was handled in aggregation (e.g., tractor with grapple) and 6 bales in transport (e.g., open trailer) to represent the most basic equipment available in the field. It was also recognized that with the latest equipment, it was possible to handle multiple bales during aggregation (e.g., advanced automatic bale picker) and increase the number of bales ($\geq$6) during transport. The lower left corner (origin) of the field was assumed to serve as the outlet. It was also assumed that the distances involved in aggregation and transport were obtained through linear distance connecting the bales and the stack location coordinates, and that between the stack and the outlet, respectively.

2.3. Process simulation and parameters considered

The processes involved in determining the efficient location of bale stack from the bales layout along with analysis and visualization in the developed program are presented in the form of a flowchart (Fig. 1B). Several inputs can be varied to accommodate different scenarios to be studied. Areas representing actual field areas in the form of fractional parcels of a "section" of land (259 ha) were considered. Thus, for the purpose of primary analysis, the areas in hectares used in the simulation were 0.41, 0.51, 1.01, 2.02, 4.05, 8.09, 16.19, 32.38, 64.75, 129.5, and 259 ha. Furthermore, several areas at finer intervals (2 ha) from 0.5 to 520 ha were used in the statistical analysis. The other parameter considered in the simulation study were: length by width ratio of 1.0; biomass yield per hectare of 5 Mg/ha; harvester swath of 6 m; bale mass of 600 kg; percentage variation of biomass yield of 5%, 7%, and 10%; number of bales moved during aggregation/trip was 1; and number of bales moved during transport/trip was 6; and the random seed arbitrarily chosen and used for random number generation in R that was 2015. Three simulated replications are derived from the biomass yield percentage variation (5%–10%).

2.4. Optimum bale stack location methodologies

Optimum location is the most favorable spot on the field for stacking the bales so that the total aggregation distance is the least. Many bale grouping/clustering (aggregation) methods based on mathematical techniques of grouping points that are distributed on a two-dimensional plane were considered. These geometrical points used in the grouping were replaced by the layout of bales